National Aeronautics and Space Administration

Science Program for NASA's Astronomy and Physics Division

2006

Every sentence

I utter must be

understood not

as an affirmation,

but as a question.

—Niels Bohr

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Executive Summary

Science is now poised to answer some of humanity's deepest questions, such as how the universe came into being, how it formed the galaxies, stars, and planets that set the stage for life, and whether there is life on other worlds. The scientific pursuit of our origin, evolution, and destiny requires deep and detailed explorations into space and time, challenging the limits of America's technical capabilities in space. In this document, the Astronomy and Physics Division of NASA's Science Mission Directorate articulates a long-term plan for scientific exploration of the universe and the search for life beyond the solar system.

The Beyond Einstein program explores the ultimate extremes of nature: the birth of the universe, the edges of space and time near black holes, and the darkest and emptiest space between the galaxies. The cornerstone missions are the Laser Interferometer Space Antenna (LISA), the first antenna in space to measure spacetime ripples called gravitational waves; and Constellation-X (Con-X), a path-breaking X-ray telescope that can study matter near black holes. A focused line of more specialized Einstein Probe missions is dedicated to specific studies of black hole discovery, the cosmic inflation that powered the Big Bang, and the dark energy propelling the cosmic expansion today. Forward-looking technology development, as well as foundational and exploratory studies in theory, modeling, and predictive simulation, aim ultimately toward two Vision Missions: the Big Bang Observer, an ultrasensitive gravitational-wave observatory; and the Black Hole Imager, an X-ray interferometer.

The simple Big Bang eventually creates a rich structure, giving rise to galaxies, stars, and planets — a global history that can be traced by direct observations of distant space. The Wilkinson Microwave Anisotropy Probe (WMAP) all-sky images of the primordial background radiation show the faint vibrations in matter and light half a million years after the Big Bang; the more advanced ESA–NASA Planck Surveyor mission, and ultimately the Inflation Probe, will measure them in exquisite detail. The weak ripples in gas and dark matter later create the first stars, quasars powered by supermassive black holes, and finally the great cosmic web of galaxies like our own Milky Way. The formation and early evolution of these systems will be explored by large infrared telescopes built on the historic legacy of the Hubble Space Telescope — the airborne Stratospheric Observatory for Infrared Astronomy (SOFIA), the James Webb Space Telescope (JWST), and the Single-Aperture Far-Infrared (SAFIR) telescope — as well as Con-X, LISA, and the Einstein Probes.

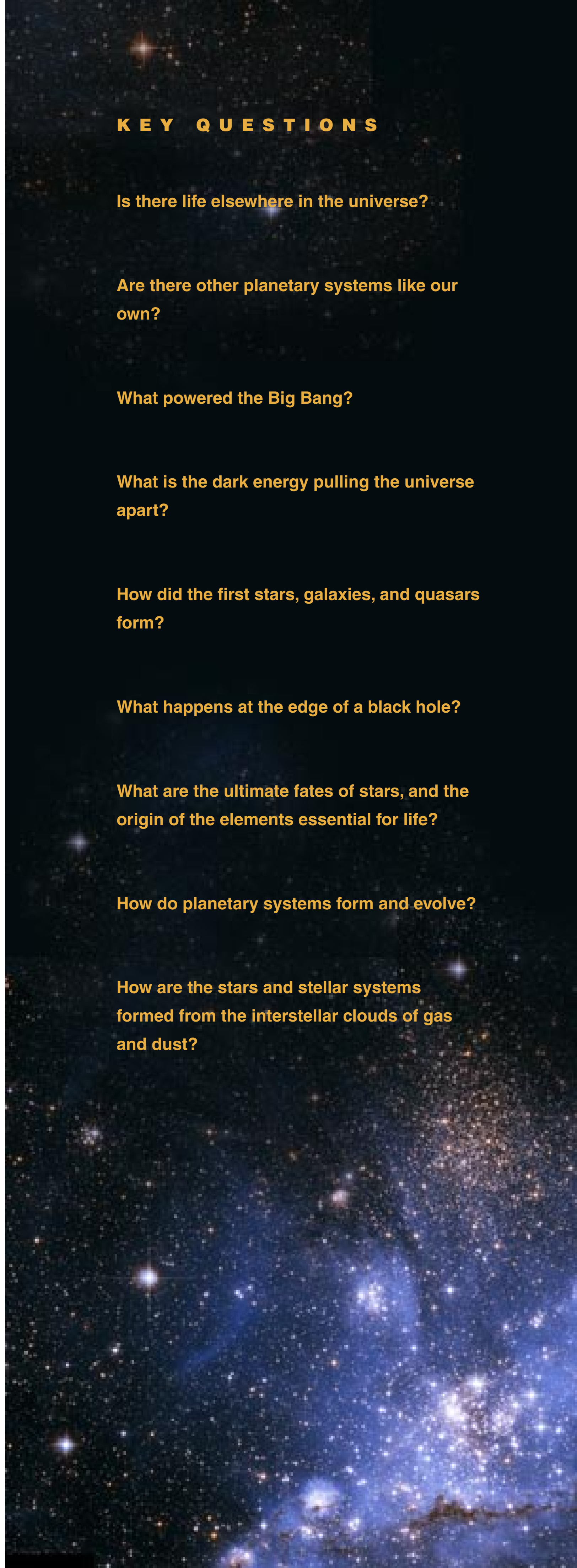
As the universe evolves to the present day, stars play increasingly dominant roles in the evolution of matter and complex structure. They are the sources of the energy, light, and chemical elements that drive the cosmic cycling of matter into new generations of stars, planets, and eventually life. Ground-based interferometers and new missions, such as SOFIA, the Wide-field Infrared Survey Explorer (WISE) telescope, the Gamma-ray Large-Area Space Telescope (GLAST), the Space Interferometry Mission (SIM PlanetQuest), JWST, Con-X, LISA, and SAFIR will study the dramatic lives of the stars from birth, to spectacular death, and then again to rebirth. The births of stars accompany the formation of new planets; studies with SOFIA, SIM PlanetQuest, JWST, and SAFIR will unravel the details of planet formation around young stars.

To find out whether life exists elsewhere, and ultimately discover whether we are alone in the universe, the Navigator program aims to study habitable environments and signs of life on Earth-like planets near other suns. These new worlds beyond our solar system will be discovered and explored in detail with a series of radically innovative telescopes: Kepler, which will find signs of planets shadowing stars; SIM PlanetQuest, which will measure the motion of stars caused by nearby planets, and the masses of those planets; Terrestrial Planet Finder Coronagraph (TPF-C), which in optical light will image a dim "Earth" from under the glare of its bright companion star and probe its atmosphere; Terrestrial Planet Finder Interferometer (TPF-I), which is the even more sensitive infrared counterpart to TPF-C; and, finally, the spectroscopic telescope Life Finder, which will study the atmospheres of distant planets to seek definitive evidence of life there. Each mission in this ambitious series builds on the technological and scientific legacies of those that precede it.

All of these explorations require the development of complex space missions with unprecedented capabilities, from new ultrasensitive detectors and precision optics to multiple spacecraft flying in formation to subatomic accuracy. New technology development is systematically incorporated into the multiple stages of the Beyond Einstein and Navigator programs. The overall plan maximizes investment return by focusing on strategic technologies, where each development pays off multiple times.

Beyond the strategic space missions, NASA's scientific success depends on rapid and flexible response to new discoveries, inventing new ideas and theoretical tools leading to tomorrow's space science initiatives, converting hard-won data into scientific understanding, and developing promising technologies that are later incorporated into major missions. These activities are supported through a balanced portfolio of competed Research and Analysis (R&A), Probe, Discovery, Explorer, and suborbital programs, which collectively are designed to guarantee the continued vitality of NASA's overall space science vision, reduce major mission risks, and optimize the return on NASA's capital, technology, and workforce investments. Importantly, NASA, through its education and public outreach programs and through the R&A program's support of student and postdoctoral researchers at America's universities, plays a critical role in educating the nation and training the next generation of explorers.

This document describes a framework for exploration on the grandest scale. It lays out a scientific and technological agenda to discover the origin, structure, evolution, and destiny of space and time, matter and energy, atoms and molecules, the stars and galaxies that animate and enrich the cosmos, and ultimately, life itself.



Key Questions

Is there life elsewhere in the universe?

Are there other planetary systems like our own?

What powered the Big Bang?

What is the dark energy pulling the universe apart?

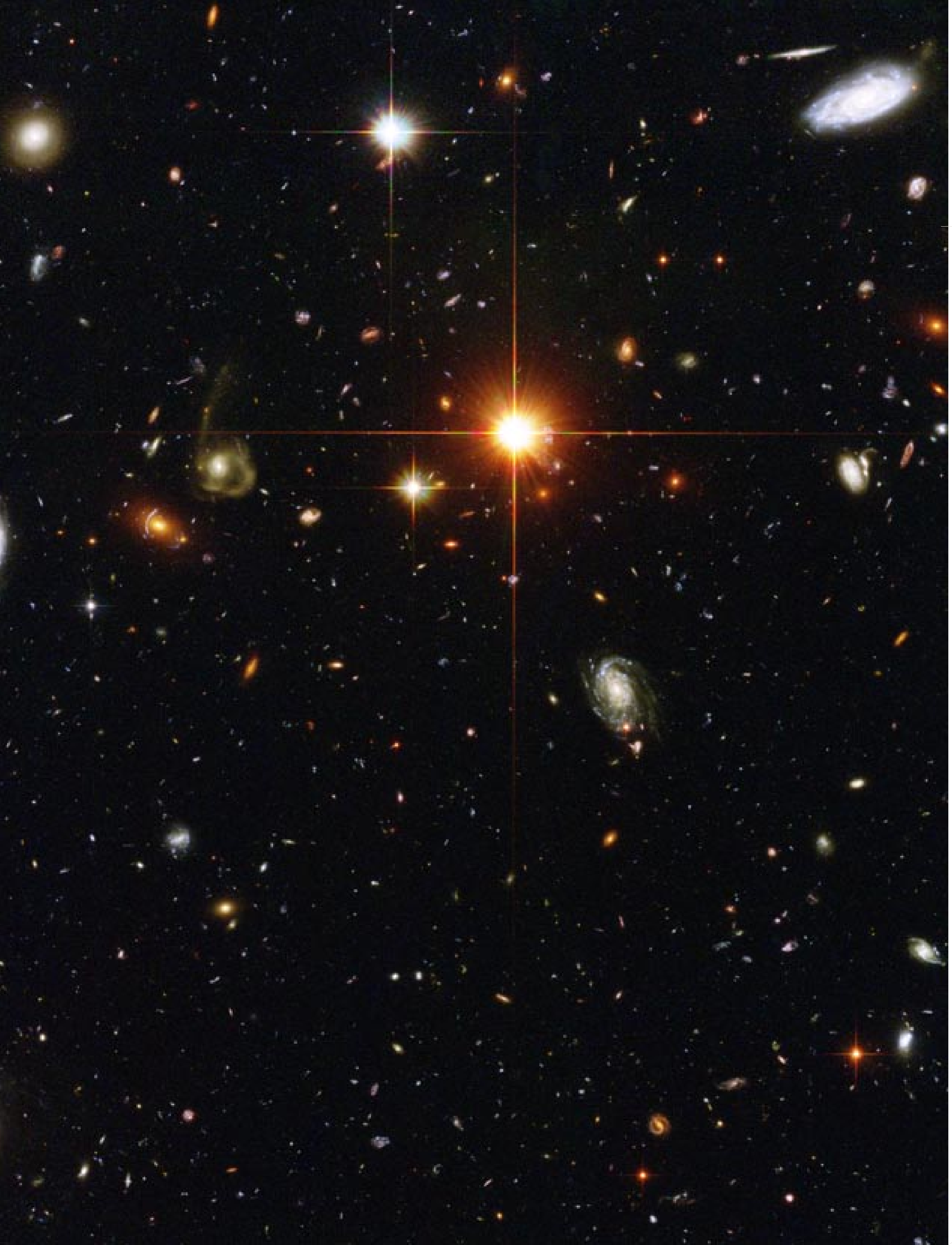
How did the first stars, galaxies, and quasars form?

What happens at the edge of a black hole?

What are the ultimate fates of stars, and the origin of the elements essential for life?

How do planetary systems form and evolve?

How are the stars and stellar systems formed from the interstellar clouds of gas and dust?



Looking billions of years back in time, the Hubble Space Telescope captured this image of galaxies and protogalaxies just after they formed.

2006

Overview

What are the origin, evolution, and fate of the universe?

How do planets, stars, galaxies, and cosmic structure come into being?

When and how did the elements of life and the universe arise?

Is there life elsewhere?

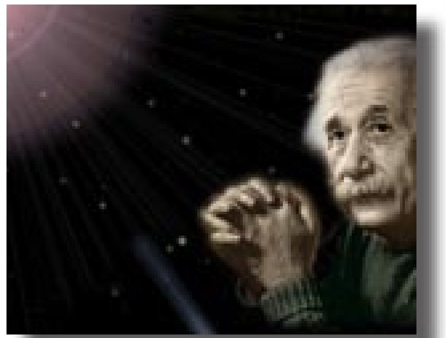
In one form or another, humanity has been asking these compelling questions for millennia. However, we are privileged to live in a time marked by scientific and technological advances so rapid and so brilliant that these elusive questions can now be pursued not only with philosophical speculation, but also with scientific observation. While the questions are simple, the scientific and technical capabilities needed to answer them are challenging. With vision and planning, they can be answered.

In this document, the Astronomy and Physics Division of NASA's Science Mission Directorate articulates the scientific case for its exploration beyond the solar system and maps out a set of implementing strategies and missions that will lead to the answers to these and other central questions concerning the universe and humanity's place in it.

We begin with Chapter 1, "Beyond Einstein: Exploring the Extremes of Spacetime." Beyond Einstein is a bold attack on the deepest mysteries of nature. The program will study the building blocks of our own existence at the most basic level: the matter, energy, space, and time that create the living universe. Beyond Einstein missions will extend the reach of humanity to the ultimate extremes: the birth of the universe, the edges of space and time near black holes, and the darkest spaces between the galaxies. Together these studies will help us understand how the matter and energy of the universe come to life.

The Beyond Einstein program has three major elements that work together to explore the farthest extremities of space and time. The first element is composed of the program's cornerstone missions, the two Einstein Great Observatories — the Laser Interferometer Space Antenna (LISA) and Constellation- X (Con-X). These will provide dramatic new ways to answer questions about black holes, the Big Bang, and gravitational waves. The second element is a focused line of more specialized Einstein Probe missions, each dedicated to the study of a specific deep question: black hole discovery, inflation, and dark energy. The third element is a supporting program, including forward-looking technology development, which includes two Vision Missions — the

Big Bang Observer and the Black Hole Imager; foundational and exploratory studies in theory, modeling, and predictive simulation; and education and public outreach. Together, the three elements will enable us to grasp these questions, create the technology to enable missions that realize the visions of the Beyond Einstein program, and inspire and train the next generation of scientists and engineers.



CHAPTER 1

The Beyond Einstein program is motivated by three major questions: What powered the Big Bang? What happens at the edge of a black hole? What is the dark energy pulling the universe apart?

The document continues in Chapter 2 with the "Origin and Evolution of Cosmic Structure." The Beyond Einstein program asks the question: Why does the universe exist at all? But we must also ask why the universe is not a formless continuum of matter, but is filled instead with rich structure that extends from the cosmic horizon down to galaxies, stars, and planets. The images of the infant cosmos from the Cosmic Background Explorer (COBE) and the Wilkinson Microwave Anisotropy Probe (WMAP) show that, half a million years after the Big Bang, the universe was extraordinarily smooth, with temperature fluctuations of only one part in 100,000. The ESA–NASA Planck Surveyor mission, and ultimately the Inflation Probe, will measure the properties of these primordial fluctuations in exquisite detail. In the next stage of the Astronomy and Physics Division's science program, we seek to understand how these tiny inhomogeneities grew into the structures that we observe today: a "cosmic web" of dark matter and baryons, punctuated by galaxies and clusters and enriched with heavy elements. The key questions about the formation of the first stars, galaxies, quasars (and the supermassive black holes that power them), and the Milky Way will be explored using the strategic missions James Webb Space Telescope (JWST), Con-X, LISA, Space Interferometry Mission (SIM) PlanetQuest, the Single-Aperture Far-Infrared (SAFIR) mission, and the Einstein Probes.

It is in the galaxies described above that stars and planetary systems reside. Stars play central roles in the formation and evolution of galaxies, but are primary components of the universe in their own right. Chapter 3 on the "Origin and Destiny of Stars" continues the central exploration theme by looking at local sites of star formation, probing fundamental physics within the compact objects left by dying stars, and tracing the path of the heavy elements they eject as the cosmic cycle of matter carries them into new generations of stars, planets, and life. Space missions have recently provided the first peeks at the secret lives of stars, the stages of stellar and planetary evolution that were hidden from centuries of ground-based optical studies. New missions such as ground-based infrared interferometers, JWST, SIM PlanetQuest, the Wide-field Infrared Survey Explorer (WISE), the Gamma-ray Large-Area Space Telescope (GLAST), Stratospheric Observatory for Infrared Astronomy (SOFIA), Con-X, LISA, and SAFIR will increase our understanding immensely.

Planets and planetary systems are formed in the context of star formation. Chapter 4, "Exploring New Worlds," describes this formation drama, explains how the missions such as JWST, SIM, SOFIA, and SAFIR will unravel it, and then transitions to a central theme of the Astronomy and Physics Division program: the quest for Earth-like planets, habitable environments, and signs of life outside the solar system. Are we alone? In the vast blackness of the universe, our home planet is a sparkling oasis of life. Whether the universe harbors other worlds that can support life is a question that has been asked for millennia. The "Exploring New Worlds" chapter articulates the plans to answer this age-old question with a staged series of spaceborne telescopes: Kepler, SIM PlanetQuest, Terrestrial Planet Finder Coronagraph (TPF-C), Terrestrial Planet Finder Interferometer (TPF-I), and Life Finder, each building on the legacy of and information derived from the previous one. The Navigator program has been organized by NASA to manage this endeavor and directly supports *A Renewed Spirit of Discovery: The President's Vision for U.S. Space Exploration* (2004), which calls for "advanced telescope searches for Earth-like planets and habitable environments around other stars" as one of the foundations of NASA's exploration goals.

CHAPTER 2

We seek to understand how the complex universe, filled with galaxies, stars, and planets came to be, and how the "cosmic web" of dark matter and baryons, punctuated by galaxies and clusters, enriched with heavy elements, emerged.

The explorations described in this document will require the development of complex missions with unprecedented capabilities. Focused programs (e.g., Navigator and Beyond Einstein) responsible for conducting the precursor and supporting science activities, for the technology development, and for implementing the associated missions have been established. The "Strategic Mission Summary," Chapter 5, describes the overall implementation philosophy, summarizes the strategic missions that support its exploration science agenda, describes the strategic missions, and draws approximate timelines.

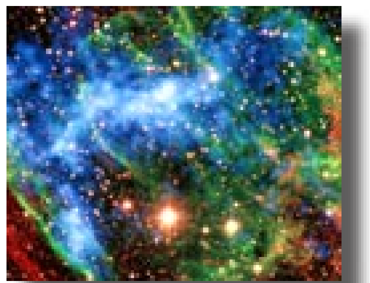
Current NASA missions incorporate extraordinary technological achievements that allow them to accomplish extraordinary science. The primary mirror of the Hubble Space Telescope is so smooth that if the mirror were expanded to the size of the Pacific Ocean, the highest waves would be 5 centimeters high. The Spitzer Space Telescope has the sensitivity to detect the heat from an ordinary camping flashlight wrapped in black felt cloth at the distance of the Moon. The X-rays that glance off Chandra's extremely smooth mirror are focused so accurately that they could hit the bull's eye of a dartboard placed 6 kilometers away. The technological demands of future missions are even more extraordinary, and their scientific goals even more ambitious. JWST's gigantic mirror and exquisite sensors would enable it to detect an ordinary light bulb at the distance of Jupiter. SIM PlanetQuest will resolve angles equivalent to that subtended by the edge of a dime on the surface of the Moon. LISA will sense the relative positions of its components, measuring their 5-million-kilometer separations with phenomenal accuracy — to within a small fraction of an atomic diameter.

Chapter 6, "Technology Enables Discovery," describes the implementation strategies to sustain the technological development efforts needed to acquire the above capabilities, the technological linkages and dependencies between successive missions, and the classes of technology investments necessary for sustained success. It also discusses the exploratory, enabling, and mature technologies in four key areas, but identifies strategic technologies that are important across the mission suite. Strategic technologies represent the core capabilities required by multiple missions. NASA maximizes its investment return by focusing on strategic technologies, where each development pays off multiple times.

NASA science is driven by creativity and imagination, and priorities must allow for rapid and flexible response to new discoveries. Success depends on generating the new ideas that will be the basis of tomorrow's space science initiatives, incubating new detector concepts, nurturing the next generation of researchers, converting hard-won data into scientific understanding, and testing promising technologies that may later be incorporated into major missions. These are the functions of the highly competed Research and Analysis (R&A), Discovery, Explorer, and suborbital programs, which are designed to guarantee the continued vitality of NASA's overall space science vision, reduce major mission risks, and optimize the return on NASA's capital, technology, and workforce investments. Moreover, R&A's technology incubation investments are the "seed corn" for NASA's future and must be a central component of any successful program. Chapter 7, "Sustaining the Vision," explains the importance of these efforts to current and future Astronomy and Physics Division goals.

CHAPTER 3

We are just now penetrating into the sites of star formation, probing fundamental physics within the compact objects left by dying stars, and tracing the path of the heavy elements they eject as the cosmic cycle of matter carries them into new generations of stars, planets, and life.



NASA's role in educating and training the next generation of explorers and in educating the nation is one of its most critical functions. Chapter 8 on "Engaging Students and the Public" addresses the unique community outreach initiatives of the Astronomy and Physics Division's program of exploration, the educational opportunities that NASA missions create, and a coherent strategy for public and student engagement.

In crafting the strategies to accomplish the challenges described in this document, NASA has adhered to certain overarching principles. First, flagship missions must be multipurpose. JWST, the infrared successor to the Hubble Space Telescope (HST), is designed to probe the first stars and galaxies of the universe. The optical and ultraviolet light from these structural beginnings is redshifted as it traverses the vastness of space into the infrared bands where JWST is most sensitive. However, JWST's infrared sensitivity also enables it to penetrate the dense cocoons in which stars and planets in the Milky Way are born. Otherwise shrouded in mystery by profound opacity in the optical, protostars and protostellar/protoplanetary disks are revealed to JWST's searching gaze. The multiple capabilities of JWST are the genius of its conception and will multiply its scientific return many times. SIM PlanetQuest is programmed to detect and weigh Earth-like planets around neighboring stars. However, its core capacity to measure the positions of stars to exquisite precision will also yield the distances and speeds of stars to unheard-of accuracies. Such a capability will allow us to measure the motion of globular clusters and galactic companions for the first time, witness stellar evolution, and definitively establish the geometry of our Milky Way.

LISA is a central component of the Beyond Einstein program described in Chapter 1 and is designed to measure gravitational waves from merging black holes across the universe, providing cosmological information of unique import. However, it will also discover binary white dwarf stars by the thousands in our own Galaxy, thereby simultaneously illuminating both cosmological and stellar realms, and exploring directly the dynamical behavior of space and time. The Terrestrial Planet Finders (TPF-I and TPF-C) are to target nearby stars to spectroscopically acquire and characterize Earth-like planets. This will be their primary mission. However, their exquisite angular resolution and large collecting areas will provide astronomical performance that will dwarf that of HST or JWST and will enable astronomical investigations both in the Galaxy and at cosmological distances. This multiple function does not drive their design, but ensures that the nation will derive the optimum benefit from its investment in these cutting-edge space science resources. Similarly, Con-X and the SAFIR mission are being driven to answer core questions, but will bring unique capabilities that bear across the spectrum of astronomical puzzles. Time and time again, our experience with strategic missions has demonstrated that their new capabilities not only enable multiple uses, but novel ones as well; when the Space Telescope Imaging Spectrograph (STIS) instrument on HST was built no one envisioned that it could be used, as it has been, to study planetary atmospheres.

The second guiding principle is that the flagship missions must represent quantum leaps in performance. JWST will be 100 to 1,000 times more sensitive than Spitzer. It will have 10 times the collecting area of HST. In the X-ray region, Con-X will have 25 to 100 times the effective area for high-resolution spectroscopy as Chandra. In the far-infrared, SAFIR will be more than 100 times as sensitive as SOFIA. Planck Surveyor will have 10 times the sensitivity of WMAP. WMAP was Science Magazine's "Breakthrough of the Year" in 2003. Furthermore, TPF-I will have 100 times the contrast capability of JWST, and TPF-C will have

CHAPTER 4

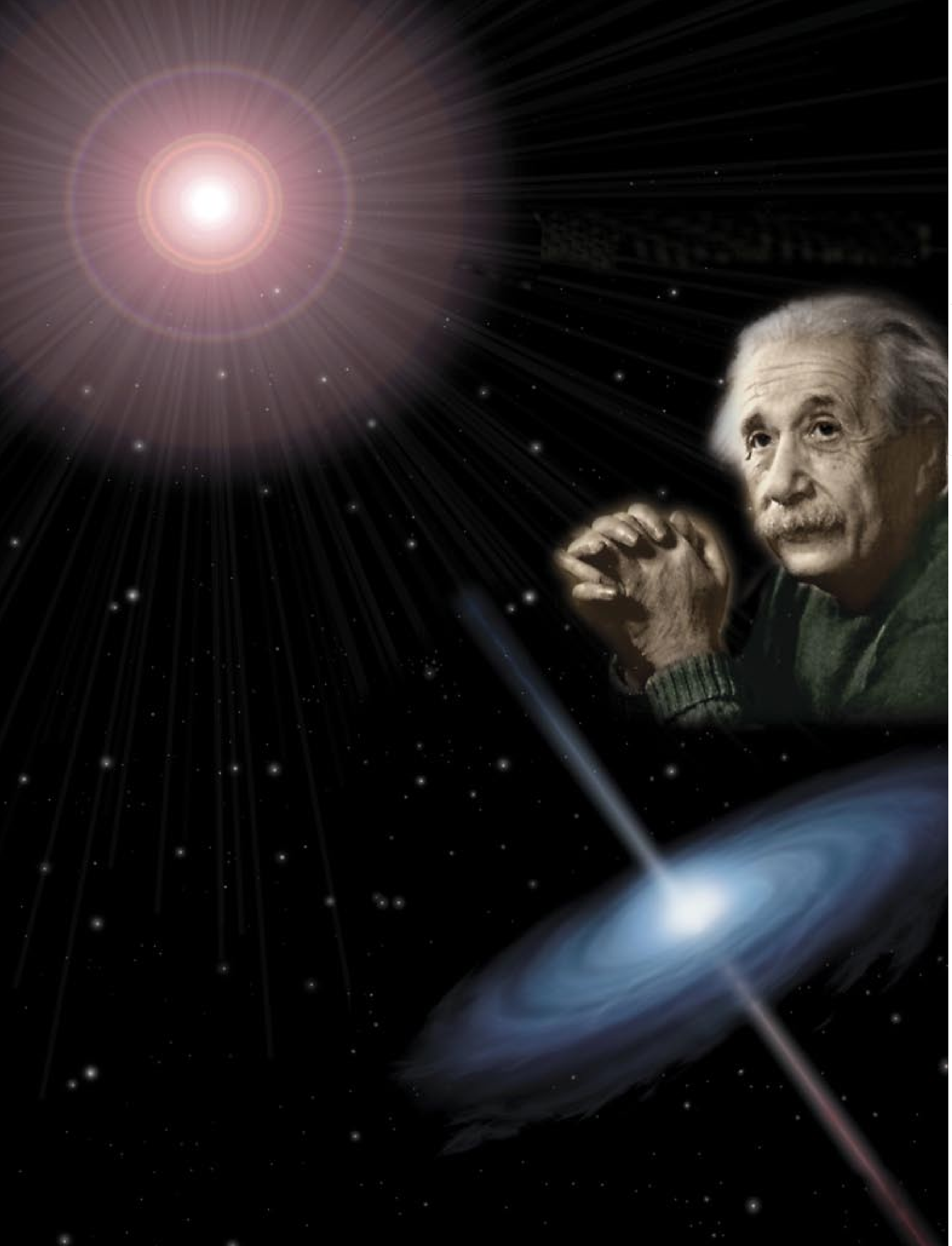
The quest for Earth-like planets, habitable environments, and signs of life outside the solar system is emerging as a vigorous, quantitative science that within our lifetimes may answer the question: Are we alone?

10^5 times that of HST. LISA is to begin an entirely new era in gravitational-wave astronomy and represents the inauguration of a new astronomy. With all these missions, the opening up of new "discovery spaces" is a major theme. What energizes the explorations described in this document is not only that known territory will be probed deeply and with precision, but that unanticipated new territories must inevitably be revealed.

The third guiding principle is that technology development for a given mission must be part of an integrated implementation plan that leverages technological developments across the entire mission portfolio. It is crucial that investment for a mission reduce the risks and costs for its successor missions. Bolometer technology on the Balloon Observations of Millimetric Extragalactic Radiation and Geophysics (BOOMERANG) mission is being used in Planck Surveyor and the Herschel Space Observatory. Detectors in the far-infrared developed for SOFIA will pave the way for those on SAFIR and the Inflation Probe. Cryogenic research for Spitzer and JWST will lead to the low-temperature capabilities necessary for SAFIR, TPF-I, and Life Finder. Interferometric and/or formation-flying capabilities for SIM PlanetQuest and LISA will inform developments for TPF-I, Black Hole Imager, Life Finder, and the Big Bang Observer. Developments in large telescope apertures for JWST will be employed for TPF-I and TPF-C, SAFIR, and Life Finder. In the realms of detectors, telescopes, coolers, and distributed spacecraft, technology for a given mission must pay off multiple times in subsequent missions. Therefore, an integrated plan of crosscutting technology investment is one of the pillars of the science program.

This document is a framework for exploration on the grandest scale, leveraging NASA's considerable experience to achieve what only NASA can. It is an answer to NASA's Vision "…To find life beyond." It is the response to NASA's Mission statement " …To explore the universe and search for life" and "…to inspire the next generation of explorers." If fully implemented, it would be the partial realization of the space exploration vision as described in the report of the President's Commission on Implementation of United States Space Exploration Policy. This vision calls for the exploration of the beginnings of the universe, planetary systems, and life. It advocates a scientific agenda that would reveal the origin, evolution, and fate of the elements, the stars, the galaxies, and the cosmic web that animate and enrich the known cosmos. The vision also challenges NASA to search for Earth-like planets and to conduct a comprehensive program to explore the origin, evolution, and destiny of the universe. Further guidance comes from the National Academy of Sciences Decadal Survey (*Astronomy and Astrophysics in the New Millennium*), *Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century*, and *A 21st Century Frontier for Discovery: The Physics of the Universe, A Strategic Plan for Federal Research at the Intersection of Physics and Astronomy*, all of which endorse forefront science goals and missions that can be accomplished only by NASA's Astronomy and Physics Division. This document describes the plan to realize, using space, these policy and exploration visions.

Some of the discoveries to emergecould fundamentally shift our understanding of our place in the universe, with implications as profound as the early work of Copernicus, Kepler, and Galileo. A viable science program must take full advantage of this potential to ignite the public imagination, while fulfilling its obligation to inspire the students of the future who will carry out its programs of discovery — it is a legacy to them.



Einstein's theory explained how the expanding universe works, but not what made the Big Bang happen.

1 Beyond Einstein

Exploring the Extremes of Spacetime

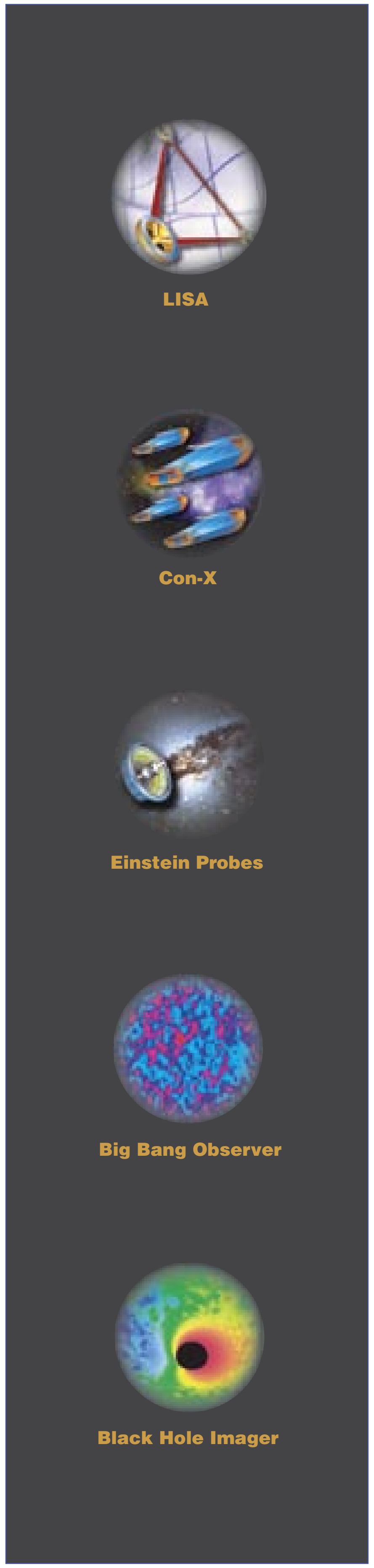
A century ago, Albert Einstein began creating his theory of relativity — the ideas we use to understand space, time, and gravity — and took some of the first steps towards the theory of quantum mechanics, the ideas we use to understand matter and energy. *Time* magazine named Einstein the "Person of the Century" because his ideas transformed civilization, but his work is not finished: the spacetime and quantum views of reality have not yet come together into a unified story about how nature works.

Einstein's general theory of relativity opened possibilities for the formation and structure of the universe that seemed unbelievable even to Einstein himself, but which have all been subsequently confirmed: that the whole universe began in a hot, dense Big Bang from which all of space expanded; that dense matter could tie spacetime into tangled knots called black holes; that "empty" space might contain energy with repulsive gravity. Despite these discoveries, we still do not understand conditions at the beginning of the universe, how space and time behave at the edge of a black hole, or why distant galaxies are accelerating away from us. These phenomena represent the most extreme interactions of matter and energy in the whole universe, and may lead us to discover the origin and destiny of all of space and time. They are the places to look for the next fundamental revolution in understanding and the origin of the three questions that motivate the Beyond Einstein program:

- **What powered the Big Bang?**
- **What happens at the edge of a black hole?**
- **What is the dark energy pulling the universe apart?**

To pursue the answers to these questions, the Beyond Einstein program has three major elements that work together to explore the farthest extremes

"The most beautiful thing we can experience is the mysterious. It is the source of all true art and science. Those to whom this emotion is a stranger, who can no longer pause to wonder and stand rapt in awe, are as good as dead: their eyes are closed."
—Albert Einstein



of space and time. The first element comprises the program's cornerstone missions, the two Beyond Einstein Great Observatories — the Laser Interferometer Space Antenna (LISA) and Constellation-X. These missions will provide dramatic new ways to answer questions about black holes, the Big Bang, and gravitational waves. The second element is a focused line of moderate-size Einstein Probe missions, each dedicated to the study of a specific deep question: black hole discovery, inflation, and dark energy. The third element is a supporting program, including forward-looking technology development, which includes two Vision Missions, the Big Bang Observer and the Black Hole Imager; foundational and exploratory studies in theory, modeling, and predictive simulation; and education and public outreach. Together, the three elements will enable us to grasp these questions, create the technology to enable missions that realize the visions of the Beyond Einstein program, and inspire and train the next generation of scientists and engineers.

The Beginning of Time

The universe is expanding, and abundant evidence now shows that it began in a hot, dense state — the Big Bang. Einstein's general theory of relativity explains how the expanding universe works, but on its own it does not explain what made the Big Bang happen in the first place.

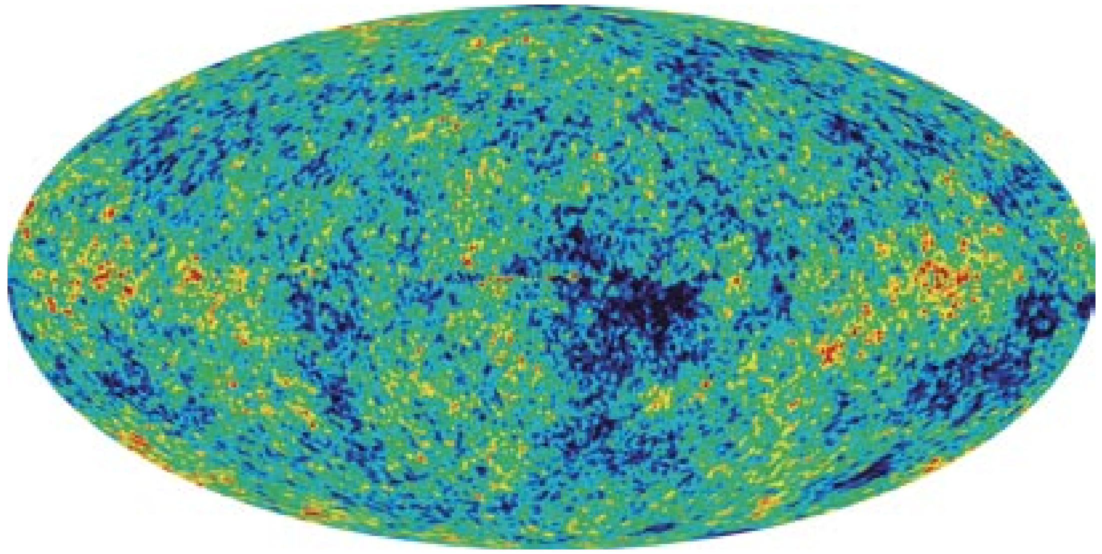
Clues to the origin of the Big Bang have been found in its relic heat, the cosmic microwave background (CMB): light that has been traveling to us since the universe was 380,000 years old. Observations reveal slight variations in the brightness of the CMB that show that the matter content of the universe, while remarkably smooth when the relic heat began its journey to us, had already been imprinted with small perturbations at a much earlier time. These tiny imperfections have now grown into the galaxies of stars, dust, and gas that illuminate our sky.

Beyond Einstein missions will probe the extremes of space and time.

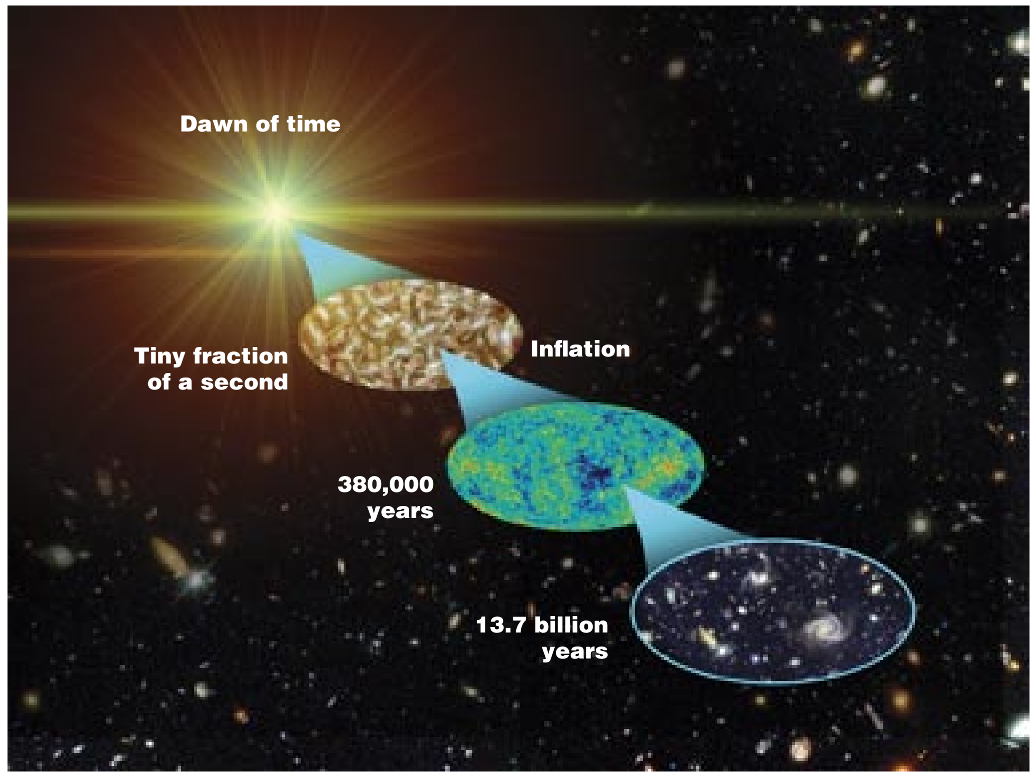
The growth of those small imperfections into galaxies, stars, and the complex universe of today — driven first by the gravity of cosmic dark matter and later by the gas that eventually became stars, planets, and life — is an exciting frontier of exploration further described in the next chapter. But we also want to know how the Big Bang began, and how it became an enormous, nearly uniform universe.

Inflationary cosmology provides one set of ideas for making a Big Bang happen, including an explanation of why the universe is very smooth, yet not perfectly so. A still-mysterious form of energy generated a repulsive force that caused the early universe to expand at a fantastic rate. This expansion made space large and smoothed out the spacetime. But the inflation field, like all energy fields, was made of discrete packets of energy called quanta, which led to imperfections in the cosmic expansion — the Big Bang got a slightly bigger kick in some places than in others. The effect of a single quantum fluctuation was imprinted on the spacetime and inflated to enormous size along with the universe itself. Sky maps of the CMB show a pattern of fluctuations very much like that predicted by inflation. According to this remarkable synthesis of ideas from gravity and quantum mechanics, entire galaxies trace their origin to single elementary particles during inflation.

Nevertheless, we are far from certain that the inflationary scenario is correct. Even if inflation is the right story, the details of the plot remain a mystery. We need new data



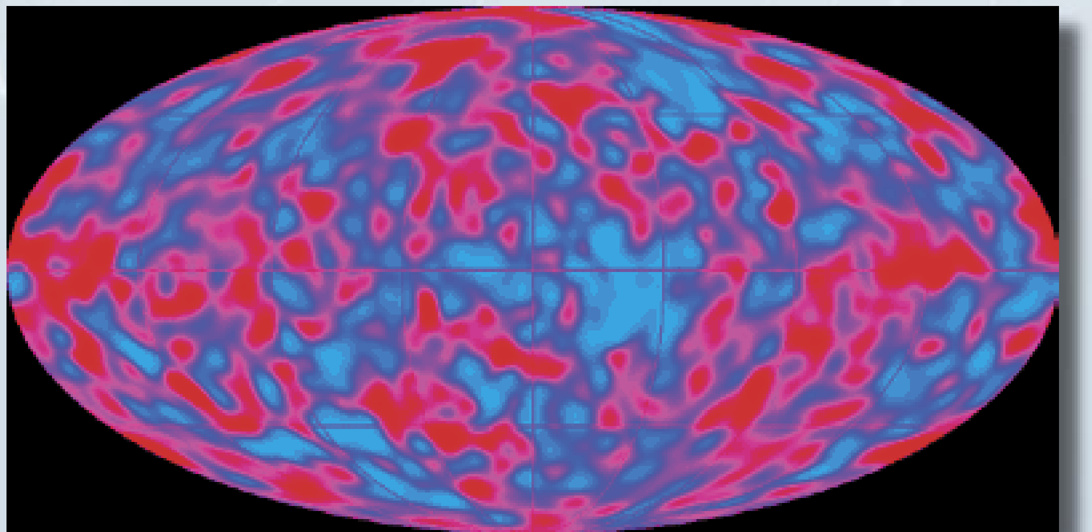
WMAP image of the cosmic microwave background. The data bring into high resolution the seeds that generated the cosmic structure we see today. These patterns are tiny temperature differences within an extraordinarily evenly dispersed microwave light bathing the universe, which now averages a frigid 2.73 degrees above absolute zero. The new data support and strengthen the Big Bang and inflation theories.



Quantum fluctuations during the Big Bang are imprinted in gravitational waves, the cosmic microwave background, and in the structure of today's universe. Studying the Big Bang means detecting those imprints.

Concordance cosmology

A remarkable series of measurements over several decades — from the ground, from balloons such as BOOMERANG, and from satellites such as COBE and WMAP — have precisely mapped the radiation reaching us from the Big Bang. These measurements show details of the ringing effect of primordial fluctuations on the hot matter/radiation plasma of the early universe. The behavior of the whole cosmic system can also be studied in other very different ways, such as supernova measurements of the cosmic expansion history and three-dimensional maps of the galaxy distribution showing large-scale structure today. These experiments now all agree with considerable precision on the basic parameters describing the behavior of the universe on large scales: how old it is, how fast it is expanding, its composition (the amount of atoms and stars, dark matter, and dark energy it contains), how close it is to being geometrically flat, and what kind of perturbations inflation left behind.



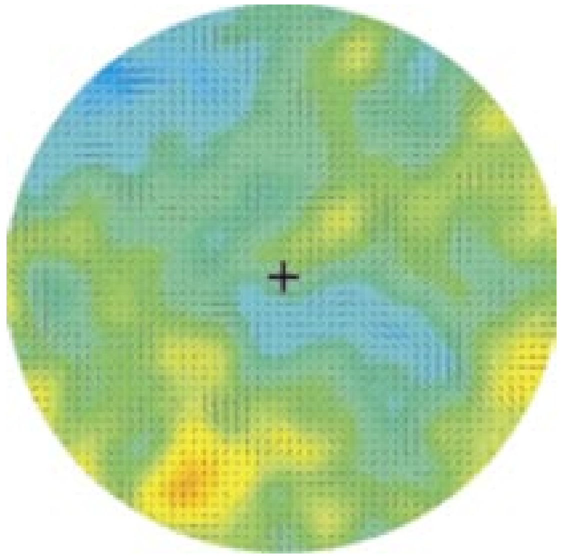
COBE map of the cosmic microwave background (dipole and Galactic emission subtracted). COBE's map of the microwave sky was described by Stephen Hawking as "the discovery of the century, if not of all time."

to help decide whether the early universe underwent a period of rapid inflation, and if so, what was the mechanism responsible for driving it.

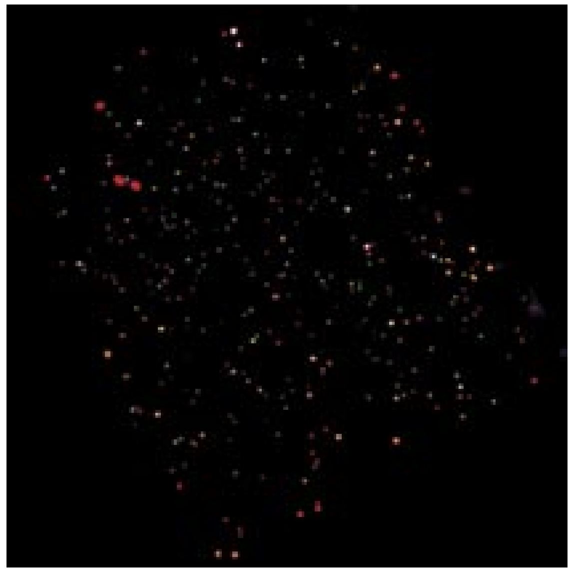
We now understand a way to uncover these secrets. Calculations predict that in addition to its tiny energy fluctuations, inflation would have also generated gravitational waves. Observing these inflationary waves — faint ripples in the structure of spacetime itself — is a way of "seeing" as close to the beginning of time that we can ever, in principle, observe. The Inflation Probe will find correlations that indicate a unique signature of gravitational waves from inflation. (One candidate Inflation Probe is an ultrasensitive sky-mapping mission to uncover the subtle but distinctive pattern of gravitational waves imprinted in the microwave background.) Ultimately, if the universe is quiet enough to allow it, Big Bang Observer will make direct measurements of these gravitational wave signals.

Exploring Edges of Spacetime: Black Hole Horizons

Most of what we know directly about gravity comes from experiments within the solar system, where gravity is weak. These experiments confirm Einstein's theory that gravity is the one universal force connecting all forms of matter and energy. It is universal because it is a property of space and time itself. Einstein's general theory of relativity predicts that gravity should appear in its purest form in two ways: in vibrations of spacetime called gravitational waves and in dense knots of curved spacetime called black holes. So far, we have only indirect evidence that these two astonishing predictions are true. Beyond Einstein missions will obtain direct evidence. Only data collected from these so-far-invisible regimes can enable us to find out whether Einstein's theory is correct and to complete Einstein's work.



This simulation of the cosmic microwave background shows the curl of the polarization field by gravitational waves with wavelengths as long as the universe is large.



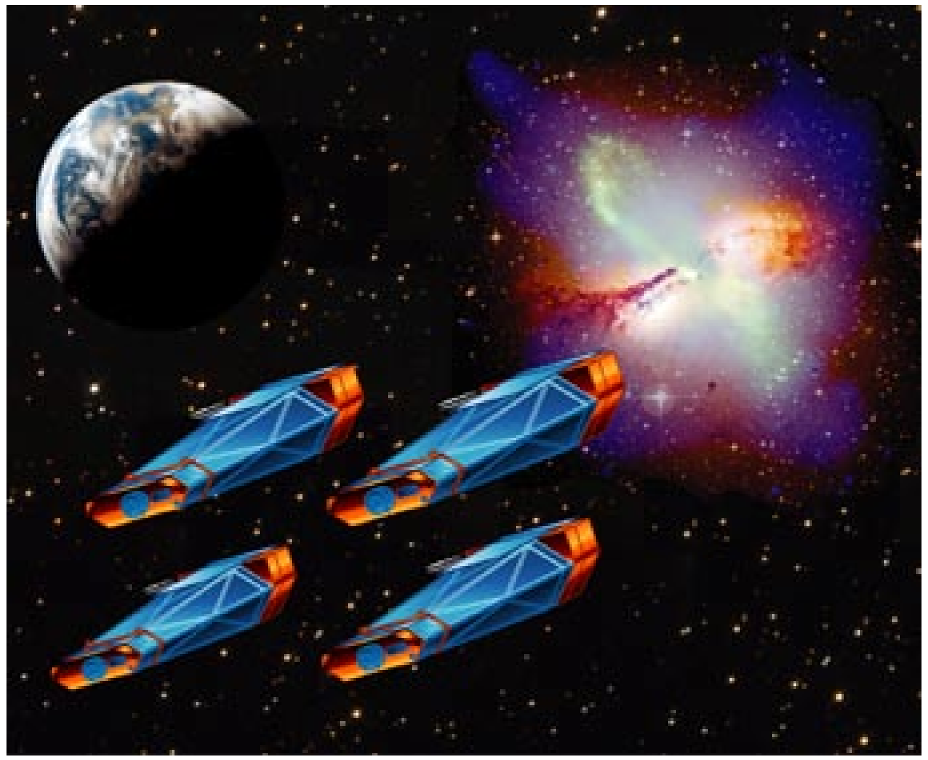
A deep X-ray Chandra image of the Lockman Hole, a patch of sky that avoids most of the X-ray absorbing gas of the Milky Way. By combining this image with the Chandra deep fields, astronomers have been able to construct the most complete black hole census to date of the universe. Virtually each of these dots — with the red objects usually cooler than the blue objects — represents a supermassive black hole.

Einstein's theory tells us that a black hole is made of pure gravitational energy. A black hole has mass and spin but should contain no actual surviving matter of the kind we are familiar with; anything whatsoever that falls into a black hole is quickly converted to pure gravity. Though we infer that the universe contains many black holes, we have yet to see one in detail. The general theory of relativity provides a mathematical picture of what one should be like. At a black hole's heart is a singularity, where space and time are infinitely curved and energy is infinitely concentrated. Surrounding the singularity is a region from which nothing can escape. The edge of this region is called the event horizon. There, time is so warped that it seems, from outside, to have stopped.

How could we find out if such objects really behave in this weird way? We could drop an astronaut near a black hole. As the astronaut fell in, Einstein predicts that the hands of the astronaut's watch would appear to us to slow down and practically stop as the event horizon is approached. But astronaut and watch would simultaneously fade from view so rapidly that we could never see them cross the event horizon. Yet to the falling astronaut, everything would seem normal crossing the event horizon. Unfortunately, once across, the astronaut would be ripped to pieces by the curvature of spacetime near the central singularity.

Fortunately, there are more humane ways to find out if black holes are really as Einstein predicts. Instead of observing a watch on a falling astronaut, we can observe the radiation from atoms of gas as they fall in. The frequency of the light these atoms emit is like the ticks of a clock. Changes in that frequency are caused by the motion of the gas — the familiar Doppler effect change in tone heard as an ambulance races past — and by the gravitational redshift due to spacetime curvature. Watching the spectra of these flows can thus reveal many details of the matter and its spacetime environment.

Artist's impression of the formation of a supermassive black hole. Matter that has passed the black hole's event horizon (point of no return) cannot be seen; material swirling outside this threshold is accelerated to millions of degrees and radiates in X-rays. After formation, the black hole is shrouded in gas and dust, obscuring it from most angles at wavelengths other than those of the X-rays picked up by Constellation-X.



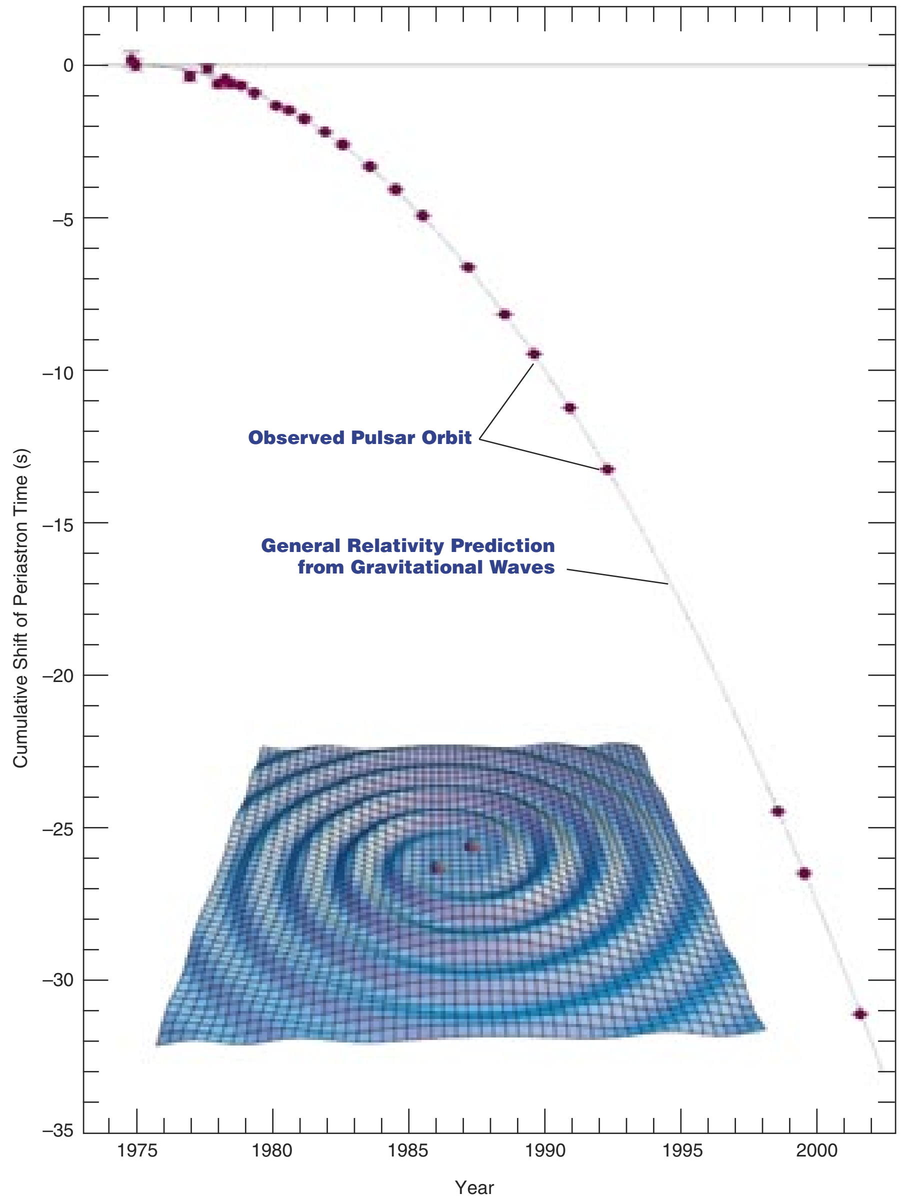
The light from these atoms can be very bright. Streams of matter falling into a black hole accelerate to nearly the speed of light; when they collide, they heat up and radiate enormous amounts of light. Mass-energy not radiated falls into the hole, adding to its mass and spin. The spin of the hole can give matter nearby a kick and, with the aid of magnetic fields, can even accelerate it into powerful jets of outflowing particles.

The Beyond Einstein program will systematically determine the fate of this matter. The Black Hole Finder Probe will survey the universe seeking radiation from matter falling into black holes and mapping their locations; Constellation-X will study the spectrum of light coming from atoms as they fall into black holes for clues to the structure of spacetime in the neighborhood of the event horizon; and in the distant future, the Black Hole Imager will create moving images of the swirling matter right down to the edge of the event horizon.

Einstein's Cosmic Cacophony: Gravitational Waves

The Beyond Einstein program will explore things that happen at the edges of the universe, including especially the extreme environments of black holes and the Big Bang, not only by looking at the light emitted near these edges, but also by listening for the "sounds" created there — the vibrations of spacetime itself. The new technology of Beyond Einstein will open up a whole new sense of the cosmos; suddenly, after centuries of silence, science will no longer be deaf to the sounds of spacetime.

Since ancient times, astronomers have used one form of energy to study the universe. Called simply light, it includes X-rays and radio waves and all the colors



In 1974 Russell Hulse and Joseph Taylor discovered the first binary pulsar, PSR 1913+16. In 1993 they received the Nobel Prize for showing that neutron stars spiral towards each other at exactly the rate Einstein's theory predicts due to gravitational waves. Gravitational waves from binary stars like this await direct detection by LISA and LIGO.

LIGO

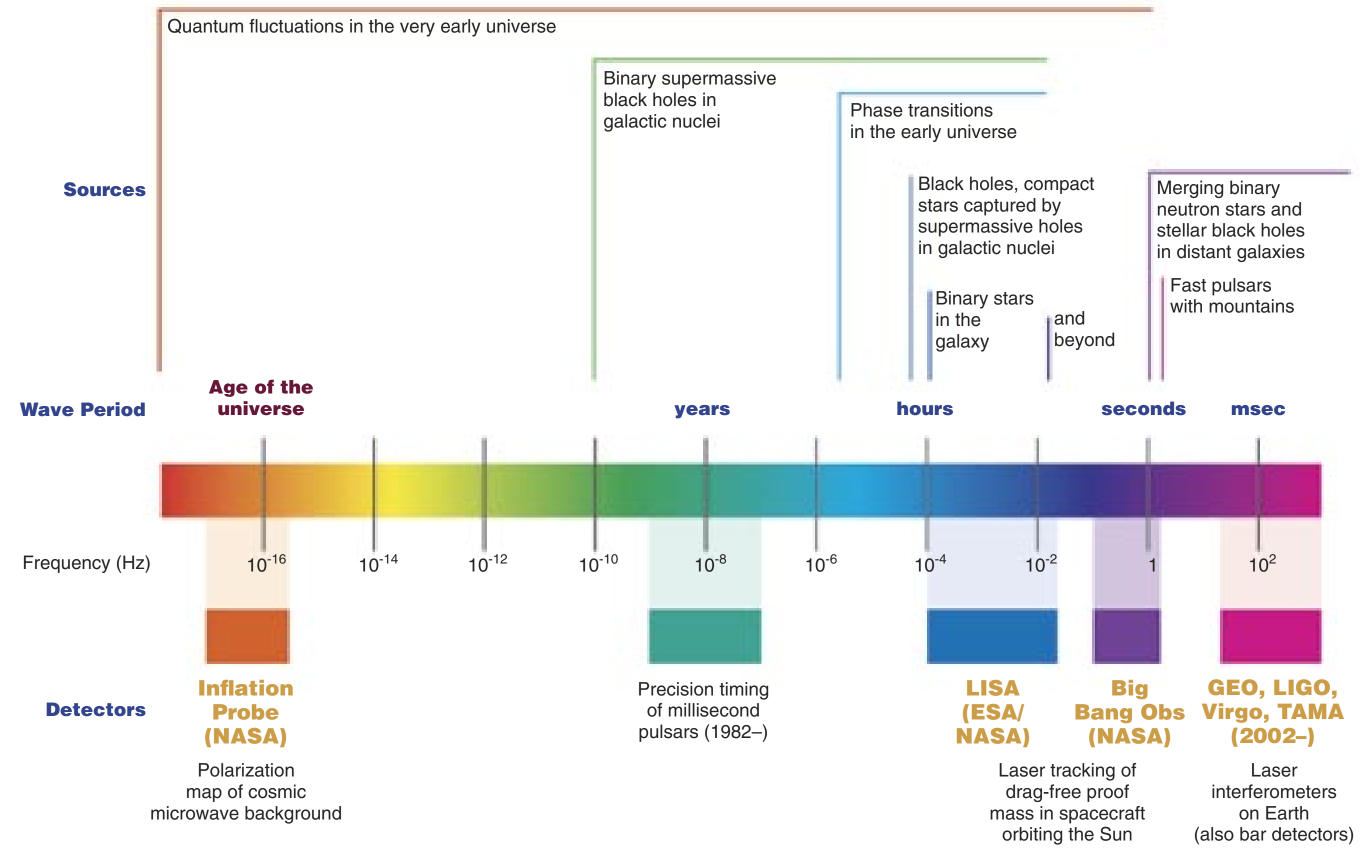
LISA will complement the National Science Foundation's ground-based Laser Interferometer Gravitational-wave Observatory (LIGO) project by detecting gravitational waves from galactic binaries and massive black holes that are beyond LIGO's reach. LISA will become the premier instrument of the emerging discipline of gravitational-wave astronomy.

LIGO site in Hanford, Washington.

of the rainbow in between that humans have always seen with their own eyes. Light is made of vibrating waves of electric and magnetic fields traveling through space and time. In Einstein's theory of gravity, vibrating waves of space and time, which also travel at light speed, can also carry energy. In the same way that black holes are made just of space and time, gravitational waves are also "pure" space and time. They interact very weakly with matter and penetrate anything without losing strength. While this makes them powerful probes of extreme conditions, it also makes them hard to detect--- so hard that they have not yet been directly detected. They interact so weakly with any measuring apparatus that only in the past few years has technology advanced to the point that we are confident we can build equipment to detect them.

Of all the outflows of energy in the universe of any kind, the most powerful outflows are carried not by light but by the gravitational waves emitted when two black holes orbit, collide, and merge into a single black hole. In the final minutes or hours before the merging of a single pair of supermassive black holes, 10^{52} watts of power is radiated in gravitational waves. This is a million times more power than all the light from all the stars in all the galaxies in the entire visible universe put together. It is possible that the universe contains more of this gravitational radiation than it does light.

Detecting gravitational waves will give Einstein's theory a workout it has never had before. We know that Einstein's theory works very well in normal circumstances — without "spacetime curvature technology" in their software, airplanes using GPS navigation would miss their runways by miles — but gravitational waves offer a much more profound test of Einstein's theory. Through gravitational wave detection we will listen to collision and mergers of black holes, the most violent events in

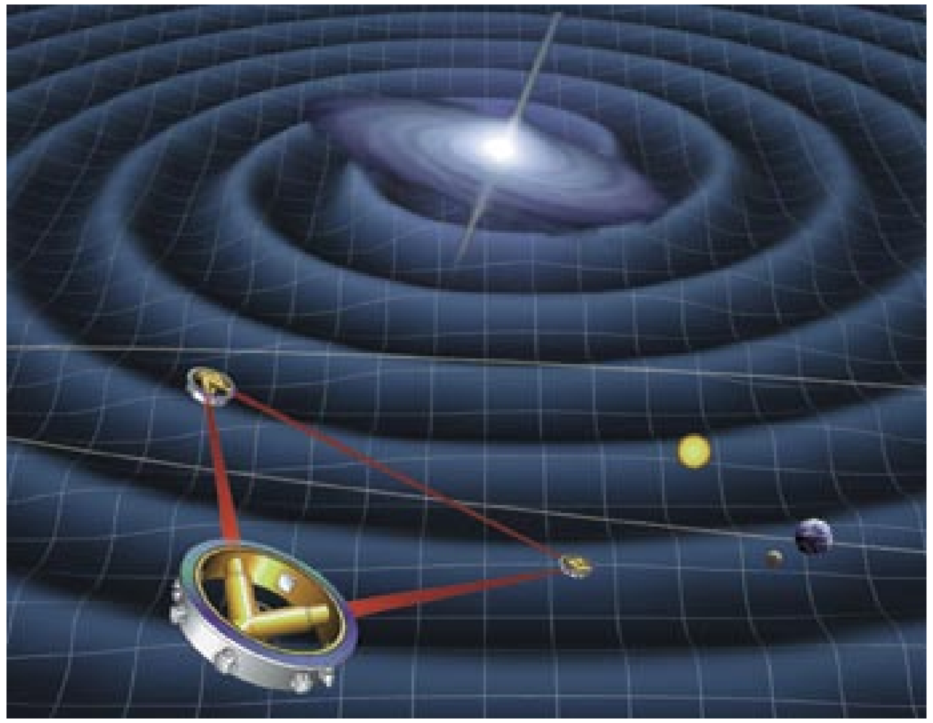


the universe. The sounds of the universe will tell us how well Einstein's ideas still work in these extreme conditions. They will also allow us to penetrate times and places impossible to see with light, such as the birth of our universe, perhaps revealing startlingly violent events, such as the formation of our three-dimensional space from an original space with more dimensions.

Gravitational waves produce tiny jiggles in the distance between masses that are floating freely in space, isolated from all forces other than gravity. The distances between the masses can be monitored using laser interferometry. An early generation of such systems has now been deployed on the ground — the NSF-funded Laser Interferometer Gravitational-wave Observatory (LIGO) in the U.S. and similar systems worldwide. It is hoped that these systems will make the first detection of gravitational waves from some sources of high-frequency waves. The Beyond Einstein Great Observatory LISA will operate in a broad band at much lower frequency. It will detect entirely different sources in great numbers and with exquisite precision.

The most powerful gravitational waves come from quickly changing systems with very strong gravity, so LISA's strongest signals will probably come from black holes

The gravitational wave spectrum.



Artist's concept of the LISA gravitational-wave satellite intercepting the ripples in spacetime emitted by an active galactic nucleus or quasar.

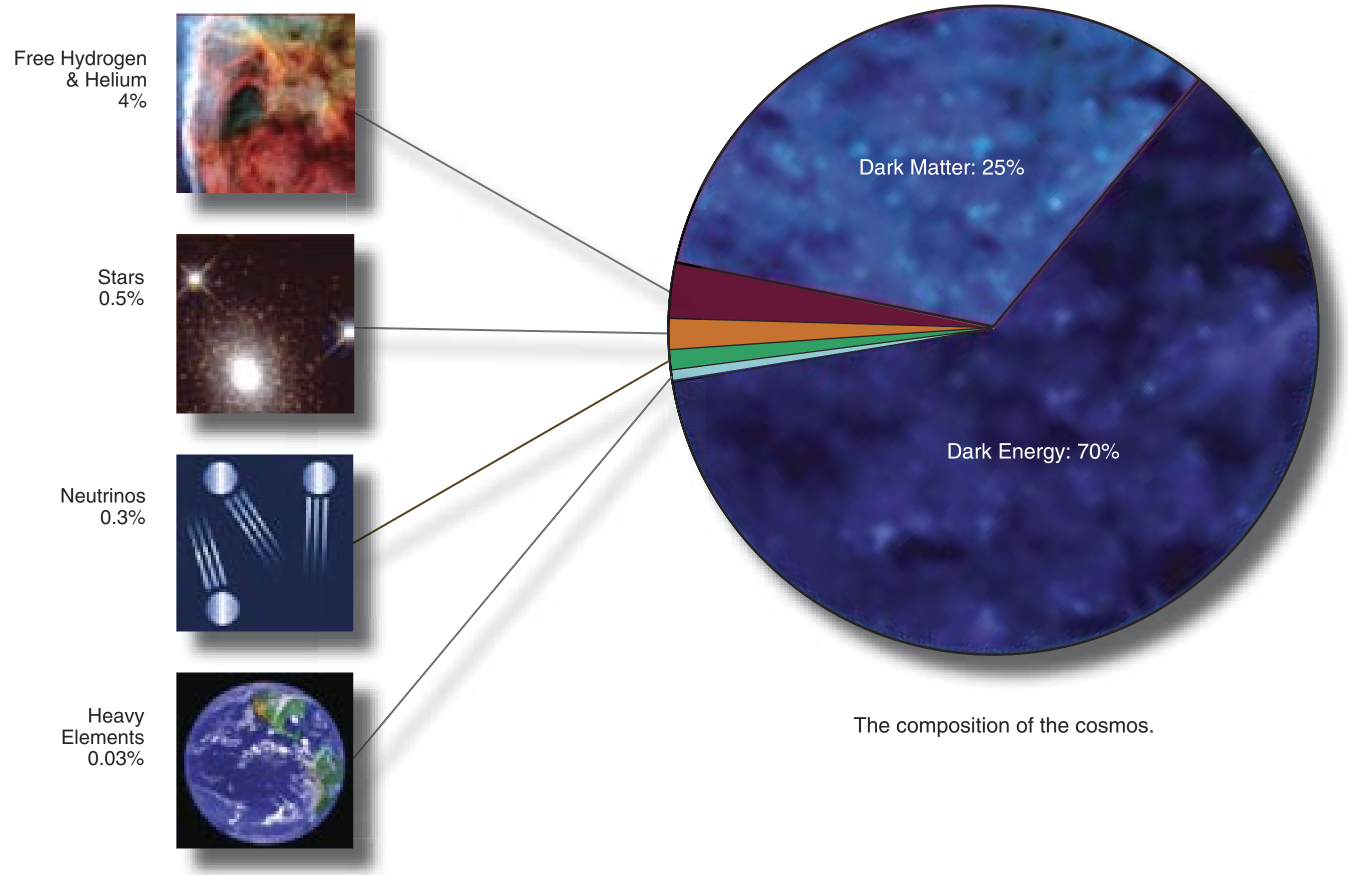
spiraling into other supermassive black holes. In addition to detecting sources like these, which cannot be detected in any other way, LISA will break new ground in yet another way. By detecting for the first time gravitational waves from sources (such as orbiting pairs of white dwarf stars) that can be studied by optical telescopes, LISA will introduce gravitational waves as an entirely new way to study a wide range of astronomical objects.

LISA will break ground for the new science of gravitational-wave astronomy. The Vision Mission Big Bang Observer will extend the reach of gravitational-wave astronomy towards its ultimate limit — detecting the quantum noise from the inflationary universe.

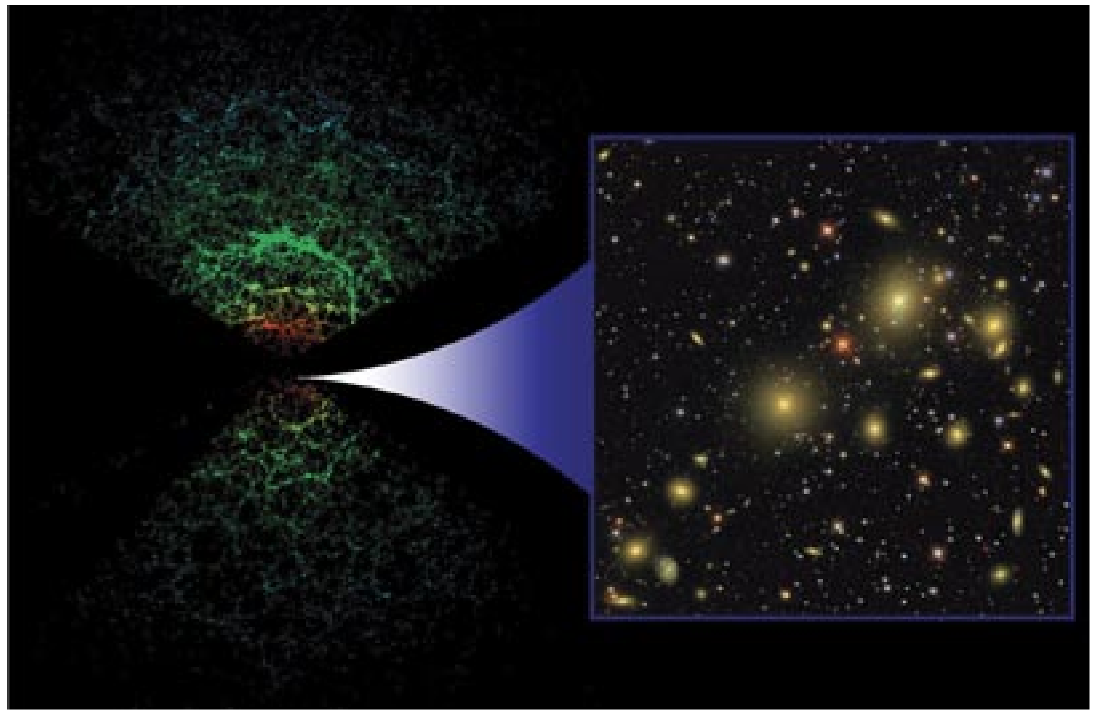
Dark Energy and Cosmic Acceleration: Discovering the Destiny of the Universe

Deep as Einstein's general theory of relativity may be, it remains silent on a profound question: Is empty space really empty? Inflation models predict that it was not so in the past, and suggest that it may not be so today either. Einstein introduced a cosmological constant into his equations to represent the possibility that even empty space has energy and couples to gravity. The unknown magnitude of the cosmological constant is set by parts of physics beyond Einstein's understanding — and, at present, our own. The recent discovery that the expansion of the universe appears to be accelerating suggests the presence of something dubbed dark energy that drives space apart. It seems likely that we have measured the value of a cosmological constant, or something like it.

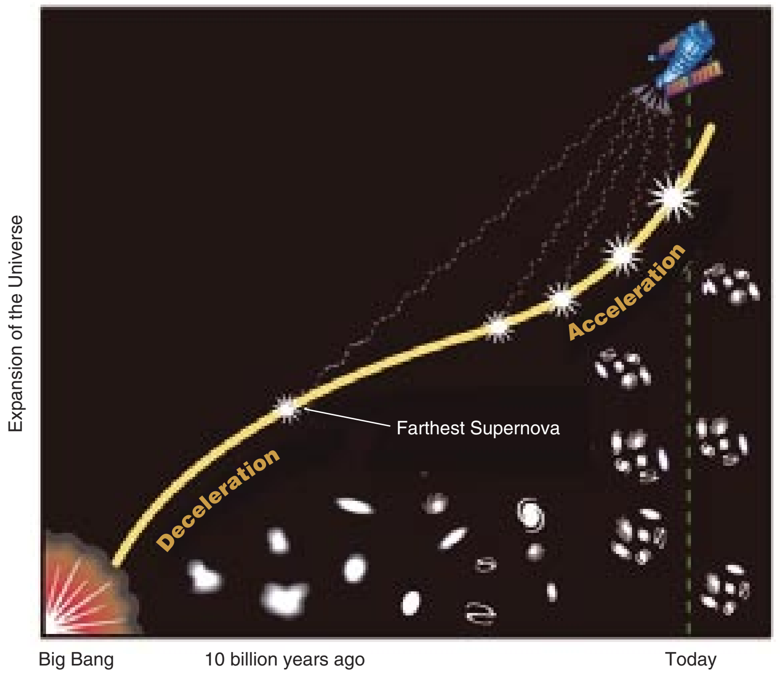
The presence of dark energy is already widely accepted because it explains many observations. The first indication that the rate of expansion of the universe is increasing was revealed by observations of Type Ia supernovae and was confirmed in detail by the Wilkinson Microwave Anisotropy Probe (WMAP). Supporting evidence for the increasing rate of expansion also comes from studies of global geometry, structure formation, cosmic age, galaxy clustering, and X-ray–emitting galaxy clusters. All these observations leave little doubt that in some sense Einstein's cosmological constant is a reality: the energy of the universe is dominated by "empty" space whose gravitational effect is to pull the universe apart.



The composition of the cosmos.



The Sloan Digital Sky Survey (SDSS) consists of two separate surveys in one: galaxies are identified in 2-D images (right), then have their distances determined from their spectra to create a 2 billion light-years deep 3-D map (left) where each galaxy is shown as a single point, the color representing the luminosity — this shows only these 66,976 out of 205,443 galaxies in the map that lie near the plane of Earth's equator.



Supernovae are used to map the expansion of the universe — the rate at which galaxies are moving apart. Distant supernovae offer a glimpse of the past when gravity was slowing the expansion of the universe, then dominated by matter. In contrast, observations of nearby supernovae show that the universe's expansion is now speeding up as the pull of dark energy overwhelms the gravitational attraction of matter.

Since we have no theory of dark energy, anything we learn is an unexpected discovery. A simplistic unification of quantum mechanics and gravity predicts an amount of dark energy larger than that observed by a factor of 10^{120}. Some modern scenarios predict that the amount of dark energy decreases with time, instead of staying constant as in Einstein's concept. For these reasons, dark energy is among the most exciting new developments in fundamental physics. Because dark energy seems to control the expansion of the universe, we cannot predict the fate of the universe without understanding the physical nature of dark energy. As we develop this understanding, we will be poised to answer the profound question: will the universe last forever?

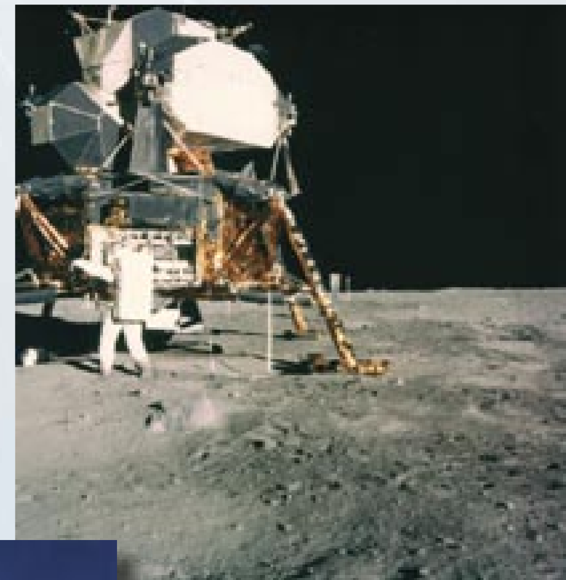
As we look at the universe today, we estimate that it consists of about 4% ordinary matter, made of the familiar elements from the periodic table (in the form of stars, planets, gas, and dust); 26% nonbaryonic dark matter, thought to be a new kind of particle left over from the early universe; and 70% dark energy (which can be considered to have mass, too, because energy $E = mc^2$). To learn how dark energy really works, we need to measure its properties in more detail. It is spread so thin that it can only be studied in the enormous volumes of deepest space, where its cumulative effects make its presence evident. The first step in the exploration of the dark energy will be to measure its density and pressure and how they change with time.

Initial observations by the Hubble Space Telescope (HST) point the way toward a dedicated, special-purpose instrument that could provide a much better measurement of the bulk properties of the dark matter than Hubble can. These measurements can determine whether the dark energy is really constant, as Einstein conjectured, or whether it has changed over cosmic time, as suggested by some string theorists. Real data on this question would help us discover where dark energy comes from, and what the future of our universe will be.

The Dark Energy Probe, which will be executed jointly with the Department of Energy as the Joint Dark Energy Mission (JDEM), will deploy the best available technology to study this effect. Constellation-X, LISA, and the Inflation Probe will provide independent constraints to verify the measurement and increase its precision.

Tests of General Relativity

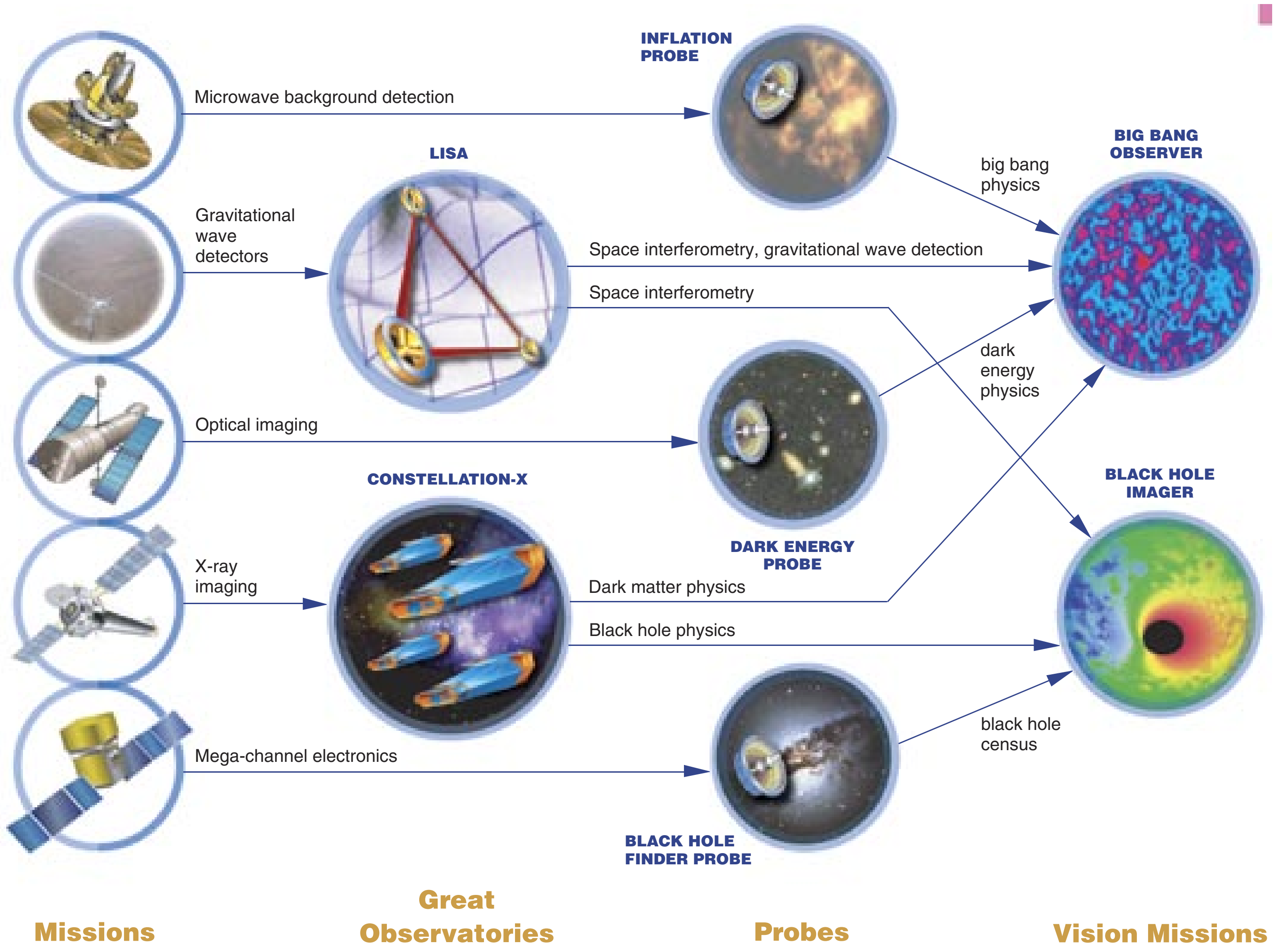
Beginning with the Apollo program, careful monitoring of the distance to the Moon, with a precision of better than 1 centimeter, has led to some of the most sensitive tests of Einstein's general relativity theory to date.

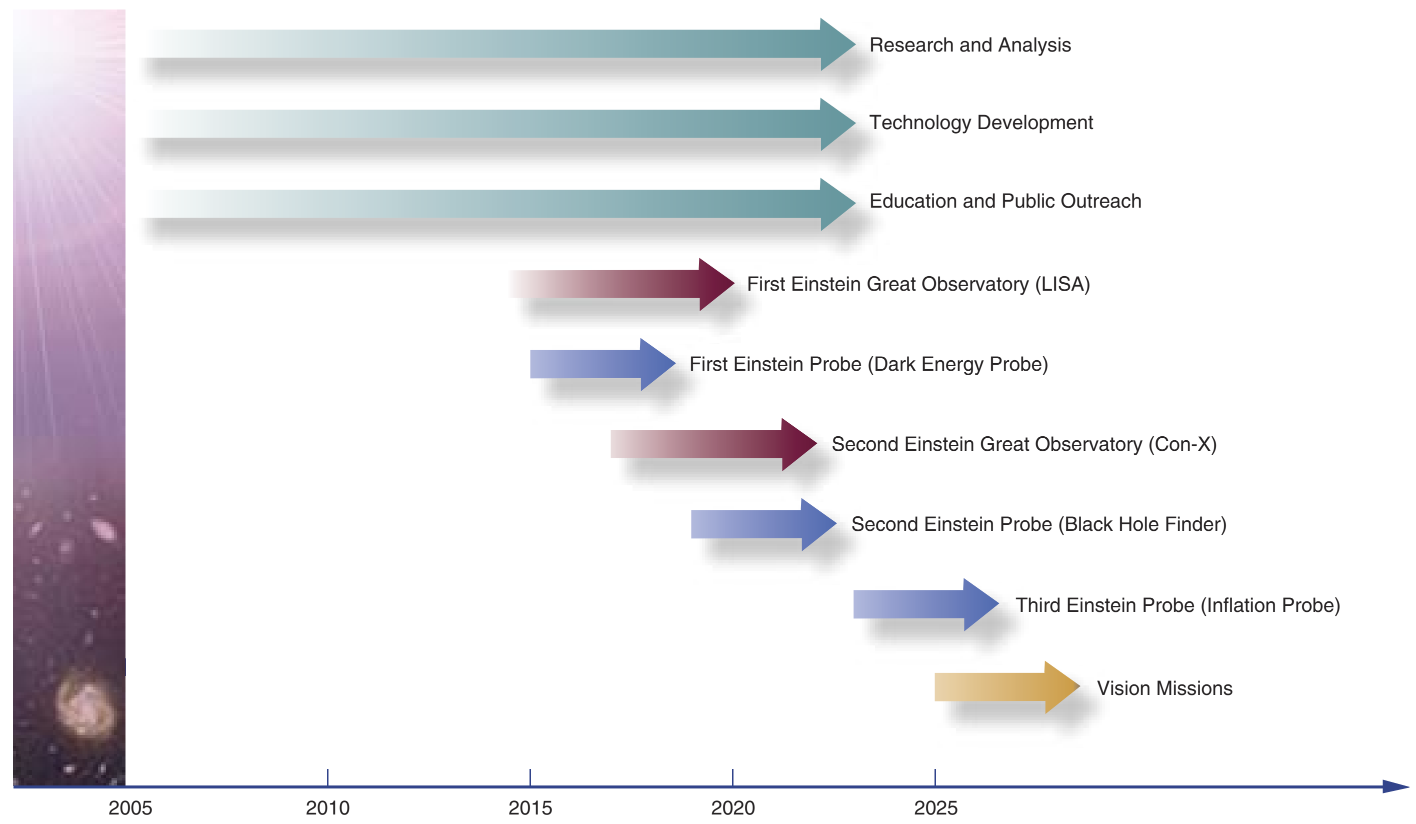


"Gravity is the force that rules the universe. To understand its workings, to the finest degree, is to understand the very nature of our celestial home." —M. Bartusiak in *Einstein's Unfinished Symphony*

Beyond Einstein: Connections with the Fundamental Physics of Gravity

The Beyond Einstein science program lies at the forefront of the nation's agenda in basic research. The questions and the framework for addressing them follow closely NASA's role in exploring the frontiers of fundamental physics, as outlined in *A 21st Century Frontier for Discovery: The Physics of the Universe*, the interagency plan published in 2004 by the White House Office of Science and Technology Policy. This is no accident, since that report was itself based on a synthesis of prioritization by many studies of various committees of the National Academies of Science that emphasize the primacy of these questions. Beyond Einstein also has a fundamental science and technology connection with NASA's other solar system science and exploration goals. Most of what we know about the validity of Einstein's general theory of relativity has stemmed from NASA's legacy in probing the curved spacetime of the solar system. These include lunar laser ranging using the Apollo astronauts' retroreflectors, radar and Doppler ranging to landers on Mars and to interplanetary probes, and radar ranging to Mercury and Venus. Though the curvature of spacetime in the solar system is weak, experiments reaching precisions of one part in 10 trillion have confirmed that Einstein's theory provides the correct description of gravity to at least 0.01% precision. As we move beyond Einstein in our unified understanding of general relativity and quantum mechanics, NASA should continue to subject gravity and its underpinnings to tests of extreme precision in its solar system missions. A departure from Einstein's theory would shed light on the dark energy problem, and could also be of key importance in interpreting results from gravitational-wave observatories. With the right instruments on NASA spacecraft, the solar system becomes a laboratory for seeking the effects of new physics: dark matter, dark energy, and perhaps even new dimensions of space.





Notional Beyond Einstein timeline showing expected progress 2005 to 2025 and beyond.

Notional timeline of the Beyond Einstein Great Observatories, Einstein Probes, and Vision Missions, with techniques and areas of study.

Beyond Einstein: The Program

The Beyond Einstein program has three major elements that work together to explore the farthest extremities of space and time. The two Great Observatories, LISA and Constellation-X, will provide dramatic new ways to answer questions about black holes, the Big Bang, and gravitational waves. The focused line of moderate-size Einstein Probe missions will each study a specific deep question: black hole discovery, inflation, and dark energy. The supporting program of forward-looking technology development; foundational and exploratory studies in theory, modeling, and predictive simulation; and education and public outreach will enable us to grasp these questions, create the technology to enable missions that realize the visions of the Beyond Einstein program, and inspire and train the next generation of scientists and engineers.

The Einstein Great Observatories

LISA and Constellation-X will use the complementary techniques of gravitational-wave and X-ray spectroscopy to study black holes. They will probe space, time, and matter in the extreme environment near black holes and track their evolution with cosmic time. These two facilities will be a major resource for a broad astronomy and physics community. The National Academy of Sciences' Decadal Survey *Astronomy and Astrophysics in the New Millennium* developed community consensus on the most important science questions and funding priorities. The survey recommended both LISA and Constellation-X as high priorities for this decade. The complementary information provided by LISA and Constellation-X is critical to answering the broad science questions that motivate the Beyond Einstein program. (Both missions also contribute critical data to other science goals, described in the following chapters of this document.) LISA's gravitational waves offer an entirely new way to sense physical activity throughout the universe.

The Einstein Probes

The Einstein Probes will be fully competed, scientist-led mission opportunities focused on the specific scientific mysteries identified in this document. To minimize cost and maximize science return, multiple approaches to each goal will be developed and scrutinized before mission selection. An associated technology program will enable this. Some Einstein Probes may include substantial contributions from other agencies (national and international). The goal is to launch one every three to four years.

The Einstein Probes address focused science questions identified as high priorities by the science community. The Committee on the Physics of the Universe (CPU) gave high priority to determining the nature of dark energy. Polarization of the cosmic microwave background, an imprint of gravitational waves from the period of inflation, will set limits on the amplitude and frequency distribution of these waves. The study of the polarization of the cosmic microwave background was identified as an important area by the Astronomy and Astrophysics Survey Committee (AASC) report, and an Inflation Probe is a high priority recommendation in the CPU report.

The Einstein Probes also support the Einstein Great Observatory missions and serve as scientific and technical pathfinders for the Beyond Einstein Vision Missions of the following decades, Big Bang Observer and Black Hole Imager. For example, the Inflation Probe is an essential prelude to eventually embarking on a much more ambitious mission to detect the cosmic gravitational radiation directly with a Big Bang Observer. A survey of black holes by a Black Hole Finder Probe will find targets for the Black Hole Imager and complement Con-X and LISA. The importance of such a mission is highlighted in the AASC report.

The Dark Energy Probe (Joint Dark Energy Mission) is prioritized first among the Einstein Probes. The order in which subsequent Einstein Probes are flown will be determined by both science priority and technological readiness. NASA will conduct mission concept studies for all the Einstein Probes to assess mission concepts and evaluate technical needs. These studies, proposed and conducted by community-based collaborations, will be fully competed and will provide the information necessary to define the technology program and later set the launch order for the Einstein Probes.

Technology and Foundation Science

Vigorous technology development is essential for the success of the Beyond Einstein program. For the Einstein Great Observatories — LISA and Con-X — technology plans are in place, and the Beyond Einstein program includes the resources needed to implement them. For the Einstein Probes, key technologies must be further developed and demonstrated before the mission competitions can occur. The Vision Missions require a sustained, long-term, focused program to develop necessary new technologies.

The National Academy of Sciences reports endorse a technology program leading towards the Vision Missions: the AASC recommended investment in X-ray interferometry (for the Black Hole Imager), and the CPU report recommended development for a multi-interferometer gravitational-wave mission capable of nulling out astrophysical foregrounds, needed for the Big Bang Observer. The technology development plan for the Beyond Einstein program is described in Chapter 6.

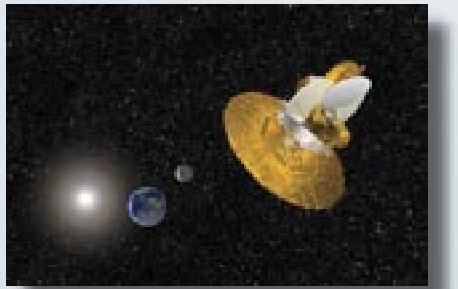
The successes of COBE, WMAP, and many other NASA science missions owe a considerable debt to theoretical studies that shaped their concept, design, and data analysis. These missions resemble laboratory experiments as much as they do astronomical observatories, and their success emerged as a result of sophisticated quantitative planning at all stages of development, with the universe itself regarded as part of the experimental setup. The programs described here are similarly complex and require an investment in theoretical modeling at all levels from astrophysics to instrument response. Early, explicit, and stable support for foundational theory will lay the conceptual foundations of projects, develop mission-critical analysis and simulation and modeling software, foster the growth of teams, provide training for a larger community, and help provide leadership in education and outreach. The Beyond Einstein program addresses these needs by including theory as part of the advanced technology needed for program success; this is consistent with the recommendation of AASC.

CENTAURUS A AT DIFFERENT WAVELENGTHS

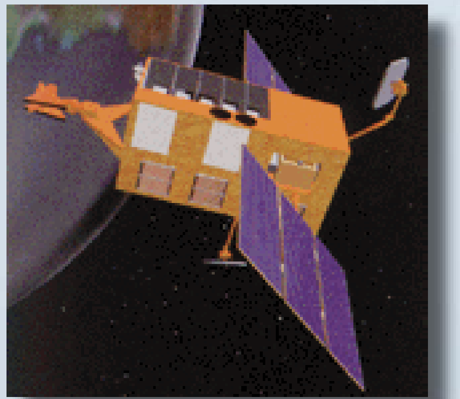
Astronomical objects show many different faces to the universe. The same object — in this case, the peculiar galaxy Centaurus A — looks unrecognizably different when viewed from different perspectives. Only by combining these different views can we gain a true understanding of their underlying nature. LISA and Constellation-X will reveal yet a different face to objects like merging galaxies, enabling us to come that much closer to understanding the evolution of the universe.

Centaurus A at X-ray, ultraviolet, visible, mid-infrared, and radio wavelengths.

OPERATIONAL MISSIONS



WMAP **The Wilkinson Microwave Anisotropy Probe** was launched in 2001 and released its first all-sky map in 2003, showing the universe at 379,000 years old. WMAP observes the entire sky from its position at L2, and measures the angular size of the temperature fluctuations (fluctuation spectrum) of the cosmic microwave background from 22 to 90 GHz. WMAP measures the fluctuations with differential microwave radiometers that take the difference in temperature between two regions. These fluctuations are generated by various physical processes that produce different amounts of energy and different angular scales. Peaks in the fluctuation spectrum can help scientists determine if the universe is open or closed. WMAP has a sensitivity of 20 microkelvins per 0.3 pixel. The results of WMAP today favor the inflationary model of cosmic fluctuations over the topological defect model for producing the structure that we see in the universe today. In addition, WMAP has also detected the signature of the first stars in the universe, emerging a mere 200 million years after the Big Bang.



RXTE **Rossi X-ray Timing Explorer** has been observing the X-ray sky since 1996. It uses timing signals to study the dynamics of strong gravity around black holes and neutron stars and was able to see the movements of accreting material orbiting black holes and neutron stars, discovering evidence for angular momentum of black holes and accreting pulsars with millisecond periods, which are probable precursors to radio pulsars. The RXTE All-Sky Monitor (ASM) has discovered many X-ray novae and facilitates observations by many other observatories.

An Integrated Program

The three elements of the Beyond Einstein program are tightly linked and are interwoven with other parts of the Astronomy and Physics Division science program. The Einstein Great Observatories will provide broad capabilities that will explore far beyond anything that has gone before. The Einstein Probes address focused questions of primary importance to the fundamental science community. Both elements will influence the design and observations of the more ambitious Vision Missions to come in the following decades. The overall program, supported and knitted together by shared theory, technology, research, education, and outreach, lays a foundation for achieving even more ambitious goals in the decades beyond. Explorers and the suborbital program are also expected to contribute to the science goals of Beyond Einstein.

Ultimately, Beyond Einstein missions will make direct measurements of signals from as close to the boundaries of the universe — the edges of space and time — that we can ever, in principle, observe. This program carries human exploration to the most extreme science frontier that humans can currently imagine: a frontier that only NASA can explore.

"...It was pretty amazing...After seeing this [exhibit] we thought, you know what, I'd like to go into space on the side. How it would be possible to do that as a career. It changed our thinking on how possible that is."

—16-year-old girl

Partnering with Science Museums

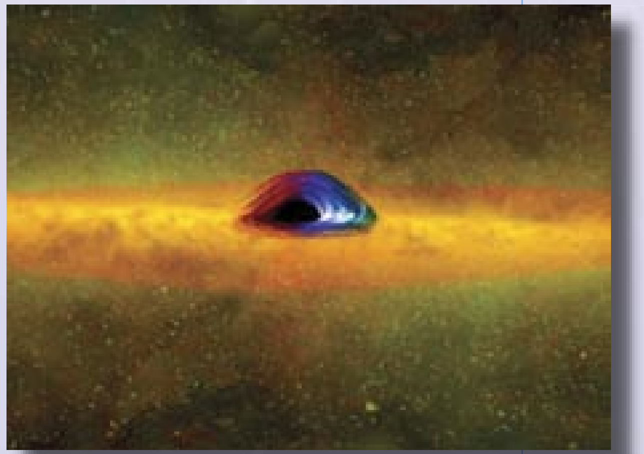
Cosmic Questions — a traveling exhibition on the Big Bang, black holes, dark energy, and space missions such as Chandra — has been visited by more than one million people and held over at each science museum on its national tour. The popularity of exhibits like *Cosmic Questions* reflects the public's high interest in research in astronomy and physics. Such exhibits engage not only the public; they provide professional development for science museum professionals and for the many teachers who visit with their students.

Theory Challenges

Global Simulations of Accreting Black Holes

In this frame from a sequence showing a turbulent accretion disk surrounding a nonrotating (Schwarzschild) black hole as seen by a distant observer, relativistic beaming and light bending distorts the image of the accretion disk. During the sequence, the view moves from a face-on (I=1 degree) view of the disk to an almost edge-on angle (I=80 degrees). The relativistic effects of beaming and light bending become increasingly apparent at higher inclinations.

Black Holes in a Radar Trap



European astronomers succeeded for the first time in confirming the signatures predicted near black holes by Einstein's theory of relativity in the light of the cosmic X-ray background. They observed a strong, relativistically smeared iron line in the average spectrum of roughly 100 active galaxies, whose X-ray light had been emitted when the universe was less than half its current age. The figure is an artist's concept of the relativistic flow of matter around a fast rotating black hole in the center of an accretion disk (orange). In the immediate vicinity of the black hole, the characteristic spectral fingerprint of iron atoms is smeared out by relativistic effects. The light from those atoms that moves towards the observer appears shifted to shorter wavelengths (blue) and much brighter than that on the receding side of the disk (red). In addition, the image of the disk in the vicinity of the black hole appears warped by the strong curvature of spacetime.

BEYOND EINSTEIN

SUMMARY of MISSIONS

For the Beyond Einstein science program, LISA will:

- Hear for the first time the sounds of roiling and ripping of spacetime in the mergers of giant black holes, and the death spirals of stars they capture and swallow.
- Map the knotted structure of space and time around a black hole and determine if the astonishing predictions of Einstein's theory — the apparent freezing of time and dragging of space around a black hole — are correct.
- Set important limits on background radiation and catastrophic events from the early universe, such as phase transitions in the vacuum or changes in the dimensionality of space.

Constellation-X will extend our capability for high-resolution X-ray spectroscopy by 25 to 100 times. Its key goals for Beyond Einstein science are to:

- Determine the structure of spacetime near event horizons of black holes by observing how matter releases energy as it spirals into a black hole horizon.
- Trace the evolution of black holes with cosmic time by obtaining detailed spectra of faint quasars — which are homes to supermassive black holes — at high redshift.
- Study very distant clusters of galaxies as to help discern the effects of dark matter and the evolution of the dark energy with time.

The Einstein Probe line is designed to address those critical science goals of the Beyond Einstein program that do not require facility-class observatories. The first three probes will conduct the following science:

The Dark Energy Probe (Joint Dark Energy Mission) will determine the nature of the dark energy that dominates the universe.

- The Inflation Probe will search for the unique signature of gravitational waves from inflation.
- The Black Hole Finder Probe will survey the universe for black holes.

The Vision Missions aim at long-term goals and guide exploratory technology development.

- The Black Hole Imager will observe swirling matter right down to the edge of the event horizon.
- The Big Bang Observer will detect signals from all important sources of gravitational waves since the Big Bang, and may directly detect gravitational waves from inflation.

2 Origin & Evolution of Cosmic Structure

How did the complex universe, filled with stars, galaxies, and planets, come to be? This is one of humanity's oldest and deepest questions. The Beyond Einstein program addresses how the universe began. We must also ask why the universe is not a formless continuum of matter but is instead filled with rich structure that extends from the cosmic horizon to galaxies, stars, and planets.

The images of the infant cosmos from the Cosmic Background Explorer (COBE) and the Wilkinson Microwave Anisotropy Probe (WMAP) show that, half a million years after the Big Bang, the universe was extraordinarily smooth, with temperature fluctuations of only a part in 100,000. The ESA–NASA Planck Surveyor mission, and ultimately the Inflation Probe, will measure the properties of these primordial fluctuations in exquisite detail. In the next stage of the Astronomy and Physics Division science program, we seek to understand how these tiny inhomogeneities grew into the structures that we observe today:

This HST image of the Whirlpool Galaxy (M51) delineates the structure of a classic spiral galaxy. New stars are forming in the bright pink regions; the yellow central core is the home of older stars.

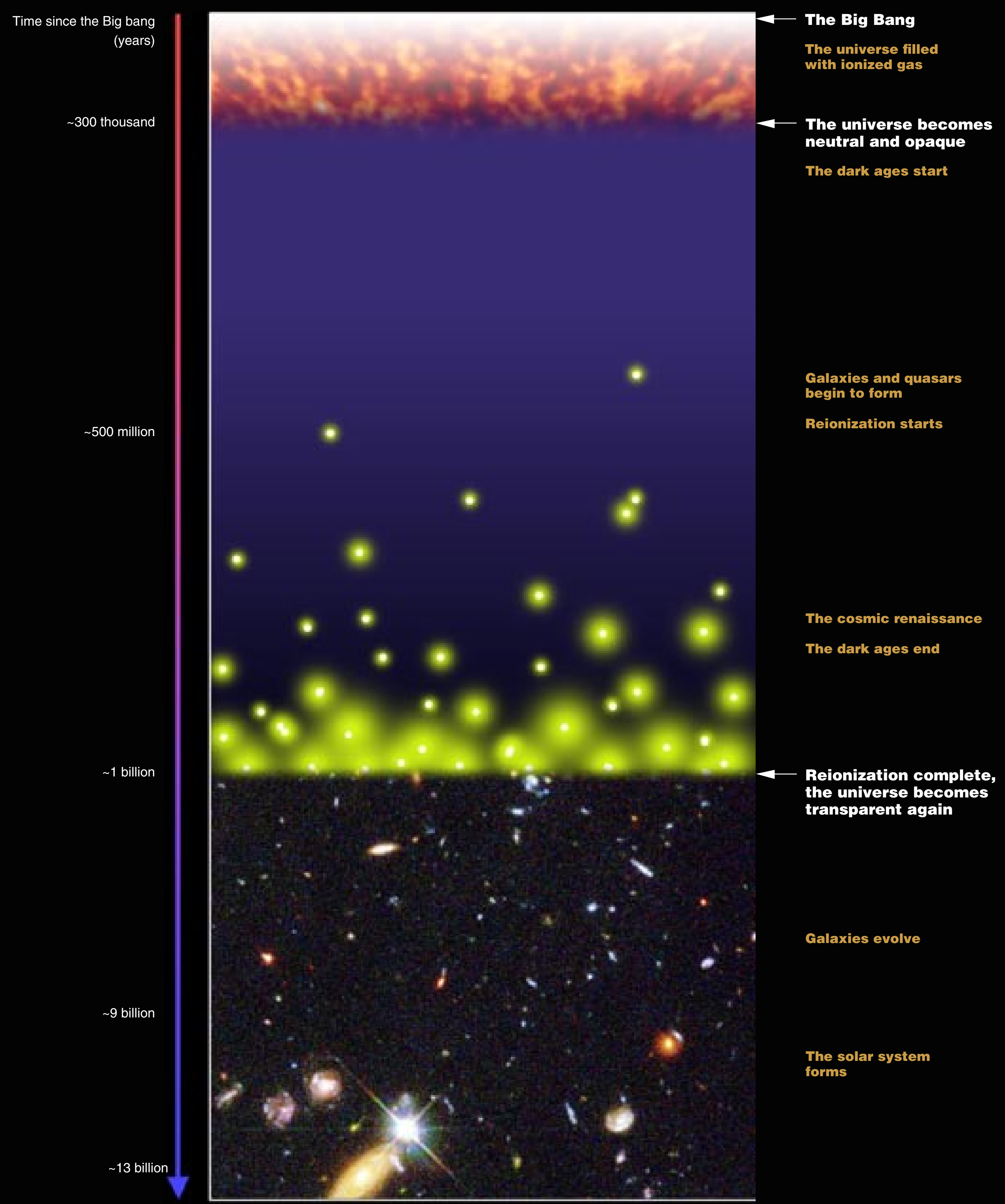
a cosmic web of dark matter and baryons, punctuated by galaxies and clusters, and enriched with heavy elements. Given a description of the primordial fluctuations and the matter and energy contents of the universe, numerical simulations can accurately calculate the evolution of dark matter clustering down to the scales of individual galaxies. For the first time in history, it appears that we know enough about these initial conditions and cosmological parameters such that they are not the major source of uncertainty in understanding cosmic structure formation. Today's frontier is understanding how gas dynamics, star formation, feedback from young stars and accreting black holes, and metal enrichment operate within this background of dark matter.

The key questions that guide our exploration of the origin and evolution of cosmic structure are:

- **How did the first stars, galaxies, and quasars form, and how did they influence their surroundings?**
- **How do baryons and dark matter interact to form galaxies and systems of galaxies?**
- **How do supermassive black holes form and grow, and how do they interact with their galactic hosts?**
- **How does the distribution of intergalactic baryons change over time?**
- **What is the formation history of our own Galaxy, the Milky Way, and its immediate neighbors?**

"The most incomprehensible thing about the universe is that it is comprehensible."

—Albert Einstein



Investigations that trace the evolution of cosmic structure rest on the ability of telescopes to function as time machines. Light travels at a finite speed, so we see distant objects not as they are today but as they were when they emitted their light. By studying the populations of galaxies and quasars out to great distances, we can map the changes of these populations over cosmic history. As photons traverse the expanding universe, their wavelengths stretch in proportion to the cosmic expansion factor, so their redshifts encode their times of flight. The most distant galaxies and quasars presently known emitted their light when the universe was about 800 million years old, 6% of its present age. Cosmic expansion has stretched their light by a factor of seven or more, shifting visible photons to infrared wavelengths of 3 to 4 microns.

The search for this redshifted light from the most distant objects in the universe mandates high sensitivity in the infrared, such as will be achieved by the James Webb Space Telescope (JWST) and the Single-Aperture Far-Infrared Telescope (SAFIR). This capability is also crucial for studying stars or accreting black holes that are obscured by interstellar dust, which re-radiates its absorbed energy at these wavelengths. Other probes of cosmic structure, such as the high-energy radiation from black holes and the absorption and emission by highly ionized atoms, demand sensitive ultraviolet, X-ray, or gamma-ray observations. Systematic surveys that cover wide areas over a broad spectrum of wavelengths are essential for comprehensive characterizations of the evolving populations of galaxies and quasars. High-precision measurements of the positions and motions of stars can provide unique insight into the structure and history of the Milky Way and its galactic neighbors.

Cosmic history is shown from recombination 300,000 years after the Big Bang (z~1089), through the first light sources era (<500 million years after the Big Bang, or z>9), through the epoch of reionization (1 billion years after the Big Bang, or z~6), to the present day (13.7 billion years after the Big Bang, or z=0).

Discover the First Stars, Galaxies, and Quasars

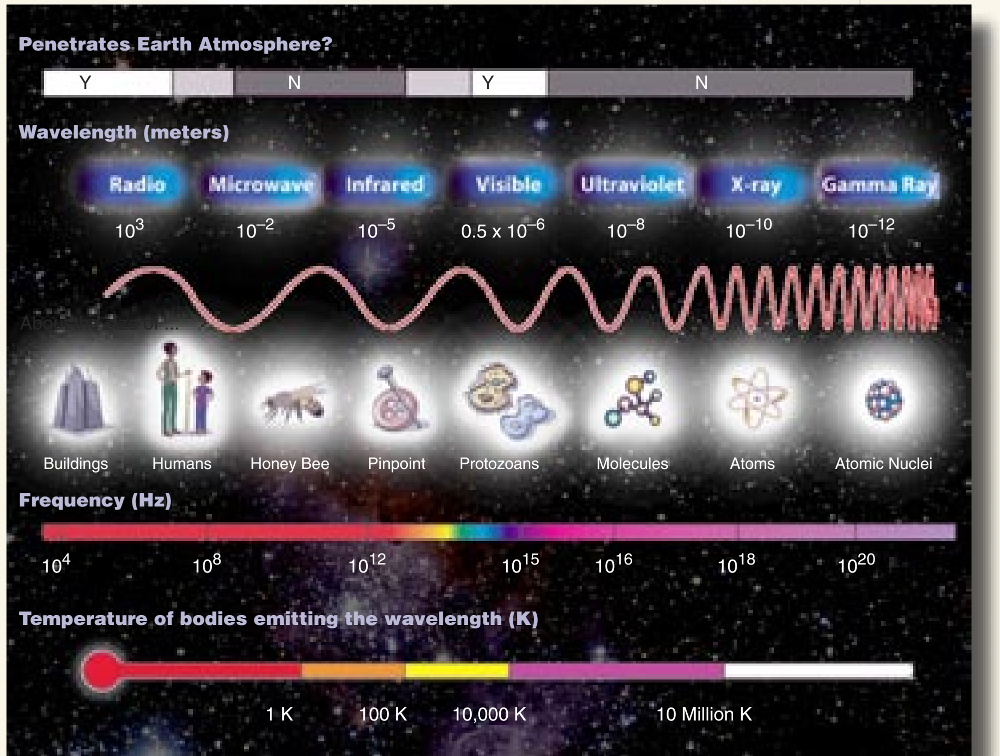
The new Astronomy and Physics Division missions, with their high sensitivity and wide wavelength range, will extend our vision to the epoch of the first stars and galaxies. Individual stars are too faint to see at cosmological distances, but young versions of today's globular clusters, containing hundreds or thousands of hot stars, are detectable to early times, as are exploding supernovae. Stars convert mass into energy via nuclear fusion, the same process that powers hydrogen bombs. Gas falling into the deep gravitational well of a black hole heats up and emits radiation, a process that can be 10 to 100 times more efficient than fusion. Accreting supermassive black holes, up to several billion times the mass of the Sun, are the central engines of the most luminous objects in the universe, quasars, and of their fainter cousins, generally referred to as active galactic nuclei (AGN).

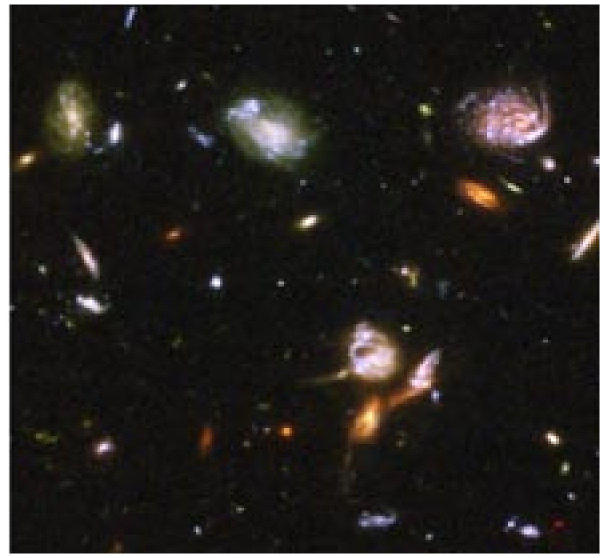
In observational terms, the distant frontiers of cosmic structure are the "dark ages," when neutral hydrogen made the universe opaque to ultraviolet light, and the epoch of reionization, when radiation from the first galaxies and accreting black holes ionized the hydrogen and lifted this intergalactic fog. Polarization measurements by WMAP suggest that reionization started as early as 200 million years after the Big Bang, but studies of the most distant quasars and galaxies suggest that this phase transition was not completed until half a billion years later. Present evidence about the beginning and end of reionization is sketchy, and its interpretation is controversial. We do not know whether the ionizing radiation came primarily from hot stars or accreting black holes, and whether it comprised mainly ultraviolet photons that slowly pushed out the edges of their local ionized bubbles or X-ray photons that penetrated through the neutral medium and reionized it more homogeneously. We have only speculative ideas about the galactic hosts of the ionizing sources, the mechanisms by which they formed, and their influence on their surroundings.

Extraordinary sensitivity at infrared wavelengths will make JWST the premier instrument of the next decade for investigating the dark ages and the sources of reionization. Deep-imaging surveys with JWST can detect star-forming systems with mass comparable to today's globular clusters out to a redshift of 20, a mere 200 million years after the Big Bang. These surveys could also discover hundreds of active

THE ELECTROMAGNETIC SPECTRUM

Just as the wavelength of a sound wave determines its pitch, the wavelength of a light wave determines its color. And just as sound waves can lie outside the range of human hearing, light waves, or, more generally, electromagnetic radiation, can lie far outside the range of human vision. The Astronomy and Physics Division science program includes missions that span the electromagnetic spectrum from radio/microwave wavelengths to the far-, mid-, and near-infrared (IR), optical light, ultraviolet (UV) light, X-rays, and gamma rays. The human eye sees less than one of these 100 octaves of wavelength. Electromagnetic radiation travels in discrete energy packets called photons. The energy of an individual photon depends on its wavelength: a single gamma-ray photon is a trillion times more energetic than a microwave photon.





black holes at redshifts of six and beyond, where only a handful of ultraluminous objects are currently known. Spectroscopic studies of the bright quasars at redshifts of 6 to 10 will probe the late phases of cosmic reionization, tracing the evolution of the surviving neutral hydrogen and mapping the variation in ionization from one line of sight to another. The brief but brilliant afterglows of gamma-ray bursts may also provide background lighting for these studies of intervening matter.

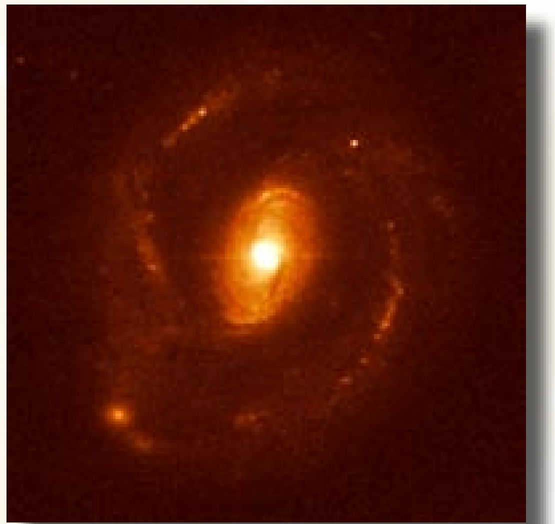
Beyond JWST, SAFIR will achieve another revolutionary advance in infrared sensitivity and diagnostic ability. While JWST will detect the brightest systems in the dark ages, SAFIR will probe the full population of sources. SAFIR's advantage over previous missions will be especially dramatic in the far-infrared, making it vastly more sensitive to redshifted thermal emission from the heated dust that may enshroud young stars or accreting black holes. Spectroscopy at these far-infrared wavelengths can provide crucial diagnostics of the cooling mechanisms that regulated the formation of the first cosmic structures. In the longer term, a Far-Infrared and Submillimeter Interferometer (FIRSI) mission could achieve the high angular resolution needed to map the internal structure of these early objects.

The Inflation Probe described in Chapter 1 will provide an entirely different window on this era. One technique measures the minute polarization signal from cosmic microwave background (CMB) photons that are scattered by free electrons during and after reionization. Observations from all of these missions will map out the history of reionization, showing when the first ionizing sources "turned on" and indicating whether the radiation from these sources suppressed (or perhaps triggered) gas condensation and star formation in other low-mass dark matter halos.

Finally, we will gain indirect information about the first stars and galaxies by studying the fossil record of heavy elements in intergalactic gas and in the oldest stars of the Milky Way and nearby galaxies. Ground-based telescopes and the Far-Ultraviolet Spectroscopic Explorer (FUSE) presently provide the necessary spectroscopic tools for such observations at optical and ultraviolet wavelengths, re-

(Left) The Hubble Ultra-Deep Field (HUDF), the deepest image of the universe ever obtained. Nearly all the objects visible in this image are galaxies. The light from most of these galaxies has traveled for 5 to 12 billion years to get to us. (Right) A detail from the HUDF image, revealing dynamical interactions between galaxies. Galaxies in the early universe are typically more irregular and asymmetric than galaxies today.

Cosmic redshift and lookback time

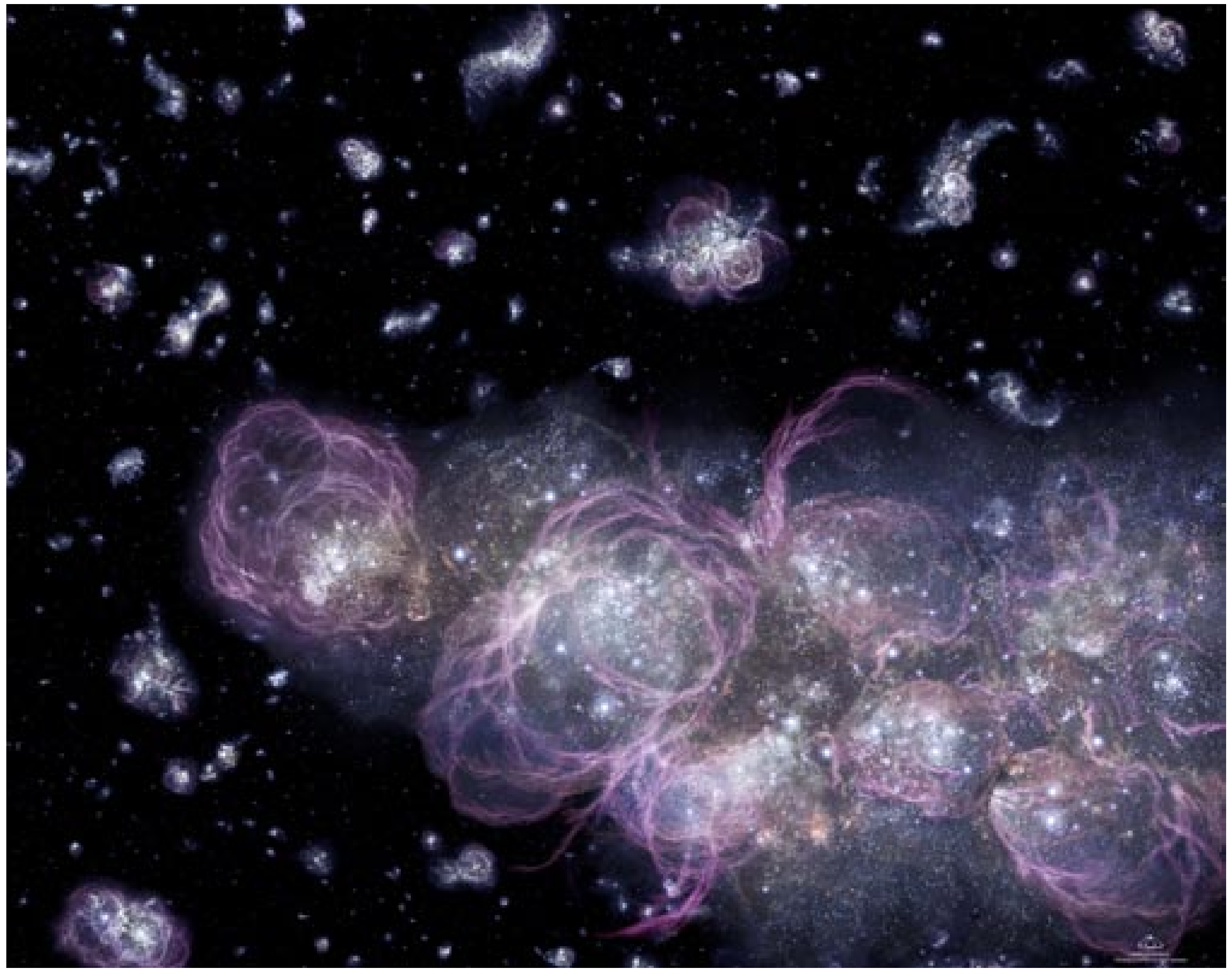


As the universe expands, the wavelengths of any photons traveling through the universe grow in proportion. Different species of atoms emit and absorb light at specific wavelengths, so we can often tell the factor by which the light from a distant object has been stretched, or redshifted, by the cosmic expansion. This redshift factor tells us how much the universe has expanded since the light was emitted, and from this we can deduce the light travel time, or lookback time, to the emitting source. Since the redshift is directly measurable, astronomers often refer to epochs of cosmic history by the corresponding redshift. Light redshifted by a factor of two was emitted 9 billion years ago, roughly 5 billion years after the Big Bang. A redshift of five corresponds to a lookback time of 13 billion years, 1 billion years into cosmic history. Redshifts of 10 and 20 represent epochs 100 million years and 150 million years after the Big Bang, respectively. The quasar in the HST image above emitted its light billions of years ago.

spectively. Much more sensitive measurements could be obtained with the Cosmic Origins Spectrograph (COS) designed for HST or by a future mission providing ultraviolet spectroscopic capabilities. The Terrestrial Planet Finder Coronagraph (TPF-C) mission described in Chapter 4, with an order of magnitude larger collecting area than HST, will be a powerful tool for stellar population investigations at optical wavelengths.

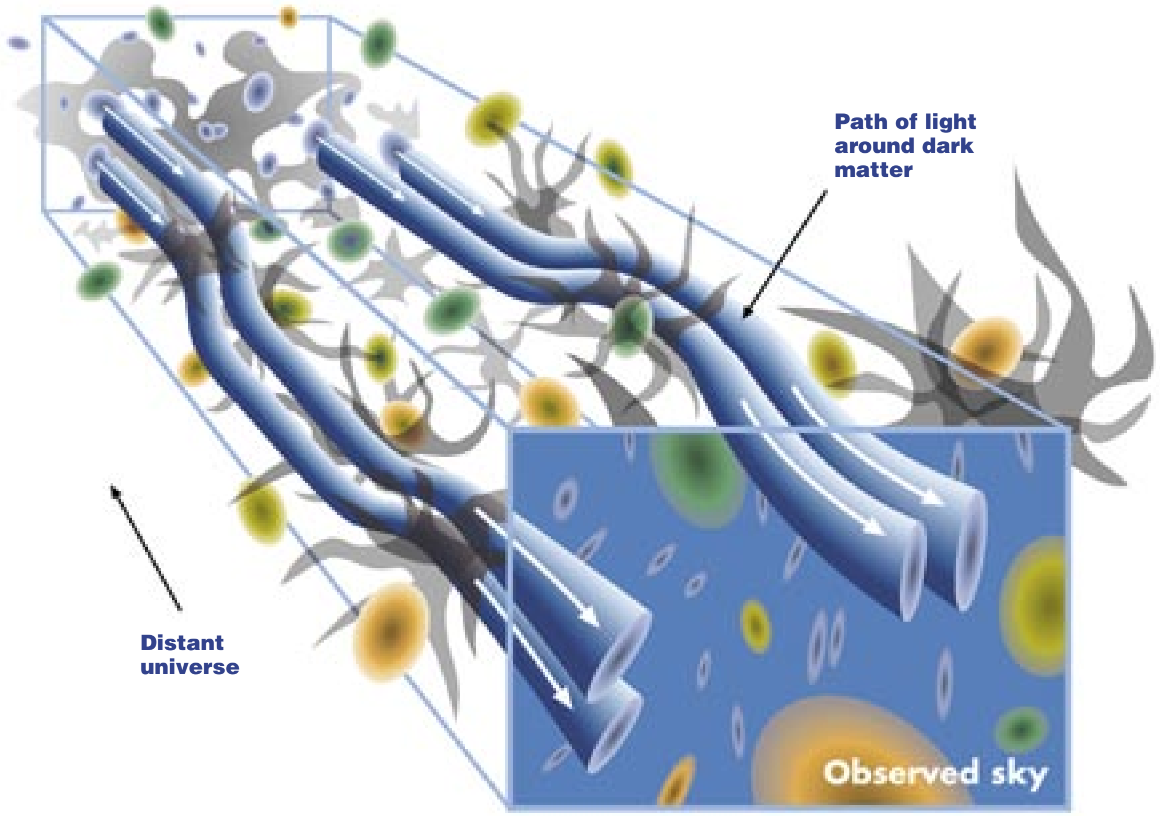
Trace the Formation and Evolution of Galaxies

Moving to later times, the grand challenge is to understand the mechanisms of galaxy formation and evolution, including the history of cosmic star formation, the growth of galaxy masses, and the processes that determine the morphologies, sizes, luminosities, and colors of present-day galaxies. HST has been the premier instrument for such investigations over the last decade and a half, with its unprecedented ability to resolve the structure of distant galaxies and to measure their emission from ultraviolet to near-infrared wavelengths. The 1996 Hubble Deep Field campaign revolutionized the study of galaxy evolution, and more recent campaigns like the Hubble Ultra-Deep Field, Galaxy Evolution from Morphology and SEDs (spectral energy distributions), and the Great Observatories Origins Deep Survey have taken advantage of HST's Advanced Camera for Surveys (ACS) to reach even greater depth or cover much wider area. The Wide- Field Camera 3 would substantially expand HST's survey power by providing a much wider field of view and greater sensitivity at near-infrared wavelengths.



Artist's impression of the universe at age 1 billion years. The scene is dominated by starburst galaxies with bright knots of blue stars and hot bubbles from supernova explosions.

Vigorous star formation often occurs in dense clouds thick with interstellar dust. The ability to penetrate dust with near-infrared observations and to observe the dust emission itself at mid-infrared and far-infrared wavelengths is crucial to unraveling the story of galaxy evolution. The combination of Spitzer and HST observations is now rapidly advancing our understanding of dust obscuration and the relative contributions of quiescent star formation and violent starbursts to the growth of galaxies' stellar masses. Continuing surveys with these facilities and with the upcoming Herschel Space Observatory will greatly increase the numbers of comprehensively studied galaxies from the "adolescent" universe, 2 to 5 billion years after the Big Bang, the era in which galaxies developed the shapes and characteristic features that we still see today. Large samples are needed to trace the evolution of these properties and reveal the physical mechanisms at work. The combination of high-resolution images from space with spectroscopic measurements of internal galaxy dynamics from large ground-based telescopes is especially powerful.

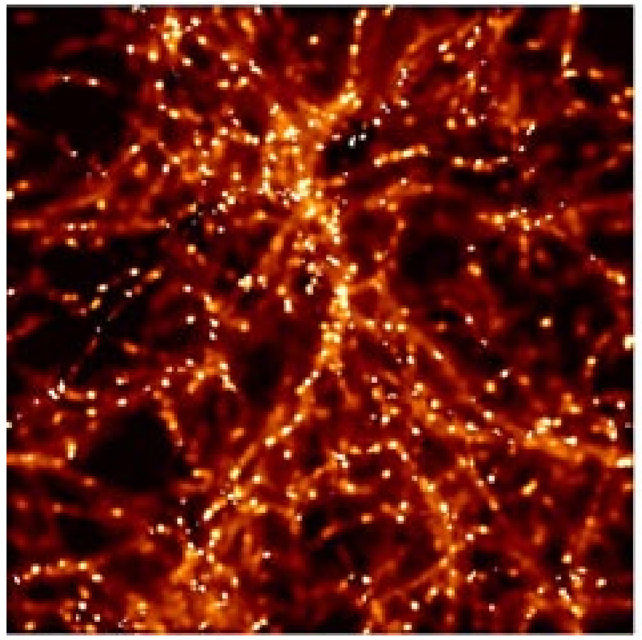


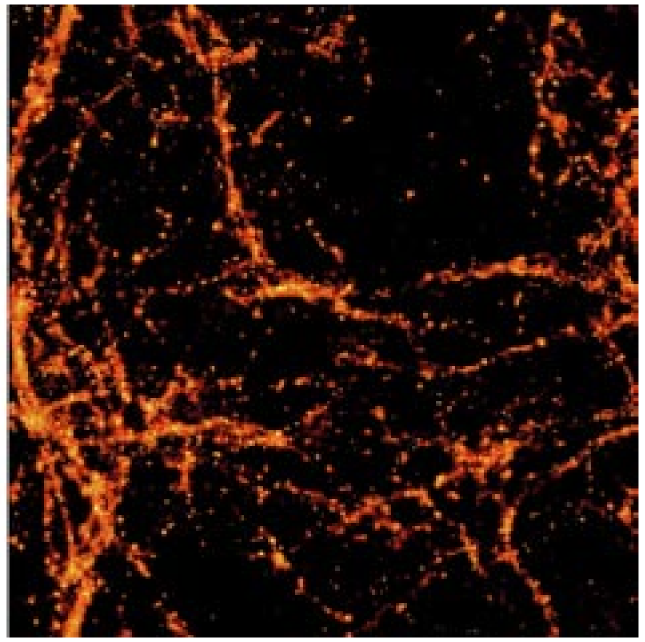
(Left) Light rays from distant galaxies travel a tortuous path through a universe filled with a web of clustering dark matter. Every bend in the path of a bundle of light from a distant galaxy stretches its apparent image. The orientation of the resulting elliptical images of galaxies contains information on the size and mass of the gravitational lenses distributed over the light path. (Right) HST Advanced Camera for Surveys image of the galaxy cluster Abell 1689. The blue, arc-like features are background galaxies whose images have been distorted by the gravitational lensing effect of the cluster. These distortions can be used to measure the dark matter content of the cluster. Individual galaxies in more typical regions of the universe produce weaker distortions; these can be measured statistically to determine the average mass profiles of galaxies.

For the most luminous systems of the adolescent universe, and the full population at more recent epochs, the Galaxy Evolution Explorer (GALEX) adds vital diagnostic power with its all-sky survey at the ultraviolet wavelengths dominated by emission from hot young stars. The Wide-field Infrared Survey Explorer (WISE) will soon provide a complementary capability at near-infrared wavelengths, where the red giants of old stellar populations are dominant. Panchromatic studies of well-resolved, relatively nearby galaxies will help decipher the cascade of physics that ties the global dynamics of a galaxy to the molecular clouds where stars and planets form.

JWST, and eventually SAFIR, can take these studies of galaxy assembly and evolution much further. Their greater sensitivity will enable deeper surveys, revealing the small galaxies that are the building blocks of larger, more mature systems. More importantly, they can provide detailed physical diagnostics of galaxies over a wide range of cosmic history, using high angular resolution and spectroscopy to characterize global structure and dynamics, and to measure the distributions of temperatures and chemical composition among the galaxies' stars and interstellar gas. JWST spectra will also show when complex organic molecules, the interstellar precursors of biology, first appeared in the evolving universe.

Other missions could provide major new capabilities for wide-area surveys. One design for the Dark Energy Probe is a wide-field optical and near-infrared imager, which would be used to measure cosmic acceleration by finding distant supernovae and to track the growth of dark matter clustering through measurements of weak gravitational lensing. The surveys carried out for these purposes would also revolutionize the study of galaxy and quasar evolution, reaching a depth similar to that of the deepest HST images over an area hundreds or thousands of times larger. With high angular resolution and a wide wavelength range, these surveys will trace the growth of galaxy sizes, the rise and fall of their star formation rates, the aging of their stellar populations, and the transformation of their morphologies over most of cosmic history. Wide area is especially important for tracing galaxy evolution through to the present day, since the volume probed by any deep and narrow survey inevitably becomes small at low redshift. Alternative designs for the Dark Energy Probe of the Beyond Einstein program supplement or replace deep imaging with low-resolution spectroscopy, enabling massive galaxy redshift surveys at moderate redshift. These would map the evolution of galaxy clustering and galaxy spectral energy distributions over a large span of cosmic history.





(Left) The network of intergalactic filaments in a hydrodynamic cosmological simulation at redshift of two, as traced by neutral hydrogen. The faintest structures shown would be readily detectable at optical wavelengths by Lyman-alpha absorption against background quasars. The brightest knots correspond to young galaxies. The simulation is 17 million light-years on a side at this redshift.

(Right) The network of filaments in a larger volume simulation at the present day, as traced by highly ionized oxygen atoms (OVII). Detecting this hotter, shocked gas requires X-ray measurements. The faintest structures shown would be detectable in absorption measurements by Constellation-X if the oxygen abundance in these regions is 1/3 the solar abundance. The simulation is 230 million light-years on a side.

The formation of a galaxy is initiated by the condensation and cooling of gas within a dark matter halo, but theoretical studies leave many open questions about the complex interplay between baryons and dark matter. Weak gravitational lensing, which measures the subtle distortion of the shapes of distant galaxies as their light is bent by the gravity of foreground objects, provides a remarkable new tool for mapping the extended distributions of dark matter around galaxies. The high resolution of space-based images offers a huge advantage for such studies, and extensive weak-lensing surveys are underway using ACS on HST. JWST will be still more powerful in this regard because of its higher resolution at red and infrared wavelengths and its ability to measure fainter, more numerous background sources. The wide field of view of an imaging Dark Energy Probe would make it ideal for weak-lensing studies; this would be one of its major tools for studying dark energy, and the same surveys would trace the evolving relationship between galaxies and their dark matter halos.

The most vexing challenges in galaxy formation theory involve feedback from supernovae, stellar winds, and accreting black holes. Many lines of argument suggest that feedback plays an essential role in regulating star formation and enriching the intergalactic medium, and that it may control the baryonic masses of galaxies by ejecting large amounts of gas before it can form into stars or by preventing gas from cooling and accreting onto galaxies in the first place. However, the specifics of these interactions are largely a matter of speculation, guided by a limited amount of anecdotal evidence. The key to developing an empirically grounded picture of feedback is to obtain sensitive observa-

Dark matter and baryons

All of the matter that we encounter in our everyday world is made up of protons and neutrons, referred to collectively as baryons, and the much lighter electrons that accompany them. Stars and planets are made of baryons, in gas, liquid, or solid form. Most of the baryonic matter in the universe is hydrogen and helium; the heavier atoms that are the backbone of solid materials and the building blocks of life are created in the cores of stars and dispersed into space during the last phases of a star's life, or ejected violently at its explosive demise.

We learned in the 20th century that all baryons together comprise only a minority fraction, about 1/6, of the matter in the universe. The nature of the remaining 5/6, the dark matter, remains one of the great puzzles of modern astrophysics, though it is usually thought to be a new type of exotic elementary particle. Dark matter and baryons interact with each other via gravity, and it is the gravitational pull of dark matter that drives the assembly of galaxies.

The image above was taken by the Roentgen Satellite (ROSAT) X-ray observatory and shows a huge concentration of dark matter 150 million light-years from Earth. The image shows a small group of galaxies immersed in a cloud of hot gas about 1.3 million light-years in diameter. The clue to the presence of dark matter is that the hot gas should have dissipated into space long ago unless it was held together by the gravity of an immense mass.

tions of the full range of galaxy types over a wide range of wavelengths. Such observations can detect the many phases of gas that may be present, characterize their dynamical state and metallicity, and correlate their presence with star formation, nuclear activity, and galaxy mass. Many of the Astronomy and Physics Division missions can contribute to this effort through the kind of systematic studies described above. Especially important diagnostics of the large-scale outflows observed in rapidly star-forming galaxies come from ultraviolet and X-ray spectra, which detect the main transition lines from highly ionized atomic species. Chandra and FUSE are both valuable tools for this purpose, but Constellation-X and ultraviolet spectrometers like COS will be much more powerful, measuring the mass, composition, and velocity structure of these outflows in a wide range of nearby galaxies. In the longer term, high angular and spectral resolution from a large ultraviolet/optical telescope and a large-area, high-resolution X-ray mission could extend these studies to the early epochs when most of the stars in the universe formed.

Unveil the Galaxy–Black Hole Connection

While galactic-scale outflows driven by supernovae and stellar winds have been studied for many years, it has only recently become apparent that black holes may play a key role in galaxy formation. This realization has emerged largely from studies with HST, which show that essentially all nearby galaxies with substantial stellar bulges harbor central supermassive black holes. The ubiquitous presence of these central objects shows that most massive galaxies must once have hosted quasars or lower-luminosity AGN, even if they are quiescent today. Furthermore, there are tight correlations between the mass of the black hole and the mass or velocity dispersion of the stellar bulge. Either the bulge properties determine the amount of fuel that is fed to the growing black hole, or feedback from black hole accretion terminates the growth of the galaxy itself.

Deep observations with the Chandra X-ray Observatory have resolved the diffuse X-ray background into discrete sources, which are predominantly accreting black holes. Many of the fainter sources are hosted by optically normal galaxies, suggesting that the ultraviolet and optical radiation from the accretion flow is absorbed by dust in the active nucleus or in the host galaxy itself. Spitzer is now providing a crucial complement to HST and Chandra with measurements at near-infrared wavelengths that are less easily obscured by dust, and at mid-infrared wavelengths that detect the thermal dust emission. Joint wide-area surveys with these three Great Observatories should take us much further in understanding the connections between quasar and galaxy evolution.

Future Astronomy and Physics Division missions will provide revolutionary new capabilities for investigating these problems. Higher angular resolution at near-infrared and optical wavelengths is crucial for studying the galaxies that host AGN and bright quasars in the nearby and distant universe, and for measuring the masses of dormant black holes in local galaxies via their influence on stellar motions. These investigations are central to understanding the galaxy–black hole connection and the history of black hole growth. JWST will be a significant advance over HST, especially for host galaxy studies at the red and near-infrared wavelengths that offer the best contrast between a faint galactic host and the glare of its active nucleus. Large optical telescopes, including TPF-C, will achieve higher resolution and be substantially more powerful for both types of investigations. The Black Hole Finder Probe described in Chapter 1 will conduct an all-sky survey, achieving a complete census of bright AGN. One technique proposes to use hard X-ray wavelengths that are least affected by obscuring gas. The Nuclear Spectroscopic Telescope Array (NuSTAR) will examine the brightest of these. These hard X-rays provide vital diagnostics to the mechanisms of black hole accretion and the physical conditions close to the event horizon. At the opposite end of the spectrum, JWST will have much greater sensitivity than Spitzer to the warm dust emission from obscured AGN. SAFIR will achieve another giant leap in sensitivity, and its large aperture should allow it to resolve the dusty tori of molecular gas that are thought to surround rapidly accreting black holes.

High-resolution X-ray spectra from Chandra and the European Space Agency's X-ray Multi-Mirror (XMM)–Newton mission are now yielding extraordinary new insights into the physics of accretion flows around supermassive black holes. However, these detailed physical measurements are possible only for the nearest AGN, which are much fainter than the luminous systems of the "quasar era," 2 to 6 billion years after the Big Bang, when large black holes experienced most of their growth and emitted most of their energy. Constellation-X will have 10 to 100 times the effective area of Chandra and XMM-Newton, so it can achieve detailed physical characterization of objects that current telescopes can barely detect, and it can push the X-ray detection boundaries

"It is what teachers of science need — professional scientists who have done research in science education and can provide ideas and concrete models to show how we can improve our own classes."
—Workshop participant, Boston

Professional Development for Astronomy Instructors

The Center for Astronomy Education is a national program dedicated to the professional development of introductory astronomy instructors (particularly community college instructors), with the primary goal of supporting a "community of practice." This model has been effective in improving instruction in systems where instructors often feel isolated from their professional peers. The Center's major initiative involves training through Teaching Excellence Workshops, offered at a dozen regional venues through a partnership with the University of Arizona's Conceptual Astronomy and Physics Education Research (CAPER) Team, and teaching resources and discussion available on the Center for Astronomy Education website (http://astronomy101.jpl.nasa.gov). More than 500 instructors are given individualized attention through the workshops each year.

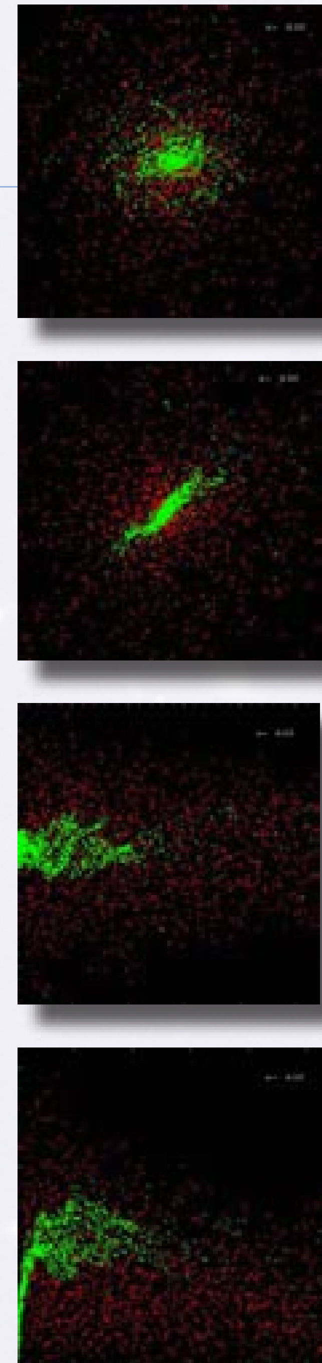
Theory challenges

Galaxy Collisions Awaken Dormant Black Holes

Snapshots from a computer simulation of the time evolution of a collision of two spiral galaxies with massive black holes at their centers. Color indicates temperature and brightness of the gas density. When the galaxies and their black holes collide, a quasar is ignited, which expels most of the gas in a strong wind. The remaining galaxy contains a large supermassive black hole but very little gas. The black hole mass and the end result is related to the size of the galaxy in agreement with observations.

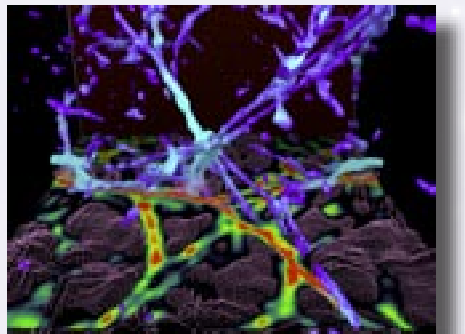
Merger of Black Holes

A supercomputer calculation of the gravitational waves produced in the merger of two supermassive black holes. The ripples represent the strong perturbations of spacetime expected when black holes collide and form one, even more massive, rotating black hole. LISA should be able to identify these collisions from across the universe.



Galaxy Formation through Hierarchical Clustering

In these simulations of the formation of galactic disks within dark matter halos, note that the gas (particles in green) decouples from the surrounding dark matter (particles in red) and settles into a centrifugally supported disk that broadly resembles typical spiral galaxies. The face-on and edge-on views show particle plots of a gaseous disk formed through dissipational collapse within a dark matter halo. The radial and rotational velocity views show radial and tangential velocity profiles of the gas and dark matter. Note that the gaseous disk is centrifugally supported and that the rotation curve is approximately flat out to about 20 kiloparsecs.



Cosmic Gas Density at Redshift 3

A hydrodynamic simulation of the cosmic gas density at redshift 3 for a sample box 8 million light-years on a side. These dense filaments are detected as the Lyman-alpha forest in absorption-line spectra of distant quasars.

themselves back to the threshold of the reionization epoch. A combination of deep surveys and targeted spectroscopic observations with Con-X will chart the evolution of the masses, spins, and accretion rates of active black holes. Con-X will also play a pivotal role in unraveling the galaxy-black hole connection by measuring the mass and energy of gas outflows from accretion disks. Chandra and XMM-Newton have discovered evidence for such outflows in a handful of nearby systems, and the Japan–U.S. Suzaku (Astro-E2) mission will be able to map them. Con-X observations will show whether these outflows are a ubiquitous feature of active galaxies and whether they have the properties needed to sweep up a galaxy's interstellar medium and drive it far into the dark matter halo. Following Con-X, an X-ray mission with much larger collecting area and angular resolution could extend studies of black hole accretion flows and their accompanying winds to high redshifts.

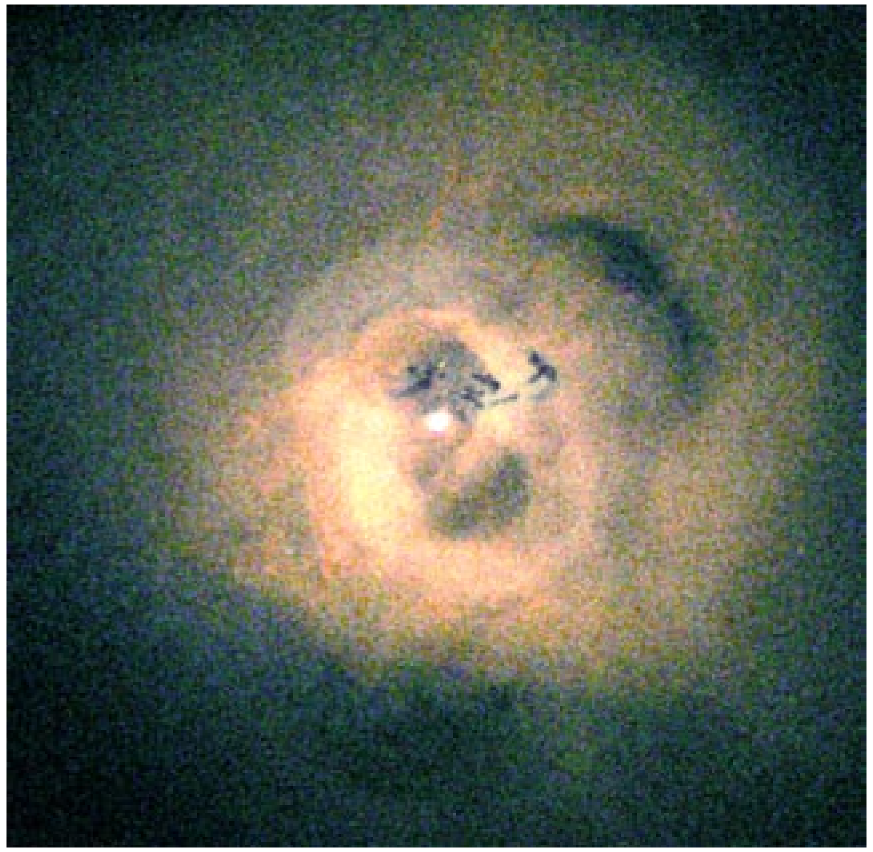
LISA will open a new window on the mechanisms of supermassive black hole growth by observing the signals from merging black holes in the previously unexplored spectrum of gravity waves. Today's massive galaxies are built in part by merging of smaller systems, and one of the unknowns of black hole evolution is whether they also gain much of their mass by mergers, following the mergers of their galactic hosts. LISA will trace the history of black hole mergers from the redshifts of the highest known quasars through to the present day. LISA is sensitive enough to detect even relatively low-mass systems merging at high redshifts, offering unique insight into the early growth of the black hole population. The gravitational-wave signature of a merger event can be decoded to reveal the masses, orbits, and spins of the merging objects, and precision spin measurements will yield important clues to the physics of black hole gas accretion. With the simplest form of gas accretion, growing black holes quickly spin up to approach the maximum spin that is physically possible. Recent accretion models based on sophisticated computer simulations predict spins that are rapid but still noticeably below this maximum rate, a distinctive and testable prediction. Mergers will, on average, slow down rapidly spinning black holes, so observations showing a wide range of spins would indicate that smooth accretion is frequently punctuated by merger events. Finally, LISA can determine the extent to which black holes grow by "silently" swallowing whole stars before they can be shredded by the black hole's tidal gravitational field. These giant gulps of mass accretion produce no significant electromagnetic radiation, but they still reveal themselves through the telltale ripples of gravity waves.

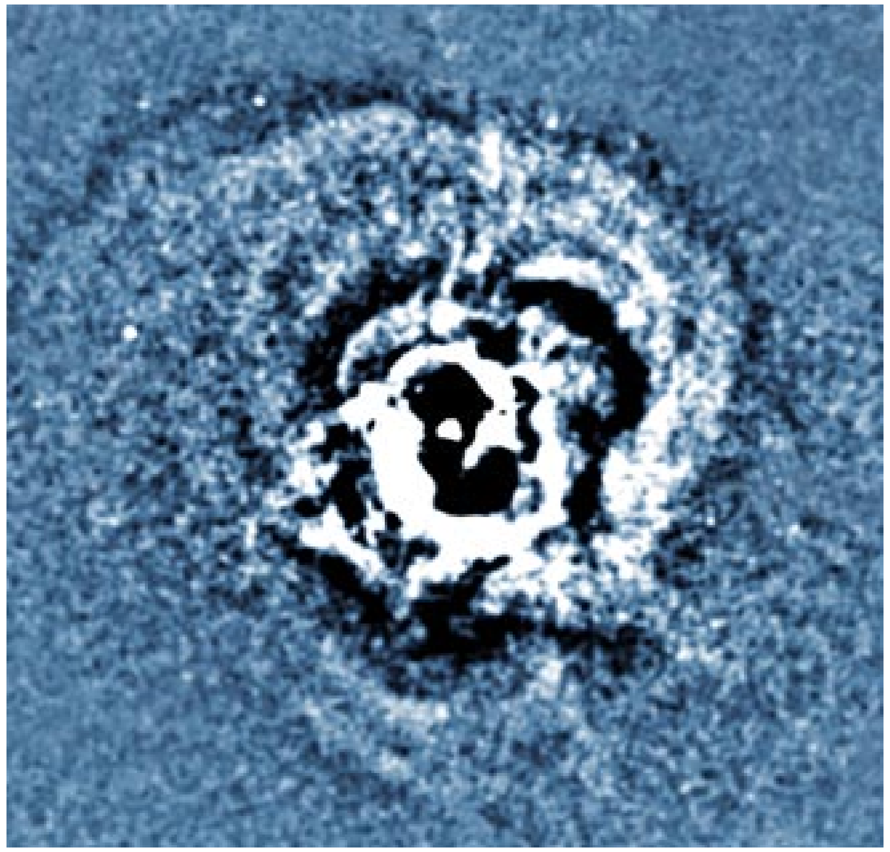
AGN are physically extreme objects, and blazar AGN are the most extreme objects of all, changing brightness by a factor of two or more on time scales of a few hours and emitting detectable gamma rays at energies a trillion times higher than optical photons. The leading hypothesis is that blazars represent jets of high-energy particles emanating from accreting black holes, moving toward us at more than 99% the speed of light. The physical processes that accelerate particles to these enormous energies are poorly understood. The international Gamma-ray Large Area Space Telescope (GLAST) mission, scheduled for launch in 2007, will detect thousands of blazars with high sensitivity. In combination with high-resolution radio imaging, it will directly probe the sites and mechanisms of particle acceleration. Relative to the Compton Gamma-Ray Observatory (CGRO), its nearest predecessor, GLAST will have much higher sensitivity and much greater positional accuracy, which may allow it to discover entirely new classes of objects that produce these energetic photons. These investigations will also show whether the diffuse cosmic background of gamma-ray emission comes from a currently unresolved population of faint blazars or a different physical process, perhaps megaparsec-scale shocks in merging galaxy clusters or the annihilation or decay of previously undiscovered, exotic particles. Finally, the most energetic gamma rays can lose energy as they traverse cosmic distances and interact with much lower energy infrared photons. Studies of the energy spectra of distant blazars will therefore allow a unique measurement of the infrared background, which is the cumulative product of star formation throughout cosmic history.

Reveal the Intergalactic Medium

In a large-scale view of the universe, galaxies are the basic unit of visible matter, but they account for only 10% of the cosmic baryon budget. Most of the remaining baryons are thought to reside in a diffuse intergalactic medium (IGM) that traces the cosmic web of dark matter filaments and sheets. Neutral hydrogen atoms in this filamentary web of photoionized gas can be detected at high redshift by the forest of Lyman-alpha absorption lines they produce in the spectra of background quasars. A thinner forest is present in the low-redshift universe, but theoretical models predict that much of the intergalactic gas is shocked to temperatures and densities where it is no longer detectable in hydrogen Lyman-alpha. HST and FUSE have detected absorption lines of ionized oxygen that trace the cooler phases of this shocked gas. Chandra has recently detected X-ray lines from hotter, more highly ionized oxygen. These results provide tentative support for the predictions of cosmological simulations, but if these predictions are correct, then the current observations trace just the highest peaks of the mountainous intergalactic terrain.

Chandra and XMM-Newton allow high-resolution spectroscopy, the indispensable capability for absorption measurements of intergalactic gas. The high sensitivity of Constellation-X will provide a further revolutionary advance in this capability. If the standard account of the missing baryons is correct, then Con-X will reveal an "X-ray forest" of oxygen, carbon, neon, silicon, and iron lines, which trace the dominant, hotter phases of the shocked





Chandra images of the core of the Perseus cluster of galaxies. (Left) Holes in the X-ray emission created by outflows from a supermassive black hole at the cluster center, which have pushed the hot gas aside. (Right) Enhanced contrast shows "sound waves" rippling out through the cluster, like the circular rings that form in water when a rock is dropped into a pond.

IGM. Completing the picture will require comparable new capabilities at ultraviolet wavelengths to map the cooler gas traced by hydrogen absorption and by less highly ionized heavy elements. The Cosmic Origins Spectrograph (COS) would be a valuable step along this path. A wide-field ultraviolet spectral imager could map line emission from the denser regions of the diffuse IGM, producing true three-dimensional images of the cosmic web. In the long term, a large-aperture ultraviolet telescope and a successor to Con-X could trace intergalactic metals down to very low densities, revealing the lush undergrowth of the ultraviolet/X-ray forest. In addition to mapping the evolving distribution of baryonic matter, these studies with Con-X and future ultraviolet/X-ray missions will measure the enrichment of the IGM, showing how heavy elements spread from galaxies to their surroundings.

Clusters of galaxies lie at the nodes of the cosmic web, where filaments intersect. Most of the baryons in clusters reside in the intergalactic gas, and higher density makes this portion of the IGM readily detectable in X-ray emission. Clusters were long thought to be relatively simple structures, containing gas in quasi-hydrostatic equilibrium, with typical central cooling times of a few hundred million years. Observations by Chandra and XMM-Newton reveal the situation to be much more complex, with intricate structures at the centers of many clusters and virtually no cooling of gas below 10 million degrees. There are hints that the central black holes of the massive central galaxies play a key role in creating these structures and suppressing gas cooling, but the case is far from proven.

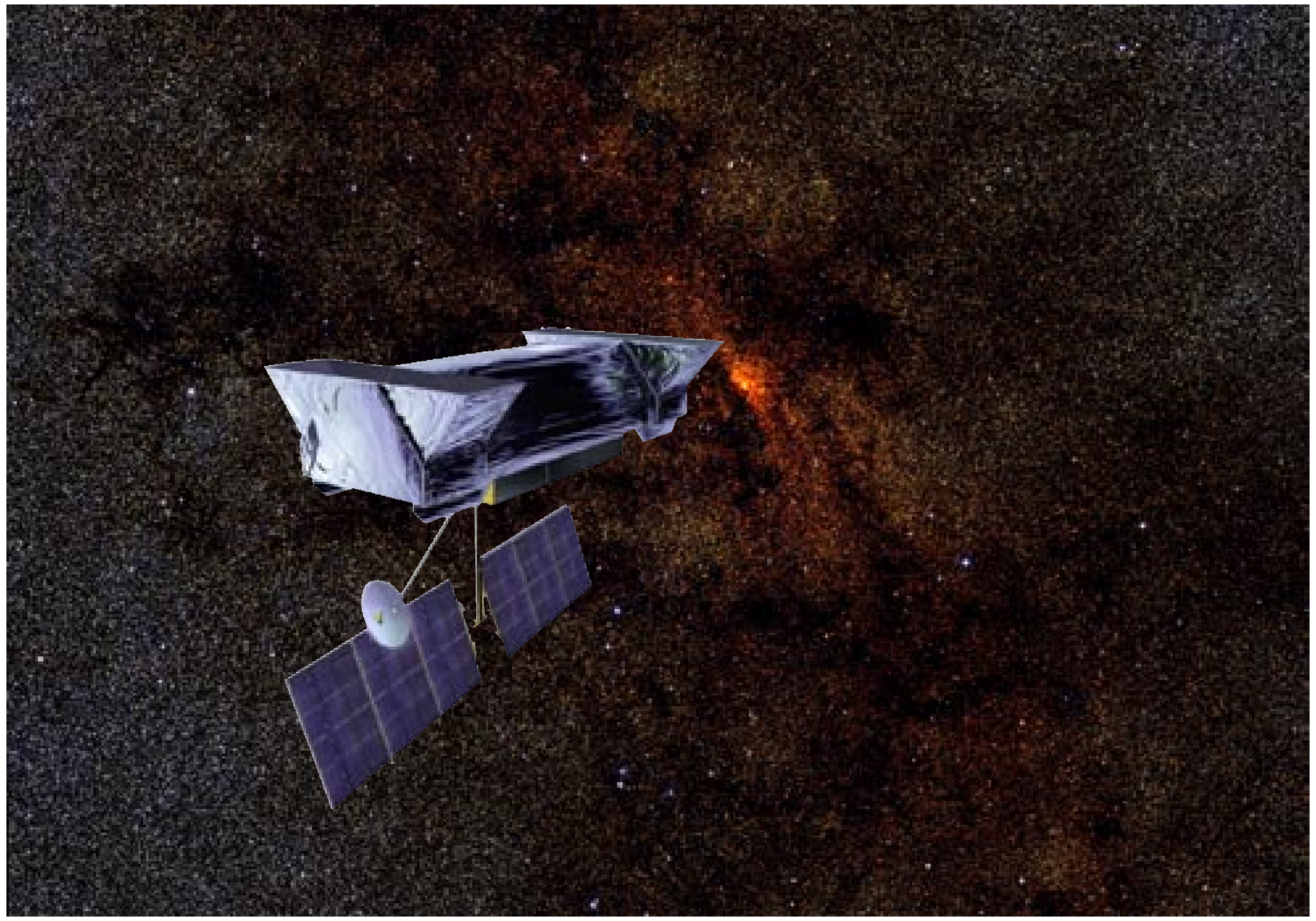
Con-X will be a superb instrument for unraveling the physical processes that govern the hot intracluster medium. In contrast to present X-ray telescopes, which mostly map the central 50% or so of rich clusters, Con-X will measure gas density and temperature profiles out close to the clusters' dynamical boundaries. With high spectral resolution, it can detect bulk flows and turbulence within the intracluster gas, testing the standard assumption of hydrostatic balance between pressure and gravity. It will measure the abundances of multiple atomic species from the centers of clusters to their outskirts, distinguishing models for the origin of intergalactic metals and pinning down the relative contributions of Type I (thermonuclear) and Type II (core collapse) supernovae. Con-X can also measure the history of cluster enrichment, obtaining accurate abundance measurements at lookback times as large as 10 billion years, when the universe was 25% of its present age. Basic luminosity and temperature measurements can be made out to still higher redshifts, revealing the early stages of cluster assembly. The Inflation Probe of the Beyond Einstein program will provide complementary measurements of intracluster gas via the Sunyaev-Zel'dovich effect, a distortion of the CMB spectrum by intervening hot electrons.

The high sensitivity of Con-X will also allow many of the traditional measurements of galaxy clusters to be extended to the hot gas halos of individual galaxies, providing new probes of dark matter distributions and revealing the interactions between gas accreted from the intergalactic medium and gas expelled by galactic winds.

One of the emerging questions in galaxy formation is whether the processes that apparently suppress cooling of hot gas in rich clusters also operate in the galactic mass range. If so, they could naturally explain the sharp cutoff at the bright end of the galaxy luminosity function and the surprisingly clear division between actively star-forming disk galaxies and "red and dead" bulge-dominated galaxies, which usually show no signs of star formation in the last several gigayears. Studies with Con-X and future ultraviolet and X-ray missions will show whether the hot gas halos of large galaxies are a reservoir that fuels their growth or merely a blanket that separates them from the infalling IGM.

Explore the Milky Way and Its Neighbors

Studies of cosmic structure formation probe observable phenomena over an immense range of space and time. However, we also gain crucial insights into galaxy formation by studying the galaxy we know the best, our own Milky Way, and the small number of neighboring galaxies that we can resolve star-by-star. The main components of the Milky Way are its gravitationally dominant dark matter halo, the thin stellar/gas disk in which the Sun resides, the puffier thick disk, the spheroidal bulge that dominates the central 1 to 2 kiloparsecs, and the diffuse stellar halo that extends to roughly 100 kiloparsecs, more than 10 times the Sun's Galactocentric radius. Similar features are seen in many other bright galaxies. Understanding the structure and origin of these components requires accurate measurements of chemical abundances, stellar distances, and stellar velocities, from which we can piece together the Galaxy's star formation and assembly history. Abundances and line-of-sight velocities can be measured with spectrographs on large ground-based telescopes, but the high angular resolution of space-based imaging makes it a uniquely powerful tool for geometric measurements of distances and proper motions (angular speeds), which together yield transverse velocities. Much of our present understanding of the Milky Way's dynamics rests on results of the ESA Hipparcos satellite, which measured the distances and proper motions of all bright stars within a few hundred parsecs of the Sun.



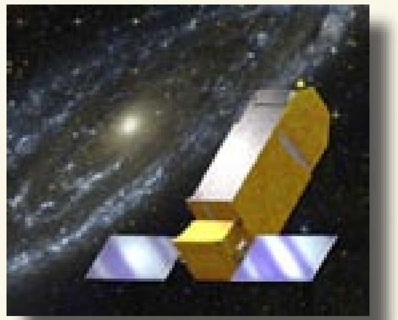
By precise measurements of star motions in the Milky Way, SIM PlanetQuest will help us understand the Galaxy's formation and its dark matter.

SIM PlanetQuest will transform this field by measuring the distances and motions of stars across the full extent of the Milky Way and within its nearest galactic neighbors. SIM PlanetQuest can measure proper motions of stars more than 1,000 times fainter than the Hipparcos limit with precision as high as 3 microarcseconds per year, roughly the angular speed of a snail crawling across the surface of Pluto. SIM PlanetQuest's high-precision measurements of faint stars, roughly 20,000 over the anticipated mission lifetime, will perfectly complement the all-sky survey of brighter stars by ESA's Gaia mission. Accurate distance measurements for faint field and globular cluster

OPERATIONAL MISSIONS

CHANDRA The **CHANDRA X-ray Observatory** — one of NASA's Great Observatories — was launched in 1999 and has unequalled spatial (0.3 arcseconds) and energy resolution in the X-ray band from 0.08 to 10 keV. Chandra is in a highly elliptical, 64-hour orbit, taking it about one-third of the way to the Moon and back again. Chandra uses grazing incidence mirror technology to focus (at 10 meters) the X-rays onto its instruments — a high-resolution camera, an imaging spectrometer, and two high-resolution grating spectrometers. In its five years in orbit, Chandra has made a host of important discoveries, including finding two supermassive black holes in a single galaxy (NGC 6240), which will one day merge together; discovering the lowest-frequency sound wave coming from the central region of the Perseus cluster (Perseus A), the result of a supermassive black hole explosion; finding the first case of a large black hole outside the nucleus of a galaxy; and owing to its superior angular resolution, producing the most detailed map of supernovae remnants (such as Cassiopeia A), showing details of the shock wave structure more clearly than ever, and jets of particles and rings of material never seen before (for example, in the Crab Nebula).

The Chandra education and outreach program is a leader in engaging science museums, planetariums, and classrooms in the nature of multiwavelength astronomy. The program emphasizes professional development for educators and access to scientific visualizations and authentic data.



FUSE The U.S.–France–Canada **Far-Ultraviolet Spectroscopic Explorer**, launched in June 1999, explores the universe at ultraviolet wavelengths that are inaccessible by HST. In particular, FUSE is determining the abundance of deuterium, an isotope of hydrogen that was formed in the Big Bang. Determination of its abundance is essential to constraining conditions in the Big Bang. Beyond this, FUSE will also investigate the hot interstellar gas, in order to understand the life cycle of matter between the stars, as gas cycles between stellar death and rebirth. A highlight of the education and public outreach program of the FUSE mission is its highly visible role in the Maryland Science Center in Baltimore, which is visited by over 600,000 persons per year.

HST The **Hubble Space Telescope** was launched in April 1990, and — thanks to regular upgrades of its instruments via space shuttle servicing missions — remains NASA's most productive scientific program. This impressive record of achievement continued into the second decade of HST's operation, with the installation in early 2002 of the Advanced Camera for Surveys (ACS) and a new active cooling system to reactivate the Near Infrared Camera and Multi-Object Spectrometer (NICMOS). The planned final 2004 space shuttle servicing mission to install the highest-performance ultraviolet spectrograph ever flown in space, the Cosmic Origins Spectrograph (COS), as well as the first truly panchromatic imaging system ever flown in space, the Wide-Field Camera 3 (WFC 3), has been held in abeyance since the Space Shuttle Columbia accident. Some engineering systems, in particular gyros and batteries, are in a degraded state. NASA is examining its options for servicing and safely de-orbiting HST.

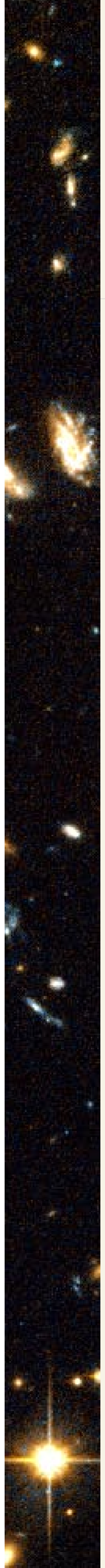
The importance of HST to the scientific community is matched by the positive role that the mission has played in educating the public about science. The observatory may be the best-known scientific facility in the world, with its results used in classrooms globally.

stars in the stellar halo will allow a robust reconstruction of its chemical enrichment history, showing whether the first stars in the forming halo produced the heavy elements that enriched subsequent generations or whether the halo was built by merging stellar systems that had already enriched themselves. Accurate motions of stars in the thick disk will show whether it is the remnant of an ancient act of galactic cannibalism.

SIM PlanetQuest will be a unique tool for studying the nature of dark matter, which dominates the mass of the Milky Way and the universe as a whole. The cold dark matter (CDM) hypothesis — that dark matter consists of massive, weakly interacting elementary particles — has had spectacular success in explaining structure from scales of the cosmic horizon down to individual galaxies. However, its success on subgalactic scales is an open and controversial question. The CDM scenario predicts dark matter halos that are ellipsoidal and contain substantial amounts of lumpy substructure. SIM PlanetQuest will map the gravitational potential of the Milky Way's dark halo, using the motions of individual stars, star clusters, and dwarf galaxies to pin down the halo's total mass, spatial extent, radial profile, and three-dimensional shape. The distant tidal streams emanating from dwarf spheroidal satellites and globular clusters will provide especially powerful constraints on departures from spherical symmetry and the presence of substructure, both of which tend to thicken the streams as they spread away from their source. Beyond the Milky Way's zone of influence, SIM PlanetQuest will measure the motions of 20 to 30 galaxies at distances up to 10 megaparsecs. With this detailed snapshot of positions and velocities in the Local Supercluster, we can use theoretical modeling to "run the movie backwards" and reconstruct the assembly of structure in our own cosmic neighborhood. This reconstruction will further test our ideas about dark matter and the origin of galaxies and large-scale structure.

While the dominant form of dark matter is probably some type of elementary particle, we have very limited knowledge of the possible contribution of "dim" objects: low-mass stars, free-floating planets, and the white dwarfs, neutron stars, and black holes that are the remnants of burned-out stars. One of the only ways to detect such objects individually is through gravitational microlensing, the temporary amplification they produce in background sources as they pass in front of them and gravitationally focus their light. Microlensing events have been detected towards the Magellanic Clouds and the Milky Way bulge, but the distances and masses of the lensing objects remain ambiguous because light curves alone have limited information. SIM PlanetQuest will definitively resolve the nature of microlensing objects in the Milky Way by observing events from a vantage point significantly displaced from Earth and by measuring tiny positional deflections of the amplified stars. SIM PlanetQuest will also determine the total mass distribution of the Milky Way disk, and thus the amount of dim matter that it contains, by measuring the vertical motions of stars.

In the years after SIM PlanetQuest and after JWST, our understanding of the Milky Way and the local cosmic environment could be transformed once again by a large ultraviolet/optical telescope. With very high angular resolution and sensitivity at the wavelengths richest in atomic structure lines, such a telescope would be able to measure chemical abundances and line-of-sight velocities of bright red giant stars in dozens of nearby galaxies, and of Sun-like stars throughout the Milky Way and some of its closest neighbors. The former measurements could extend the archeological studies that we presently apply to the Milky Way to representative examples of the full population of galaxies, while the latter would deepen our understanding of our own Galactic home.



SUMMARY *of* MISSIONS

Future Astronomy and Physics Division missions will make vital contributions to our understanding of the origin and evolution of cosmic structure.

JWST will:

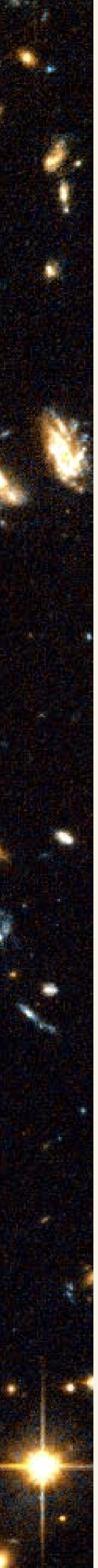
- Observe the first generations of stars, galaxies, quasars, and supernovae, and discover the sources that reionized the universe.
- Measure reionization of the intergalactic medium through spectroscopy of background sources.
- Detect the infrared emission from dust-obscured star-forming galaxies and quasars.
- Map the history of cosmic star formation and the assembly of galaxies using deep imaging and spectroscopic surveys and weak gravitational lensing.
- Image the host galaxies of quasars.
- Identify the first appearance of organic molecules in the universe.

Constellation-X will:

- Constrain supernova and AGN feedback mechanisms by measuring gas in galactic outflows.
- Trace the evolution of the cosmic black hole population by measuring masses, spins, and accretion rates as a function of redshift.
- Map the "missing baryons" in the diffuse intergalactic medium by measuring the absorption they produce in the spectra of background quasars.
- Discover the physical mechanisms that govern the state of hot gas in galaxy clusters.
- Determine the metal enrichment of hot gas in clusters, groups, and intergalactic filaments.

LISA will:

- Measure the merger history of supermassive black holes.
- Determine the distribution of black hole spins, probing gas accretion mechanisms and the relative contribution of mergers and accretion to black hole growth.
- Determine the frequency with which black holes "silently" swallow whole stars.



Dark Energy Probe may:*

- Map the history of galaxies and accreting black holes, complementing JWST deep surveys with much wider area imaging surveys at optical wavelengths and/or with low-resolution spectroscopic surveys.
- Use weak gravitational lensing to measure the growth of dark matter clustering and the evolving relationship between galaxies and dark matter.

Inflation Probe may:*

- Determine the global history of reionization by measuring the polarization of rescattered CMB photons.

Black Hole Finder Probe may:*

- Trace the evolution of the cosmic black hole population, complementing Constellation-X by surveying the full sky and measuring hard X-ray emission that penetrates obscuring gas and dust.

SIM PlanetQuest will:

- Reveal the early assembly and enrichment history of the Milky Way Galaxy by accurately determining distances and ages of stars and star clusters.
- Map the gravitational potential of the Milky Way's stellar disk and dark matter halo.
- Test the leading hypothesis for the nature of dark matter by measuring the shape and lumpiness of the dark halo.
- Determine distances and velocities of galaxies in the Local Supercluster, enabling reconstruction of the history of our cosmic neighborhood.
- Conduct the first survey of all objects, dark and luminous, in the Milky Way disk and bulge, and determine the nature of objects causing microlensing towards the Magellanic Clouds.

SAFIR will:

- Probe the full population of galaxies and accreting black holes out to very high redshifts.
- Diagnose the physical processes operating in high redshift galaxies by molecular spectroscopy.
- Measure redshifted emission from heated dust in quasars and star-forming galaxies.
- Resolve the structure of dusty gas tori thought to surround accreting black holes.

**Einstein Probes will be selected through a competitive process and their final implementation is not yet determined.*

GLAST will:

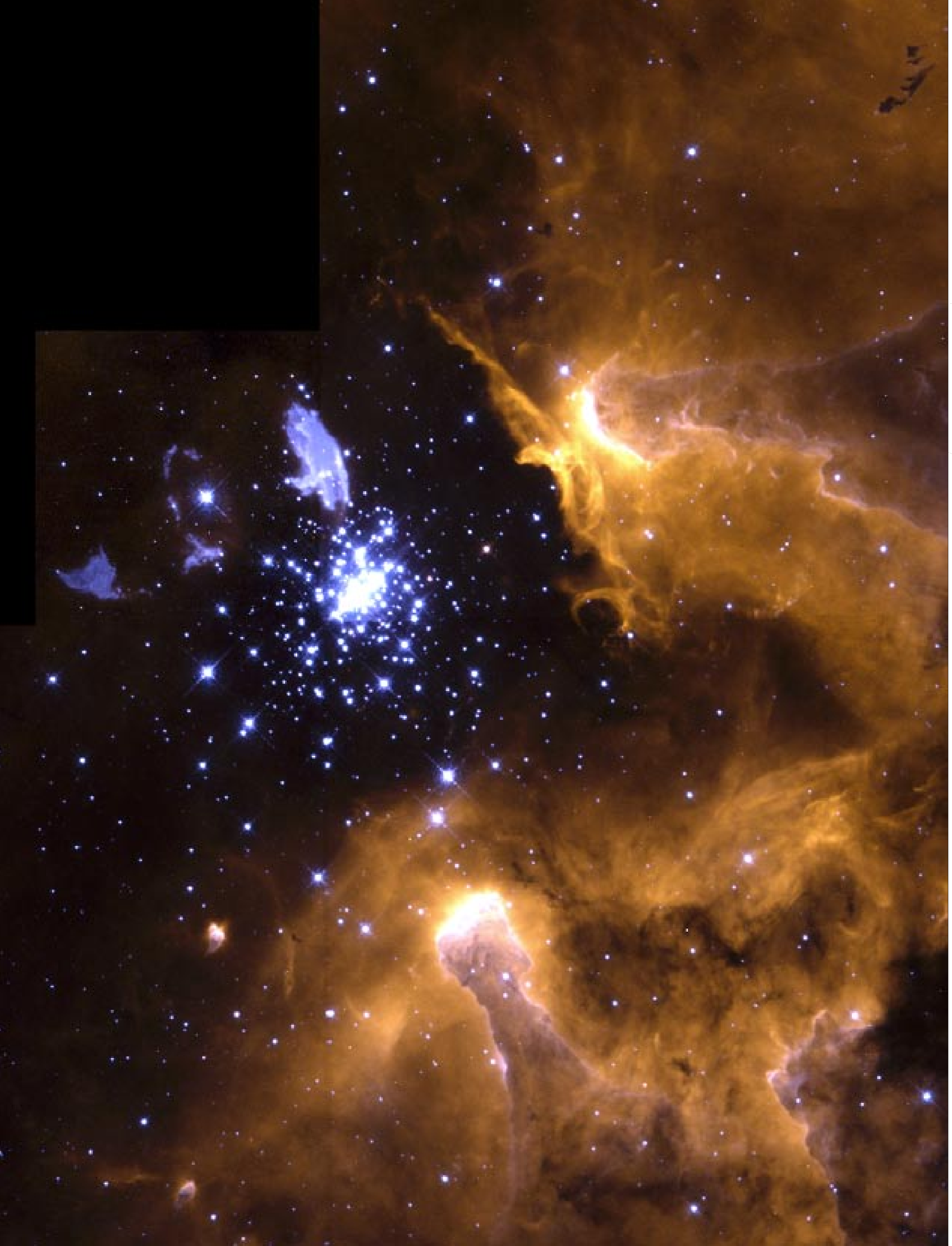
- Study the physical processes that accelerate particles to extremely high energies.
- Reveal the sources of the cosmic gamma-ray background.

Future large ultraviolet/optical missons will:

- Constrain feedback mechanisms by measuring gas in galactic outflows.
- Measure the masses of dormant black holes in nearby galaxies.
- Map the "missing baryons" in the diffuse intergalactic medium, complementing X-ray measurements by providing higher sensitivity to cooler gas.
- Determine the metal enrichment of the diffuse intergalactic medium.
- Map the chemical enrichment and line-of-sight velocities of Sun-like stars throughout the Milky Way and of red giant stars in many neighboring galaxies.

NuStar will:

- Conduct a census for black holes over selected regions of the sky.



3 Origin & Destiny of Stars

To the ancients, much about the natural world was strange, exotic, and mysterious. As culture and science developed over the centuries, humans obtained awareness and insight into the nature of the Sun and Earth, the stars and the universe. What was previously mysterious is now understood and serves as the foundation for deeper knowledge. However, many fundamental aspects of the lives of stars require sophisticated space observatories for full study, and hence have been cloaked in secrecy until the past few decades. We can now build the tools to determine how systems like the solar system form and evolve toward suitable sites for life. We can also explore a fascinating variety of bizarre and exotic objects such as black holes, neutron stars, and cosmic rays, gaining new insights into the laws of nature and the behavior of the universe.

This HST image of the giant galactic nebula NGC 3603 captures various stages of the life cycles of stars in one single view, from a starburst cluster of young, hot Wolf-Rayet stars and early O-type stars (near the center) to the evolved blue supergiant Sher 25 (upper right of center), which marks the end of the life cycle.

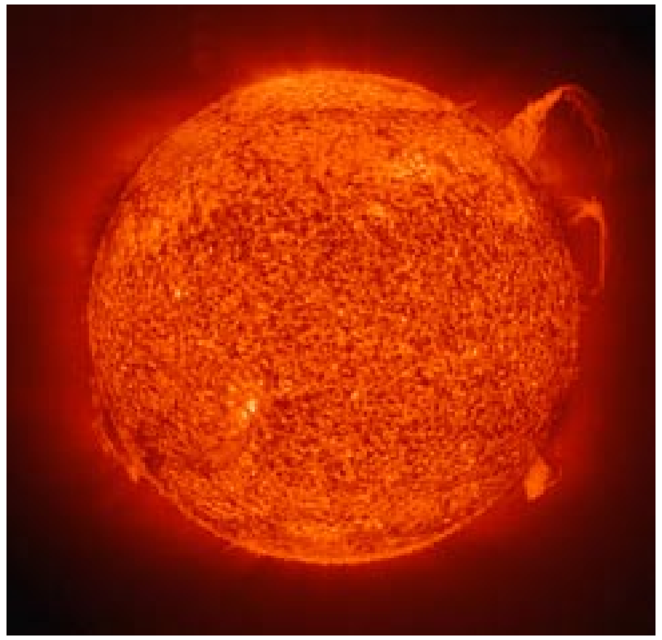
Stars also play central roles in the formation and evolution of galaxies (Chapter 2). Here we discuss the greater understanding achievable within our own Galaxy looking at local sites of star formation, probing fundamental physics within the compact objects left by dying stars, and tracing the path of the heavy elements they eject, as the cosmic cycle of matter carries them into new generations of planets and forms of life.

The key questions that guide our exploration of the origin and destiny of stars are:

- **How are stars and stellar systems formed from interstellar clouds of gas and dust?**
- **What is the nature of the exotic objects left by dying stars, and how are the elements essential for life created?**
- **How do planets form in disks of gas and dust around young stars?**

"All of us are truly and literally a little bit of stardust."

—William A. Fowler



An image of a pair of similarly shaped prominences taken by the Extreme Ultraviolet Imaging Telescope on the Solar and Heliospheric Observatory. Material in the HEII line shown here is at temperatures of 60,000 to 80,000 kelvins.

The center of the Milky Way Galaxy at a distance of 25,000 light-years, visible in the top left corner. The Milky Way contains about 100 billion stars. Only a fraction of the galaxy is captured in this 2MASS image, covering about the same area as a fist held out at arm's length.

Trace the Path from Interstellar Clouds of Gas and Dust to Stars

Investigate molecular clouds as cradles of star and planet formation

We are immersed in a very dilute sea composed of atoms of gas and grains of dust. Large-scale forces can compress this material into clouds so dense that atoms join into molecules. Turbulence and magnetic fields control the configuration of these molecular clouds, twisting and shredding them into sheets and filaments. These structures sometimes collapse, forming cold dense cores shielded by dust from damaging ultraviolet photons. Star formation begins deep within these cores.

We detect this dense gas and dust throughout the observable universe, comparing it with tracers of newly formed stars. We are puzzled. Why does the efficiency of star formation vary by huge amounts? For example, in our neighborhood stars are born at a low rate, but there is runaway star formation in the centers of some galaxies that is consuming the molecular gas virtually instantaneously. The answer must lie in the means by which magnetic fields and turbulence support clouds against compression, support that must be overcome for them to collapse and stars to be born. The first steps toward life may also take place in the dense molecular cores, where chemical processes drive the synthesis of complex molecules, solids, and ices. How does the flow of the elements shape the molecular clouds, the formation of stars, and the nature of their attendant planetary systems? What drives prebiotic chemistry in these environments?

We will use the far-infrared and submillimeter spectrometers on the Stratospheric Observatory for Infrared Astronomy (SOFIA) and ESA's Herschel Space Observatory to probe the controlling influences on star formation. They will provide the first complete determination of the temperatures, densities, and velocity structures within molecular clouds and collapsing cloud cores by observing emission lines that are the dominant coolants, molecular lines from warm gas, and the continuum emission from cold dust. SAFIR will improve on these studies by extending them to the critical size scale of planet-forming disks.

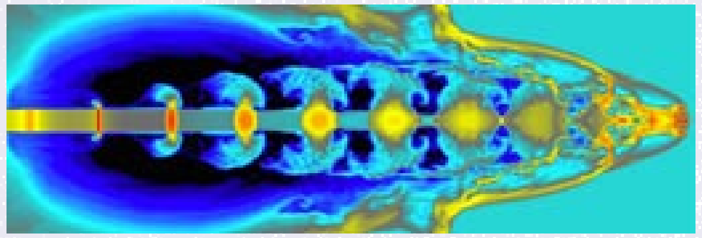
The spectrometers on JWST will search for prebiotic molecules and probe the chemistry occurring in the central regions of the youngest protostars at unprecedented spatial and spectral resolution near 6 and 15 microns, where the interstellar material is relatively transparent. Other important molecules will be studied in the far infrared. Progress also depends on a vigorous Research & Analysis program that investigates the chemistry, physical structure, turbulent and magnetic effects, and the fragmentation of molecular clouds and star formation within them.

Study the emergence of stars and stellar systems

After a dramatic initial collapse, a protostar grows for a few hundred thousand years as gas and dust flow onto it from the surrounding cloud. Eventually the new star stabilizes, heated by the energy released as gravity continues to compress it. These processes are only vaguely understood. What sets the mass of the final star? Why do stars have a specific distribution of masses strongly favoring low-mass stars over high-mass ones, nearly everywhere both within and beyond our Galaxy? The similar distribution of stellar masses persists over a wide range of conditions for star formation and despite the variety in star-forming efficiency. This defies the theoretical prediction that the amount of mass that can collapse gravitationally into a star depends on the temperature and density of the ambient gas. We need to study star formation over a wider range of elemental abundances, gas pressures, and magnetic field strengths to determine how the starting conditions influence the resultant mass distribution. We must search for low-mass brown dwarfs down to the mass of Jupiter to detect clearly the minimum mass formed in the fragmentation process, predicted to be a few times larger than that of Jupiter. A related issue is how conditions are established that allow formation of planets. Millimeter-wavelength observations reveal that significant amounts of gas and dust, usually more than enough to form a planetary system, are left in disks around new stars. How

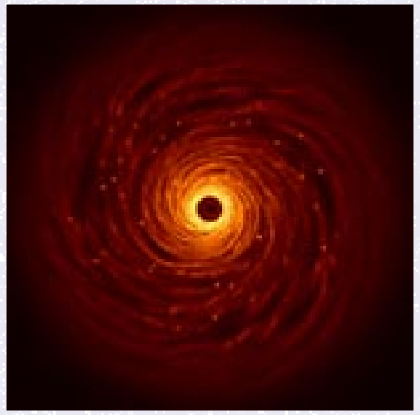
A Spitzer infrared image of the star-forming region RCW49. A cluster of young stars (center) has blown a hole in its surrounding molecular cloud.

Theory challenges



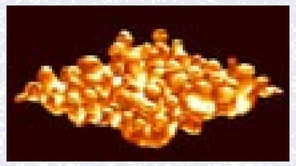
Propagation of a Pulsed Protostellar Jet

Logarithm of the density at late time in a two-dimensional hydrodynamical simulation of a "pulsed" protostellar jet (dark blue are the highest densities, light green to lowest). The jet velocity is varied sinusoidally in time, producing shocks and dense knots in the jet beam. Such models have been invoked to explain internal knots in Herbig-Haro jets, and more recently gamma-ray bursts.

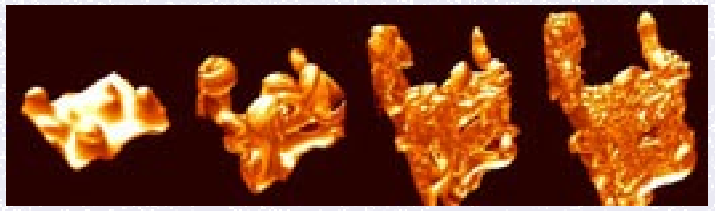


Gravitational Instability in Accretion Disks

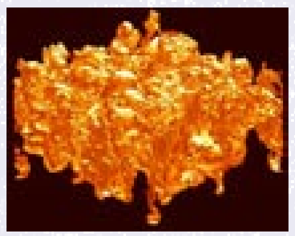
Accretion disks around protostars (at early epochs) and in AGN (at large radii) are vulnerable to gravitational instability. This can lead either to stable angular momentum transport or to fragmentation of the disk into substellar objects (in protoplanetary disks) or stars (in AGN).



(Left) Early in the evolution



(Above) A time sequence of a small region of the flame showing the transition to turbulence



(Right) Late, showing the turbulent flame

Type Ia Supernova

A sequence showing a three-dimensional simulation of a Rayleigh-Taylor unstable thermonuclear carbon flame in a Type Ia supernova. Hot ash lies below the cool fuel in the presence of a strong gravitational field — a configuration that is unstable. The image shows the interface between fuel and ash. The hot ash buoyantly rises upwards and the fuel falls downwards, greatly wrinkling the flame and consequently accelerating the burning. At late times in the evolution, the fluid becomes turbulent.

is the star built up while leaving the surrounding preplanetary material? What determines if the surrounding material forms a planetary system, a second star, or merely escapes back into empty space?

Several specific observations are needed to probe these questions. First, we need to compare the mass distribution of prestellar cold cloud cores to the mass distribution of newly formed stars to see how a cloud fragments. Second, we need to understand how prestellar and star-forming cores lose rotational energy to avoid spinning apart as they collapse into the youngest stars. Third, we need to understand the powerful jets and winds associated with young stars, including the mechanical energy they transfer into the surrounding material. It is possible that these flows eventually overpower the gravitational attraction of the remnant matter, terminating the growth of the star. Fourth, we need to probe the material around forming stars to understand what controls its fate. Finally, we need to identify the products of individual star-forming clouds over a wide range of age and mass down to the mass of Jupiter.

To understand the processes controlling the fragmentation of molecular clouds, we need high-resolution far-infrared spectroscopy with Herschel and SOFIA, and eventually imaging and spectroscopy with SAFIR. These facilities will provide sufficient spatial and spectral resolution to measure the rotational velocities and masses in prestellar and star-forming cores. Combining the spectral resolution achievable with Herschel and SOFIA with the angular resolution of SAFIR will trace the shocked gas and determine the physical conditions within jets and flows.

To understand the formation of planet-forming disks and the related tendency of stars to form as binary or multiple systems, JWST will probe cold cloud cores in the interstellar windows near 6 and 15 microns to resolve them at the relevant scale. Increasingly deeper understanding will come with finer resolution, such as can be achieved by SIM PlanetQuest, the Keck and Large Binocular Telescope interferometers, and the two TPF missions. The new data will also show how the process of secondary star formation differs from the process of planet formation, once we have a more complete census of extrasolar planets.

Existing observatories, such as Spitzer, Chandra and GALEX, are identifying young stars, measuring the energy they release, and allowing us to estimate their masses. To extend this work down to the mass of Jupiter, we will require very sensitive near-infrared imaging and multi-object spectroscopy with JWST.

Smoking gun for gamma-ray burst in the Milky Way. A composite Chandra X-ray (blue) and Palomar infrared (red and green) image of the supernova remnant W49B reveals a barrel-shaped nebula consisting of bright infrared rings around a glowing bar of intense X-radiation along the axis.

Sharpless 140 is a cloudy star-forming region in Cepheus, almost 3,000 light-years from Earth. At its heart is a cluster of three deeply embedded young stars, each several thousand times brighter than the Sun. Obscured in visible light, they blaze brightly as seen through the Spitzer Space Telescope's infrared array camera.

To expand our understanding to older stars we need to study isolated stars like the Sun, since the rich clusters where most stars form disintegrate within a few tens of million years once their surrounding molecular gas and its accompanying gravitational field dissipate. We must relate stars that formed together if we are to understand the mass distributions in their original clusters or the evolution of their planetary systems. Precision positional data with SIM PlanetQuest can trace back the motions of nearby stars to their common birthplaces. Eventually, an all-sky astrometric survey will expand this study. GALEX and WISE will identify most nearby young stars (up to about 10 million years old) from their ultraviolet and infrared signatures, and SIM PlanetQuest will be well suited to study their motions in a Galactic context.

Explore the Exotic Objects Left by Dying Stars and the Creation of the Heavy Elements Essential for Planets and Life

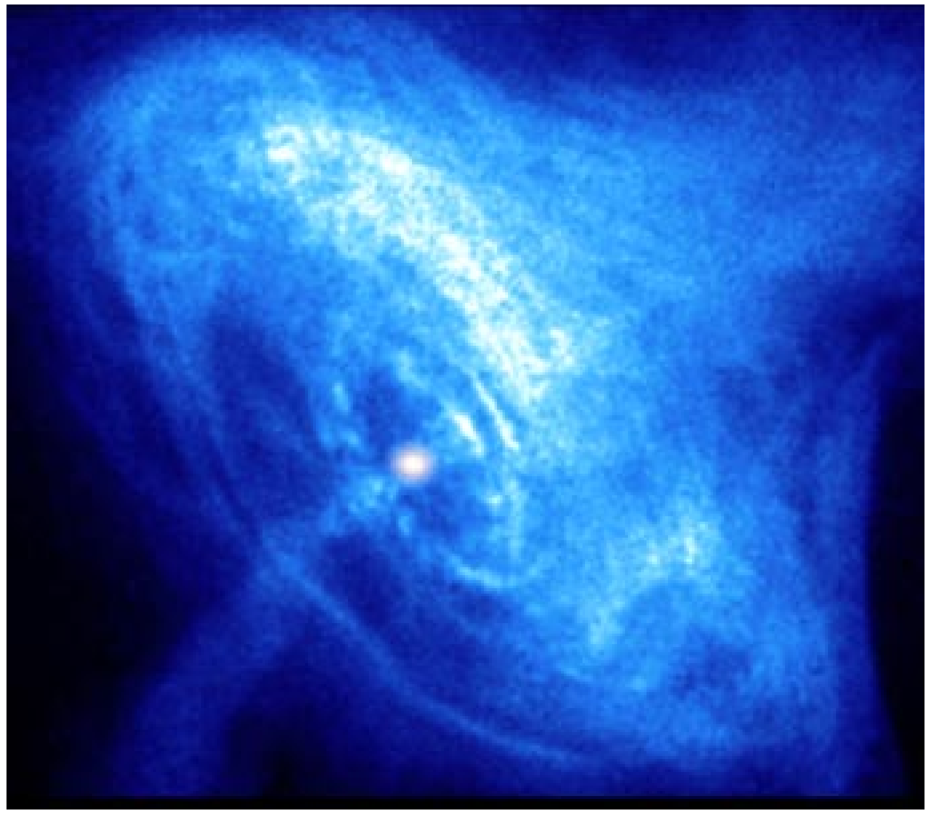
The formation of stars and planetary systems described above is one of the key problems to be addressed in modern space science. The life of mature, hydrogen-burning stars is relatively well studied, in part because Earth orbits a star in this stage. Of commensurate importance is an understanding of what happens to stars at the end of their normal lives.

Study the extreme physics at (and beyond) the ends of normal stellar lives, and understand its implications

The death spasms of stars produce compact objects that are the sites of some of the most extreme physics that has taken place since the Big Bang. As with normal stars, these compact objects are in states where gravity and thermal pressure balance. When their thermal pressure is not sustained by nuclear reactions, gravity continues to compress their matter, while pressure forces from electrons and neutrons resist the compression. Stars like the Sun end as white dwarfs, while those initially more massive than about eight solar masses undergo a Type II supernova and may leave a neutron star behind. Stars that begin their lives with more than 30 solar masses will likely leave a postsupernova object that will collapse into a black hole.

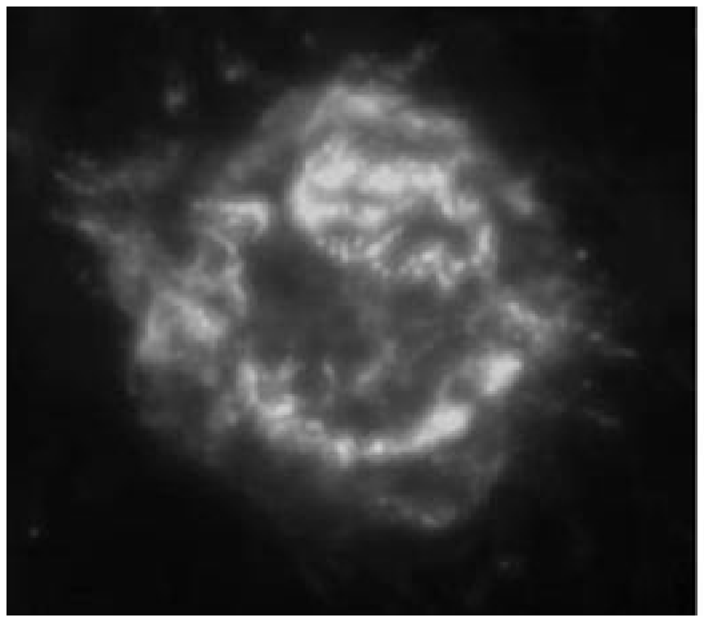
Neutron stars and black holes are unique environments with gravity, magnetic fields, and densities that are far beyond the range available on Earth. Frequently they become observable because they accrete matter from a surrounding disk that gets extremely hot and glows brightly at high energies. These circumstances push fundamental physical theories to their limits. How does matter behave under these conditions? Despite nearly 40 years of study, the physics of accretion itself is still poorly understood. Why are accretion disks stable in some systems, but

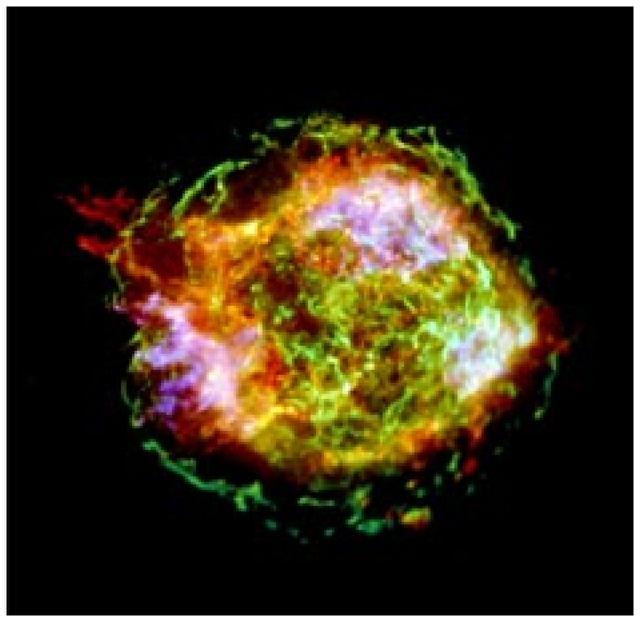
The Hubble Space Telescope's Advanced Camera for Surveys captured the spectacular Cat's Eye Nebula (NGC 6543), one of the most complex planetary nebulae. The nebula's structure suggests that a Sun-like star ejected its mass in a series of pulses at 1,500-year intervals.



Chandra image of the Crab Nebula pulsar. The jet and its energization of the surrounding region are readily apparent.

Cassiopeia A at 24 microns (left) and X-ray (right). At 24 microns (from Spitzer), we see small dust grains heated by the hot gas. The bright arc at the top and slightly to the right in the image is the front where the outward-going shock is encountering an interstellar molecular cloud. The X-ray image (Chandra) shows hot gas filling the remnant and highly excited emission lines from the gas. A jet on the left side of the image (also seen in the infrared) may indicate the path taken by particularly violent ejected material. The color codes indicate X-ray energy: red = 1.78–2.0 keV; green = 4.2–6.4 keV; blue = 6.52–6.95 keV.





highly unstable in others? How does the emergent X-radiation affect the accreting flow? How are relativistic jets formed in these sources? Can matter fall into black holes without radiating huge amounts of energy? The neutron stars and black holes are often thought to be evolutionary "dead ends," but they still have pivotal roles to play in the evolution of a galaxy. For example, do the inward spiral and merger of a black hole and a neutron star lead to a gamma-ray burst and a hypernova? Do stellar black hole mergers lead eventually to the supermassive black holes in active galactic nuclei?

Neutron stars are born with a distribution of magnetic fields and spins. As pulsars, they radiate beams of light into the Galaxy. They also emit jets of material that energize their surroundings. As the neutron stars age, their spin slows and most of their light is emitted by their very hot surfaces. SIM PlanetQuest will help probe this evolution by directly determining distances to, and thus total energy outputs of, a wide variety of stellar remnants. A number of these systems are likely to be detected as double-lined spectroscopic binaries by Con-X, thereby allowing the derivation of their masses. Through detection of the gravitational redshift of the light from the surfaces of neutron stars, Con-X may provide a direct measure of the mass/radius ratio. The relation between mass and radius strongly constrains the behavior of the material in neutron stars, and may reveal exotic forms of ultradense matter. A future, more-sensitive X-ray mission can improve on these constraints. A spectroscopic gamma ray mission would probe the neutron-star equation of state in other ways, by detecting the gamma-ray spectral line due to the capture of neutrons on the compact object.

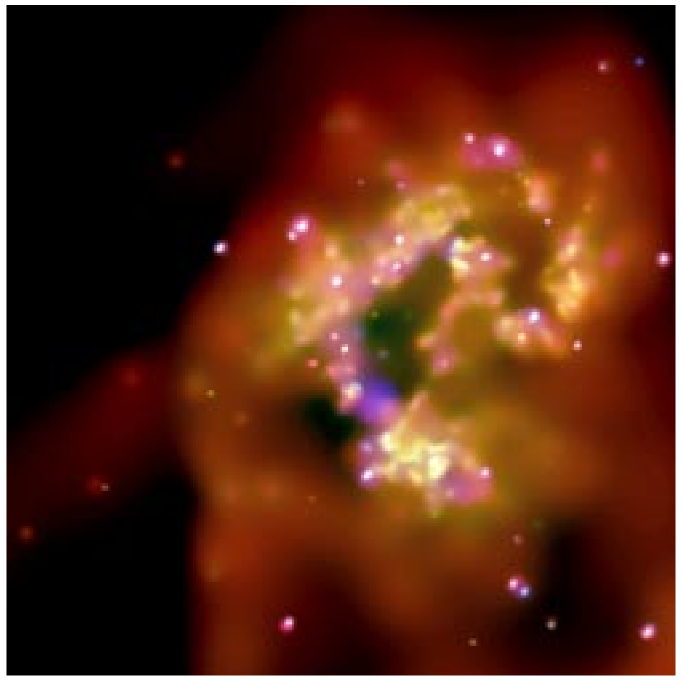
Compact binary star systems are one of the most interesting astrophysical laboratories. In some cases, it appears that a neutron star in a binary system may completely evaporate its larger companion star, a form of stellar death even more bizarre than a supernova. Time-resolved high-resolution X-ray spectroscopy of binaries with Con-X will provide crucial constraints on the structure of the accreting flows. Series of spectra of individual X-ray bursts (with Con-X) will teach us how the atmospheres of neutron stars respond to the intense heating produced by thermonuclear explosions. In some X-ray binary systems, the Rossi X-ray Timing Explorer (RXTE) observes frequent, sometimes quasi-periodic, drops in the X-ray flux. This phenomenon is thought to be associated with the "disappearance" of the inner portion of a thermal accretion disk, perhaps into the black hole, and is accompanied by the ejection of plasma in a relativistic radio jet. More detailed observations of such phenomena will have relevance far beyond our own Galaxy. The nearby stellar-mass objects produce their jets much more rapidly than the supermassive black holes in the distant active galactic nuclei, and thus may provide the key observations to understand the physics of these more powerful cousins.

In some nearby galaxies, we have found sources with X-ray outputs larger than expected for an accreting neutron star or stellar-mass black hole. We do not know whether they are stellar-mass objects accreting at unexpectedly high rates, "normal" X-ray binaries with their X-ray emission beamed toward us, or intermediate-mass black holes with masses of hundreds to thousands of times that of the Sun. LISA will be able to take a complete census of massive, compact-object binaries in nearby galaxies. Deep X-ray spectroscopy of such objects with Con-X (and a future higher resolution X-ray mission) will enable them to be related to the X-ray binaries in our own Galaxy. The mystery of these high-output objects will likely be solved with the new observations.

In recent years, supernovae from massive stars have been identified at the core of gamma-ray bursts (GRBs), among the most powerful explosions seen in the universe since the Big Bang. These GRBs are seen at great distances; some have occurred when the universe was less than half its present age. However, only one class of GRBs, the so-called "long" bursts, has been identified. The "short" bursts, lasting from a few milliseconds up to a second, still have no counterparts at other wavelengths. The recently launched Swift mission has begun to detect hundreds of GRBs per year, and is poised to solve the mystery of the short bursts. GLAST will study GRBs over a wide range of energies and will help relate the recently discovered X-ray flashers to GRBs. The broad spectral range will let us identify bursts at much larger distances than currently. These GRBs may serve as the markers for the most distant (and earliest) star formation that can be detected. A hard X-ray survey telescope, such as a candidate Black Hole Finder Probe of the Beyond Einstein program, would be much more sensitive than Swift to GRBs and X-ray flashers, with a much wider field of view. The additional capability with an advanced Compton telescope to measure the gamma-ray spectral lines from a number of bursts would let us compare their explosive mechanisms and nucleosynthesis to those of more "normal" supernovae.

Determine how the chemical elements were made and how they are distributed and processed into succeeding generations of stars

Recent missions such as Chandra, XMM-Newton, HST, and Spitzer are making important contributions to our understanding of Type II supernovae. Although we have learned much about the neutron stars and black holes they leave behind, we still do not understand exactly how the explosions occur. Supernovae also violently eject the outer layers of the former star. These ejecta, moving at speeds of up to 10,000 kilometers per second, contain vast quantities of oxygen, silicon, iron, and other, heavier elements that were synthesized in the original star and during the supernova explosion. A blast wave is driven ahead of the ejecta, similar to a sonic boom. The resulting shocks heat and accelerate the surrounding gas, playing important roles in a number of areas. They pump significant amounts of energy into the interstellar medium, heating it, and even, in some cases, punching holes through a galactic disk and driving galactic winds. They drive turbulence in molecular clouds that may trigger star formation. In fact, there is evidence that a nearby supernova explosion might have played an important role in the formation of the Sun. However, other processes are also suggested to trigger star formation. What exactly is the role of supernova shocks in producing stars? How do the heavy elements disperse into molecular clouds to be incorporated in new generations of stars and planets? It is also suggested that cosmic rays are accelerated in supernova shocks. Cosmic rays are high-energy atomic nuclei that reach Earth with speeds that are very close to the speed of light, coming to us from far beyond the solar system. They propagate to Earth via circuitous paths, thus appearing to originate from all directions. They cause genetic mutations and may have played a significant role in the evolution of life on Earth. Are supernovae really their source, or do they originate in some other way?



Spitzer (left) and Chandra (right) images of Antennae interacting galaxies. The Spitzer image reveals a region of very intense, dust-embedded star formation at the interface between the two merging galaxies (red in the false-color image) and substantial levels of star formation elsewhere (blue). Chandra shows very hot gas (red) being blown from the galaxy by supernovae in the star-formation regions, and a harder X-ray spectrum within them (green and blue) marking the sites where supernovae are enriching the interstellar gas with heavy elements.

Con-X will allow us to map in detail the velocities and compositions of the hot gaseous ejecta in Galactic supernova remnants. Gamma-ray and high-energy X-ray spectroscopy, such as with NuSTAR and an advanced Compton telescope, will probe the composition of the radioactive ejecta produced closest to the center of the explosion. Not only do such studies probe the mechanism of core-collapse supernovae, they also reveal directly the heavy elements produced both in the original star and in the supernova.

Infrared emission lines accessible to SOFIA and SAFIR can be used to trace the dispersion of heavy elements into the interstellar medium and molecular clouds. These lines suffer little extinction, are relatively easy to interpret, and are orders of magnitude stronger than the visible lines from the same elements. For example, in many nebulae, a common state of ionized nitrogen has only extremely weak visible recombination lines, but a strong line at 57 microns.

Interstellar dust appears very early in the evolution of the universe. We know that small amounts of very refractory grains, heated by very hot electrons, cause the remnants of supernovae to glow in the infrared. It is hypothesized that much larger amounts of cold dust may be produced in Type II supernovae or their predecessor stars, a suggestion that can be probed well by observing nearby supernovae in the far infrared with SAFIR. In general, star formation and the generation and recycling of heavy elements into interstellar gas and eventually into new stars are closely linked. Herschel, JWST, and SAFIR will build on the results from Spitzer and Chandra to trace this process in the early universe as galaxies and quasars formed and evolved.

By studying supernova shock waves with Suzaku (Astro-E2) and Con-X, we can probe the acceleration process and determine the maximum energy of cosmic rays that are produced in them. Gamma rays can only be produced by energetic particles and so gamma-ray sources are likely sources of cosmic rays. GLAST will search for the sources of cosmic ray nuclei. A future mission designed to measure the composition of cosmic rays up to energies of a few hundred trillion electron volts would explore their connection to supernovae.

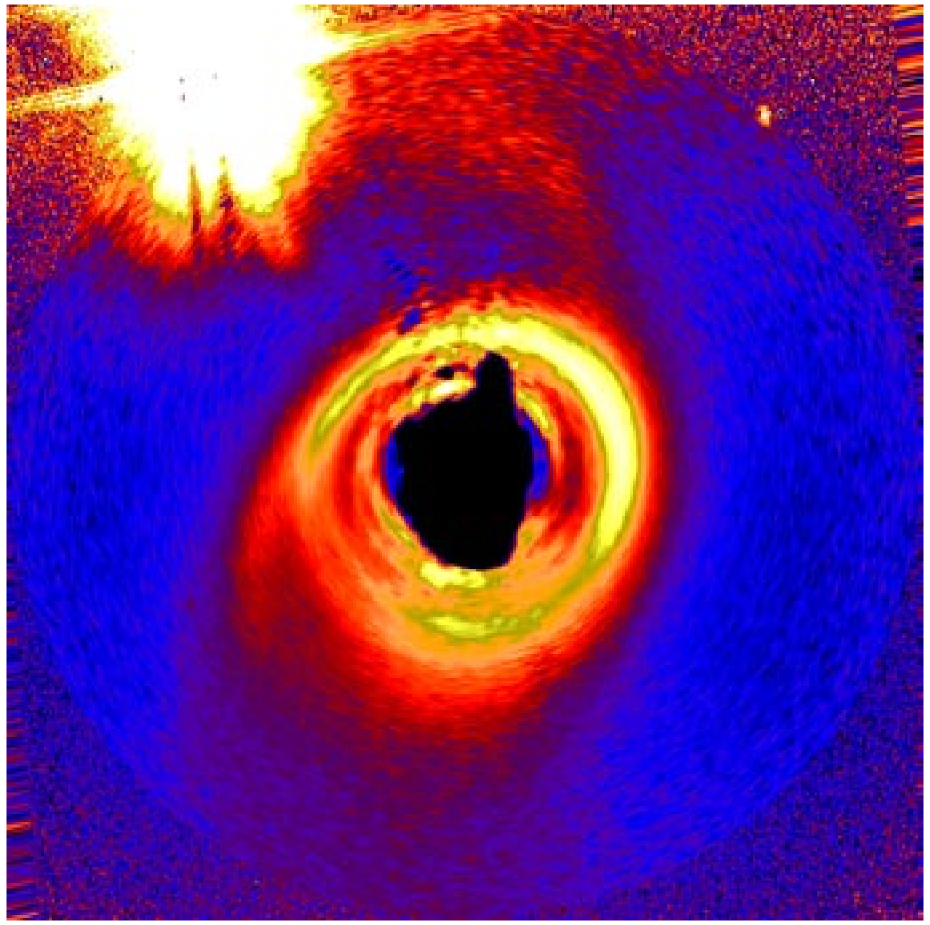
At still higher energies, we detect cosmic rays that cannot be confined by the magnetic field of our Galaxy and probably come from great distances. Although ground-based observatories are currently used to detect huge showers of particles produced by these very energetic particles, space instruments looking back down on Earth would be more effective, creating a detector as wide as the entire Earth. They would allow us to learn more about astrophysical particle accelerators that can produce energies far beyond those we can achieve on Earth, accelerators involving the intense gravity around black holes and neutron stars and the largest electromagnetic fields known.

Determine How Planets Form in Dense Disks of Gas and Dust Around Young Stars

The heavy elements manufactured in massive stars and released into interstellar space by supernovae are the raw material for Earth-like planets and for life. The planets of our solar system orbit the Sun very nearly in the same plane, indicating that they formed out of a swirling flattened structure of gas and dust. Indeed, images of such disks around young stars dramatically confirm this picture. What governs the formation and evolution of planets in these disks? We suspect there is a relationship between disks and stars that causes the disks to affect the ultimate characteristics of these stars, such as mass and rotation speed, while the stars drive mixing and chemical processes in the disks. In the early stages, rapid accretion of disk material is still building up the mass of the central star. Observations show stars retaining material in disks for only 1 to 10 million years. How does the flow of material inward to the star avoid carrying the nascent planets to a fiery doom? The classic picture is that solid particles of dust coalesce early and stick to each other in collisions, slowly building a core around which a planet grows: gas giant planets grow quickly before the system loses most of its gas, and Earth-like planets grow over a longer period. This picture explains many of characteristics of the solar system, but it is now running into trouble elsewhere. Can gas giants form quickly through gravitational instability in the young disk without waiting for cores to form? How and when are rocky, Earth-like planets formed? Most of the gas not captured in giant planets quickly escapes. However, some must be retained in the system if it is ever to form life. Chemical processes to make complex, heavy molecules that can be captured as ices are strongly affected by the presence of dust and ionizing radiation. But how exactly are otherwise semi-inert, nonreactive molecules transformed into highly reactive radicals that ultimately drive the production of life's raw materials? While the disks are clearing, asteroids and comets left over from the formation intensely bombard the Earth-like planets. Does this bombardment deliver the carbon-rich material and start the development of life?

X-rays and ultraviolet photons generated in the hot plasma of accreting gas impinge on the disk and ionize its upper layers, feeding more accretion. The central star is spinning rapidly from conservation of angular momentum as it collapses and continues to accrete matter from the spinning disk. Magnetic fields may connect the stellar surface with the disk through these ionized layers, and brake the rotation while enhancing stellar activity. This process may enhance the inward flow of material and disk accretion. Analysis of the X-ray emission lines in the nearby young star TW Hydra indicates abnormal elemental abundances in the gas, perhaps because the heavy elements have largely formed into dust that is collecting into planetesimals. The gain in sensitivity with

HST images of protoplanetary disks around young stars in the Orion Nebula.



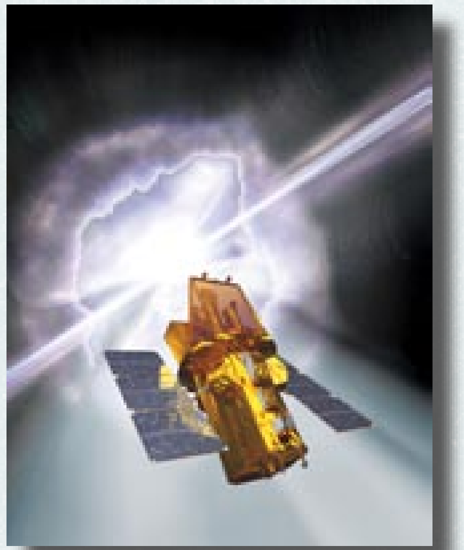
HST image of the disk around the 5-million-year-old star HD 141569A. The image has been enhanced and geometrically altered to simulate a face-on view.

Connecting Educators to Real Data

There's no substitute for real data and real discoveries, and educators know this. But the challenge of making raw data into a meaningful educational experience is daunting. Spitzer is collaborating with the Research-Based Science Education (RBSE) program on a program for teacher and student research using observing time on the Spitzer Space Telescope. Participating teachers attend workshops to become familiar with the Spitzer Science Center Archives, observation planning process, and telescope and instrument capabilities in order to plan observations. They also receive training in infrared astronomy and infrared observational techniques. Teachers will be mentored by scientists and others as they plan, submit, and carry out their observing programs. Teachers will also have the opportunity to present their results at both the American Astronomical Society and the National Science Teachers Association conventions.

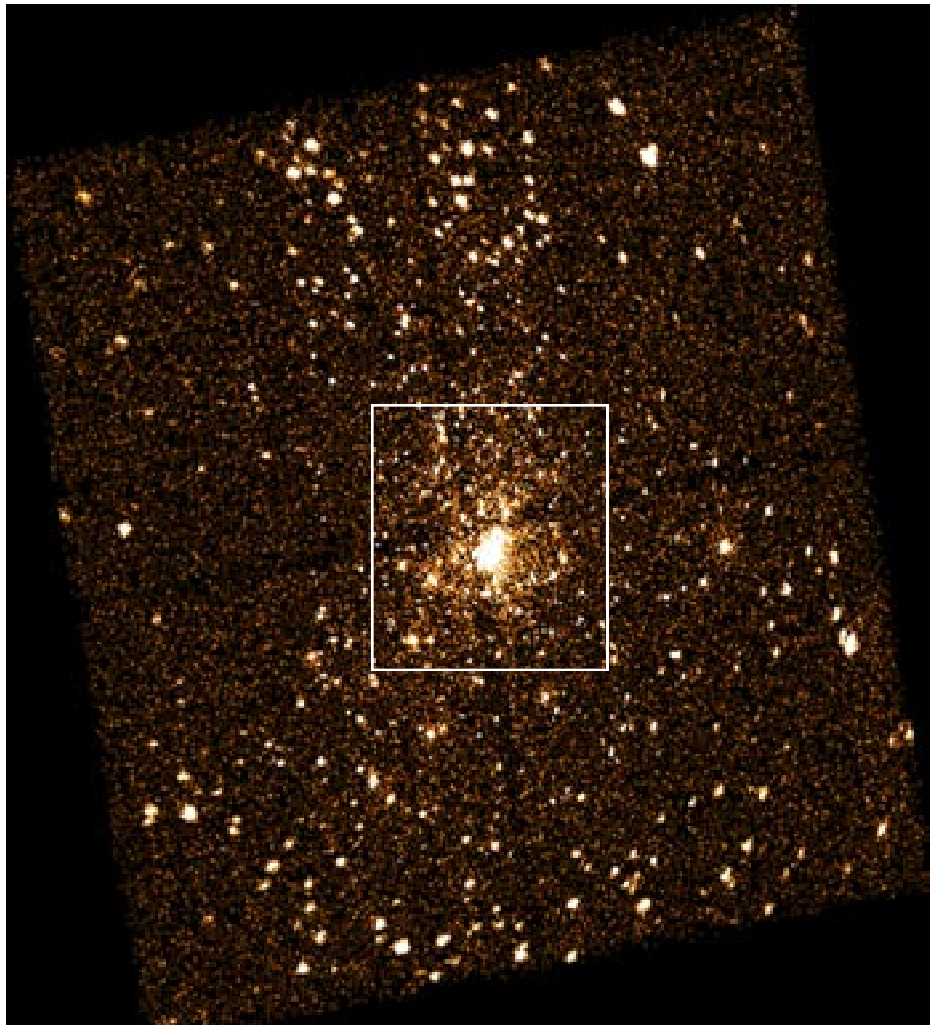
OPERATIONAL MISSIONS

SPITZER The Spitzer Space Telescope is the fourth of NASA's Great Observatories, launched in August 2003. Formerly known as the Space Infrared Telescope Facility, this mission is using infrared technology to study celestial objects that are too cool, too dust-enshrouded, or too far away to otherwise be seen. Spitzer, along with the Hubble Space Telescope, the Chandra X-ray Observatory, and the Compton Gamma-Ray Observatory are all part of NASA's Great Observatories program. Spitzer uses imaging and spectroscopy at infrared wavelengths from 3 to 180 microns to investigate the formation of stars and planets and the formation and early evolution of galaxies. Spitzer will provide key information on the dust environments TPF will need to penetrate to find and characterize planets. A very important component of Spitzer science will be the legacy programs, in which very large and scientifically important data sets will be made available rapidly to the entire scientific community. Six teams with broad community participation have been competitively selected to execute legacy programs. Spitzer is a cryogenic mission with an expected cryogenic lifetime of over five years. The wide applicability of infrared technology is highlighted in the mission's extensive education and public outreach program.



SWIFT The Swift spacecraft was launched in November 2004 on a mission to study the most powerful events since the Big Bang — gamma-ray bursts. With its rapid slewing capability and multiwavelength capability, Swift will enable precision studies of these mysterious bursts of gamma rays in the ultraviolet, optical, and gamma rays of energies up to 150 keV. Swift uses a large cadmium-zinc-telluride (CZT) array with a coded aperture mask to survey a large fraction of the sky at one time. When a gamma-ray burst is detected, the spacecraft slews automatically to point two narrow field instruments at the burst location for follow-up studies of optical and UV afterglows and to provide improved (arcsecond) positions. Swift is detecting 90–100 bursts per year and is providing an all-sky survey between 10–150 keV.

A Chandra image of the Orion Nebula (left) shows a huge number of young, X-ray-emitting stars. An HST image (right) of the area surrounded with a white box in the Chandra image was taken at a wavelength that highlights the excited gas that comprises the familiar nebula.



Con-X will allow such studies to be extended from a small handful of favorable objects to many more distant and lower luminosity sources. As a disk ages, X-rays and ultraviolet photons help destroy and disperse it; a large ultraviolet-sensitive telescope could study this process.

To understand the formation and behavior of gas-giant planets, we need to document the gas-clearing process thoroughly. The most abundant gas in protostellar disks is molecular hydrogen. However, its quantity until now has largely been inferred from trace molecules such as carbon monoxide, which may not accurately indicate the total amount of gas throughout the lifetime of the disk. In order to probe gases directly with the necessary sensitivity and angular resolution, direct measurements of molecular hydrogen are needed in infrared emission lines with Spitzer and JWST, in the ultraviolet with FUSE (or a large ultraviolet telescope) where the extinction is small, and eventually with SAFIR in the far-infrared.

Interstellar dust contains amorphous silicates, but the comets in our solar system and dust in disks contain a significant fraction of crystalline silicates. These crystals must be formed in hot regions of the disk or in the searing heat of collisions between asteroid-like objects. Exactly where and how they are produced will tell us how the disk is mixed by turbulence, inward accretion, and stellar winds. High-angular-resolution spectral studies in the near-infrared (with the Keck and Large Binocular Telescope interferometers, and with JWST) and far-infrared (SOFIA, SAFIR) are necessary to trace the distribution of these important planetary constituents.

To understand the crucial steps towards life, we need to 1) conduct systematic searches for and inventory the molecules in planet-forming disks, and 2) improve our knowledge of the physical conditions in this environment. Although the initial steps take place behind dense and opaque screens of interstellar dust, there are windows near 6 and 15 microns through which we can peer. SOFIA, and particularly JWST, will be able to detect and study complex carbon-bearing molecules and water, the raw materials for life, by taking high-resolution spectra through these windows. An understanding of where these molecules form and how they are processed will indicate how many systems are likely eventually to become homes to living organisms.

Over the course of a few million years, disks go from the massive gas-rich remnants of star formation to containing no more than a lunar mass of dust and gas, but perhaps containing much more mass in planets. Studies of stellar clusters show that at any given age, there is a wide range of disk masses, suggesting a broad variety in planetary system evolution. Missions such as WISE, JWST, Herschel, and SAFIR that can measure the dust content of disks with time can be combined with theoretical studies to explore this phase of planetary system development. We may also learn how giant planets direct material from one part of the disk, perhaps water-rich, to the inner regions where Earth-size bodies are growing. This process brought volatile materials to the early Earth and allowed life to form on our planet.

Space missions have recently provided the first peeks at the secret lives of stars, the stages of stellar and planetary evolution that were hidden from centuries of ground-based optical studies. New missions, such as ground-based infrared interferometers, JWST, SIM PlanetQuest, WISE, GLAST, SOFIA, NuStar, Con-X, LISA, and SAFIR will elevate our understanding immensely. For the first time, we will trace in detail the cosmic cycle of matter, showing how the elements that make Earth-like planets are produced and then gathered up into new stars and planetary systems. These steps set the scene for planets where life may form, the topic pursued in the following chapter.

SUMMARY *of* MISSIONS

To explore the origin and destiny of stars,

JWST will:

- Probe the interiors of star-forming cloud cores through the windows at 6 and 15 microns.
- Trace the shocked gas and determine the physical conditions within jets and flows.
- Identify brown dwarfs down to the mass of Jupiter.
- Trace the generation of heavy elements in the early universe.
- Search for molecular gas in protoplanetary disks and probe formation of giant planets.
- Document the mineral content and evolution of protoplanetary disks.

Constellation-X will:

- Measure the masses and radii of neutron stars.
- Explore ultraluminous X-ray sources, possible indicators of intermediate-mass black holes.
- Map the detailed velocity and composition of the hot ejecta in supernova remnants.
- Probe the acceleration process of cosmic rays in supernova remnants.
- Explore the effects of X-radiation on protoplanetary disks.

SIM PlanetQuest will:

- Associate stars with their sites of formation to advance studies of their evolution.
- Assist in measuring the masses and luminosities of compact stellar remnants.
- Probe the formation of binary stars.

SAFIR will:

- Explore molecular clouds to understand conditions for star formation.
- Measure dynamics in protostellar disks and in jets and outflows from young stars.
- Test whether Type II supernovae produce the heavy elements in the early universe.
- Trace dispersion of heavy elements into the interstellar medium.
- Document the process of gas dispersion from protoplanetary disks.
- Search for prebiotic materials in forming planetary systems.

GLAST will:

- Search for the sources of cosmic rays.
- Study the spectra of gamma-ray bursters.

SOFIA will:

- Probe the processes controlling star formation in molecular clouds.
- Measure dynamics in protostellar disks and in jets and outflows from young stars.
- Trace the dispersion of heavy elements into the interstellar medium.
- Observe the loss of gas from protoplanetary disks.
- Search for prebiotic molecules around young stars.

The Keck and LBT Interferometers will:

- Explore the distribution and composition of the material in the terrestrial planet zone of protoplanetary disks.
- Study forming binary stars.

WISE will:

- Identify virtually all young stars in the solar neighborhood.
- Explore the evolution of infrared emission from circumstellar disks.

LISA will:

- Obtain a complete census of compact object binaries in the Milky Way and nearby galaxies.

NuStar will:

- Map radioactive material in young supernova remnants.

4 Exploring New Worlds

Are we alone? In the vast blackness of the universe, our home planet is a single sparkling oasis of life. Whether the universe harbors other worlds that can support life is a question that has been pondered, yet remains unanswered, for over two thousand years. While we continue to search for subsurface life on other worlds in our solar system, we are privileged to live in a time when technological advances allow us to expand the search for life beyond the confines of our own solar system and out into the wider universe. Over the next two decades, NASA will launch a series of spaceborne telescopes that will build on one another's achievements to address the goals of finding Earth-size planets around other stars and examining those planets for signs of life. This program directly supports *A Renewed Spirit of Discovery: The President's Vision for U.S. Space Exploration* (2004), which calls for "advanced telescope searches for Earth-like planets and habitable environments around other stars" as one of the foundations of NASA's exploration goals.

As described in the previous chapter on the origin and destiny of stars, the search for habitable worlds begins with an understanding of the formation of planetary systems in protoplanetary disks to learn how planetary systems form and around which types of stars, how often planets form, and how the disk properties affect the distribution of final planet sizes and orbits. The formation and dynamical evolution of gas-giant planets is also important because their gravitational influence plays a crucial role in the formation of smaller worlds, in the stability of their orbits, and in controlling the delivery of organic-rich material into the inner solar system. Toward the ultimate goal of finding life on other planets, we will address these questions:

- **How do planetary systems form and evolve?**
- **Are there other planetary systems like our own?**
- **Is there life elsewhere in the universe?**

A centuries-long, continual search for knowledge and understanding has led humans to seek answers to the most fundamental questions: Where did we come from? Are we alone?

"To explore the diversity of other worlds and search for those that might harbor life...."

A composite photograph of images of Earth — the only body in the solar system known to harbor life — and the Moon taken by the Galileo spacecraft.

The search for extrasolar planetary systems is well underway, and we now know of more than 160 planets outside our solar system, many discovered by NASA-supported ground-based telescopes. However, the extrasolar planets discovered so far are not the terrestrial planets that could potentially be habitable, but rather are gas-giant planets like Jupiter and Saturn, hundreds of times more massive than Earth. A few Uranus-mass planets, only about 14 times the mass of Earth, have been identified orbiting very close to their parent stars.

The technology required to detect and characterize potentially habitable worlds is enormously challenging, and no single mission can provide all the measurement capabilities. Nor can any one mission be as productive operating alone when compared with its power working as part of a carefully planned program. To understand whether life is common or rare in the universe, we must meet the technological challenges and embark on a series of complementary and interlocking explorations, each activity supporting and extending our efforts to characterize planetary systems and search for terrestrial planets and life. The key NASA missions that are central to planet finding are discussed later in this chapter.

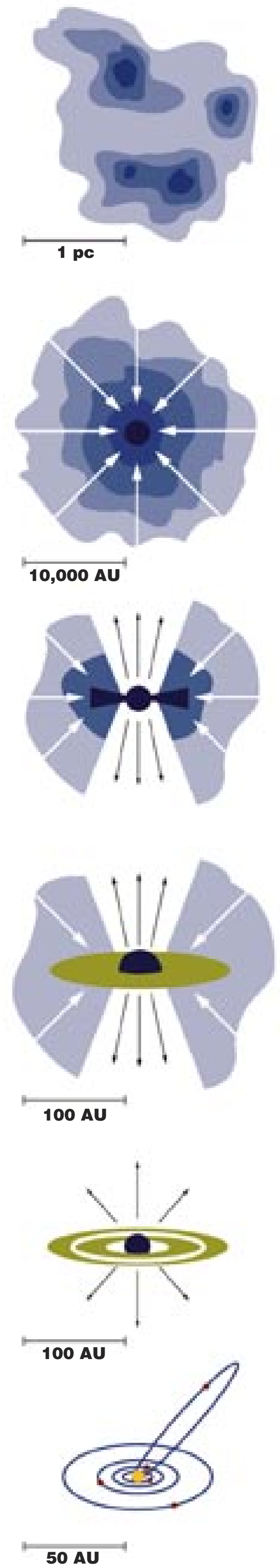
In the following sections we address the formation of planetary systems, a census of existing planetary systems, and the search for Earth-size, potentially habitable planets. The missions described in this chapter, supported by a number of smaller projects and ground-based activities, will meet our measurement objectives and accomplish the goals of this program.

Linking these flagship missions together will be precursor observations with a variety of space-based and ground-based telescopes, as well as a rich program of research and analysis, laboratory astrophysics, and theoretical investigations supported by the Research & Analysis program, including the TPF Foundation Science program, Michelson Science Fellowships, and the NASA Astrobiology Institute.

Study the Formation and Evolution of Planetary Systems

To learn how common (or rare) planetary systems like our own are, we need to understand the evolution and nature of existing planetary systems. The seeds of future planets are sown and nurtured in the protoplanetary disks.

Many fundamental questions remain about how the final configurations of gas-giant and terrestrial planets arise from these seeds. An ambitious research program of theory and observation will discover the relationship between gas-giant and terrestrial planet formation and how the materials necessary for life on terrestrial planets become plentiful.



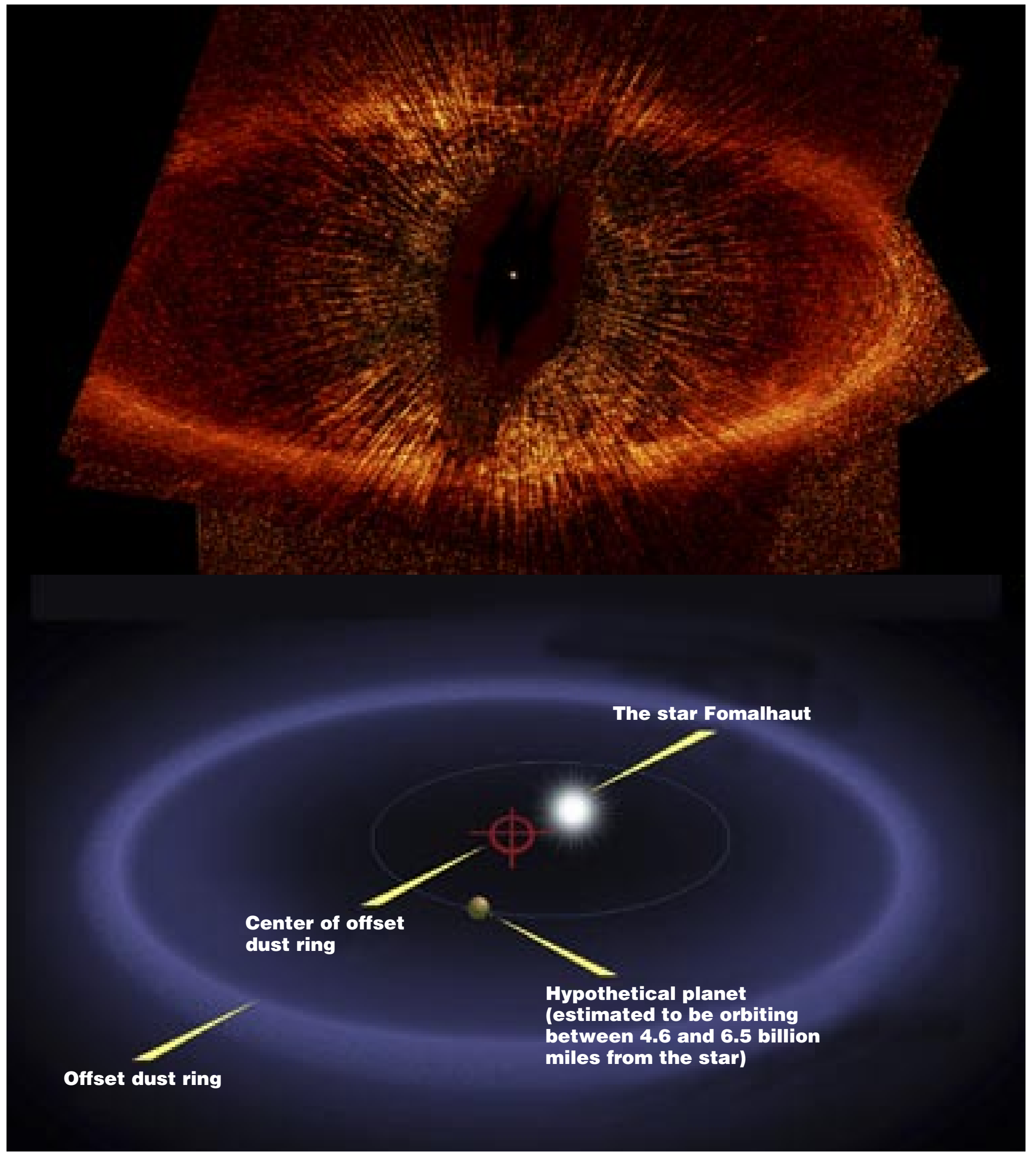
Major stages in the formation of stars and planetary systems from the densest cores of molecular clouds. Each of these transitional states yields characteristic signatures that can be observed.

The flagship mission for observing the formation of planetary systems will be JWST. As described in Chapter 3, JWST will probe the earliest moments of star and planet formation. But JWST will also study planetary debris disks, the remnants of the planet-formation process, to yield new information on the distribution and composition of dust arising from collisions in cometary and asteroid belts. This provides the raw material for organic material eventually responsible for making life possible. SIM PlanetQuest will play an important role by carrying out a census of Jupiter-size planets around young stars in the immediate vicinity of the ice-condensation line where such planets are thought to form.

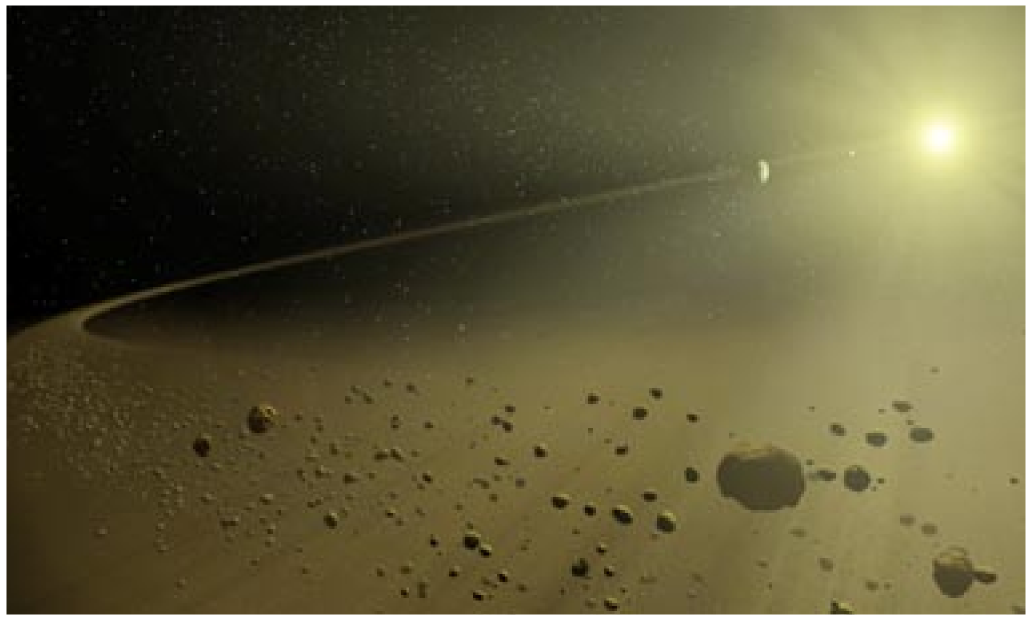
Probe planet formation

Ongoing planet formation induces structures in young disks that may be observable with new large telescopes and interferometers. High-spatial-resolution and high-contrast-coronagraphic imaging can reveal ripples and gaps in disks that help locate a perturbing planet and provide estimates of its mass. JWST, as well as the ground-based Keck Interferometer (KI) and Large Binocular Telescope Interferometer (LBTI), will address these observational problems. High-resolution infrared spectroscopy with SOFIA will be able to resolve planet formation within the habitable zone. However, the detection of a gap associated with a proto-Jupiter, located 5 astronomical units (AU) from

The Hubble Space Telescope captured this visible-light image of the nearby star Fomalhaut (HD 216956), clearly showing the star's narrow, dusty ring. The center of the dust ring is about 15 astronomical units away from the star, a distance equal to nearly halfway across our solar system. Hubble observations show that Fomalhaut is off-center from its surrounding ring, most likely because of an unseen planet orbiting the star and shepherding the ring material.



An artist's rendering of a hypothetical planetary system outside the solar system.



a star in a nearby star-forming region, will require an angular resolution beyond the capabilities of JWST, but will be well-suited to the TPF Interferometer mission or to spectroscopy with the SAFIR mission operating in the far-infrared.

As terrestrial planets grow, small dust grains coagulate into planetesimals that are stirred by the presence of gas giants. The interplay between the rocky planets and their giant siblings will change the structure of asteroid belts around other stars over time.

Comparing the dust signatures from planetesimal debris belts with the presence or absence of planets will reveal this dance. Infrared telescopes such as SOFIA, JWST, Herschel, and SAFIR will allow us to determine the evolving location and composition of dust in planet-forming disks.

Detect the youngest planets

With sufficiently high spatial resolution, it will be possible to image young planets directly. Adaptive optics imagery from ground-based telescopes and interferometry using KI and LBTI will give us first glimpses of embedded young Jupiters, while JWST's coronagraphs in its near and mid-infrared cameras may find young Jupiters around nearby young stars (150–500 light-years). JWST's near-infrared camera may possibly even detect directly a handful of old, cold Jupiters around the nearest main sequence stars.

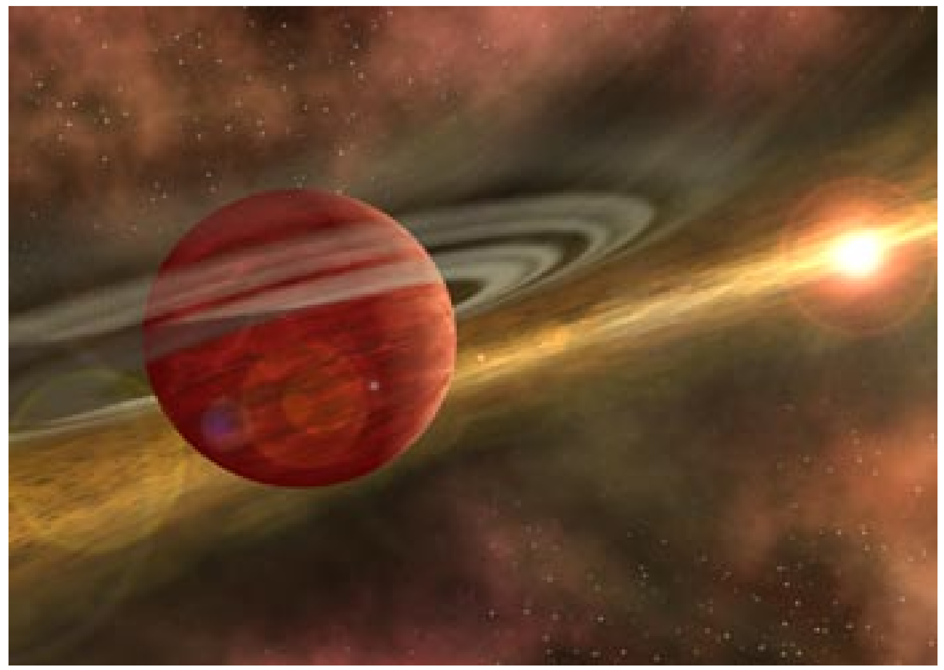
SIM PlanetQuest will be able to find gas-giant planets around young stars (1–100 Myr) in the immediate vicinity of the habitable zone, near where Jupiter and Saturn sit today in our solar system. Radial velocity detection of planets is impossible because of photospheric activity and rapid rotation while imaging searches are limited to planets located tens of astronomical units away from their parent stars. SIM PlanetQuest will survey approximately 150 stars looking for planets with masses larger than that of Saturn's in orbits from less than 1 AU to beyond 5 AU. SIM will investigate formation scenarios for giant planets and study migration mechanisms that might explain the puzzling presence of gas-giant planets orbiting mature stars well inside 1 AU.

The TPF-I mission, operating in the mid-infrared, will glimpse deep within dust-enshrouded protoplanetary disks to cleanly separate planets, disk, and star. Together theory and observations will begin to explain the influence of planets like Jupiter on the formation of terrestrial planets.

Understand the creation and delivery of organics to planets

The next big step in understanding the formation and evolution of habitable planets is to study how terrestrial planets receive and store the materials they need to foster life. Research has shown that organic molecules, the building blocks of life, likely permeate the universe, but their identities, abundances, and distribution still need to be understood in our own and other galaxies. Planets like Earth formed too close to the Sun to keep their initial water content. Planetesimals, the building blocks for planets, formed in the gas-giant region and provided a reservoir for water and other volatiles necessary for terrestrial life. The organic content of the material left over in the debris disk phase depends largely on the extent of processing during the gas-rich disk phase described in Chapter 3. The compounds frozen onto rocky bodies when the disk clears provide most of the carbon that will be available to developing planets, but delivery of volatiles and organics by small planetary system bodies will continue throughout a planet's history.

In this artist's concept, a possible newfound planet spins through a clearing in a nearby star's dusty, planet-forming disk. This clearing was detected around the star CoKu Tau 4 by the Spitzer Space Telescope. Astronomers believe that an orbiting massive body, like a planet, may have swept away the star's disk material, leaving a central hole.



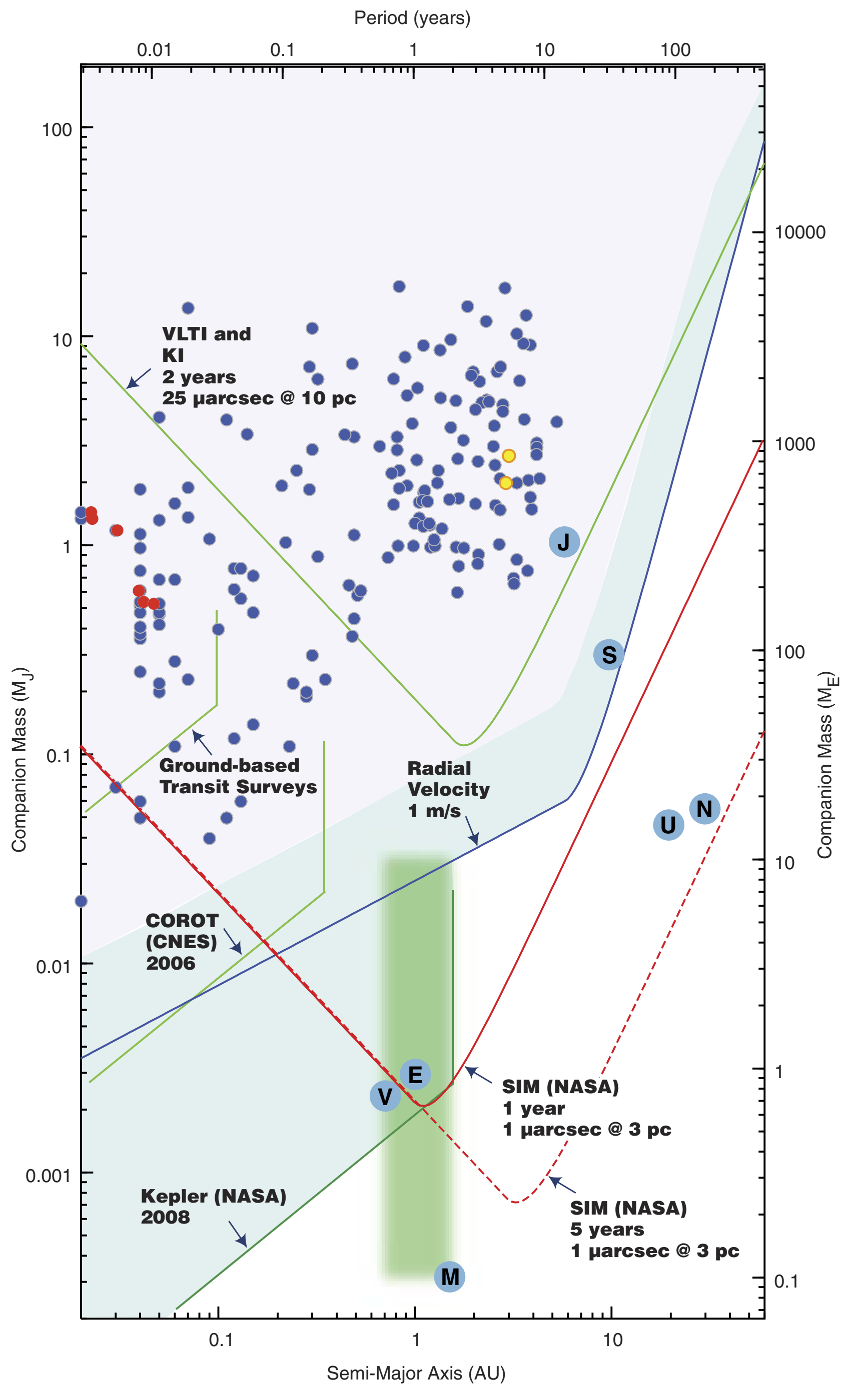
Observations of ice and organic compounds in disks with JWST, TPF-C, TPF-I, and SAFIR and other future missions with spectroscopic capability can be combined with theories of organic chemistry, volatile processing, and orbital dynamics to place constraints on the formation and evolution of prebiotic compounds and their delivery to terrestrial planets.

Explore the Diversity of Other Worlds

Although we will learn about the formation of planetary systems from studying the very youngest stars, an exploration of older systems will help us better understand our own solar system and provide us with clues to its ultimate fate. Our solar neighborhood includes stars that span ages from stellar birth to twice as old as the Sun, and studies of any planetary systems around these stars will allow us to better understand how planetary systems evolve over time. A broad census of planetary systems will also form the observational foundation for our understanding of how common planetary systems are and the diversity of their architectures.

A comprehensive census of the planetary systems in our solar neighborhood using ground-based observations and observations from Spitzer, SOFIA, Herschel, JWST, SIM PlanetQuest, TPF-C, and TPF-I will enable investigation of the relationship between all the main components of a planetary system, gas-giant and rocky planets, cometary systems (Kuiper Belts), and asteroid belts (zodiacal clouds). These studies will set the stage for follow-up observations to understand the properties of the planets that we find and allow us to understand the larger context of our own planetary system.

No single instrument or technique is capable of finding all planetary system components around stars of all ages. Instead, our understanding of other planetary systems will be achieved with an integrated suite of ground- and space-based missions that



Sensitivity of various techniques to planets as a function of mass (vertical axis) and orbital location (horizontal axis). Blue dots indicate planets detected by radial-velocity surveys; red dots indicate planets detected by the transit surveys; yellow dots indicate planets discovered by microlensing surveys. The green shaded region highlights where Earth-like planets would be found.

will use complementary instrumentation and techniques to explore the majority of planetary-discovery-phase space. Four fundamental techniques will be used to determine the architecture of planetary systems: radial velocity measurements, transit observations, astrometry, and direct detection. The breadth of discovery space is broad, and the combination of these techniques promises to provide a complete census of Earth-size and giant planets.

Giant planets: signposts of a planetary system

Giant planets, which are unlikely to directly harbor life, dynamically constrain the orbits available for terrestrial planets. Giant planets are the older siblings — both the bullies and protectors of the terrestrial planets. How they stir up the disk determines how many comets and asteroids survive to bombard smaller worlds with either sterilizing intensity or with life-bringing chemicals. Giant planets in eccentric orbits are less likely to allow terrestrial planets to orbit stably in the habitable zone. However, gas giants might be necessary for shielding terrestrials from life-damaging impacts of comets.

One of the exciting and unexpected results of the planet searches to date is the discovery of large numbers of systems unlike our own. Gas-giant planets have been found to orbit closer to their stars than Mercury orbits about the Sun. Among the unsolved problems in planet formation today is not just how to form giants, but how to move them to their present locations. Some appear to have migrated large distances while others, such as Jupiter, appear to have mainly remained in place. Many gas giants also have substantial eccentricities — coming closer and farther from their stars over their orbits. However, these systems exist only for a minority (10 to 20%) of stars, leaving open the possibility that many stars have planetary systems more like our own.

A Very Large Telescope infrared image of a young hot planet approximately five times more massive than Jupiter orbiting 55 AU from its parent star.

More than 160 planetary systems have now been discovered through ground-based observations. Despite such success, our knowledge of other planetary systems is still very rudimentary. Most planets have been discovered with the radial-velocity technique, which infers the presence of a planet based on its gravitational pull on the parent star. However, the sensitivity of the radial-velocity technique is currently limited to giant planets no smaller than Uranus's mass, and it preferentially detects planets orbiting close to their parent stars. Only 15 of the newly discovered planetary systems have more than one detected planet. These planets have been, almost without exception, giant planets that lie closer to their parent star than the giant planets in our own solar system.

In the coming decade, ground-based astrometric observations with the European Space Observatory's Very Large Telescope Interferometer (VLTI) and the Keck Interferometer will provide another avenue to precisely determine planetary orbits and masses. Although these surveys are challenging, requiring velocity precision of

1 meter per second or astrometric precision of 20 microarcseconds (achievable by the Keck Interferometer), they are relatively inexpensive and can be implemented with existing technology. These observations will determine the abundance of planets and the relationship between stellar properties (such as mass, metallicity, and binarity) with the properties of their giant planets (such as mass and orbital parameters). Of particular interest is the discovery of solar system analogs, planetary systems with giant planets on near-circular orbits many astronomical units from the parent star.

Space-based observations of giant planets with SIM PlanetQuest will provide detailed information on the eccentricity and inclinations of the planetary orbits for planets within 5 AU of their parent stars. This will be our best tool for disentangling the dynamics of systems with multiple giant planets. TPF-C and TPF-I will also be capable of detecting giant planets. Spectroscopy of giant planets with TPF-C and TPF-I will be of particular importance in understanding the chemical composition, physical structure, and overall evolution of these objects. With TPF-C and TPF-I, we will have a sample of hundreds of planets to compare and contrast to one another.

Understand the frequency of Earth-size planets

Although current observations suggest that Earth-size rocky planets *may* be common, their abundance is quite uncertain. The information to date, however, is encouraging:

- Roughly 7% of all nearby stars harbor a giant planet within 3 AU.
- The number of planets increases as mass decreases towards the mass of an "Earth."
- Stars that contain higher abundance of metals are more likely to have planets.
- Multiple planets are common, often in resonant orbits.
- The number of planets increases with distance from the star.
- Eccentric orbits are common, with only 10% being nearly circular.

While some of these planets are gas giants similar to Jupiter and Saturn in our solar system, some of the newly discovered planets have masses as small as 7.5 times the mass of Earth. The increasing number of planets with smaller mass suggests that planets with masses below 7.5 Earth masses, currently undetectable, are even more numerous. Moreover, the correlation with heavy elements supports current planet-formation theory that suggests rocky planets would be more numerous than the gas giants. The observations suggest that many nearby stars harbor rocky planets.

The inherent limitations of the radial-velocity technique preclude detection of small, Earth-like extrasolar planets around stars of similar temperature to our Sun. To move to lower-mass planets, we will employ two space telescopes: Kepler and SIM PlanetQuest.

Kepler will monitor hundreds of thousands of distant stars looking for rare transits of planets as small as Earth as they pass in front of their parent stars. It will photometrically monitor 100,000 stars up to 600 parsecs away and should discover tens of terrestrial planets and hundreds of gas-giant planets. From Kepler we will derive a statistical knowledge of how rare or common planets like Earth are.

SIM PlanetQuest will perform the first census of Earth-like planets around the nearest stars — planets that we will be able to observe through direct detection of light to learn more about their physical properties, accurately measuring their masses and orbits. SIM PlanetQuest will have the ability to determine the complete catalog of planetary and orbital parameters needed to understand planetary systems down to terrestrial planet masses. SIM PlanetQuest will detect the "wobble" in the parent star's apparent motion as the planet orbits, to an accuracy of one millionth of an arcsecond — the thickness of a nickel, viewed at the distance of the Moon. SIM PlanetQuest's census of nearby stars will optimize target selection for TPF-C, and will improve the latter's observing efficiency and sensitivity, speed the rate of discovery, and ultimately enhance our ability to characterize the planets we find.

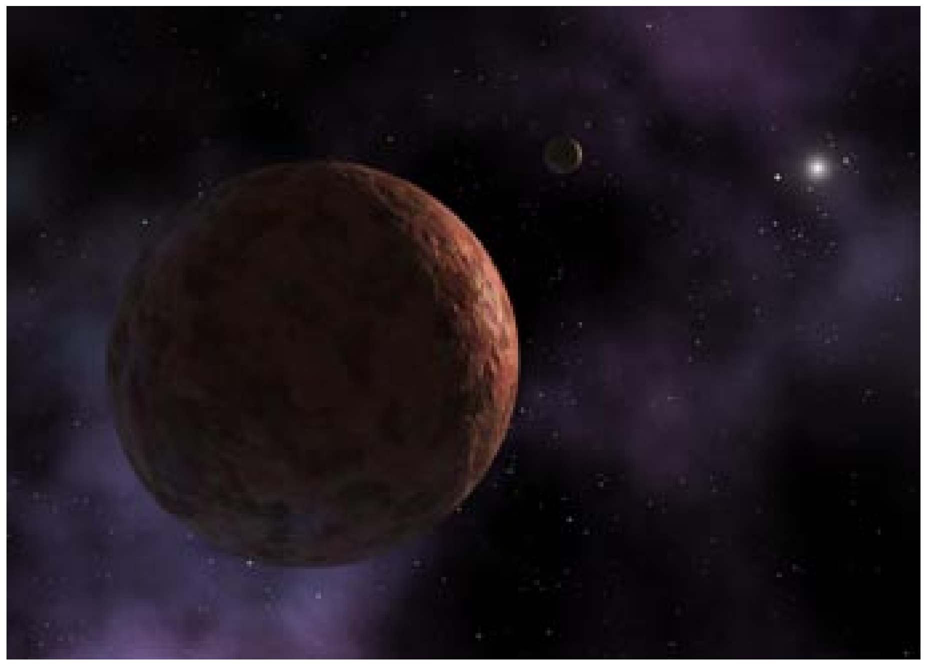
In their respective roles, Kepler and SIM PlanetQuest are highly complementary: Kepler provides statistics on the frequency of Earth-size planets using distant stars, and SIM PlanetQuest surveys the nearest stars and finds targets suitable for subsequent observation by the Terrestrial Planet Finder missions.

Search for Habitable Planets and Life

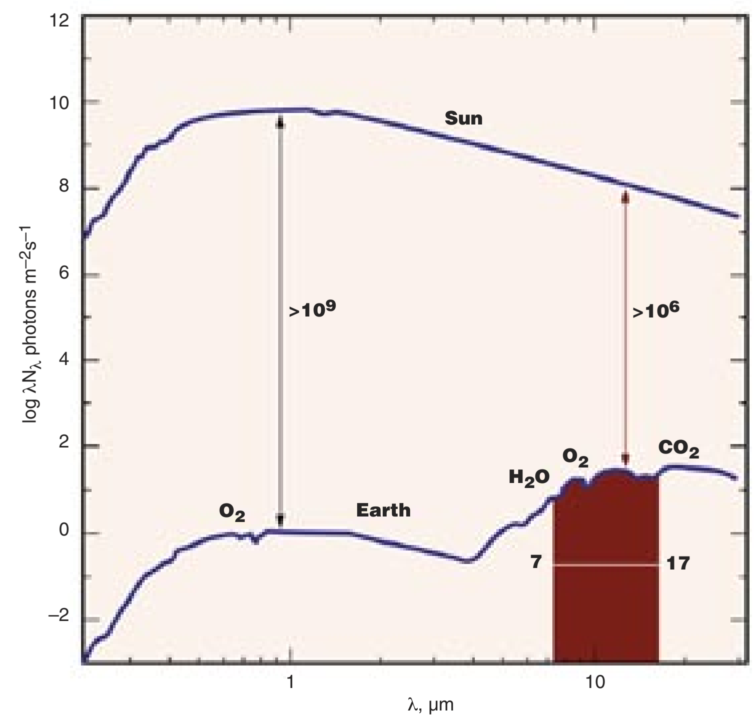
To determine whether a planet is habitable, we must build observatories capable of directly detecting the light from the planet, with the planet illuminated by the light of its parent star or glowing at infrared wavelengths by the warmth of the planet itself. The direct detection of Earth-like planets is an enormous technical challenge; telescopes are required that can suppress the overwhelming glare from a star so that its faint orbiting planets can be seen. At mid-infrared wavelengths, a typical star would be a million times brighter than an Earth-like planet in its orbit, and at optical wavelengths the star may appear a billion times brighter than the planet. The detection of other Earths has been compared to detecting a firefly in the glare of a searchlight — on a foggy night — where the observer is on the Pacific coast and the searchlight and firefly are in New York.

The search for habitable planets and life is founded upon the premise that the effects of even the most basic forms of life on a planet are global, and that evidence for life, or biosignatures, from the planet's atmosphere or surface will be recognizable in the spectrum of the planet's light. Observations across as broad a wavelength range as possible are needed to fully characterize a planet's ability to support life and to search for signs of life.

Direct imaging detection and spectroscopic characterization of nearby Earth-like planets will be undertaken by the Terrestrial Planet Finder missions. The first, the TPF Coronagraph (TPF-C), will operate



An artist's visualization of the planet-like object dubbed "Sedna," seen where it resides at the outer edges of the known solar system. The object is so far away that the Sun appears as an extremely bright star instead of the large, warm disc that is observed from Earth.



A comparison between the spectrum of Earth and the spectrum of the Sun from optical to mid-infrared. The dark band indicates the sensitivity range of a version of TPF-I.

Habitable planets

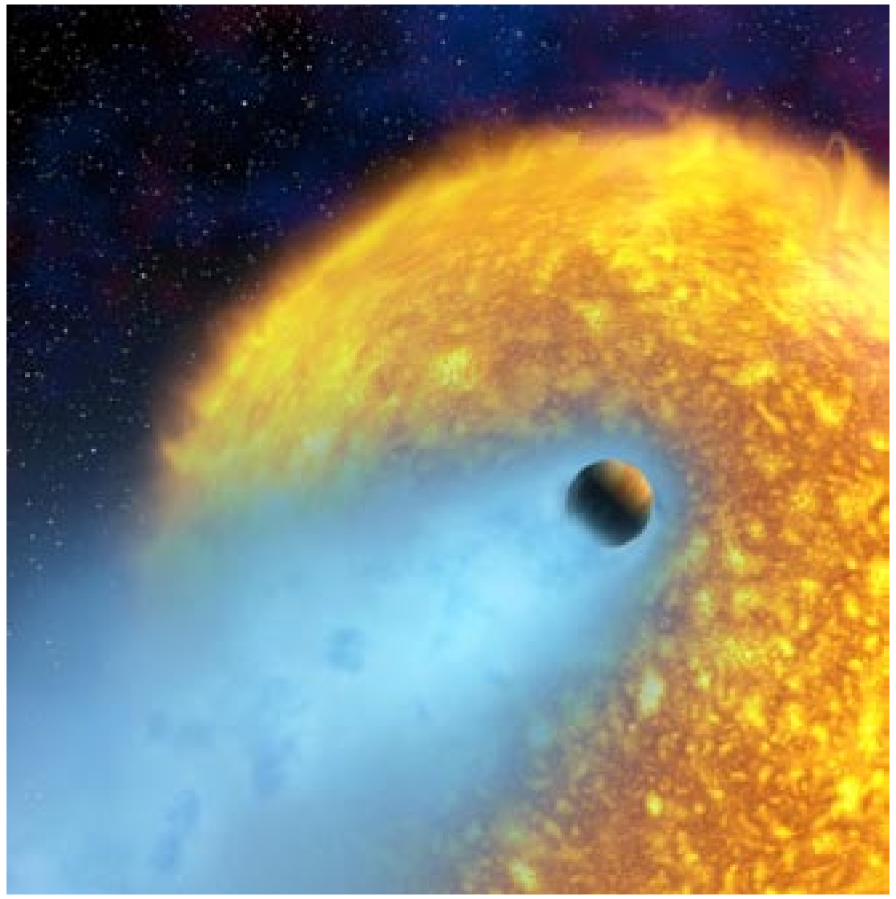
In its simplest definition, a habitable planet is one that has environmental conditions that could support life. Based on our own solar system, the most reasonable home for life elsewhere in the universe is a terrestrial planet — a rocky, roughly Earth-size world that also has an atmosphere and lies within its star's habitable zone where liquid water can exist on its surface. In our solar system, there are four terrestrial planets: Mercury, Venus, Earth, and Mars. The latter three have atmospheres, but only Earth is considered habitable; Venus is too hot and Mars is too small and cold. Planetary habitability also depends on many other factors, including the nature of the parent star and neighboring planets.

at visible wavelengths. It will suppress the light of the central star to unprecedented levels, allowing it to search for terrestrial planets in ~150 nearby planetary systems. TPF-C will be followed about five years later by the TPF Interferometer (TPF-I). TPF-I will operate in the mid-infrared and will survey a larger volume of our solar neighborhood, searching for terrestrial planets around up to 500 nearby stars.

Characterize extrasolar giant planets

The characterization of extrasolar gas-giant planets is the logical first step along the path to the discovery of other Earths. The first successes will doubtless be with young Jupiters, orbiting at tens of astronomical units from their young parent stars; these newly formed planets are thousands of times brighter than planets seen only in reflected light. For gas giants, near- or mid-infrared spectra, even at low spectral resolution would yield temperatures and the abundance of key chemical species like water, methane, or ammonia. Direct detection will also enable time- and phase-resolved observations of planetary brightnesses, orbital motions, and planetary rotation, and allow detailed studies of the time-dependent composition of their atmospheres.

Ground- and space-based transit observations have already been used to characterize the eight transiting giant planets that are presently known. HST observations of the giant planet HD 209458b have shown sodium in its atmosphere, yielding the first-ever composition measurement of a planet outside the solar system. Spitzer has observed the passage of this same planet (as well as TrES-1) behind its star, thus measuring the drop in total light and allowing the temperature of the planet to be determined. In cases where transits have been measured and radial velocity data are available, a lower limit on the planet mass can be accurately measured.



This artist's impression shows a dramatic close-up view of the scorched extrasolar planet HD 209458b in its orbit 7 million kilometers from its Sun-like star. This gas-giant planet, a "hot Jupiter," orbits a star that is 150 light-years from Earth, completing its orbit in less than four days. The upper atmosphere of the planet is so hot that it boils hydrogen off into space.

Follow-up studies of known transits using ground-based 30-meter-class telescopes, SOFIA, and space telescopes (e.g., Spitzer, JWST, Herschel, and SIM PlanetQuest) will provide more detailed information. The Kepler mission can measure the tiny change of the system's total brightness of planet and star as the planet orbits from "new" to "full moon" phase, especially for closer-in Jovian planets.

Ground-based interferometry with the Keck Interferometer and the Large Binocular Telescope Interferometer also provides a path to the detection and characterization of extrasolar giant planets. A next-generation infrared interferometer in Antarctica could detect many young Jupiters and perhaps a few mature gas giants in reflected light around the nearest stars.

In the coming decade, a space-based Discovery-class mission would enable the detection and characterization of giant planets using high-contrast imaging and low-resolution spectroscopy. This would lead to a major near-term advance in understanding of the nature of gas giants, their formation and evolution, and the planetary systems in which they occur.

For nearby stars, and as a precursor to the TPF missions, SIM PlanetQuest will provide the most accurate and most comprehensive statistics on Jovian planet masses; SIM PlanetQuest is particularly sensitive to planets in the outer region of planetary systems (5 to 10 AU) where gas giants are likely to be more populous. Indirect information from astrometry and transits, together with theoretical analysis, will expand our knowledge of giant planets beyond the few examples in our own solar system, and will tell us a great deal about their atmospheres and interiors, including the likely composition of their mysterious central cores.

Characterize terrestrial planets

Thorough characterization of a planet is a fundamental part of the search for life. The exploration of our own solar system and ongoing astrobiology research have taught us that signs of life can only be conclusively recognized in the context of the overall planetary environment. The diversity of rocky worlds is likely much greater than that represented by Mercury, Venus, Earth, and Mars. SIM PlanetQuest, TPF-C, and TPF-I will begin the process of exploring these new planets by measuring their fundamental properties, many of which have strong interdependencies. The table below summarizes the scientific synergies between these missions.

Mass. The SIM PlanetQuest mission will directly measure the masses of the larger rocky planets, providing a fundamental planetary property, and discriminating ice-giants from rocky planets that might otherwise have similar brightnesses. The geochemical and thermal structure of the interior of a planet depends on the planet's mass. A more massive planet is also more likely to have plate tectonics that can recycle surface material (to maintain habitability over long periods) or generate a planet-wide magnetic field that can protect the surface from cosmic rays. A planet's ability to retain an atmosphere also depends on its mass. A substantial atmosphere contributes to habitability by reducing large surface-temperature variations, and by producing greenhouse effects, which can raise the surface temperature to support liquid water.

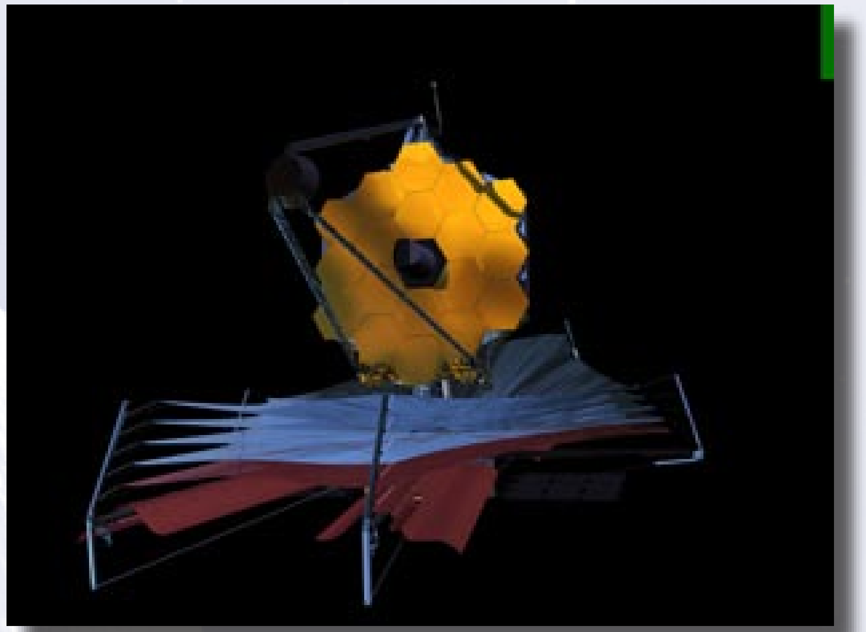
Temperature and Radius. The effective temperature of rocky planets (the temperature of the observed or "emitting" surface, which may be the actual surface, or a cloud deck or other atmospheric level) will be best measured by combining TPF-C and TPF-I data with SIM PlanetQuest orbital measurements. By combining TPF-C measurements of the reflected visible fluxes with the mid-infrared fluxes made by TPF-I, we can constrain the radi-

PARAMETERS	SIM	TPF-C	TPF-I
Orbital parameters			
Stable orbit in habitable zone	✓		
Characteristics for habitability			
Temperature			✓
Temperature variability due to distance changes	✓		
Radius		◆	◆
Albedo		◆	◆
Mass	✓		
Surface gravity	◆	◆	◆
Atmospheric and surface composition		✓	✓
Atmospheric conditions		✓	✓
Presence of water		✓	✓
Temporal variability of composition		✓	✓
Solar system characteristics			
Influence of other planets	✓		
Presence of comets or asteroids		✓	
Indicators of life			
Atmospheric biosignatures (e.g., O_2, O_3, CH_4)		◆	◆
Surface biosignatures (e.g., vegetation red edge)		✓	

◆ = all the missions are required to determine the parameter
✓ = parameter can, in principle, be obtained by the one mission alone

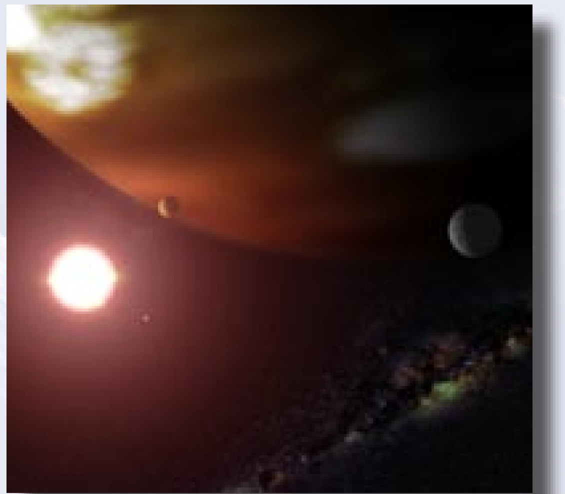
Physical Parameters Determined by SIM, TPF-C, and TPF-I.

Investigating the Birth of Planets



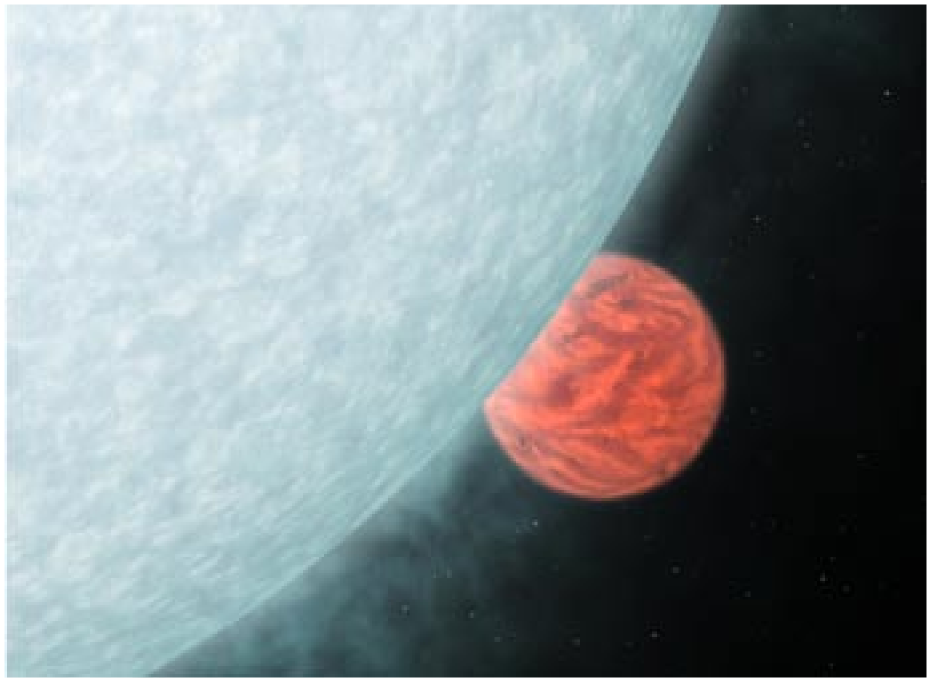
The great cosmological goals of the James Webb Space Telescope (JWST) include observing the first objects to ignite in the universe and studying the formation of the first galaxies. Astronomers will use the observatory's near- and mid-infrared sensitivity and resolution to discover and study dusty disks around solar systems like our own, analyze the molecular composition of extrasolar planet atmospheres, and directly image Jupiter-size planets orbiting nearby stars. While we have a fairly good understanding of what the universe is like today, what it was like in the recent past (when it was between 10–15 billion years old), and what it was like when it was quite young (less than about 1 million years old), there is a lack of observational information for the time period between 1 million and a few billion years old — when the first structures that we see today began to form. JWST is designed to study this period of the earliest galaxies and some of the first stars formed after the Big Bang. Harnessing JWST's infrared capability, astronomers will probe and penetrate the dusty structures of optically opaque star- and planet-forming clouds, helping to unravel the mysteries of how protoplanetary systems develop within circumstellar disks. JWST will help us understand how planets form and how they can survive to maturity in the hostile environs of hot newborn stars. JWST will also scrutinize the atmospheres of giant planets around stars within about 30 light-years of the Sun, and search for the source of water and organic molecules for planets in their stars' habitable zones, where conditions are such that water could exist on the planet's surface.

Terrestrial planets and SIM PlanetQuest



At the end of this decade, SIM PlanetQuest will provide the first comprehensive survey for planets down to a few Earth masses around 250 nearby stars. SIM PlanetQuest's initial reconnaissance will optimize target selection for the Terrestrial Planet Finder missions by identifying systems that are most likely to contain habitable planets and providing masses for the known planetary components of those systems. Moreover, the mass of the majority of the planets found by the TPF missions can be estimated from the results of the SIM PlanetQuest mission. Mass is a crucial planetary characterization parameter because it readily discriminates between terrestrial and Jovian planets, and provides an indication of the planet's ability to retain an atmosphere and buffer a stable climate.

Information from SIM PlanetQuest and the TPF missions can be synergistically combined to enhance physical characterization. For example, the masses determined by SIM PlanetQuest can be combined with the sizes determined from the combined data sets of TPF-C and TPF-I to yield planetary densities, which unambiguously characterize the object as rocky, icy, or gaseous, and surface gravities that determine whether the planet can retain various atmospheric gases over time. The combination of SIM PlanetQuest, TPF-C, and TPF-I data sets also strengthens the goals of each mission. For example, a planetary orbit characterized by TPF can be used to enhance the sensitivity of the SIM PlanetQuest data set to retrieve more Earth-mass planets; or if a planet and its orbit are known from SIM PlanetQuest, TPF can obtain the planet's spectrum far more efficiently with a priori knowledge of its position.



This artist's concept shows what a fiery hot star and its planetary companion might look like viewed in infrared light. In visible light, the star would shine brilliantly, overwhelming the fainter light reflected by the planet.

us, surface reflectance (albedo), and effective temperature of the emitting surface. For planets with atmospheres, spectroscopic observations of greenhouse gases and other atmospheric properties by both TPF-C and TPF-I can be combined with atmospheric models to infer the surface temperature and pressure, which are our best indicators of habitability.

Atmospheric Composition. TPF-C and TPF-I will acquire low-resolution spectra of planets to measure the chemical composition and physical properties of their atmospheres. The spectroscopic observations will be designed to detect oxygen, ozone, carbon dioxide, methane, other absorbing gases, and clouds if present in the planet's atmosphere. These spectroscopic observations will be essential to our search for signs of habitability and life.

Surface Properties. TPF-C and TPF-I will search for temporal variability in the brightness of the planets caused by the rotation of surface features and clouds. For planets that are not entirely covered by clouds, TPF-C can get direct spectral measurements of planetary surface composition (rock, ocean, ice, vegetation). TPF-I may also be able to constrain the surface composition on these planets. These observations will be used to determine whether the planet has clouds, oceans, and continents. Spectral observations at different points in the planet's orbit will be used to search for seasonal global variations in planetary properties. Because of the relatively slow rate of change of the planet-wide physical properties being considered here, it will be possible to combine the TPF-C and TPF-I data sets in a meaningful manner after taking into account orbital location, phase-function effects, etc.

SIM PlanetQuest and the TPF missions will thus not only determine if there are terrestrial planets around nearby stars, but will also explore their suitability for hosting life. This work will phase directly into the next and most exciting step in the science program — the search for actual signs of present or past life on the most promising candidates.

Search for life beyond our solar system

The search for life elsewhere in the universe begins with an understanding of the biosignatures of our own world. Earth has surface biosignatures due to vegetation, and several atmospheric biosignatures, including the characteristic spectra of life-related compounds like oxygen — produced by photosynthetic bacteria and plants — and its photochemical product, ozone. The most convincing spectroscopic evidence for life as we know it is the simultaneous detection of large amounts of oxygen and a reduced gas, such as methane or nitrous oxide, which can be produced by living organisms. Oxygen, methane, and nitrous oxide are produced in large amounts by plants, animals, and bacteria on Earth today, and they are orders of magnitude out of thermodynamic equilibrium with each other.

However, we should not expect other habitable worlds to be exactly like our own. We must furthermore be able to

BIOMARKERS IN THE OPTICAL AND INFRARED

The combined information from the Terrestrial Planet Finder missions (TPF-C and TPF-I), spanning both visible and mid-infrared wavelengths, will yield important information on the physical properties of extrasolar terrestrial planets and provide a solid foundation for the search for life. The National Research Council's (NRC) Committee on Astronomy and Astrophysics (2004) endorsed this multiwavelength approach, stating, "the identification of biomarkers (i.e., spectroscopic features indicative of chemical balances attributable to biogenic activity) requires observations in spectra that span not only the optical but also the mid-infrared bands," and "what can be learned from the combination of TPF-C and TPF-I data is... far greater than what either mission alone would yield."

Life on extrasolar planets, and the conditions under which life thrives there, may not be identical to those conditions found on Earth. We must therefore design missions that are capable of characterizing planets that are very different from Earth and able to detect the byproducts of metabolisms that may not be familiar to us. To do this, we will need to observe over the largest wavelength range possible, spanning the visible and infrared spectral regions. This will allow us to observe the same biosignatures in different wavelength bands and will increase our overall chances of detecting and correctly interpreting them.

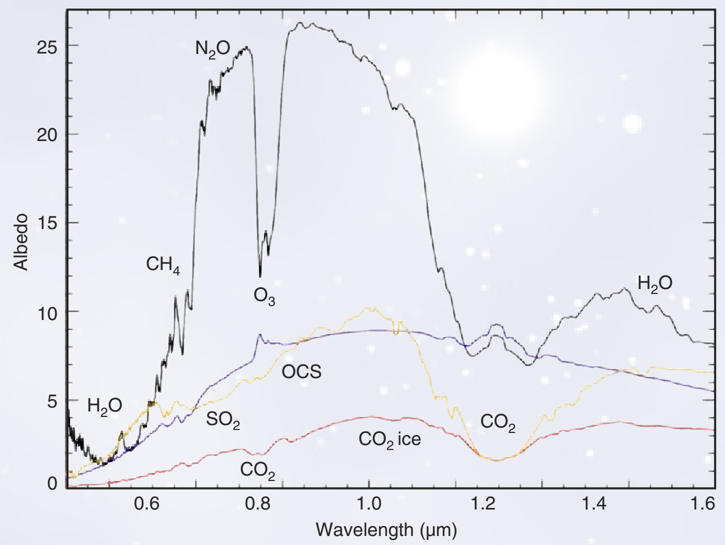
The ability to study multiple lines provides confirmation of initial detections and a robust diagnostic for many different types of planetary environments. Even though it is easier to detect the CO_2 15-micron band, it is impossible to determine the column abundance of this important greenhouse gas (or the surface pressure) from the band alone. However, a simultaneous solution for the strengths of the 15-micron band and the mid- and near-infrared lines (1 to 2 microns) of CO_2 would allow one to extract information on CO_2 concentration, vertical temperature profile, and atmospheric pressure that would be impossible to obtain from visible or infrared observations alone. Comparable arguments could be made for other species where unraveling the effects of optical depth, the presence of clouds, and vertical temperature gradients demand a great deal of information for accurate modeling.

Having data in two different wavelength regions would also help with the identification of the secondary biomarker gases CH_4 and N_2O. CH_4 can be observed in both the visible and the thermal infrared, although detection in the mid-infrared can be problematic in the presence of strong absorption from water vapor, whereas N_2O can only be seen in the latter wavelength region. Moreover, surface signatures of life, such as those from leafy plants, can only be detected in the visible range, but many metabolic byproducts of life have absorption features that are accessible only in the mid-infrared.

Sizes of extrasolar terrestrial planets can only be determined with observations of both thermal emission at infrared wavelengths and reflected sunlight at visible wavelengths. This is true as well for determining the sizes of unresolved asteroids or minor planets in our own solar system.

Understanding the global energy balance of a planet also requires observations at visible and mid-infrared wavelengths and is crucial for making a first-order assessment of a planet's habitability. The mid-infrared can give us the temperature and characteristics of the emitting surface, but the detection of spectral features at visible wavelengths will determine if the temperature is actually that measured at the surface.

Multiwavelength observations are also useful because there may be many planets that are so faint that detailed spectroscopy is impossible in first-generation missions. However, comparison of low-resolution visible and mid-infrared flux densities would allow us to understand these planets well in advance of a more capable spectroscopic mission.



Mid-infrared spectra of planets in our solar system showing the many different atmospheric gases that can be detected in this wavelength region. Earth with a clear sky (black) and with cloud cover (blue), Mars (red), and Venus (yellow).

identify potential "false-positives," the nonbiological generation of planetary characteristics that mimic biosignatures. For example, while atmospheric methane may be a possible biomarker on a planet like Earth, especially when seen in the presence of oxygen, on a body like Titan it is simply a component of the atmosphere that is non-biologically-generated. Theoretical and experimental research and analysis is a crucial part of our quest for life. We must have a detailed understanding of the biosignatures that might be found. This is especially true for habitable planets that differ from modern Earth in age or composition. The results of this research will help set the requirements for the Terrestrial Planet Finder missions and aid in the design of even more advanced future telescopes. These ongoing studies are supported by the NASA Astrobiology Institute and the TPF-Foundation Science program.

By characterizing the basic properties of planets, the planned suite of missions will determine whether any of the nearby planets have suitable environments for detectable life. The TPF-C and TPF-I missions will make intensive observations of the systems that contain a terrestrial planet in the habitable zone and explore the planet's brightness and spectrum in detail. TPF-C and TPF-I will have sufficient spectroscopic capability to detect evidence for gases such as carbon dioxide or water vapor. The visible and infrared spectrum, in conjunction with theoretical and empirical models, can tell us about the amount of atmosphere, the gases present in the atmosphere, the presence of clouds, the degree and variability of cloud cover or airborne dust, and the presence of a greenhouse effect. The concentration of greenhouse gases can determine whether the surface is warm enough to maintain liquid water, even if (as for Earth) the equilibrium temperature without such gases would result in a frozen surface. Clouds and dust aerosols can determine the amount of light absorbed and reflected, and, thus, the surface temperature. Spectra can also tell us about the surface, whether it is rock-like with little or no overlying atmosphere, or covered with an ocean.

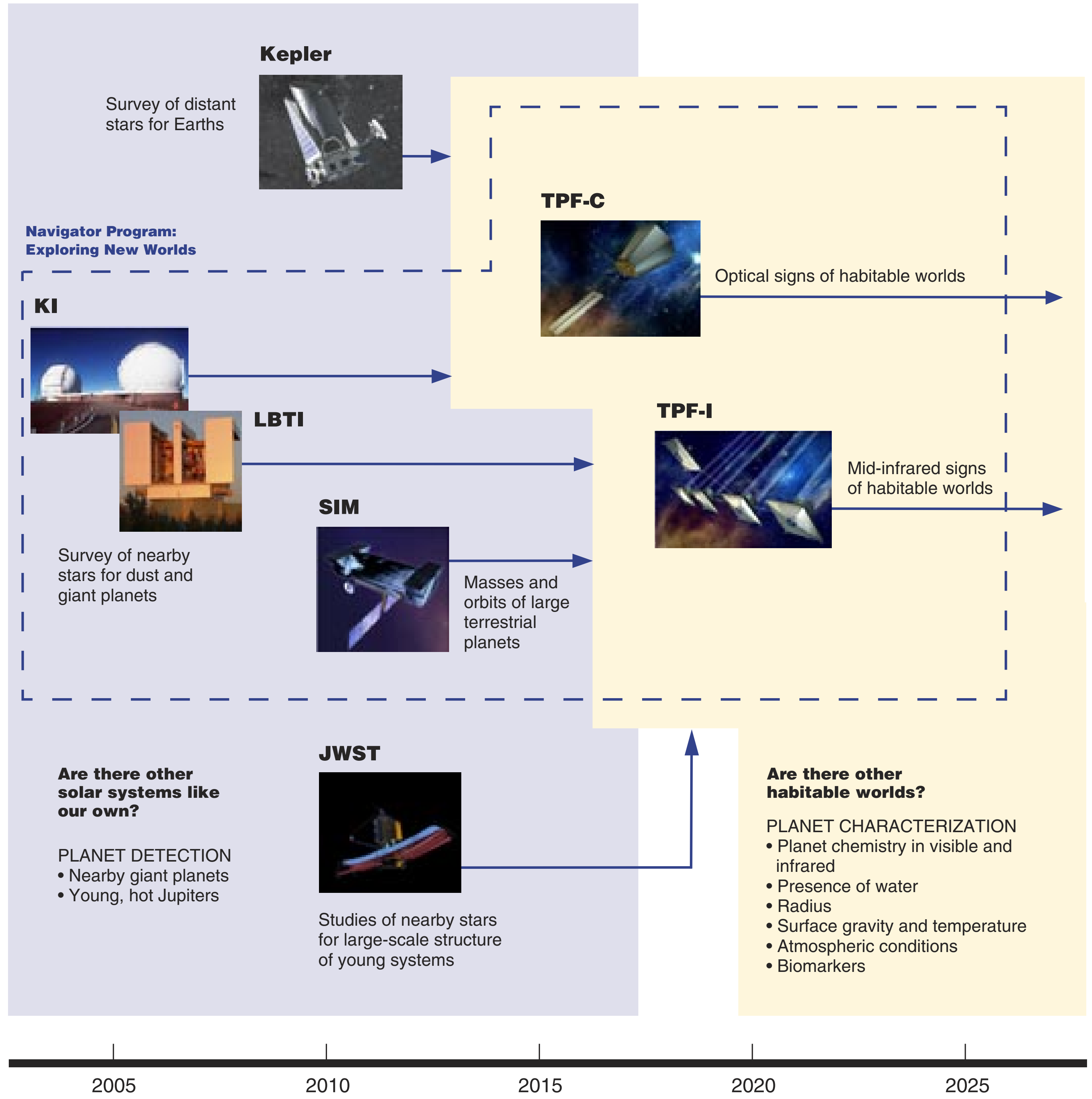
Beyond the TPF missions, the next-generation Life Finder mission would use a greater collecting area and spectral resolution to provide a more sensitive search for additional biosignatures and extend our search for Earth-like worlds to perhaps thousands of stars. The dual goals of extending our search to more planetary systems and providing greater time-resolved spectral information will challenge our imagination and technical prowess for decades to come. The Decadal Review (*Astronomy and Astrophysics in the New Millennium, 2001*) strongly endorsed the search for life beyond our solar system, noting that "*This goal is so challenging and of such importance that it could occupy astronomers for the foreseeable future.*"

Navigator Program: Exploring New Worlds

To realize this bold exploration agenda, NASA has established the Navigator program, a suite of inter-related missions to explore and characterize new worlds. The program embodies the Presidential directive to enable advanced telescope searches for Earth-like planets and habitable environments around neighboring stars. Each successive mission provides an essential step toward the ultimate goal of revealing signs of life elsewhere in the universe. The Navigator program is structured in a cohesive effort leading towards the Terrestrial Planet Finder missions, which serve as the focus of the program. The search will begin in this decade with the Keck Interferometer and the Large Binocular Telescope Interferometer, which will observe nearby stars to probe exozodiacal dust disks, thus revealing gaps and features created by planets that have so far remained unresolved. The stage will then be set for more advanced telescope searches in space that are capable of detecting Earth-like planets.

Navigator advanced telescope searches

In the following decade, large terrestrial planets down to several times the size of Earth will be detectable with SIM PlanetQuest. With the ability to make exquisitely fine measurements of the relative motions of stars, SIM PlanetQuest will discover planets even smaller than those detectable from the ground, probe the planetary systems uncovered by KI and LBTI, and characterize the orbits and measure masses of terrestrial planets for the TPF missions that follow. The Terrestrial Planet Finder missions will build upon the legacy of all that have gone before. With a broad database of stars and planets discovered through prior Navigator missions, TPF-C and TPF-I will target the most promising nearby stars and begin the search for habitable worlds. These missions will have unprecedented dynamic range and angular resolution, enabling the first studies of the planetary atmospheres and habitability of other worlds.



Notional timeline of planet-finding missions from 2005 to beyond 2020.

Universe probes

Compelling science in support of the quest for planets and our origins can be conducted through a line of mid-size competed missions along the lines of the Einstein Probes. The Universe Probes, which are moderate-size, fully competed missions, include the Einstein Probes and would address compelling questions that are not undertaken through current or planned missions. Establishing such a line of competed missions will be a goal for a future initiative.

Technology and foundation science

The Navigator program encompasses a cohesive set of flight and ground activities that have a common scientific purpose and share many technological challenges. The common framework for technology and project development benefits all Navigator missions. Each major mission in the Navigator program builds upon the scientific and technical legacy of past missions and develops new capabilities for those that follow. The technology development plan is described further in Chapter 6.

A broad community of scientific endeavors, spanning all aspects of experimental and theoretical research in planet finding, is supported by the Navigator program through the NASA-supported TPF Foundation Science. The suite of Navigator science and the excitement of planet finding are conveyed to the public through a unified education and public outreach effort, most visible through Navigator's award-winning PlanetQuest website (http://planetquest.jpl.nasa.gov/).

An integrated program

Common resources for mission and community support are coordinated within the Navigator program. As part of its portfolio of activities for finding extrasolar planets, the Navigator program includes the Michelson Science Center (MSC). MSC is named in honor of Albert Michelson, the first American to receive the Nobel Prize in Physics and the pioneer of laboratory and astronomical interferometry. The primary purpose of the MSC is to develop the science and technology of detection and characterization of planets and planetary systems about other stars.

The center provides common resources for data processing, archiving, and support for new observers; the Michelson Fellowship Program, managed through the MSC, provides support to a new generation of young graduate students and scientists engaged in Navigator science and technology. MSC actively promotes its services in the astronomical community and is host to practitioners of techniques specific to this endeavor, including interferometry, coronagraphy, and astrometry. Projects of this nature that are too large or require specialized expertise beyond that of a typical university department are particularly well served by the MSC, including support of the Keck Interferometer and SIM PlanetQuest missions. Supporting activities, such as proposal administration, long-term archives, community workshops, and fellowship oversight are also part of the MSC's mandate from NASA to expand our knowledge of planets about other stars. 12

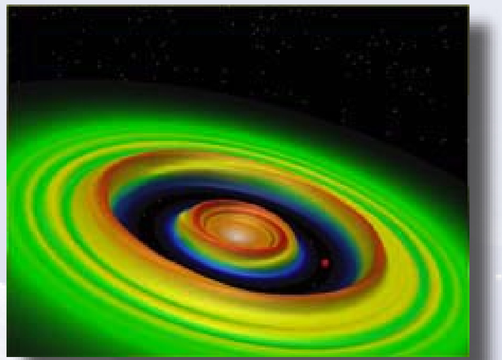
The goals of the Navigator program are in turn a key component of NASA's long-term goals. Embodied in the NASA Vision and the NASA Mission is the quest "To find life beyond" and the objective "To explore the universe and search for life." Moreover, the science objectives of NASA's *Vision for Space Exploration* highlight the exploration of other planetary systems with the challenge to "conduct advanced telescope searches for Earth-like planets and habitable environments around other stars." The Navigator program embodies all these goals.

"EVEN 'SUPER COOL' HIGH SCHOOL KIDS WILL PAY ATTENTION TO THIS STUFF!"
—NEW JERSEY ASTRONOMICAL ASSOCIATION

INFORMAL EDUCATION PARTNERS

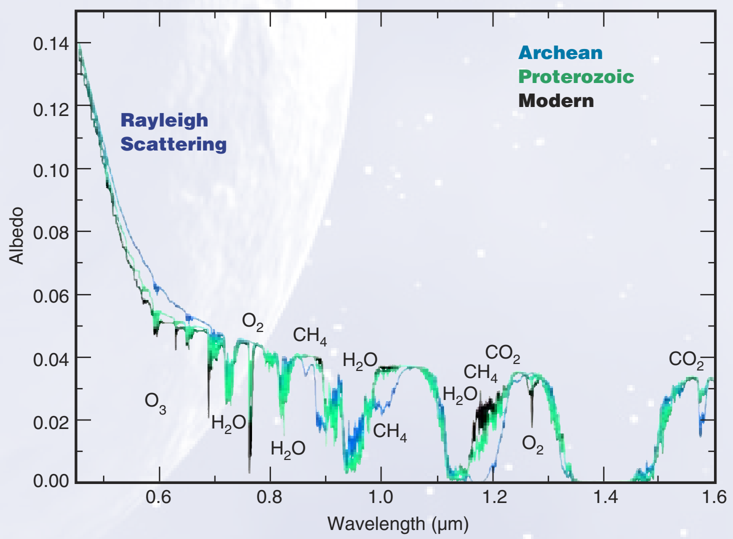
Amateur astronomers represent a significant source of outreach energy and enthusiasm, with more than 675 astronomy clubs in the United States and over 50,000 affiliated members. JPL's Navigator program has partnered with the Astronomical Society of the Pacific to create the Night Sky Network, an umbrella organization designed to inspire and support astronomy clubs in bringing the wonders of the universe to the public. Outreach toolkits convey the reasons we place telescopes in space, how we find planets around other stars, and the vast distances to celestial objects studied by NASA space science missions. These types of easy to use, low-cost resources and professional development opportunities enable centers of informal learning to share space science discoveries and technology with their communities, inspiring young and old alike. Over 1,000 Night Sky Network events were held in the first year around the country.

Theory Challenges



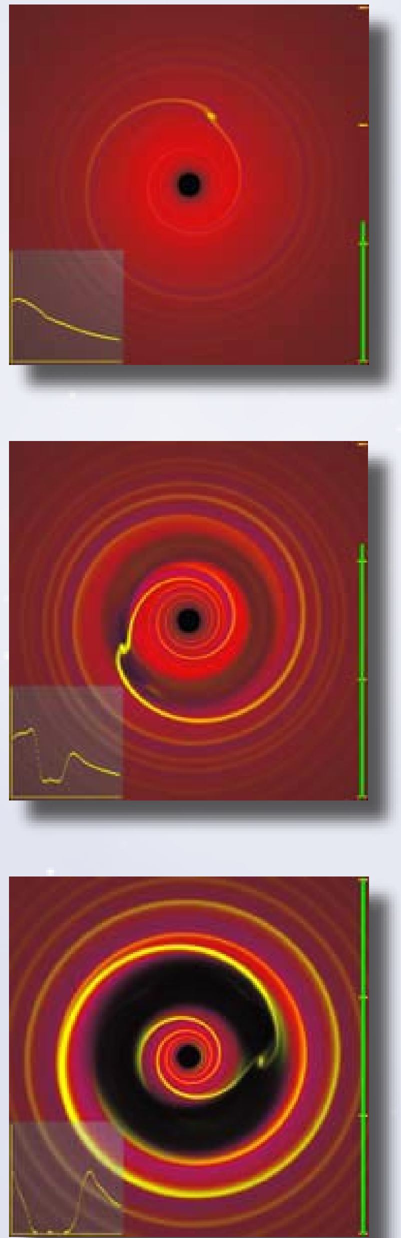
Evolution of a Protostellar Disk

This computer rendering is based on a hydrodynamic model that calculates the evolution of a protostellar disk as a giant protoplanet forms. In particular, the model follows the interaction between the planet and the disk. With the newly formed protostar in the center of the disk, a Jupiter-mass protoplanet forms at Jupiter's distance to the Sun (seen as a small red sphere). The protoplanet excites density waves in the gas, which propagate away from the protoplanet. These waves, which push the protoplanet and are responsible for the planet's orbital migration, are easily visible in the plot as spiral patterns. (In the plot, color and "height" are used to show the disk surface density — high red bumps indicate high surface density, green is the original, unperturbed density, and blue is low surface density.) Because the disk has a certain amount of prescribed viscosity, the waves are damped out as they ripple away from the planet; if a lower viscosity were used, the waves would travel farther and the spiral pattern would continue out toward the disk edge. Most important, the gas–protoplanet interaction clears out a gap in the disk. Once this gap forms, there is no longer any gas left to accrete onto the protoplanet, and it stops growing. In this particular model, the surface density in the gap is less than a millionth of its original value.



Spectra of the Ancient Earth

Modeled spectra of Earth in the visible, as seen throughout its 4.6-billion-year history. Up until 2 billion years into its history, Earth had little or no oxygen, but instead showed stronger absorption from carbon dioxide and methane. These models can help us discriminate terrestrial planets at different stages of evolution.



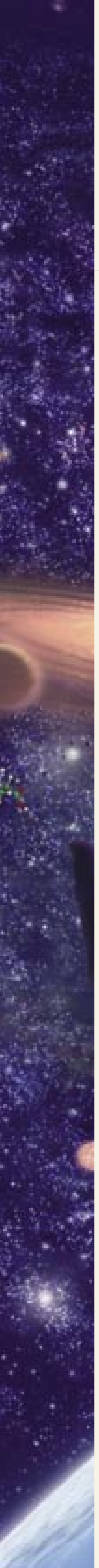
(Top) Low-mass planet: Type I migration

(Middle) Gap formation: Type II migration

(Bottom) Suppression of accretion at high planet masses

Gap Opening and Planet Migration

These frames above are part of a sequence that illustrates how planets of different masses interact with the gaseous protoplanetary disk. In the sequence, the mass of a planet on a fixed circular orbit grows exponentially in time from an initial mass of three Earth masses to a final mass of 10 Jupiter masses. Meanwhile, the response of a viscous protoplanetary disk is calculated using a high-resolution, 2-D hydrodynamic simulation, and displayed in an almost corotating frame. The actual simulation ran for more than 600 orbits (far too many to display in an inertial frame), so the disk response to each mass planet is almost in a steady state. Three distinct stages can be identified.



EXPLORING NEW WORLDS

SUMMARY *of* MISSIONS

To explore the universe for habitable planets and life, the Keck Interferometer and Large Binocular Telescope Interferometer will:

- Image dust disks around nearby stars to estimate the density of material in the habitable zone.
- Search for gaps and asymmetries in dust disks indicative of perturbations by planets.

SOFIA will:

- Provide high-resolution images of planetary debris disks around nearby stars.
- Search for the spectral signatures of planet formation in the habitable zones of young stars.
- Observe transits of large extrasolar planets.

Herschel will:

- Find cold material in the outer debris disks around nearby stars corresponding to our own outer solar system regions.
- Inventory water and other gaseous molecules in the disks and clouds around young stars that may be forming planets.

Kepler will:

- Monitor hundreds of thousands of distant stars for transits of planets as small as Earth.
- Derive a statistical knowledge of whether Earth-like planets are rare or commonplace.

JWST will:

- Probe the earliest moments of star and planet formation.
- Study the distribution and composition of dust in planetary debris disks.
- Search for young Jupiters around nearby young stars.
- Provide spectroscopic follow-up of gas-giant planets detected by Kepler.

SIM PlanetQuest will:

- Search for terrestrial planets around nearby stars and measure planetary masses.
- Characterize the orbital ellipticity and inclination of multiple-planet systems to determine the stability and the evolution of planetary systems.
- Search for solar system analog systems with giant planets at 5–10 AU.
- Perform the only census for gas giants near the habitable zones around young stars (1–100 Myr).
- Investigate formation and migration scenarios that might explain the puzzling presence of hot Jupiters in very short-period orbits.
- Optimize target selection for TPF-C.

TPF-C will:

- Characterize environments of terrestrial planets using visible-light spectroscopy.
- Combine spectra with SIM PlanetQuest masses to robustly characterize the planet and its atmosphere.
- Image dust disks around nearby stars to help build a complete picture of the formation of planetary systems.
- Combine detections with SIM PlanetQuest detections to derive masses down to one Earth mass.
- Determine which planets have conditions suitable for life.
- Search for signs of life.

TPF-I will:

- Characterize terrestrial planet environments using mid-infrared spectroscopy
- Combine detections with those of SIM PlanetQuest and TPF-C to derive a full set of physical parameters describing a planet and its atmosphere — including temperature, surface gravity, etc.
- Image dust-enshrouded protoplanetary disks with milliarcsecond resolution to cleanly separate protoplanets or planets, disk and star.
- Combine detections with SIM PlanetQuest detections to derive masses down to one Earth mass.
- Determine which planets have conditions suitable for life.
- Search for signs of life.

SAFIR will:

- Extend Spitzer studies of the temperature structure in circumstellar disks, including characterizing gaps due to planets.
- Provide high-resolution images of planetary debris disks around many stars.
- Search for water and other molecules in the disks and envelopes of young stars that may be forming planets.

Life Finder will:

- Provide additional spectroscopic resolution to detect signs of life beyond those available to TPF-C and TPF-I and for planets around thousands of stars.
- Provide higher time-resolved observations to monitor diurnal and seasonal cycles.

5 Strategic Mission Summary

"A ship in port is safe, but that is not what ships are for. Sail out to sea and do new things."

—Admiral Grace Hopper, USN

A three-color composite of the Trifid Nebula taken by the Spitzer Space Telescope infrared array camera and multiband imaging photometer.

The rich science program described in this document draws upon a vast array of activities including ground- and space-based observations, data analysis, theory, and modeling. The sources of observations include ground observatories, balloon and sounding rocket instruments, small- to moderate-size competed missions, and the major strategic missions. This chapter describes the overall implementation philosophy and strategic programmatic approach and summarizes the strategic missions that are called for to implement the vision of exploration of the universe.

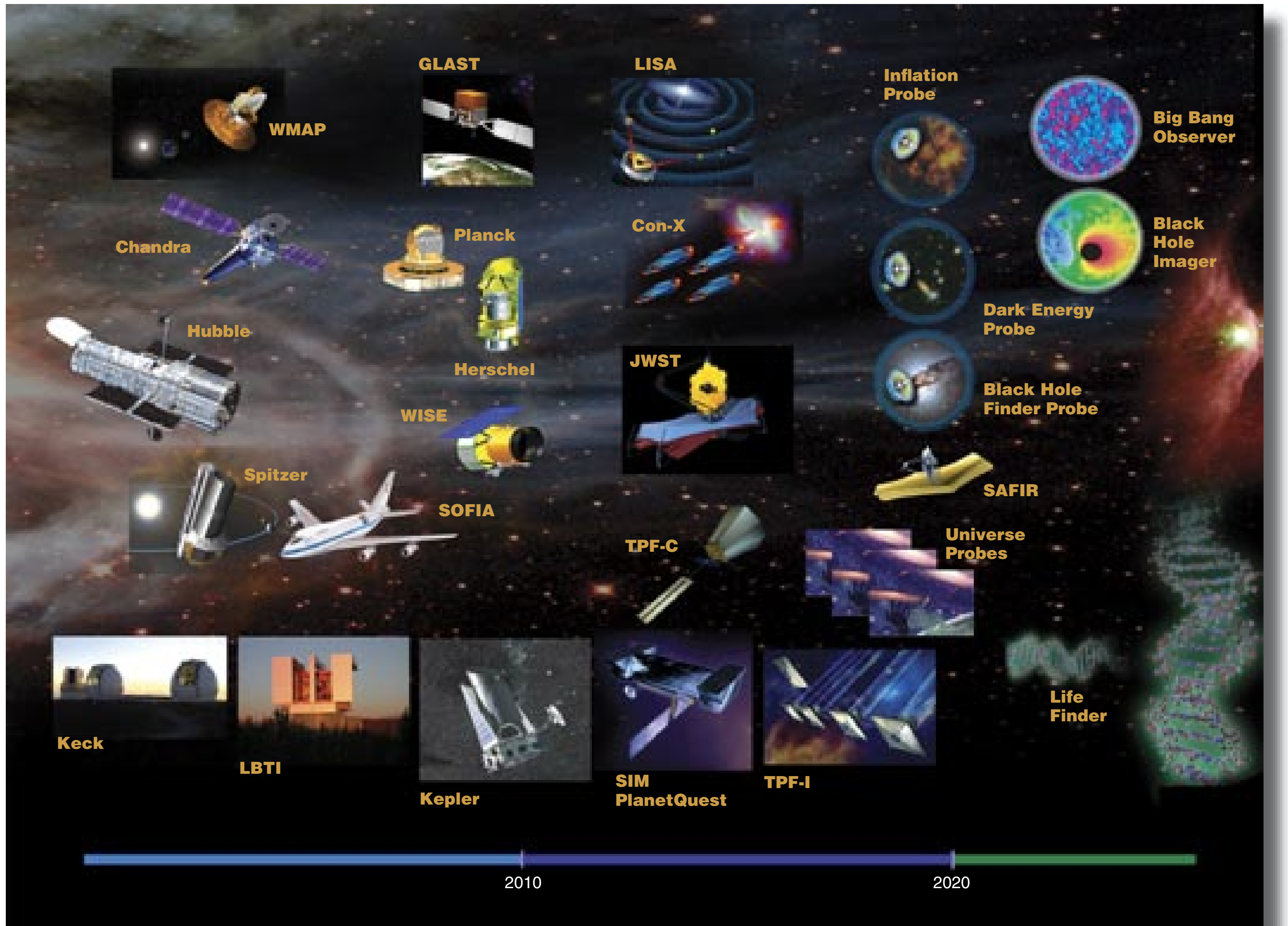
Implementation Philosophy

The explorations described in this document will require the development of missions with unprecedented capability. The challenges this presents have led to adoption of certain philosophical principles in the implementation of the Astronomy and Physics Division investigations. These include:

- The most challenging investigations will be carried out through strategic missions identified and endorsed through the strategic planning exercise and the National Academy of Sciences decadal survey of astronomy. These strategic missions will be led by NASA Centers, with science teams, key investigations, and instruments drawn from the broad scientific community through open peer-reviewed competition.
- Strategic missions will be initiated through an extended pre-formulation (pre-Phase A) period where all of the high-risk technologies will be developed before the mission is allowed to proceed into the higher cost-rate period of formal formulation and implementation. This provides an essential cost-risk mitigation strategy that has served NASA well.
- Where important scientific investigations can be accomplished without significant new technology development, and without excessive development risk, a series of competed Principal Investigator–led mission opportunities at a variety of cost levels will be invoked. These investigations may be identified in this document or may be proposed ab initio by the Principal Investigator. Mission lines exist at low (~$200M Explorer Program), mid (~$400M Discovery Program), and moderate (~$600M Universe Probes) levels. The Einstein Probes of the Beyond Einstein program are a coherent and integrated subset of the Universe Probes. A Universe Probe is a competed mission on a scale between a Discovery and a strategic mission that is an essential component of a well-balanced program that can take advantage of new developments as they arise.

- In order to focus the complex relationships of the scientific and technological activities involved in carrying out the science described in this document, NASA has organized the implementation of closely related missions into two major programs that are responsible for conducting the precursor and supporting science activities, technology development, and implementation of the missions — Navigator program: Exploring New Worlds, and Beyond Einstein.
- The concept of "Vision Missions" has been introduced to provide NASA with a series of concrete long-term scientific and technological goals. These are missions that would drive NASA's future investments and plans in space science and would constitute the most capable suite of scientific instruments currently imaginable. Crafted to address the most challenging and exciting questions of humankind, Vision Mission concepts are meant to exercise the limits of our creativity. Examples of Vision Missions are Life Finder, SAFIR, the Big Bang Observer (BBO), a large UV/Optical telescope (LUVO), a UV/Optical Interferometer (UVOI), a Far-Infrared and Submillimeter Interferometer (FIRSI), the Nuclear Astrophysics Compton Telescope (NACT), the Early Universe X-ray Observer (EUXO), and the Black Hole Imager (BHI).

Strategic missions from 2005 to 2020 and beyond.



Missions for 2005–2015

Gamma-ray Large-Area Space Telescope (GLAST)

A follow-up mission to the Compton Gamma Ray Observatory Energetic Gamma-Ray Experiment Telescope (EGRET) instrument, the international Gamma-ray Large-Area Space Telescope (GLAST) mission will study the sky in the highest-energy gamma rays (extending out to over 100 MeV). GLAST will identify EGRET sources, discover new high-energy gamma-ray sources, probe supernova shocks, and map the entire sky with higher precision. By probing AGN, GLAST will study jet formation in supermassive black holes. In addition, it will study transient events such as gamma-ray bursts at higher energies than Swift.

GLAST consists of a precision tracker (with silicon strip detectors) and a segmented CsI calorimeter to track incoming high-energy photons and measure their energy. The tracker can provide the location of an object on the sky to between 0.5 and 5 arcminutes. GLAST is a large instrument with 8000 cm^2 of effective area and energy resolution of better than 10% at high energies. It will have a field of view twice as wide as EGRET on CGRO and 50 times the sensitivity. GLAST will be launched on a Delta II rocket in 2007.

Keck Interferometer (KI)

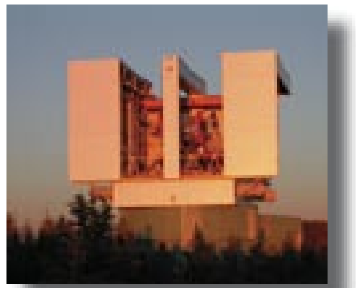
The Astronomy and Physics Division supports a broad science program in conjunction with the W. M. Keck Observatory in Hawaii. This program has two main thrusts: first, the sponsorship of community-accessible time on single Keck telescopes to pursue Astronomy and Physics Division science goals; and second, the development and operations of the Keck Interferometer (KI). The single-Keck program has been in place since 1996, and has been extremely successful in producing important scientific results such as radial velocity exoplanet detections, spectral characterizations of L and T dwarfs, and mid-infrared imaging of planetary debris disks. KI has combined the infrared light collected by the two 10-meter Keck telescopes to undertake a variety of supporting astrophysical investigations. Among the issues addressed by KI will be the location and amount of zodiacal dust in other planetary systems and the astrometric detection and characterization of exoplanetary systems around stars in the solar neighborhood. This first in-depth and long-term census of planets will be an important contribution to our understanding of the architecture and evolution of planetary systems, and will be key in helping to define TPF requirements and architecture.

Extrasolar planets are a reality: more than 150 planet-size objects have been indirectly detected around neighboring stars and their number is growing rapidly. But the techniques available from the ground today are capable of detecting only the most massive such objects. The Keck Interferometer will push this mass limit significantly lower, possibly to below the mass of Neptune. However, it will require space-based techniques to detect objects that approach the mass of Earth and allow the first in-depth search for objects in space like our home planet.

Planck Surveyor

Planck Surveyor is an ESA mission to study the cosmic microwave background, and will be launched with Herschel. Planck will have a 1.5-meter mirror and two instruments. One instrument is an array of 22 tuned receivers operating between 30 and 100 GHz; the second is an array of 52 bolometric detectors. Planck and Herschel are set to be launched in 2007.

Large Binocular Telescope Interferometer (LBTI)



The Large Binocular Telescope Interferometer (LBTI) will further a variety of science goals in star, planet, and galaxy formation through both nulling and wide-field imaging interferometry. Primary among these goals is a planned systematic survey of nearby stars to understand the prevalence of zodiacal dust and gas-giant planets and to determine a system's suitability for terrestrial planets. The modest baseline and common mount design of the dual 8.4-meter LBTI allows uniquely sensitive infrared observations of candidate planetary systems through nulling interferometry. The development of nulling technology and observing techniques will help create a mature technological basis for a TPF mission. The LBTI also allows wide-field, high-resolution imaging of objects down to brightness levels similar to filled aperture telescopes. This is applicable to a wide variety of related imaging and astrometric observations.

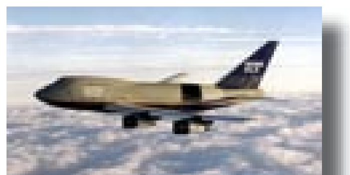
Herschel Space Observatory

The Herschel Space Observatory is the European Space Agency's fourth Cornerstone Mission and deploys a passively cooled 3.5-meter telescope to observe the far-infrared and submillimeter universe. Herschel is planned as a three-year observatory mission, with a launch date scheduled for early 2007. It will be launched on the same vehicle as the Planck Surveyor mission, where both will orbit independently around the second Earth–Sun Lagrange point. Herschel has three instruments, which cover the wavelength range from 57 to 670 microns. Herschel will investigate the birth of stars and their influence on the interstellar medium and will be able to identify specific molecules in the ISM. Herschel is a precursor to SAFIR.

Kepler

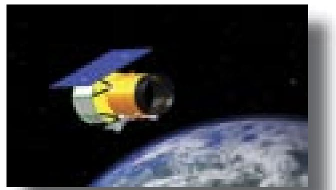
Kepler was selected through the Discovery program and is scheduled for launch in 2008. Kepler provides an excellent example of the kind of mid-scale missions that can contribute to Astronomy and Physics Division science in important ways. The mission is specifically designed to photometrically survey the extended solar neighborhood to detect and characterize hundreds of terrestrial and larger planets in or near the habitable zone and provide fundamental progress in our understanding of planetary systems. The results will yield a broad understanding of planetary formation, the frequency of formation, the structure of individual planetary systems, and the generic characteristics of stars with terrestrial planets. These results will be instrumental in determining how deep TPF will have to look to find an adequate sample of planetary systems to find and characterize habitable planets.

Stratospheric Observatory for Infrared Astronomy (SOFIA)



The Stratospheric Observatory for Infrared Astronomy (SOFIA) will study sites of star formation, the cold interstellar medium, and the center of our Galaxy at high-spatial resolution at far-infrared wavelengths. It is a joint U.S. (80%) and German (20%) observatory consisting of a 747 aircraft with a telescope as large as HST. SOFIA will also function as a unique platform for developing, testing, and reducing risk of new instrument technologies, particularly detectors for future missions such as SAFIR. It will have a prominent education and public outreach program, including involving high school teachers and students in its flights and observations. SOFIA will be making observations in 2006.

Wide-field Infrared Survey Explorer (WISE)



The Wide-field Infrared Survey Explorer (WISE) is a MIDEX-class explorer mission to conduct an all-sky survey from 3.3 to 24 microns up to 1,000 times more sensitive than the Infrared Astronomical Satellite (IRAS) survey. Among other things, WISE will measure the local mass function of brown dwarfs down to a few Jupiter masses. WISE has a 40-centimeter telescope and reimaging optics giving 6″ FWHM resolution. It consists of a single instrument with HgCdTe and Si:As arrays at 3.5, 4.6, 12, and 23 microns. WISE is scheduled for launch in 2009 aboard a Delta rocket.

Space Interferometry Mission (SIM) PlanetQuest

Space Interferometry Mission (SIM) PlanetQuest will take a major step forward in answering one of the defining questions in our exploration of the universe: "Are we alone? Are there other worlds like our own home planet, existing within planetary systems like our own solar system?" SIM PlanetQuest will extend the Keck census of nearby planetary systems into the range of the rocky, terrestrial planets, permitting scientists to refine their theories of the formation and evolution of planets like Earth. SIM PlanetQuest will provide all-important data on planetary masses, which, when coupled with data from TPF-C and TPF-I, will yield density and surface gravity information crucial to complete physical characterization.

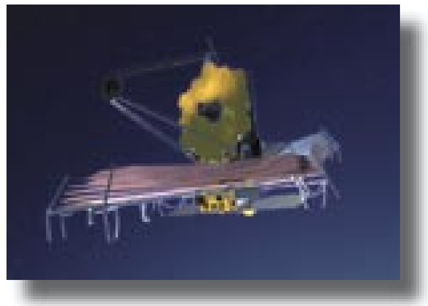
In addition to its scientific goals, SIM PlanetQuest will develop key technologies that will be necessary for future missions, including precision location of optical elements to a fraction of the diameter of a hydrogen atom (picometers) and the precise, active control of optical pathlengths to less than a thousandth the diameter of a human hair.

SIM PlanetQuest's extraordinary astrometric capabilities will permit determination of accurate positions throughout the Milky Way Galaxy. This will permit studies of the dynamics and evolution of stars and star clusters in our Galaxy in order to better understand how our Galaxy was formed and how it will evolve. Accurate knowledge of stellar positions within our own Galaxy will allow us to calibrate luminosities of important stars and cosmological distance indicators enabling us to improve our understanding of stellar processes and to measure precise distances throughout the universe.

Nuclear Spectroscopic Telescope Array (NuSTAR)

The Nuclear Spectroscopic Telescope Array (NuSTAR) will open the high-energy X-ray sky for sensitive study. NuSTAR consists of three focusing, high-energy X-ray telescopes that will discover collapsed stars and black holes, map the remnants of recent supernova explosions, and explore the most extreme physical environments in the universe. X-ray telescopes like Chandra and XMM-Newton have peered deep into the X-ray universe at low X-ray energy (less than 10 keV). By focusing X-rays at higher energy (up to 80 keV), NuSTAR will answer fundamental questions about the universe: How are black holes distributed through the cosmos? How were the elements that compose our bodies and the Earth forged in the explosions of massive stars? What powers the most extreme active galaxies? Perhaps most exciting is the opportunity to fill a blank map with discoveries we have not yet imagined — NuSTAR offers the opportunity to explore the universe in an entirely new way.

James Webb Space Telescope (JWST)



The James Webb Space Telescope (JWST) will have over two times the diameter of HST's mirror and about an order of magnitude more light-gathering capability. Because the prime science goals for JWST are to observe the formation and early evolution of galaxies, JWST's greatest sensitivity will be at mid- and near-infrared wavelengths, where the expansion of the universe causes the light from very young galaxies to appear most prominently. JWST will be a powerful general-purpose observatory capable of undertaking important scientific investigations addressing a very wide range of astronomical questions.

JWST is expected to have a telescope diameter of at least 6 meters and be celestial-background-limited between 0.6 and 10 micrometers, with imaging and spectroscopic instruments that will cover this entire wavelength regime. JWST has a requirement to be diffraction-limited at 2 micrometers. With these capabilities, JWST will be a particularly powerful tool for investigating fundamental processes of stellar formation and early evolution, as well as the later stages of evolution. In both cases, dust almost completely blocks our ability to observe the light from rapidly evolving stars, so that detailed observations have to be carried out at longer wavelengths.

The European Space Agency and the Canadian Space Agency have agreed to contribute to the JWST project. These contributions will significantly enhance the overall capabilities of the observatory.

Missions for 2015–2025

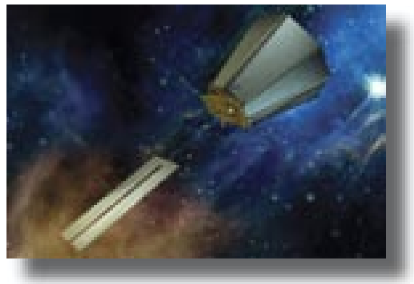
Constellation-X (Con-X)

Constellation-X (Con-X) will follow and expand upon Chandra (100 times in sensitivity) in performing X-ray imaging and high-resolution spectroscopy. Con-X is also a Beyond Einstein Great Observatory and should be ready to launch early in this time period. Constellation-X will consist of four satellites, each with a 1.6-meter-diameter grazing incidence soft-X-ray (0.2–10 keV) telescope (SXT) and a smaller diameter hard-X-ray (10–100 keV) telescope (HXT). The SXT detectors will have high energy resolution for imaging and the HXT detectors will have a lower energy resolution, but will image X-rays above 10 keV, out to 60 keV. The soft-X-ray telescopes will have 15-arcsecond or better spatial resolution and 2-eV or better energy resolution.

The Con-X spacecraft will be placed in orbit at L2 to provide an optimal environment for cryogenic cooling and to simplify spacecraft design. The combined collecting area will be more than 1.5 square meters. Con-X will measure the velocity and composition of matter as it falls onto the accretion disks surrounding black holes and investigate the interaction of spinning black holes with their surroundings. It will enable us to study in detail the processes by which energy is extracted from the black hole's rotation and the creation of jets of high-energy particles.

Emission-line studies by Con-X from AGN can help determine the mass and spin of the black holes themselves. Con-X will make the first "slow-motion movies" of matter falling into a black hole, which will allow one of the first tests of general relativity in the strong gravity regime. Also, Con-X will study in detail all of the Chandra sources to trace black hole evolution over cosmic timescales. The Con-X energy regime is relatively free of obscuration and allows clear views of otherwise shrouded AGN. Con-X observations of clusters of galaxies at a range of distances will allow the stretching of space by dark energy to be measured.

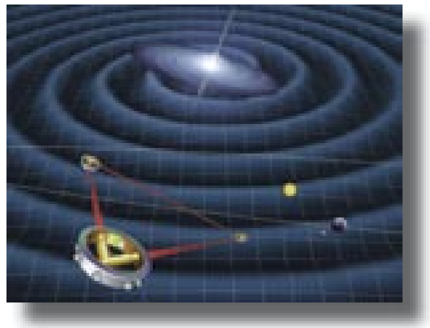
Terrestrial Planet Finder Coronagraph (TPF-C)



The Terrestrial Planet Finder Coronagraph (TPF-C) will directly detect and study planets outside our solar system from their formation and development in disks of dust and gas around newly forming stars to their evolution and even potential suitability as an abode for life. TPF-C will measure the size, temperature, and placement of terrestrial planets as small as Earth in the habitable zones of distant planetary systems as well as their gas-giant companions. In addition, TPF-C's spectroscopic capability will allow atmospheric chemists and biologists to use the relative amounts of gases like carbon dioxide, water vapor, ozone, and methane to determine whether a planet someday could or even now does support life. TPF-C's ability to carry out a program of comparative planet studies across a range of planetary masses and orbital locations in a large number of new planetary systems is an important scientific motivation for the mission. However, TPF-C's mission will not be limited to the detection and study of distant planets. An observatory with the power to detect an "Earth" orbiting a nearby star will also be able to collect important new data on many targets of general astrophysical interest.

The visible-light coronagraph will use a single telescope with an effective diameter of 8 meters, operating at room temperature and required to achieve a billion-to-one image contrast in order to isolate the signal from a planet from that of its star. Very precise, stable control of the telescope optical quality will be required. TPF-C has carried out an extensive program of technology development along multiple paths to enable this unprecedented capability, and has now demonstrated in laboratory conditions the ability to produce contrasts in the required regime.

Laser Interferometry Space Antenna (LISA)



The Laser Interferometry Space Antenna (LISA) will be the first space-based gravitational-wave detector observatory. LISA is one of the two Great Observatories of the Beyond Einstein program (along with Constellation-X). LISA will be truly revolutionary, opening up the window of gravitational-radiation astronomy from space. LISA will detect the gravitational radiation from black hole mergers and from compact stars spiraling into supermassive black holes over the frequency range from 10^{-4} to 10^{-2} Hz (periods between 10 seconds and a few hours), a region that cannot be explored from the ground.

LISA will consist of three spacecraft separated by 5 million kilometers, each with a freely falling test mass, isolated from all forces other than gravity. The three spacecraft form two independent Michelson interferometers that will detect the shift in the relative test-mass positions as the gravitational radiation plows through our solar system. LISA will have the sensitivity to measure strains of 10^{-21} (corresponding to shifts of 10^{-12} meters in the interferometer spacing).

Gravitational radiation, predicted by Einstein in 1915, has never been directly observed, although it is universally thought to be radiated in abundance by binary systems, massive colliding objects (neutron stars, black holes) and from the Big Bang itself. LISA will be able to map the spacetime geometry down to the event horizon of black holes and plot the orbit of stars around black holes.

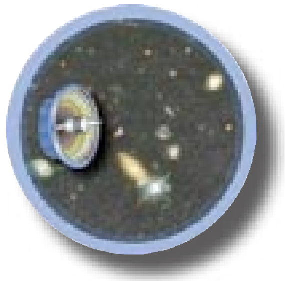
Terrestrial Planet Finder Interferometer (TPF-I)

The Terrestrial Planet Finder Interferometer (TPF-I) will be a long-baseline interferometer operating in the infrared. TPF-I will use four 3–4-meter-diameter telescopes configured as an array operated on separated spacecraft over distances of a few hundred meters. The telescopes will operate at extremely low temperatures of less than 40 kelvins, and the observatory will necessarily be large. However, the image contrast requirement, "only" a million to one, and thus the required system optical quality, will be less challenging at infrared wavelengths than the TPF-C challenge of 1 billion to one at visible wavelengths.

The European Space Agency (ESA) has been actively studying an infrared interferometer with essentially the same science goals as TPF-I, referred to as Darwin. Under a NASA/ESA Letter of Agreement, scientists and technologists in both agencies are discussing ways in which the preliminary architecture studies can lead to effective collaboration on a joint mission.

Einstein Probes

Dark Energy Probe (Joint Dark Energy Mission)

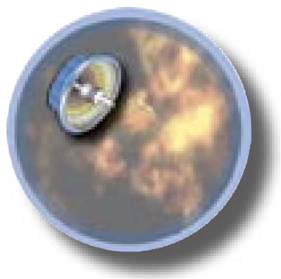


The Dark Energy Probe (Joint Dark Energy Mission) will address the important question: What is the mysterious dark energy pulling the universe apart? One of the most amazing discoveries of the past decade has been that the universe is mostly (up to 70%) composed of dark energy. This dark energy, which may be the energy of the vacuum, was originally proposed by Einstein early on, and then rejected by him once the expansion of the universe was discovered. Today, we know that this dark energy is real, and is responsible for the ever faster acceleration of the universe.

Black Hole Finder Probe

The Black Hole Finder Probe will produce large-scale surveys of black holes with greater sensitivity than any other mission, enabling a census of accreting black holes of all types: supermassive black holes in the nuclei of galaxies, intermediate class (10–100 solar masses) black holes produced in the early universe, to stellar-mass-size black holes in our own Galaxy. Black Hole Finder Probe will complement LISA, which will detect the gravitational radiation from mergers of these same black holes.

Inflation Probe



The Inflation Probe will address the question of what powered the Big Bang. COBE's measurement of the CMB was a true breakthrough for our understanding of the Big Bang. Small variations (wrinkles) in the COBE data are important clues in understanding the details of the inflation of the universe and various theories that deal with the early universe. WMAP built on these pioneering breakthroughs by obtaining further evidence of cosmic inflation. The Inflation Probe will map these wrinkles with exquisite precision.

E-Learning

The Amazing Space education program uses the Hubble Space Telescope's stunning imagery and profound scientific discoveries to inspire and educate K–14 students, educators, and the general public about the wonders of the universe. Online interactive activities offered through the Space Telescope Science Institute's Amazing Space website reinforce fundamental science, math, and reading skills through explorations of the crash of comet Shoemaker–Levy 9 into Jupiter, Hubble's deep views of the universe, and black holes. The award-winning program's online and hardcopy materials are used by formal education organizations in all 50 states, including 22 of the 50 largest US school districts. The tremendous success of online programs such as Amazing Space mirrors the rapid growth of information technology that will continue to increase access to educational programs, online telescopes, and data archives.

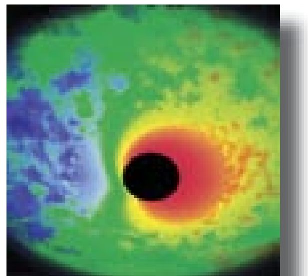
Single Aperture Far-Infrared (SAFIR)

The Single Aperture Far-Infrared (SAFIR) mission, consisting of a single 8–10-meter telescope operating in the far-infrared, will serve as a building block for the Life Finder, while carrying out a broad range of scientific programs beyond JWST, SOFIA, and Spitzer. These include 1) probing the epoch of energetic star formation in the redshift range $1<z<10$ at a wavelength regime that can easily detect continuum and cooling-line emission from dust-enshrouded primeval galaxies with an angular resolution capable of isolating individual objects at or below the limits of the Hubble Deep Field; 2) investigating the physical processes that control the collapse and fragmentation of molecular clouds to produce stars of various masses by mapping of cold, dense cores at <100 AU resolution at the peak of their dust emission and using gas phase tracers such as H_2, H_2O, CO, OI, and NII; 3) learning about the era of cometary bombardment that may have determined the early habitability of Earth by making high-spatial resolution maps of the distribution of ices and minerals in the Kuiper Belts surrounding nearby stars; and, 4) studying the nature of the recently discovered objects in the Kuiper Belt of our own solar system, which may be remnants of our own planet-formation process.

Missions for 2025–2035

A number of Vision Mission concepts are under study to address the most challenging of the scientific questions presented to us by the universe. While these missions will evolve significantly in capability and configuration by the time they are implemented, they serve now to focus long-term thinking about approaches to explore the mysteries of the universe, and to guide the development of the technology required.

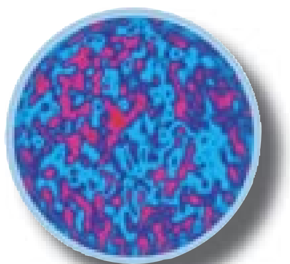
Black Hole Imager



The Black Hole Imager Vision Mission will show us exactly what is happening right up to the edges of black holes. Here we can expect exciting new discoveries. Black Hole Imager will image the matter flowing down onto a black hole with 0.1 microarcsecond resolution (a million times better than HST) at X-ray wavelengths.

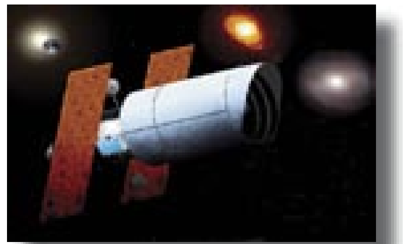
Black Hole Imager will make movies of the gaseous material just at the event horizon outside a black hole and allow us to compare what we find to detailed predictions from general relativity. A direct image of the inner regions of the accretion disk will show us the mechanism by which energy is released in this process and will help us to determine how jets of relativistic particles are produced. Black Hole Imager will provide the ultimate in our ability to study black holes up close.

Big Bang Observer



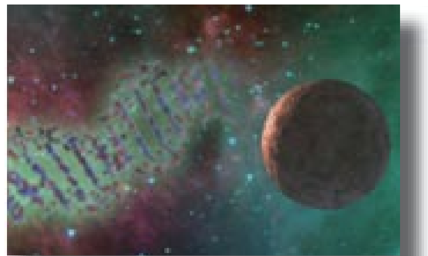
The Big Bang Observer will exceed LISA's capability to detect gravitational radiation by 10,000 times, giving us a glimpse into the gravitational waves generated in the earliest universe. Gravitational waves were generated as early of 10^{-35} seconds after the Big Bang and began their journey toward us — traveling almost completely unimpeded throughout the universe. The Big Bang Observer will detect the gravitational waves with periods between 0.1 and 10 seconds, where there is less confusion from foreground astrophysical sources at higher periods.

Large Ultraviolet/Optical (LUVO) Telescope



A successor to HST operating at ultraviolet and optical wavelengths, a Large Ultraviolet/Optical (LUVO) telescope would produce forefront science in all areas of modern astronomy and would be focused on the era from redshifts $0<z<3$, which occupies over 80% of cosmic time, beginning after the first galaxies, quasars, and stars emerged into their present form. The science to be addressed in the post-HST era includes studies of dark matter and baryons, the origin and evolution of the elements, and the major construction phase of galaxies and quasars. Key questions include: Where is the rest of the unseen universe? What is the interplay of the dark and luminous universe? How did the intergalactic medium collapse to form the galaxies and clusters? When were galaxies, clusters, and stellar populations assembled into their current form? What is the history of star formation and chemical evolution? Are massive black holes a natural part of most galaxies? A large-aperture ultraviolet/optical telescope in space will provide a major facility in the second quarter of the century for solving these scientific problems.

Life Finder



Life Finder would provide high-resolution spectroscopy on habitable planets identified by the TPF missions. This information would extend the reach of biologists, geophysicists, and atmospheric chemists to ecosystems far beyond Earth. Achieving that goal will require observations beyond those possible with TPF. For example, searching the atmospheres of distant planets for unambiguous tracers of life such as methane (in terrestrial concentrations) and nitrous oxide would require a spectral resolution of ~1,000, using a version of TPF with 25-meter telescopes.

Planet Imager

In the search for extrasolar planets capable of harboring life, Planet Imager is a mission for the far future that will serve to challenge our imaginations and our technological inventiveness. Perhaps using a formation of 100 10-meter telescopes, this mission may some day return images our children or theirs could use to study the geography of a pale blue planet orbiting a star similar to ours across the gulf of space, time, and imagination.

Ultraviolet Optical Interferometer (UVOI)

An Ultraviolet Optical Interferometer (UVOI) would be able to resolve the surfaces of stars and probe the secrets of many astrophysical objects in unprecedented detail. To interferometrically achieve the submilliarcsecond angular resolution implied, baselines of ~0.5 kilometer for approximately 20 formation-flying spacecraft at the Sun–Earth L2 might be necessary. Planet Imager and UVOI will require similar technological breakthroughs, but would constitute capabilities of almost epochal significance.

Early Universe X-ray Observer (EUXO)

The Early Universe X-ray Observer (EUXO) would be a powerful mission to study the earliest black holes in the universe. In order to observe the birth of the first black holes, trace the evolution of galaxies and the elements they produce across cosmic time, and probe in great detail the behavior of matter in extreme environments, an increase in sensitivity of 1,000 times over that of current X-ray missions is required. A mission with angular resolution 10 times finer than Chandra and effective area 30 times that of Constellation-X would be able to address these questions as well as advance X-ray studies of all classes of astrophysical objects.

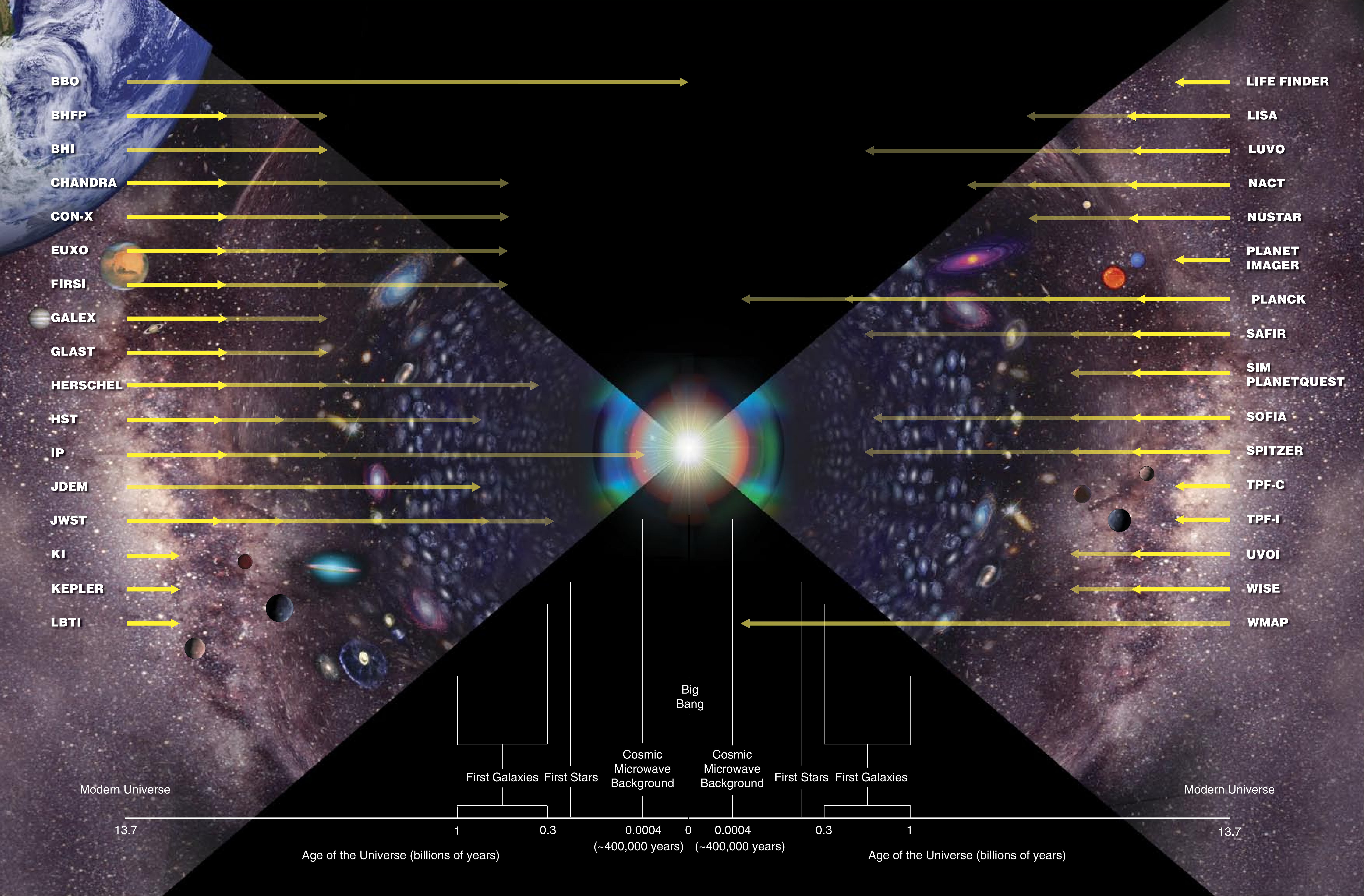
Nuclear Astrophysics Compton Telescope (NACT)

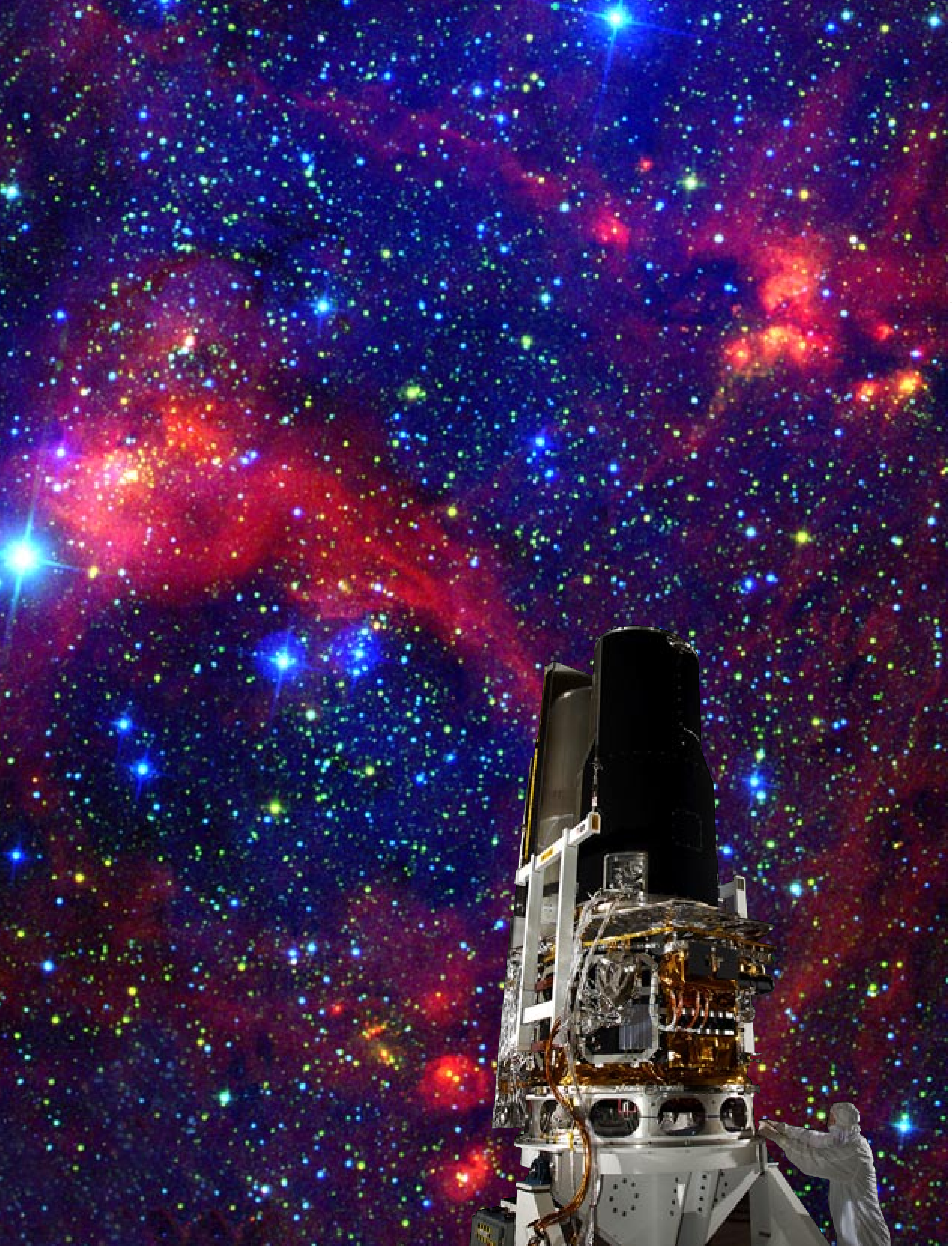
A Nuclear Astrophysics Compton Telescope (NACT) that offers high-sensitivity gamma-ray spectroscopy would provide unique measurements of the dense, hot centers of supernovae, matter accreting onto black holes, and gamma-ray bursts. NACT would be a vast step beyond the CGRO COMPTEL experiment with 100 times greater sensitivity for spectroscopy, imaging, and polarization in the 0.2–10 MeV band.

Far-Infrared and Submillimeter Interferometer (FIRSI)

A Far-Infrared and Submillimeter Interferometer (FIRSI) consisting of three 15–25-meter telescopes with a 1-kilometer baseline would have the sensitivity and angular resolution (0.02 arcsecond at 100 micrometers) needed to study the physical conditions in young galaxies. In addition to cosmological studies, the interferometer would be able to observe collapsing protostars deeply embedded in their parental molecular clouds, providing valuable constraints on models for star formation.

Looking backward in time, space missions and observatories will allow us to study the universe at various stages of development from its infancy.


BBO
BHFP
BHI
CHANDRA
CON-X
EUXO
FIRSI
GALEX
GLAST
HERSCHEL
HST
IP
JDEM
JWST
KI
KEPLER
LBTI
LIFE FINDER
LISA
LUVO
NACT
NUSTAR
PLANET IMAGER
PLANCK
SAFIR
SIM PLANETQUEST
SOFIA
SPITZER
TPF-C
TPF-I
UVOI
WISE
WMAP
Big Bang
First Galaxies
First Stars
Cosmic Microwave Background
Cosmic Microwave Background
First Stars
First Galaxies
Modern Universe
Modern Universe
13.7
1
0.3
0.0004
0
0.0004
0.3
1
13.7
(~400,000 years)
(~400,000 years)
Age of the Universe (billions of years)
Age of the Universe (billions of years)



The Spitzer Space Telescope during integration testing shortly before launch.

6 Technology
Enables Discovery

"The real voyage of discovery consists not in seeking new landscapes, but in having new eyes."
—Marcel Proust

Current NASA missions incorporate extraordinary technologies that allow them to accomplish extraordinary science. The primary mirror of the Hubble Space Telescope is so smooth that if the mirror were expanded to the size of the Pacific Ocean, the highest waves would be 5 centimeters high. This smoothness allows HST to resolve the structure of a forming galaxy halfway across the universe. The Spitzer Space Telescope operates at temperatures just a few degrees above absolute zero. This cold operating temperature gives it the sensitivity to detect the heat from an ordinary camping flashlight wrapped in black felt cloth at the distance of the Moon — or, for astronomy, to detect infant stars buried in clouds of obscuring dust, thousands of light-years away. X-rays glance off Chandra's extremely smooth grazing incidence mirrors at angles of 1.5 to 2.5 degrees, and they are focused so accurately that they could hit the bull's eye of a dartboard placed 6 kilometers away. The high reflectivity and sharp images of these superb optics have allowed Chandra to identify, one-by-one, the accreting black holes at cosmic distances that collectively make up the diffuse X-ray background.

Capabilities for the Future

The technological demands of future missions are even more extraordinary, and the scientific goals even more ambitious. Studying the edges of black holes, supernovae in the distant universe, gravity waves from merging stars, the first self-luminous objects in the universe, star-forming cocoons, and Earth-like planets around other stars will require significant advances in several key space technologies. JWST will carry a mirror 10 times larger than Hubble's that will unfurl like the petals of an opening flower on the way to its distant orbit point. The light-gathering power of this gigantic mirror will enable JWST to discover the first galaxies and quasars. SIM PlanetQuest will resolve angles equivalent to that subtended by the edge of a dime on the surface of the Moon, so that it can detect the tiny wobble of a distant star being tugged by an orbiting planet. Con-X will operate new-technology array detectors, cooled to just 0.05 degree above absolute zero, in order to track X-ray–emitting plasma falling into the event horizon of a black hole. LISA will sense the relative positions of its component telescopes, measuring their 5-million-kilometer separations with phenomenal accuracy — to within a small fraction of an atomic diameter — in order to detect the ghostly signal of a passing gravity wave as it ripples the spacetime between them.

Future capabilities flow from the high-level science questions posed in the previous chapters (see the table on the following page). The mission portfolio outlined in Chapter 5 seeks to answer these questions in stages. The mission sequence is determined largely by technology readiness, flowing from capabilities within reach in a matter of years, to the truly revolutionary capabilities that will be needed for NASA's long-term science goals.

Implementation Strategy

A sustained technological development effort will enable the success of the science program outlined in the preceding chapters. NASA flies one of a kind, state-of-the-art missions to push back the envelope of our knowledge. As a consequence, managing technology development and readiness is the key to moderating mission risk and cost. In turn, developing new technologies brings new science opportunities and new missions to NASA, and new and often unforeseen economic benefits for the country. A technology program is an investment in NASA's future, and must be managed in a similar way to managing an investment portfolio, with one eye on short-term needs and another on long-term goals.

Advanced technologies often significantly improve the performance and reduce the cost of a mission. Because of the uniqueness of the technology, it often cannot be fully tested on the ground and great effort is expended to understand how each technology component will interact with the other in the space environment. Technological developments are broadly categorized in progression of readiness for space:

Capabilities needed to reach representative science goals.

Science Goals	Capability Goals*	Missions	Prime Strategic Technology Challenges
How do black holes form?	Measure X-ray photons with energy resolution >1000	Con-X	Detectors, Coolers, Telescopes
What happens at the event horizon?	Measure a 5-million-km baseline with an accuracy of 10 pm	LISA	Distributed Spacecraft
	Wide-field high-energy X-ray imaging	Black Hole Finder	Detectors
	0.1 microarcsecond X-ray interferometry	Black Hole Imager	Distributed Spacecraft,Telescopes
What powered the Big Bang?	1 uK√s CMB polarization sensitivity (100x better than WMAP)	Inflation Probe	Detectors, Coolers
	10,000x better strain sensitivity than LISA	Big Bang Observer	Distributed Spacecraft
What is the nature of dark energy?	Wide-field imaging with large optical/near-infrared focal planes	Dark Energy Probe	Detectors
How do galaxies form?	Photon-limited detectors with a diffraction-limited telescope	JWST SAFIR LUVO	Telescopes Detectors, Coolers
How do gas and dust form planetary systems?	100–100 milliarcsecond far-infrared interferometry at the photon-noise limit	Far-Infrared and Submillimeter Interferometer	Distributed Spacecraft, Detectors, Coolers
How common are terrestrial planets?	Measure a contrast ratio of 1 part in 10^{12}	TPF-C	Telescopes
	>50-m baseline infrared interferometry	TPF-I	
Is there life on planets outside our solar system?	Achieve 10^{-8} star nulling and angular resolution	Life Finder, Planet Imager	Distributed Spacecraft, Telescopes

*For competed Principal discussions in this chapter.

Exploratory Technologies are based on new concepts with high potential. These can result in new capabilities for NASA, providing opportunities to address previously inaccessible science goals or to address existing goals much more powerfully or less expensively. Exploratory technology development is especially important for the far-future Vision Missions, which require revolutionary capabilities.

Enabling Technologies provide identified capabilities that are essential for relatively near-term missions. These technologies have demonstrated feasibility, but must require significant further development and testing before they can be flown on a major mission. Enabling technologies are key to securing the most immediate and reachable science goals described in this document.

Mature Technologies have been fully demonstrated in space and require only modest further development to adapt them to new missions. Each major mission is typically built on a secure base of such mature low-risk technologies, augmented with selected developing technologies that enable the mission's advanced capabilities. Maintaining a steady stream of maturing technologies is key for the fixed-cost Explorer and Discovery programs, which require technologies with high readiness.

The **Research & Analysis (R&A) technology incubation** program, described in the next chapter, takes the most innovative exploratory technologies through the initial development and testing phase. The R&A program also serves as a useful bridge by providing platforms such as balloons and sounding rockets for gaining confidence in new technologies before they are flown in space. The latter phases of guiding an enabling technology to full space readiness are usually carried out in the context of a specific mission under the auspices of mission project funding. A systematic program supporting the early phases of enabling technology development, prior to identified project funding, is critical. The content of this R & A program is in response to clearly defined science measurement needs as given in this document, the National Academy of Sciences report *Astronomy and Astrophysics in the New Millennium*, and the NASA planning panels on Strategic Planning and Enabling Capabilities Roadmaps.

The large strategic missions often require technology development outside the disciplines of physics and astronomy, such as technologies to engineer and control large space structures. Technology for these missions is supported outside the R&A program. In cases like JWST, a planned and managed technology development program was maintained for over 10 years. Our future strategic missions will require a similar development period before final design and construction can begin.

Strategic Technologies

Strategic technologies represent the core capabilities required by multiple missions; central capabilities required not only by the upcoming generation of missions but also by the Vision Missions beyond. NASA maximizes its investment return by focusing on strategic technologies, where each development pays off multiple times. The Astronomy and Physics Division science missions described in the preceding chapters require advances in four main strategic technology areas: **telescopes** — the structures, optics, and wavefront controls needed to focus electromagnetic radiation with superb accuracy and minimum mass; **detectors** — the devices that convert electromagnetic photons to countable units; **coolers** — the methods for cooling telescopes and detectors so that they achieve very low noise and correspondingly high sensitivity; and **distributed spacecraft** — the ability to fly spacecraft in coupled formations, measuring and maintaining their relative positions to extraordinary precision to synthesize very-large-aperture telescopes using an interferometer configuration.

A prototype mirror segment for Constellation-X being separated from the replicating mandrel.

Telescopes

Telescopes consist of optics to collect and concentrate the radiation, wavefront sensing and control technologies to compensate for unwanted surface irregularities, and metrology and structures technologies to control the separation of the optical elements and in some cases to deploy large telescope structures that must be lightweight and fold up within a launch vehicle shroud. Faint objects such as terrestrial extrasolar planets (between magnitude 30 and 35 brightness) require very large telescopes in the size range of 8 to 16 meters in diameter.

Many applications, such as detailed exoplanet science, require very high angular resolution. In this case, individual mirrors are arrayed to synthesize a large-aperture telescope system called an interferometer. Angular resolution 10 to 1,000 times that available with single-aperture telescopes is possible using an array of formation-flying telescopes in the configuration of an interferometer. These interferometer telescopes require formation-flying technology and a co-orbiting beam recombination satellite to be successful.

Telescopes and interferometers are central grand technology challenges to the Astronomy and Physics Division science goals for imaging planets orbiting nearby stars, the horizons of black holes, and galaxies near the edge of the universe.

What is it that characterizes the optical instruments that we need to build to enter this new field of science to search for life beyond our solar system? Progressively larger telescopes up to 12 meters in diameter are needed to penetrate farther and farther into the depths of space and to observe very faint objects close to stars, such as terrestrial planets in orbit about other stars. We need telescopes more mechanically stable than ever before. Pointing, tracking, image quality, innovative mechanical deployment, scattered light control, polarization properties of the optics, new highly reflective coatings, and radiometric fidelity are all fundamental to telescopes and interferometers.

In order to detect and characterize planets around other stars, the telescope for the TPF-C mission must have a primary optic large enough to collect sufficient radiation to detect the faint signal from a planet, and smooth enough to ensure that the scattered light from the much brighter, very close parent star does not obscure the image of that faint planet. The mirror must be larger and smoother than has ever before been made by a factor of 100 times, and the metrology and structures technology need to hold the structure to a precision of 200 picometers.

TPF-C will inherit a portion of the SIM PlanetQuest optical bench and structures technology, laser beam launchers, and laser metrology that give 200-picometer mechanical precision. In addition, a special-purpose optical coronagraph with new wavefront sensing, control technologies, and ultralow-scatter optical substrate and mirror coatings are required to suppress the central starlight to less than one part in 10^{10}. Innovative processes to fabricate low-scatter surfaces and precision masks are one of the many advanced telescope technologies underway today. The Life Finder and the large ultraviolet/optical telescopes will build on the success of the TPF-C telescope technologies to produce a telescope system with an aperture in excess of 10 meters diameter that will need to be precision deployed and autonomously aligned.

Shown below is the strategic infusion chart for telescopes. Technology areas in optics and mirrors, metrology and structures, and wavefront control are shown as they apply to an ensemble of missions in the mission set. For example, SIM PlanetQuest provides critically important technologies in precision deployable structures to TPF-C. Cryogenic delay lines developed for TPF-I apply directly to the Far-infrared and Submillimeter Interferometer and to Planet Imager. Technologies developed for missions early in the set are further developed to create new capabilities essential for the later missions.

TPF-I, Planet Imager, UV Optical Interferometer (UVOI), Black Hole Imager, and Big Bang Observer are all arrays of telescopes. In addition to the large-aperture telescope technologies discussed above, these telescope arrays will need that special set of technologies unique to interferometry, which includes formation-control algorithms, optical beam combiners, micronewton thrusters, laser metrology, and intersatellite navigation.

Strategic technology infusion for telescopes.

	HST	JWST	TPF-C	Con-X	DEP	BHF Probe	SAFIR	TPF-I	LUVO	Vision Missions
Optics and Mirrors										
Lightweight X-ray				First Demo, First Flight		Second Flight – Significant Modification				Mature Space Technology
Mass Fabrication				First Demo, First Flight				Second Flight – Significant Modification		Mature Space Technology
UV/Optical/IR Coatings	First Demo, First Flight		Second Flight – Significant Modification		Second Flight – Significant Modification			Second Flight – Significant Modification	Second Flight – Significant Modification	Mature Space Technology
High Smoothness	First Demo, First Flight		Second Flight – Significant Modification						Mature Space Technology	Mature Space Technology
Lightweight Panels	First Demo, First Flight						Second Flight – Significant Modification	Second Flight – Significant Modification	Second Flight – Significant Modification	Mature Space Technology
Metrology and Structures										
Precision Deployable		First Demo, First Flight	Second Flight – Significant Modification					Second Flight – Significant Modification	Second Flight – Significant Modification	Mature Space Technology
Cryogenic Structures		First Demo, First Flight					Second Flight – Significant Modification			Mature Space Technology
Cold Large Aperture		First Demo, First Flight					Second Flight – Significant Modification	Second Flight – Significant Modification		Mature Space Technology
Wavefront Control										
Active Surface Control		First Demo, First Flight	Second Flight – Significant Modification					Second Flight – Significant Modification	Second Flight – Significant Modification	Mature Space Technology
Actuators		First Demo, First Flight	Second Flight – Significant Modification					Second Flight – Significant Modification	Second Flight – Significant Modification	Mature Space Technology
Control Algorithms		First Demo, First Flight	Second Flight – Significant Modification					Second Flight – Significant Modification	Second Flight – Significant Modification	Mature Space Technology
Cryo-delay Lines								First Demo, First Flight		Second Flight – Significant Modification

● First Demo, First Flight ● Second Flight – Significant Modification ● Mature Space Technology

Constellation-X optics are lightweight, grazing incidence X-ray optics requiring an increase in the effective area-to-mass ratio of X-ray mirrors by a factor of 10 as compared with previous missions. Both the Spectroscopy X-ray Telescope (SXT) and Hard X-ray Telescope (HXT) incorporate highly nested, grazing-incidence X-ray mirror arrays, which must simultaneously meet tight angular resolution, effective area, and mass constraints. Engineering test units of both SXT and HXT mirrors are under development: glass substrates with surfaces replicated from precision mandrels for SXT and HXT, and an alternative replicated nickel shell design for HXT. The surfaces of these telescopes must be smooth to an RMS of 0.04 nanometers, and hundreds of nested shells must be aligned to tolerances of less than a micron, requiring new methods of assembly and metrology that will permit the construction of these telescopes in a timely manner.

Detectors

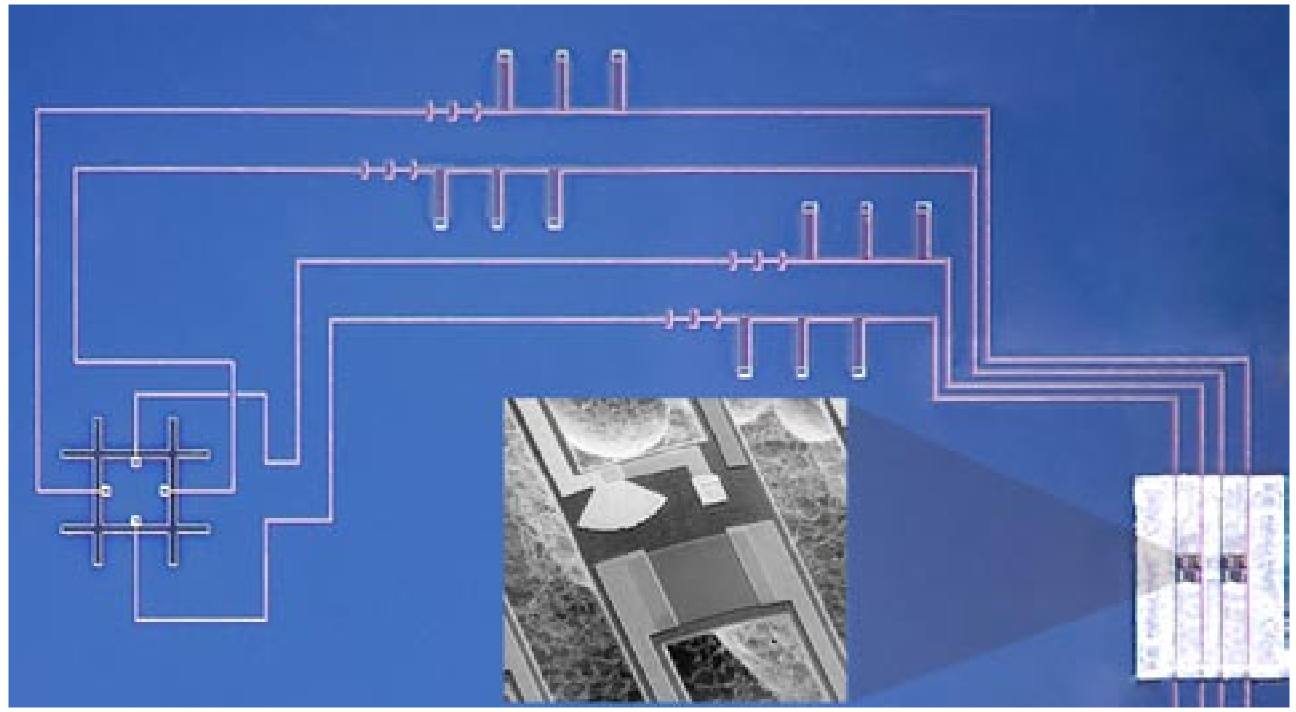
Detectors convert electromagnetic energy to recorded electrical signals. Science missions span the full breadth of the electromagnetic spectrum from gamma-ray to radio-wave radiation. High-efficiency detectors are needed to cover spectral bands of interest. In fact, detectors go beyond the electromagnetic spectrum: LISA will use optical sensors to measure gravitational-wave radiation.

The challenges and approaches to building detectors vary across the electromagnetic spectrum. In the X-ray spectral region, Con-X requires imaging spectrographic detectors with sufficient energy resolution to track matter falling into a black hole, and the Black Hole Finder Probe needs large, low-power detector arrays. In the optical and near-infrared regions of the spectrum, NASA leverages well-developed commercial capabilities to realize very large, high-quantum-efficiency focal planes with up to the one billion pixels that may be needed to discover and monitor distant supernovae for one candidate implementation of the Dark Energy Probe. In the far-infrared spectral region, NASA will develop new detectors for SAFIR that fully realize the enormous sensitivity gains offered by a cold telescope in space, enabling dramatic reductions in observatory time. In the millimeter-wave spectral region, the Inflation Probe may require arrays of superconducting detectors to measure the exceedingly faint polarization of the cosmic microwave background radiation produced by inflation, the mysterious force cosmologists believe caused spacetime to expand exponentially in the first moments after the Big Bang.

Strategic technology infusion for detectors.

Planck	HST	Chandra	Spitzer	Suzaku	Herschel/ Planck	SOFIA *	JWST	TPF-C	Swift	Con-X Probe	DEP Probe	BHF	Inflat.	LUVO	TPF-I Missions	SAFIR	Vision
Far-IR to Radio																	
Quantum-Limited Heterodyne					First Demo, First Flight	First Demo, First Flight										Second Flight – Significant Modification	Mature Space Technology
FIR/mm Bolometer Arrays					Technology Predecessor	First Demo, First Flight							Second Flight – Significant Modification			Second Flight – Significant Modification	Mature Space Technology
Superconducting MUX						First Demo, First Flight				Second Flight – Significant Modification			Second Flight – Significant Modification			Second Flight – Significant Modification	Mature Space Technology
LWIR Focal Plane Arrays			First Demo, First Flight			Second Flight – Significant Modification										Second Flight – Significant Modification	Mature Space Technology
Gamma-ray to X-ray																	
X-ray Calorimeter Arrays				Technology Predecessor						First Demo, First Flight							Second Flight – Significant Modification
X-ray CCDs		First Demo, First Flight		Second Flight – Significant Modification		Second Flight – Significant Modification			Second Flight – Significant Modification	Mature Space Technology							Mature Space Technology
Hard X-ray/γ-ray Detectors									First Demo, First Flight	Second Flight – Significant Modification		Second Flight – Significant Modification					Mature Space Technology
UV, Optical, and Near-IR																	
SWIR Focal Plane Arrays	First Demo, First Flight		First Demo, First Flight				Second Flight – Significant Modification				Second Flight – Significant Modification				Mature Space Technology		Mature Space Technology
Optical CCDs	First Demo, First Flight							Second Flight – Significant Modification			Second Flight – Significant Modification						Mature Space Technology
UV CCDs	First Demo, First Flight													Second Flight – Significant Modification			Mature Space Technology

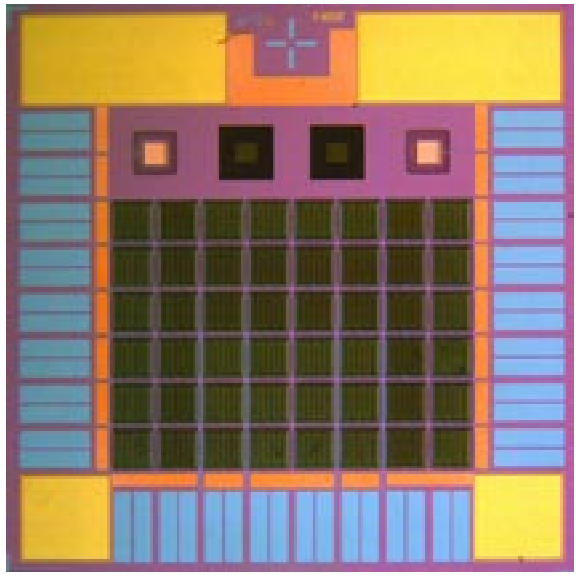
● Technology Predecessor ● First Demo, First Flight ● Second Flight – Significant Modification ● Mature Space Technology * Demo Platform



A polarization-sensitive bolometer being developed for the Inflation Probe. Optical beam formation, bandpass definition, and power detection are all incorporated on a single substrate, greatly simplifying the focal plane.

Multiplexed calorimeter and bolometer arrays are needed by Con-X to meet the energy resolution and sensitivity requirements in the soft X-ray band, and for one candidate implementation of the Inflation Probe to realize large-format, high-sensitivity polarimeters. Multiplexing readout electronics enables the construction of focal plane arrays by combining signals directly at the low-temperature focal plane, providing a large increase in an array format over the unmultiplexed detectors that were developed for Suzaku (Astro-E2), Herschel, and Planck Surveyor. There is synergy between X-ray and far-infrared/submillimeter-wave detectors. Both wavelength regimes are developing transition-edge sensors (TES) and superconducting quantum interference device (SQUID) multiplexers. Kinetic inductance detectors (KIDs) also hold promise in both bands, and may be multiplexed with room-temperature electronics. SOFIA, balloons, rockets, and ground-based telescopes serve as essential test facilities for new detector technologies prior to their application in space. The development of the Con-X and Inflation Probe low-temperature detector arrays dovetails into the large-format, ultrahigh-sensitivity arrays needed for SAFIR. An investment in this technology today leads to space maturity for the Far-Infrared and Submillimeter Interferometer and Black Hole Imager Vision Missions.

Large-area, low-power gamma-ray and hard X-ray detectors are needed for both Con-X and the Black Hole Finder Probe, and will later be available for the Black Hole Imager.



A 6 × 8 array of X-ray calorimeters being developed for the Constellation-X mission. Each pixel is 5 mm on a side.

Minimizing the detector mass and the power dissipation of the ASIC readout electronics are essential technologies for operating these detectors in a space mission.

The near- and mid-infrared and optical focal plane arrays pioneered by Spitzer and HST will feature increasingly larger formats in JWST, TPF-C, and the Dark Energy Probe, and will reach full maturity in time for TPF-I and Life Finder. However, significant efforts must be made to develop monolithic large-format, far-infrared photoconductive detectors for spectrometers on SOFIA and SAFIR.

Coolers

Equipped with new-technology coolers, NASA space observatories will take maximum advantage of the thermal environment available in space. A telescope on Earth's surface, operating at room temperature, glows brightly at infrared to millimeter wavelengths, masking the faint incoming celestial radiation. By cooling the entire observatory, a spaceborne facility is orders of magnitude more sensitive than a ground-based telescope. The mechanical specifications of planned optical, ultraviolet, and X-ray telescopes require careful management of the thermal stability of telescope structures. The advanced calorimeter and bolometer focal planes needed for the science goals described in this document require cooling to 5 hundredths of a degree above absolute zero.

Passive cooling techniques of entire telescopes was pioneered for the ESA Infrared Space Observatory (ISO) and perfected for Spitzer. This architectural innovation exploits the natural space environment, requiring no power, stored cryogens, or moving parts, and resulted in a large cost savings. With passive cooling, space missions can achieve temperatures several tens of degrees above absolute zero. This range is sufficiently cold for near/mid-infrared telescopes such as JWST, and serves as a valuable first temperature stage towards reaching lower temperatures.

Liquid-helium cryostats provide a reliable means of cooling to 2–4 kelvins. Active 4–6-kelvin coolers with high efficiency offer a significant mass savings over liquid helium, analogous to the advantages of household refrigerators that replaced the iceboxes of the past. Future applications such as cooling the entire 10-meter SAFIR telescope to a few degrees above absolute zero will require new active cooler technology.

New subkelvin coolers operating from a 4 to 6 kelvins base temperature will reach the ultralow temperatures required for calorimeter and bolometer focal planes, providing more heat lift, continuous operation, and high temperature stability. Adiabatic demagnetization refrigerators (ADRs), ^{3}He sorption coolers, and open-cycle dilution refrigerator precursor technologies show many of the attributes needed to meet these requirements. In the future, microfabricated focal plane coolers may electronically cool just the detectors themselves to low temperatures.

The Constellation-X mission will deploy active coolers to 4 to 6 kelvins, and a multistage ADR for cooling arrays of X-ray calorimeters to 0.05 kelvin. The subkelvin cooler builds on previous space technologies to provide higher heat lift and continuous operation. The Con-X subkelvin cooler technology dovetails with the needs of candidates for the Inflation Probe, which requires continuous cooling to the same temperature range, but with even more demanding temperature control requirements. The subkelvin cooling technology will be mature for the foreseen demands of future Vision Missions, including SAFIR, Far-Infrared and Submillimeter Interferometer, and Black Hole Imager.

In order to realize the potential sensitivities offered by space at far-infrared and submillimeter wavelengths, SAFIR will cool its deployed 10-meter telescope to 4 to 6 kelvins. This demanding capability will be realized by using a combination of passive cooling to minimize thermal power input, and an active 4- to 6-kelvin system to cool the distributed panels of the telescope. SAFIR's design leverages the passive cooling architecture of JWST and will find application in the future Far-Infrared and Submillimeter Interferometer, Life Finder, and Planet Imager missions.

Strategic technology infusion for coolers.

	Spitzer	Suzaku	Herschel/ Planck	SOFIA *	JWST	TPF-C	Explorers	DEP	Con-X	Inflat. Probe	TPF-I	SAFIR	Vision Missions
Cooling to 0.05–0.300 K													
Open-Cycle Dilution (0.1K @ 0.1 μW)			Technology Predecessor										
Temperature Stabilization			Technology Predecessor										
^{3}He Sorption Cooler			Technology Predecessor										
Single-Shot ADR		Technology Predecessor											
**Continuous 100 mK Cooler (50 mK @ >5 μW)				First Demo, First Flight					Second Flight – Significant Modification	Second Flight – Significant Modification		Mature Space Technology	Mature Space Technology
Heat Switches		First Demo, First Flight	Second Flight – Significant Modification						Second Flight – Significant Modification	Mature Space Technology		Mature Space Technology	Mature Space Technology
Cooling to 4–6 K													
Advanced Active Cooler (6 K @ >30 mW)		Technology Predecessor	Technology Predecessor						First Demo, First Flight	Second Flight – Significant Modification	Mature Space Technology	Mature Space Technology	Mature Space Technology
Micro-Vibration Control		Technology Predecessor	Technology Predecessor						First Demo, First Flight	Second Flight – Significant Modification	Mature Space Technology	Mature Space Technology	Mature Space Technology
Long-Duration Cryostat	First Demo, First Flight				Second Flight – Significant Modification		Mature Space Technology						
Passive Cooling													
Low-Temp Passive Design	First Demo, First Flight				Second Flight – Significant Modification		Mature Space Technology	Mature Space Technology		Mature Space Technology	Mature Space Technology	Mature Space Technology	Mature Space Technology
Large Deployed Sunshields					First Demo, First Flight					Second Flight – Significant Modification	Mature Space Technology	Mature Space Technology	Mature Space Technology
Control for Large Optics					First Demo, First Flight	Second Flight – Significant Modification					Mature Space Technology		Mature Space Technology

● Technology Predecessor ● First Demo, First Flight ● Second Flight – Significant Modification ● Mature Space Technology * Demo Platform

** The first four cooler technologies flow into the continuous 100 mK cooler for SOFIA and subsequent missions.

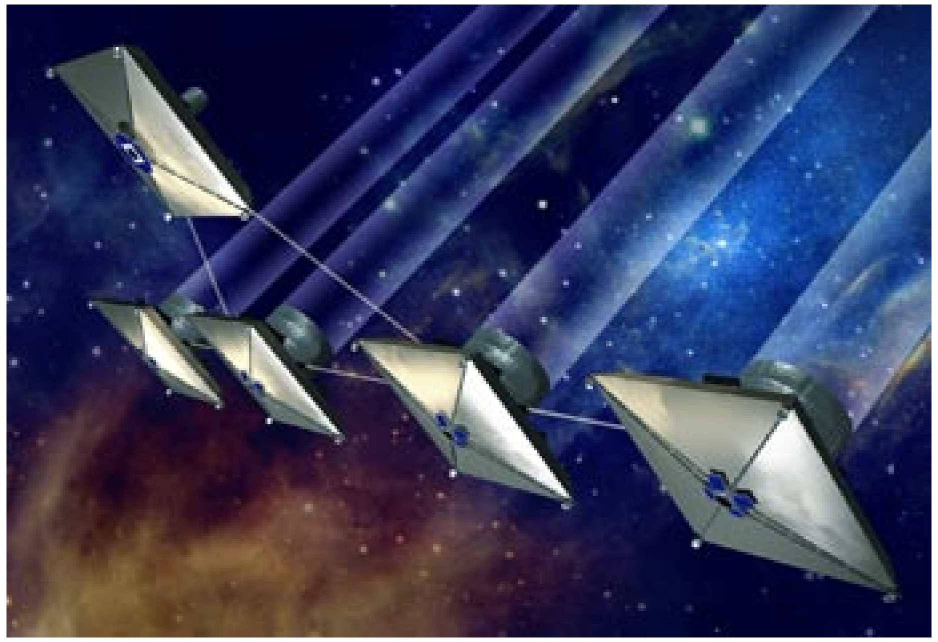
Distributed spacecraft

The science goals described in this document will soon require angular resolutions that can only be realized with optical elements spaced so far apart that they can no longer be fabricated as a single aperture, and even larger than can be deployed as a single unit in space. Fortunately, space uniquely provides an inertial low-disturbance environment that allows NASA to realize experiments with optical baselines well beyond anything possible on the ground. By deploying optical components and sensors on separate spacecraft, each of which may be easily launched separately, one can form large, extremely accurate, optical separations. Formation-flying techniques then hold the components in alignment, using precision control of the spacecraft motions to form images. Using distributed spacecraft, NASA will realize the angular resolution equivalent to a telescope effectively hundreds of kilometers in diameter.

Carrying out this type of spacecraft coordination requires extremely stable gyros, precise star trackers, laser ranging systems between spacecraft, and micronewton thrusters to perform minute adjustments. Of course thermal disturbances must also be controlled or cancelled at the same level of motion. In addition, spacecraft control algorithms need to be developed for continuous high-reliability monitoring, formation flying, reconfiguration, re-orientation, and autonomous recovery. This job is complicated by the inability to test these systems on the ground before launch and deployment.

The LISA mission will demonstrate advanced formation-flying techniques in order to detect the minute warping of spacetime as gravity waves move through the solar system. LISA will sense gravitational waves by measuring the relative displacements of inertial test masses contained in each spacecraft separated by millions of kilometers to picometer accuracy. The three spacecraft that make up the LISA interferometer will use newly developed micronewton thrusters (with cold gas or Cs ions) to control the spacecraft position, and several-watt lasers whose output needs to be stabilized to ~ 30 Hz/(√Hz) (1,000 times the stability of commercial lasers) mounted on each of the telescopes that form the interferometer. LISA is just one of many upcoming NASA missions to deploy multiple spacecraft in order to blaze pathways to new science.

The Terrestrial Planet Finder Interferometer (TPF-I) will enable high-angular resolution imaging of protoplanetary systems, gas, dust, and stars in the near-infrared to reveal the chemistry in the atmospheres of giant and terrestrial planets at high angular resolution. The interferometer comprises an ensemble of discrete telescopes flying under tight coherent control. In order to form images, TPF-I requires precision control of the optical path difference of each telescope system in the interferometer formation to within approximately 0.02 wavelength of the incoming radiation. Fine control is obtained using several sets of optical phase delay lines, at least one on each of the interferometer's free-flying telescopes. Ultimately, formation-flying techniques will be needed to image the event horizons of black holes, requiring numerous individual optic spacecraft that focus X-rays onto a detector spacecraft located tens of thousands of kilometers away, all of which are controlled to extraordinary precision.



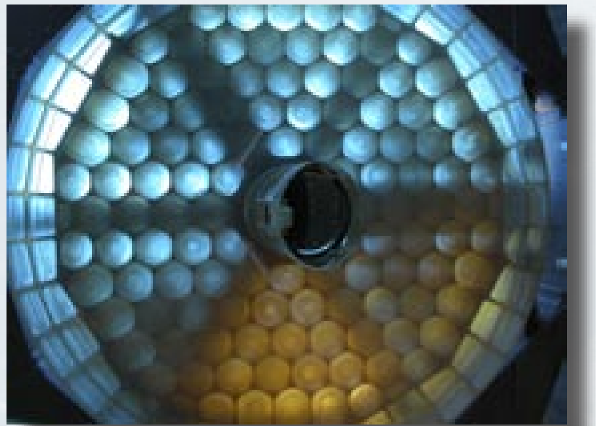
NASA is developing the technology to fly multiple spacecraft in such perfect synchronization that they become a single instrument — bigger and better than could be launched in completed form from Earth.

Strategic technology infusion for distributed spacecraft.

	GRACE *	NMP EO-1 *	MMS *	GP-B	SIM	MMS	LISA	TPF-I	Vision Missions
Formation Flying									
Formation Control		First Demo, First Flight	Second Flight					Second Flight	Mature Space Technology
Micronewton Thrusters							First Demo, First Flight	Second Flight	●
Laser Metrology					First Demo, First Flight		Second Flight	Second Flight	●
Thermal/Mechanical Stability				First Demo, First Flight	Second Flight		Second Flight		●
High-Precision/Low-Drift Gyros				First Demo, First Flight					●
Metrology and Navigation									
Intersatellite Ranging	First Demo, First Flight					Second Flight		Second Flight	●
Relative Navigation						First Demo, First Flight	Second Flight	Second Flight	●
Formation Alignment Sensor								First Demo, First Flight	Second Flight
Milli-arcsecond Star Tracker								First Demo, First Flight	Second Flight

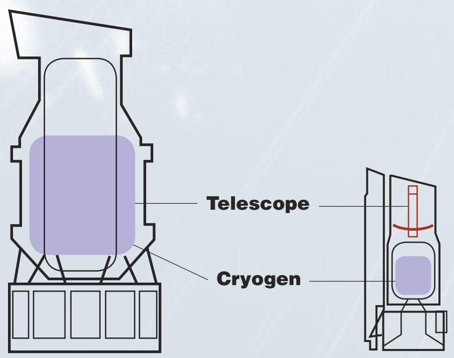
● First Demo, First Flight ● Second Flight – Significant Modification ● Mature Space Technology * Demo Platform

TECHNOLOGY SUCCESSES



SOFIA

The SOFIA observatory will consist of a 2.5-meter effective aperture telescope mounted in a Boeing 747 aircraft. The observatory uses an astronomical mirror of glass ceramic material; prior to application of a reflective coating the weight-reducing internal honeycomb structure is visible. SOFIA will fly at altitudes above 99% of the water vapor in the atmosphere, giving access to most of the spectrum from visible to millimeter wavelengths. In particular, scientifically important regions between 2 and 300 microns that are nearly opaque to ground-based observatories will be transparent for SOFIA observations. This will allow SOFIA to perform as a very versatile platform to test instrument technologies that would otherwise have to be tested in space. For example, future infrared and submillimeter SOFIA instruments, cryocoolers, and detectors will likely serve as prototypes of those that will fly on TPF-I and SAFIR. There is already rich cross-fertilization between SOFIA instruments and those of Spitzer, Kepler, Herschel, and JWST. A vigorous instrument program will ensure that SOFIA maintains state-of-the-art instruments and develops new technologies for future Astronomy and Physics Division missions.



SPITZER WARM LAUNCH

Infrared radiation, invisible to the naked eye, opens a new window for astronomy, allowing us to detect objects that are relatively cool, such as debris material in planetary disks surrounding a nearby star; hidden objects, such as new stars forming in dense regions obscured by interstellar dust; and even objects that are far away, such as the distant infrared galaxies discovered by IRAS. A spaceborne infrared observatory must cool its instrument, detectors, and telescope to just a few degrees above absolute zero in order to avoid seeing infrared radiation from the observatory itself. Spitzer pioneered passive cooling techniques that have greatly reduced mission cost. In its original design incarnation, Spitzer was to conduct observations from low-Earth orbit with a large insulated vessel filled with 2-kelvin superfluid liquid helium. In order to realize the design mission life of five years, this massive helium tank required a large launch vehicle and complex and expensive cryogenic testing prior to launch. Advances in thermal design led to a revolutionary reincarnation of Spitzer: by conducting observations from a heliocentric orbit, Spitzer exploited the natural radiative cooling available in space. This design allowed Spitzer to launch its telescope at room temperature, resulting in greatly simplified launch operations. As a result, the liquid helium tank in Spitzer shrank in volume by a factor of 10, resulting in significant cost savings, but without compromising capability. The techniques pioneered by Spitzer are now central features to the design of all future NASA infrared observatories, such as JWST and SAFIR.

Bolometers are used to detect the minute temperature and polarization fluctuations in the cosmic microwave background. The BOOMERANG receiver carried a focal plane of bolometers cooled to 0.3 degrees above absolute zero in a long-duration balloon flight in Antarctica.

DEVELOPING BOLOMETERS FOR SPACE

The cosmic microwave background gives us a view of the universe in its infancy. Minute temperature variations, hot spots, and cold spots in the CMB show the slightly over-dense regions from which galaxies and clusters were formed. The distribution of these variations contains a wealth of information on the energy and matter content of the universe. The even-fainter polarization of the background probes the existence of gravitational radiation from the first moments after the Big Bang.

How does NASA develop such detectors for highly targeted science goals? One example: the development of highly sensitive bolometers used the R&A program to maximum effect. A bolometer, cooled to a few tenths of a degree above absolute zero, senses light by converting electromagnetic energy into heat and recording the corresponding temperature rise. A millimeter-wave bolometer developed in 1994 for studying the CMB used a new concept: a "spiderweb" absorber that minimized the detector volume by using just the bare minimum of material necessary to absorb radiation.

These detectors were first developed through technology funding from the R&A and former NASA Code R programs to the point of demonstrating adequate performance for use in a scientific instrument. Spiderweb bolometers then flew successfully in the BOOMERANG, Millimeter Anisotropy Experiment Imaging Array (MAXIMA), and Archeops balloon experiments, giving us the first maps of the CMB that showed the degree-scale anisotropies characteristic of a flat universe. The results generated public enthusiasm for the spectacular science to come from the WMAP mission. These detectors will be flown on a successor to WMAP, the ESA/NASA Planck Surveyor, scheduled for launch in 2007.

TECHNOLOGY SUCCESSES (CONT'D)

X-RAY TECHNOLOGY AND HOMELAND SECURITY

The development of X-ray detectors for astronomy in the late 1960s and early 1970s was a key element for the development of X-ray baggage scanners, which ultimately evolved into the airport security scanners now in use at all US airports. The flying spot X-ray source that is at the heart of many of these scanners was patented in 1973. It provided the means to project a small spot of X-rays through baggage, and the intensity of the beam was measured in a raster scan to provide a line of intensities on a TV screen. As the object is moved though the plane of the flying spot, more lines of the image are generated until a complete 2-D view is obtained. Because objects of different materials absorb X-rays differently; the resulting image shows the outline of objects in the baggage, providing a useful signature to detect potentially dangerous items. The technologies for making high-intensity X-ray sources and detecting the X-rays passing through objects were based on the techniques that were developed for observing X-ray sources in space (and for calibrating these astronomical instruments on the ground). In 1977, these types of inspection devices were finding their way into many airports and other high security areas.

Today, this technology has evolved and improved so that images of baggage (and even people) can be made using both transmitted and backscattered X-rays, providing detailed views of otherwise hidden objects, particularly potential weapons and explosives. The technology being used today is an example of a very successful and important synergy between space science needs and commercial and national security needs.

KECK INTERFEROMETER

Interferometry is the key to high-angular-resolution astronomy. No other approach can unveil the skies with unlimited sharpness. The Keck Interferometer, shown here, is being developed by NASA to pioneer the technique of nulling interferometry that will be used in future planet-finding missions such as TPF-I. The young star DG Tau was observed on several nights with the Keck Interferometer. The high-angular resolution interferometric data recorded during these nights was interpreted scientifically and the artist's concept of DG Tau prepared based on a combination of theory and observation. The interferometer data reveal that the ring of dust comes as close as one tenth of one astronomical unit (the Earth–Sun distance) to the star. It is a young star surrounded by rings of gas and dust. The nebulosity shown at bottom left is a Hubble Space Telescope image of the Seyfert galaxy NGC 4151. Observations of the galaxy by the Keck Interferometer showed that a very compact disk of hot gas surrounds this black hole, which is known to be present within the core of our Galaxy.

"I learned skills that I hope continue even after the program comes to an end.... Learning about the universe became easier and more interesting."
—Ligaya (age 14)

Serving Underserved Communities

Technology provides a powerful "hook" for engaging youth in science and engineering. The Chandra After-School Astronomy Project (ASAP) provides activities using online telescopes to after-school programs for youngsters who previously may have only seen a few stars from the inner city. Youngsters' projects combine images they take themselves using the online telescopes, with images from the Hubble, Chandra, and Spitzer observatories. The after-school program has been so popular in both Hispanic and African-American after-school community groups that plans are underway to scale up nationally. The educational technology that makes this possible is itself a spin-off of technology driven by NASA's space missions.

7 Sustaining the Vision

"The future belongs to those who believe in the beauty of their dreams."

—Eleanor Roosevelt

The Spitzer Space Telescope captured this infrared image of embryonic stars embedded in optically opaque pillars of gas and dust near the massive star Eta Carinae.

The NASA science engine is driven by the creativity, risk-taking, and innovation of its scientists. The focus of the agency's Astronomy and Physics Division science program is necessarily on its large flagship missions, and much of the supporting research and technology is tied to those missions. Nevertheless, priorities must allow for rapid and flexible response to new discoveries. A successful program depends on generating the new ideas that will be the basis of tomorrow's space science initiatives, incubating new detector concepts, nurturing the next generation of researchers, converting hard-won data into scientific understanding, and testing promising technologies that may later be incorporated into major missions. These are the functions of the highly competed Research & Analysis (R&A), suborbital, and Explorer programs, which are designed to guarantee the continued vitality of NASA's overall space science vision, reduce major mission risks, and optimize the return on NASA's capital, technology, and workforce investments.

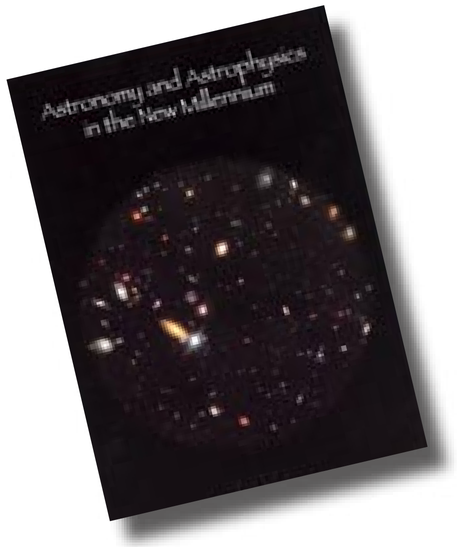
Research and Analysis

In a 2000 report, the Association of American Universities described the R&A line as "one of the most efficiently used funding lines in space science research." R&A supports scientific exploration outside budget lines of individual missions. It represents a small fraction of the NASA space science budget, but it is this fraction that leads to ideas for new missions, incubates the critical early phases of technology development, and transforms the raw data from satellite instruments into answers to scientific questions. Its technology and detector development, theoretical research and modeling, laboratory astrophysics, ground-based observation, and archival research components, together with the suborbital and Explorer programs described below, constitute the "seed corn" from which major NASA missions grow.

Technology incubation

Astronomers constantly strive for new observing capabilities: more sensitivity, better resolution, opening up new wavelength regimes. The obvious advantage of incorporating the latest technologies in new missions is tempered by the need to reduce the risk to mission success. The enormous sums of money that modern missions require cannot be gambled on unproven technologies, no matter how attractive those technologies may be. This friction between performance and reliability drives the philosophy of technological incubation within the Astronomy and Physics enterprise. Technological developments are rated in terms of a technology readiness level (TRL) that ranges from 0 (great idea) to 9 (ready for flight). Typically, missions that are ready for selection need to incorporate technologies at TRL level 6 or higher, and advancement to TRL 9 is conducted under the auspices of the mission development. However, great ideas need to be shepherded from TRL 0 to TRL 6, and it is the R&A program that is the essential link in this process.

The R&A program has supplied NASA missions with many technologies that were later incorporated into major missions, and this process continues to this day. Some example capabilities are holographic gratings, extreme ultraviolet filters, and X-ray calorimeters. Microchannel plate (MCP) detectors and their associated readouts, both developed under the Astronomy and Physics R&A program, have been the cornerstone of missions such as the Extreme Ultraviolet Explorer (EUVE), Chandra's High-Resolution Camera (HRC), the Hubble Space Telescope/Space Telescope Imaging Spectrograph (HST/STIS), the Far-Ultraviolet Spectroscopic Explorer (FUSE), Galaxy Evolution Explorer (GALEX), and the Cosmic Hot Interstellar Plasma Spectrometer (CHIPS), as well as many rocket payloads. Future ultraviolet/optical missions will require even better performance and reliability. In the near- and mid-infrared, new large-format, low-readout-noise arrays now under development will be vital to the success of JWST. At submillimeter wavelengths, the class of spiderweb micromesh bolometers that enabled BOOMERANG's first image of the CMB sky will be used on Planck Surveyor to obtain the definitive CMB map and on the Spectral and Photometric Imaging Receiver (SPIRE) instrument on Herschel to gain a new view of the universe. The effort to develop silicon pop-up detectors has led to the large-format arrays on the High-resolution Airborne Wide-bandwidth Camera (HAWC) of SOFIA and the development of new cutting-edge instruments on the ground-based Submillimeter High Angular Resolution-2 (SHARC-2) telescope at the Caltech Submillimeter Observatory. The heterodyne SIS mixers with heritage in the Astronomy and Physics Division R&A program will fly on both SOFIA and Herschel. Continued research into far-infrared and submillimeter detectors will be necessary if future missions such as SAFIR and Inflation Probe are to reach their full potential. In contrast to the situation at shorter wavelengths where megapixel arrays with high quantum efficiency and low readout noise exist (due largely to major investments by the DoD), far-infrared detectors do not yet approach these performance levels in either format or sensitivity. The detector heritage of Spitzer at far-infrared wavelengths is ripe for aggressive development to enable the much more sensitive future surveys of the birth of stars and structure in the universe envisioned under the Astronomy and Physics science program.



The National Academy of Sciences Decadal Survey: Astronomy and Astrophysics in the New Millennium.

Supporting theoretical research and modeling

Science seeks to advance human knowledge by explaining and understanding the universe in all its particulars. Theoretical research plays a fundamental role in this endeavor: it is the central process whereby data are converted into meaning. Theory provides the framework we use for structuring science, the language we use to describe the world, and the tools we use to interpret data. In the complex science of the future, theoretical studies including systems analysis, advanced modeling and simulation, and their applications to data will be even more important.

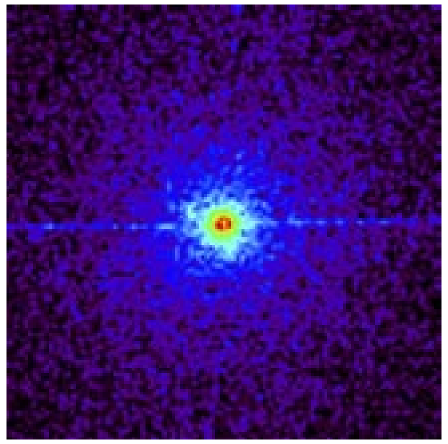
The National Academy of Sciences Decadal Survey, *Astronomy and Astrophysics in the New Millennium*, recognized theoretical studies as a central component of modern mission and technology development. Modern observations cannot be interpreted, or in some cases even made, without the pioneering theoretical work that anticipates them. Theoretical imagination conjured white dwarfs, neutron stars, black holes, the cosmic microwave background, and accretion disks, as well as the fundamental techniques and tools of atomic physics, nuclear physics, quantum physics, general relativity, physical chemistry, statistical physics, radiative transfer, and hydrodynamics. In recent years, theoretical studies include the development of software technologies supporting data exploration, astrophysical simulations, and the combinations of these that now enable a deeper understanding of complex systems. Hence, theoretical research is crucial to the progress of any scientific endeavor: it establishes the framework within which the basic questions of space science are formulated, predictions are made, and data are interpreted and analyzed, and it is the wellspring of new missions. All of these roles for theory are exemplified in the recent revolutionary development of precision cosmology, a new synthesis that will endure in the history of science as a major historical advance in knowledge.

Science seeks to advance human knowledge by explaining and understanding the universe in all its particulars. Theoretical research plays a fundamental role in this endeavor: it is the central process whereby data are converted into meaning.

When a mission is conceived, theoretical research is essential to quantitatively define science goals, necessary capabilities, and optimal observing strategies. For example, theory provides the analysis methods needed to infer the spin states of black holes from observations of relativistic iron lines, to identify the signatures of the first stars and galaxies, to translate the relative motion of formation-flying satellites into gravitational-wave signals, to extract from seeming noise the polarization signal of the cosmic microwave background, to identify the physical processes of galaxy and star formation, to determine the structure of protoplanetary disks to infer the presence of perturbing planets, to find and characterize terrestrial planets, and to interpret the photometric and spectroscopic signatures of life. Similarly, when a mission flies and returns data, theoretical modeling is the key to maximizing the scientific return on mission investment, and indeed is often integrated into the fundamental mission design. A strong, stable and sustained commitment to theory funding is needed for a healthy and balanced Astronomy and Physics Division science program.

There are currently two prominent components of NASA support for theoretical research. The first is the broad-based Astrophysical Theory Program (ATP), also complemented with the Long-Term Space Astrophysics (LTSA) program, and the NASA Astrobiology Institute. The ATP supports more theoretical astrophysics research, more efficiently, than any other program funded by the federal government. While all proposals are required to demonstrate their relevance to NASA mission objectives and are evaluated on this basis, much theoretical research cuts across individual mission lines, synthesizing results from different wavelengths or from imaging and spectroscopy. Such investigations have proven to be some of the most productive supported by NASA, explaining data from HST, Spitzer, WMAP, CGRO, Chandra, High-Energy Transient Explorer-II (HETE-II), RXTE, FUSE, and COBE. Above all, the ATP component of NASA theory support has been and will be crucial to envisioning and defining missions, identifying novel techniques that could be used to address Astronomy and Physics Division science objectives, and studying capabilities needed to achieve those objectives.

The second component of NASA support for theoretical research arose from the recommendation of the 2000 Decadal Survey that theoretical research be explicitly funded as part of each mission funding line, allocating a small fraction of its budget to theory challenges critical to the mission's key goals. The Decadal Survey made this recommendation because detailed modeling connecting the elements of a mission to the system under investigation is critical to design and even to conceive successful and cost-effective missions. Rigorous modeling is an important factor in reducing mission risk and evaluating competing mission strategies, and simulations can vividly demonstrate mission goals. With a small incremental investment, mission-oriented theory challenges multiply the science obtained by each new probe and space telescope. Furthermore, the theory component of each satellite project can be targeted to precisely that sort of theoretical work most relevant to the questions that the satellite is meant to answer. Such investments advance the science agenda of each platform and provide a flexible mechanism to strongly tie theory to the exciting discoveries to be made. The variety of satellites ensures that a healthy, full complement of theoretical problems is studied. Together with a vigorous ATP to address crosscutting and basic astrophysical research that connects them with each other and points to the next generation of missions, the theory challenge model ensures that the return on NASA's investments is optimized. To date, HST, Spitzer, and Chandra have implemented such programs, and both the TPF and Beyond Einstein Foundation Science programs have been announced in response to this recommendation.



Chandra observed a halo, caused by scattering of interstellar dust grains, around the X-ray source Cygnus X-3. (The horizontal line is an instrumental effect.)

Insets throughout the science chapters provide a few examples of potential theory challenges in support of missions.

Laboratory astrophysics

By using a combination of laboratory experiments, modeling, and theoretical calculations, the laboratory astrophysics program provides the fundamental knowledge needed to make sense of data collected by space missions and to plan them initially. Laboratory measurements are often an essential link between observations and scientific conclusions. The program explores a tremendous breadth of topics, from the very coldest regions deep in molecular clouds to the extraordinary environments around supermassive black holes. It supports NASA's space missions from conception to completion, defining mission parameters, providing post-flight analysis, and opening new discovery space for future observations.

X-ray observations of active galactic nuclei, X-ray binaries, and cataclysmic variables can be understood only with the aid of supporting laboratory measurements and theoretical analyses of the radiative and collisional ionization/recombination processes associated with highly charged ions that are poorly constrained at present. Chandra and XMM-Newton have demonstrated the power of high-resolution spectroscopy and the Con-X mission will extend this capability. Current models of weak or blended features — for example, in the complex iron line region — are inadequate to interpret all the observed line emission features. The level of precision achievable with grating spectra must be matched with continuing laboratory measurements and theoretical calculations.

Ultraviolet and visible laboratory atomic spectroscopy supports observations that test cosmological models and provide insight into the processes that created the elements during the Big Bang, the ages and metallicities of galaxies, and the sequence of galaxy formation. Similar spectroscopic data are key to interpreting the energetics of interstellar dust in a variety of environments and the nature of the diffuse interstellar bands (DIBs). DIBs are the oldest standing spectroscopic problem in the natural sciences, and are likely caused by large organic species that may be connected to the origin of life.

At longer infrared wavelengths, the unidentified infrared bands, or UIRs, are likely related to the DIBs and are responsible for much of the radiative output of gas-rich galaxies such as the Milky Way. The Spitzer Space Telescope has recently provided spectra of both the diffuse and dense interstellar medium with unprecedented sensitivity. Many new UIR features and dust-molecular ice components have been seen for the first time, as have unusual dust components around young and late-type stars. The infrared to submillimeter transitions of interstellar dust grains are extraordinarily sensitive to their specific

mineral and carbonaceous composition, leading to a variety of grain opacities in different environments. These opacities, uncertain now by an order of magnitude, are key to estimating the temperature and mass of the interstellar medium (ISM) within entire galaxies. JWST will provide even deeper, spatially resolved spectra at these wavelengths, and these spectra will pose significant challenges to laboratory spectroscopists.

Gas-phase tracers of the ISM include the fine-structure transitions of atoms and atomic ions in the far-infrared/submillimeter and the rotational lines of small molecules. These lines are the main coolants of the non-ionized ISM. This makes them key contributors to gravitational collapse, and as such they are critical to understanding the formation of stars and planets. As molecules increase in complexity, their lowest energy vibrations move into the far-infrared. Such torsional modes may provide new means of assessing the role of prebiotic chemistry in establishing the conditions necessary for the emergence of life with SOFIA and Herschel, but will only be useful provided a vigorous laboratory astrophysics and theory program continues that examines the vibrations of molecules and small grains under interstellar conditions.

Finally, future missions such as TPF will study Earth-like planets and search for signs of life. Laboratory experiments have shown that some of the raw materials for life on these planets can be created in interstellar grains of ice and dust and in the early presolar nebula. It is vital to continue these experiments, as well as others aimed at understanding the evolution of biospheres and the potential biosignatures observable spectroscopically on these planets from space missions.

Ground-based observations in support of NASA missions

Missions frequently require ground-based data to devise observing strategies, assess necessary instrumental capabilities, or allow proper interpretation of data. The Keck program to characterize planet populations, for example, complements and helps define the goals for Kepler, SIM PlanetQuest, and TPF. The new Keck High-Resolution Echelle Spectrometer (HIRES) instrument archive is supported by NASA, as is a portion of the development of the Keck Interferometer using the Palomar Testbed Interferometer (PTI), the Large Binocular Telescope (LBT), and the operation of the 2.5-meter Infrared Telescope Facility (IRTF) telescope on Mauna Kea. The LBT interferometer is tasked with determining the brightness of the exozodiacal light in other stellar systems to gauge the backgrounds

Future missions will build on the data archives and technology of the Keck Interferometer.

Until about 25 years ago, data were collected by an investigator for a single purpose, and the investigator rarely made the data available to others. NASA changed this model by archiving space-based data, thereby making it available to all interested parties.

TPF will encounter. The Near-Earth Asteroid Tracking (NEAT) system on Mt. Haleakala is supported by NASA, and ground-based studies of Type Ia supernovae are used to assess their suitability as probes for dark energy.

The ground-based Robotic Optical Transient Search Experiment (ROTSE) detected the first prompt optical transient associated with a gamma-ray burst, and is conducting a survey of the sky for optical transients associated with gamma-ray and X-ray bursts from a network of locations around the world. At higher gamma-ray energies, ground-based observations of the atmospheric Cerenkov radiation from gamma-ray-induced showers at teravolt energies will complement observations by GLAST and provide critical information about the emission models. At radio and optical wavelengths, significant progress has been made in identifying the counterparts of hitherto unidentified EGRET gamma-ray blazars. A "figure of merit" has been devised for candidate identifications using optical spectroscopy of candidate blazars, compact radio source properties, and positions within the EGRET error ellipse to find several dozen new counterparts. Such an approach is critical for GLAST, which is expected to detect ~5,000 blazars. A combined Very Large Array (VLA) and Very Long Baseline Array (VLBA) radio program has begun in order to assess likely candidates for GLAST detections and to provide radio properties and reference milliarcsecond-scale images in advance of GLAST's launch.

With the recent launch of the Swift gamma-ray burst mission, the VLA will devote up to 25 hours per month during 2005 for radio follow-up of the most compelling gamma-ray bursts detected by Swift. This correlated radio/gamma-ray observing program is aimed particularly at very nearby bursts, very distant bursts, X-ray flashers, and the class of short bursts that do not yet have identified counterparts.

The Inflation Probe, if it is based on microwave background anisotropy polarization, will require new generations of polarization-sensitive detectors, excellent control of systematic effects, and a thorough understanding of astrophysical foregrounds. Ground-based cosmic microwave background polarization experiments will be essential preparation for this implementation of the Inflation Probe, for testing of new technology, investigation of observing strategies and systematics, and providing data to test new analysis techniques. Detector technology for COBE, WMAP, and Planck Surveyor was a direct product of ground-based and suborbital programs. In the same way, a strong ground-based program may be an essential precursor to the Inflation Probe.

Whatever technique is adopted, the Dark Energy Probe will require ground-based data of unusual uniformity, quality, and completeness. If Type Ia supernovae are employed, space studies must be supported by detailed and precise ground-based spectra and photometry of a large, uniformly selected sample of relatively nearby supernovae. This is required both as a calibrating set for the high-redshift Hubble diagram and as a statistical control sample to study the systematic correlations of supernova properties — the generalization of the one-parameter fits to light curve shape currently being used. Similar foundational studies are needed for other candidate techniques for the Dark Energy Probe. Programs supporting ground-based studies of this type are already under way.

Archival research

Until about 25 years ago, data were collected by an investigator for a single purpose, and the investigator rarely made the data available to others. NASA changed this model by archiving space-based data, thereby making it available to all interested parties. The data are saved in standard formats, making it easy to work with, and the result is that the same data sets are used for many purposes, some of which are more valuable than the original purpose for which the data were collected. These data archives proved so important that most completed missions were archived and all new missions are required to have a thoughtful archiving plan. These data reside in archive centers with expertise in specific wavebands (e.g., infrared, X-ray). The centers not only archive the data, but they have helped develop software to analyze the data and they extract data products that are very broadly used, such as catalogs of sources. Furthermore, many of NASA's highest-impact programs have been aimed specifically at creating archival data sets that enable a wide range of scientific investigations, e.g., the Hubble Deep Field and Ultra-Deep Field, Chandra Deep Fields, and the Great Observatories Origins Deep Survey (GOODS). With the easy availability of the basic data, data products, and software, these archives have become indispensable and we regard them as national treasures.

A surprising development is the use of these data by non-astronomers, such as students in K–12 and college. This interest has led to the development of a wide range of educational materials that are shared with the general public. Now our archive sites are visited most frequently by people who are not professional astronomers.

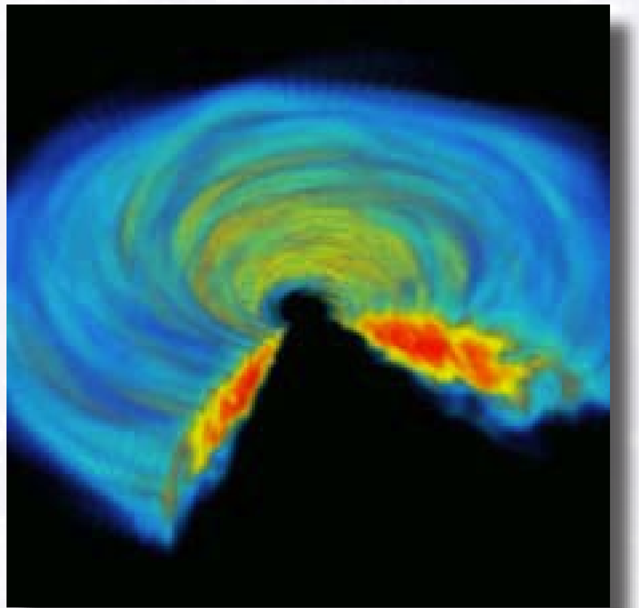
The National Virtual Observatory's objective is to enable new science by greatly enhancing access to data and computing resources.

As astronomers have gained experience with the archives, they have come to realize that there is enormous synergy between data sets, so there has been significant effort to compare data sets, opening up new avenues for research. Since different data sets may reside in different physical archive sites, the interrogation across archive sites is limited, so the next step is to remove these barriers. Nascent efforts have begun. This development stage will lead to what we refer to as the Virtual Observatory, where researchers, students, and the public will be able to call up a wide range of data from a single website and ask probing scientific questions. The National Virtual Observatory (NVO) will build on developments in computing and information technology and will have a major impact on Astronomy and Physics Division missions and science. It will also be a productive area for interagency collaboration with the NSF. The NVO will federate digital sky surveys, observatory and mission archives, and astronomy data and literature services, and provide a framework that will reduce the cost of developing and maintaining future archives and data services. The NVO will also be an unprecedented venue for science and technology education and public outreach and will be able to compare complex data products, often on very large data sets, revealing previously hidden relationships and identifying the most extreme objects in the astrophysical universe. The simultaneous enhancement of facilities to ingest new data along with the development of the NVO is the main priority for archival data activities.

Training the next generation of explorers

R&A's role in educating and training the next generation of explorers and providing hands-on experience with cutting-edge technologies is critical for supporting and nourishing the scientists, technicians, engineers, and managers who will be responsible for the scientific priorities and flagship missions of the future. The 2001 Hart–Rudman report *Roadmap for National Security: Imperative for Change* identified the failure of math and science education as the second greatest national security threat facing America. Furthermore, the Aldridge Commission report (*A Journey to Inspire, Innovate, and Discover*) recognizes that America's leadership in space, as indeed in all other domains of technical achievement, critically depends on training young Americans in science and engineering:

Theory challenge



Investigating the dynamics of magnetized, turbulent disks.

Visualization of an Accretion Disk Orbiting a Black Hole

This frame is from a computer simulation of an accretion disk orbiting a black hole. Gas density is represented by color, blue corresponding to low density, red to high density. In one quadrant, the disk is cut away to show its internal structure. Computer simulations such as this are used to investigate the dynamics of these magnetized, turbulent disks.

"The Commission suggests that NASA use strategic investments to engage universities in training the workforce capable of taking us on the exploration journey. From astronauts to systems engineers to space scientists, a workforce of great technical skill in their chosen disciplines will be required to implement the system of systems that will accomplish the space exploration vision. However, given the breadth and operational complexities presented by the vision, this next-generation workforce will need significant interdisciplinary experience as well."

The R&A program directly addresses these crucial national needs. Much of NASA's education and public outreach enterprise is directed at broad-based efforts to stimulate and motivate a large audience of K–14 students and their teachers, together with interested members of the public. The R&A program's emphasis is on in-depth training for a cadre of future scientists, engineers, and NASA investigators. The R&A program provides unique opportunities for undergraduate and graduate students to work in the laboratory with senior scientists, to gain experience with state-of-the-art techniques, and to work on cutting-edge science and instrumentation. Graduate students and postdocs have the opportunity to see a program through from conception to final science results, and young investigators have the opportunity to manage complex projects and gain the experience needed to lead future missions. Only with such opportunities can the next generation of NASA leaders be trained and developed in order to be able to lead the missions of the future. Although large space missions must remain a central focus of NASA's priorities, they do not provide the training opportunities needed to satisfy the Hart-Rudman report's concerns. The R&A program offers a unique capability for training a new cadre of scientists, engineers, and teachers, with its shorter time scales, tolerance for risk, opportunities for creativity and innovation, broad involvement of students and young investigators in a large number of research groups across the nation, and for combining exciting NASA science with cutting-edge technology.

NASA has at its disposal the world's most powerful partners in this endeavor: America's research universities. The Science Mission Directorate already partners with the faculties of these universities through its PI-level grants programs, which provide critical funding for graduate education well aligned with NASA missions, priorities, and skill-set requirements. Universities have also very successfully deployed new, creatively focused, interdisciplinary graduate programs such as the NSF-funded IGERT grants. A competitively operated program funded by NASA, based on the Integrated Graduate Education and Research Traineeship (IGERT) organizational model but explicitly aligned with NASA's technical training priorities, would be an efficient way to recruit the potential of the next generation of American technical leaders.

The Explorer Program: Rapid Access to Space for Small and Medium Missions

The Explorer program is an essential and invaluable tool for the Astronomy and Physics Division. Explorers offer frequent access to space and opportunities for small and medium-sized missions (SMEX and MIDEX) that can be developed and launched in an approximately four-year timeframe. These focused, cost-capped, peer-reviewed and competed missions address science of great importance and respond quickly to new scientific and technical developments. The Mission of Opportunity option enables collaborations with other agencies, both national and international.

The Explorer program has a track record of success:

- IMP-8 (Interplanetary Monitoring Platform-8), launched in 1973, provided data on the magnetic fields, plasmas, and energetic charged particles of the Earth's magnetotail and magnetosheath and the solar wind for over 28 years, and provided baseline data for the deep-space Voyager and Ulysses missions.

- The Infrared Astronomical Satellite (IRAS), launched in 1983, discovered the debris disks around nearby stars that are almost certainly connected with the formation of planetary systems.

- The Cosmic Background Explorer (COBE), launched in 1989, discovered fluctuations in the cosmic microwave background, revolutionizing the field of cosmology and the science of the universe as a whole. COBE's map of the microwave sky was described by Stephen Hawking as "the discovery of the century, if not of all time."

Swift, an Explorer program mission, studies gamma-ray bursts.

Explorer missions currently in operation or under development directly address high-priority science objectives of the Astronomy and Physics Division:

- The Advanced Composition Explorer (ACE), launched in 1997, has been providing high-resolution measurements of the elemental and isotopic composition of cosmic-ray particles produced in the solar corona, the interplanetary medium, the local interstellar medium, and the Galaxy. ACE's measurements bear on the question: Where does the material of which we are made come from?

- The Wilkinson Microwave Anisotropy Probe (WMAP), a MIDEX mission launched in 2001, is answering fundamental questions about the age and matter density of the universe. WMAP's results were named by Science Magazine as the "2003 Science Breakthrough of the Year." WMAP is a vital precursor to the Inflation Probe of the Beyond Einstein program.

- The Galaxy Evolution Explorer (GALEX), a SMEX mission launched in 2003, is mapping the ultraviolet emission from the local universe, providing a baseline for understanding the observations made by HST and in the future by JWST of ultraviolet emission from the very distant universe that has been redshifted into the optical and infrared.

- Swift, a MIDEX mission launched in 2004, is providing observations of gamma-ray bursts. Gamma-ray bursts are produced in the most extreme laboratories the universe provides, under conditions of high energies, high densities, and high fields that accompany the deaths of stars and the births of black holes. These intense transient events, for a short time the most luminous sources in the universe, serve as beacons allowing the study of the universe on the largest scales and the nature of matter under extreme conditions.

Future Explorers are relevant to Beyond Einstein, including both missions of opportunity and dedicated missions. For example, laser-ranging equipment attached to planetary missions will provide precision tests of relativity in the solar system. Each solicitation for Explorer proposals elicits more high-quality experiments than can be implemented. Regular and frequent peer-reviewed competitions give the Explorer program the ability to implement new, creative ideas and react quickly to discoveries. The high level of the competition, the stringent review, and the frequency of the opportunities account for much of the high science value of the Explorer program.

Suborbital Program: Balloons and Sounding Rockets

The Suborbital program, comprising the sounding rocket and high-altitude balloon programs, provides unique opportunities for high-priority science; detector and instrument development; and training of students, engineers, and future space mission Principal Investigators. It is the means by which NASA offers frequent and rapid access to space for proving new technologies and novel instrumentation. Even the smallest stand-alone space missions (SMEX, Small Explorers) cost in excess of $100M per project. This cost requires that space missions be low risk with a high certainty of science return. Untested technologies, unproven techniques, and high-risk science need a lower-cost avenue to space. From the time of Galileo Galilei, astronomy has been driven by new technology, new techniques, and new data that lead to new questions that require new observational approaches. The Suborbital program provides an opportunity for creativity, ingenuity, and the serendipity that is an essential ingredient both in scientific progress and in motivating and training

BOOMERANG mapped the anisotropies of the cosmic microwave background.

the next generation of scientists and engineers. Because suborbital projects are lower in cost than space missions, NASA can afford to take risks to develop the new technological capabilities required for future missions. Because the time scales of suborbital projects are compatible with the length of a student's undergraduate or graduate career or a postdoc's appointment, the Suborbital program can provide training for the continuing stream of skilled instrument developers that is needed for a healthy and continuing space program. And because of the flexibility to follow up quickly on new results, the Suborbital program produces a steady stream of both new instrumentation and new science that leads to new questions and the evolution of new missions within the Astronomy and Physics Division science program.

Helium-filled balloons have the capability to lift multi-ton payloads to altitudes in excess of 120,000 feet for 30-day flights, and have demonstrated the capability to launch a 200-kilogram payload to 160,000 feet. High-energy astrophysics experiments, which are difficult to fly in space because of their large size, have flown on balloons halfway around the world from Australia and around the world from the Antarctic. A 100-day ultralong-duration flight capability is being developed, which will provide extremely useful flight opportunities for observing campaigns associated with Beyond Einstein and for multi-wavelength observing campaigns involving correlated spacecraft and ground observations. Balloon instruments have produced pioneering science and developed instrumentation for follow-up space missions:

- The BOOMERANG and MAXIMA high-altitude balloon missions obtained the first point-by-point maps of structure in the CMB at a level sufficiently precise to provide tight constraints on cosmological parameters. Their maps of the anisotropies of the CMB measured the geometry of space and confirmed the inflation model of the early universe.

Untested technologies, unproven techniques, and high-risk science need a lower-cost avenue to space. From the time of Galileo Galilei, astronomy has been driven by new technology, new techniques, and new data that lead to new questions that require new observational approaches.

- Balloon-borne gamma-ray telescopes have observed positron annihilations and black hole transients in the region near the Galactic Center, and provided the first detections of gamma-ray lines from ^{56}Co decays in the debris of Supernova 1987A. The ability to organize a balloon campaign quickly was crucial in order to observe the evidence of the supernova's ^{56}Co production with its 77-day half-life.

- Balloon-borne magnetic spectrometer instruments have identified cosmic-ray antiprotons and shown them to be the result of Galactic cosmic-ray collisions with interstellar gas and dust, placing constraints on the kinds of supersymmetric particles that may comprise the dark matter of the universe.

- Upcoming balloon instruments will make measurements of the microwave foreground and can provide tests of techniques that may be needed for future satellite-borne studies of the CMB polarization.

Balloon missions are prototyping optics and detectors to extend X-ray and gamma-ray measurements in space to higher energies than are currently possible. Spiderweb bolometers, used by BOOMERANG to obtain its first image of the cosmic microwave sky, will be central components on the upcoming Planck Surveyor and Herschel missions. Balloon campaigns provided opportunities for developing and testing instrumentation for the Compton Gamma-Ray Observatory (CGRO), whose instruments were based on a combination of balloon flight and sounding rocket heritage. CMB balloon flights in the 1980s and 1990s led directly to the design of WMAP; and instruments on the Reuven Ramatry High-Energy Solar Spectroscopic Imager (RHESSI), ACE, and EOS-Aura space missions all were developed and tested on high-altitude scientific balloon flights. Finally, coded-aperture imagers and position-sensitive gamma-ray detectors developed for hard X-ray and gamma-ray astronomy have found applications to medical imaging and national security. Future balloon launches will be needed to test room-temperature cadmium zinc telluride semiconductor detectors, X-ray focusing optics, megapixel coded aperture gamma-ray imagers, and fast low-power multichannel electronics for Beyond Einstein's Con-X and a candidate Black Hole Finder Probe.

Like the balloon program, the sounding rocket program has a history of cutting-edge science and detector development leading up to future space missions. In over a hundred missions since 1995, the sounding rocket program's success rate has been 99%. High-altitude rocket flights initiated X-ray astronomy and led to the current Chandra mission and a share of the 2002 Nobel Prize for Riccardo Giacconi. Initial rocket observations of the soft X-ray cosmic background led to later measurements with Chandra, the Italy–Netherlands BeppoSAX (Satellite per Astronomia X), and the Germany–U.S.–U.K. Roentgen Observatory Satellite (ROSAT).

Funding to develop new suborbital payloads is essential for developing new instrumentation, for training new scientists, and for producing new science.

8 Engaging Students and the Public

"To inspire the next generation of explorers ...as only NASA can."
—from the NASA Mission Statement

An interactive exhibit gives viewers the opportunity to see themselves in infrared light.

The missions described in this document present a unique opportunity to advance two of NASA's top-level education and public outreach objectives:

- **to inspire and motivate students to pursue careers in science, technology, engineering, and mathematics (STEM), and**
- **to engage the public in shaping and sharing the experience of exploration and discovery.**

These lofty objectives serve down-to-earth needs. Foremost is the need to ensure an adequate workforce of scientists and engineers — some of those who will implement the missions described in this document are now only in elementary school. Equally important is to ensure a scientifically literate and engaged public, without whose support these explorations would languish. A strong education program provides a necessary return on the public's investment in science exploration.

Beyond practical needs lies a public fascination with the universe that has endured since humans gathered around the first campfires and looked into the night sky. The age-old questions "Where did we come from?" and "Are we alone?" have always been part of humanity's need to understand our existence and place in the universe. People have considered these questions in the realms of religion, myth, the arts, and the pop culture interest in the unknown. Yet the age of speculation is fast becoming the age of scientific discovery and understanding. We have measured the glow of the Big Bang — the cosmic event that gave birth to the universe — and discovered dark energy. We have observed distant galaxies and captured snapshots of the birth and death of stars. We have discovered more than 150 planets around other stars. Strong evidence suggests that liquid water once flowed on the surface of Mars and may still exist below the icy crust of Jupiter's moon Europa. On Earth, we have found that wherever there is water, there is life. With the missions envisioned in this document, we appear to be on the brink of answering some of the fundamental questions that have captured our imagination for centuries and taking a tremendous leap forward in understanding our place in the universe. The huge public interest in this journey through space and time will continue, as evidenced in part by the millions of viewers for documentaries such as PBS' *Origins* and *Runaway Universe* and exhibitions such as *Cosmic Questions* and *Alien Earths*.

The basic science concepts explored by the Astronomy and Physics Division are central to science education. For example, the National Science Education Standards mandate that all students develop an understanding of the Big Bang and the formation of galaxies, stars, and planets, and the Benchmarks for Science Literacy, published by the American Association for the Advancement of Science, cite black holes as an excellent way to introduce students to the nature of science and scientific theories. The ability to understand and carry out scientific inquiry in a technological world is increasingly important for teachers and students in all grades — as stressed by the October 2004 position statement from the National Science Teachers Association board of directors.

There has been enormous progress in meeting these objectives, yet much remains to be done. For example, a recent survey of teachers in 45 states showed that, despite very high interest astronomy and physics, many teachers still cite barriers to teaching such as inadequate materials and insufficient teacher preparation. Astronomy and Physics Division public engagement programs are designed to address these critical needs.

Strategy for Public Engagement

Understanding our audiences

The Astronomy and Physics Division public engagement programs seek to harness NASA's unique resources to help address the needs of three major audiences:

Formal education. These are classroom teachers (K–12 and college level), curriculum developers, textbook publishers, and other educators who are tasked with teaching the national science education standards and who need compelling examples, activities, and scientific visualizations, as well as professional development to make optimum use of these materials. Formal education can include the use of real research data and learning tools such as online telescopes.

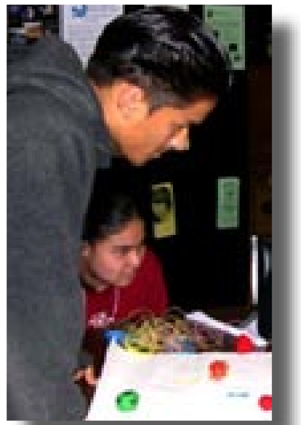
Informal education. These organizations include science museums, planetariums, and other institutions of informal learning that bring the public along on the exploration of space and require compelling stories to tell as well as the raw resources such as scientific visualizations and artifacts with which to construct these stories. Informal learning also takes place in after-school programs, and with organizations such as the Girl Scouts of the USA, amateur astronomers' clubs, and National Parks, which engage the public with demonstrations, activities, and other educational resources.

General public. Young and old alike participate in the excitement of NASA's space exploration through Web access to information, news, radio and television programs, or through talks and exhibits in public venues.

Missions create opportunities

Each mission of the Astronomy and Physics Division program provides unique opportunities to engage the public in the journey of discovery and exploration. Over the past few years, astronomy and physics mission initiatives have reached many thousands of teachers, students, and members of the general public through innovative and leveraged programs. Staying close to the goal of creating impact "as only NASA can" is an ongoing challenge for all education and public outreach programs. However, existing and upcoming Astronomy and Physics Division missions provide a rich source of opportunity and inspiration.

The first discoveries of Earth-like planets will provide a fundamental shift in our understanding of our place in the universe, with implications as profound as the early work of Galileo, Copernicus, and others.



Here are a few examples likely to have high impact:

NASA's Great Observatories and their successors will play a central role in the celebration of the Year of the Telescope (2009). The lead-up to this 400th anniversary of Galileo's pioneering observations will be national in scope and will involve both informal and classroom learning, particularly in the physical sciences, engineering, and technology education. Images from HST have become iconic, stimulating public excitement about space science in ways never dreamed of at the time the telescope was conceived. JWST will continue this tradition of including the public in our explorations of the farthest regions of space and time. After its launch in early 2003, the Spitzer Space Telescope opened a new window on the universe, permitting observations in the infrared region of the electromagnetic spectrum not fully visible from beneath Earth's obscuring atmosphere. This mission provides an opportunity to engage both students and the general public in perceiving the otherwise invisible world of the infrared.

The Astronomy and Physics Division missions span the electromagnetic spectrum and provide what is probably the clearest, most compelling introduction to spectroscopy and to seeing beyond the visible in all of science — areas that are central to both the physical and biological sciences. The Stratospheric Observatory for Infrared Astronomy (SOFIA) is also an infrared observatory, but one that uses a Boeing 747 aircraft to get above most of Earth's atmosphere. Teachers will work side by side with scientists during observing flights, providing thousands of dedicated educators a chance to participate in scientific research and discovery.

The first discoveries of Earth-like planets will provide a fundamental shift in our understanding of our place in the universe, with implications as profound as the early work of Galileo, Copernicus, and others. The search for new worlds enters a new era with the coming launches of the Kepler mission and the SIM PlanetQuest mission. Both missions will take breakthrough technology into space to detect Earth-size planets around distant stars. This search for other Earths has the potential to ignite public excitement and stimulate the public imagination akin to the greatest scientific discoveries in the history of humankind.

Even more ambitious steps in the search for life outside our own solar system are the two Terrestrial Planet Finder missions. The direct detection of an Earth-like planet, including indications of a warm, wet atmosphere, will bring the search for life from the realm of speculation and science fiction to the workbench of scientific investigation. We will need to be prepared to respond to the likely tremendous worldwide interest such a discovery will cause. The creation of thematic programs like the PlanetQuest website and the suite of engaging PlanetQuest interactives and story-telling visualizations will help carry the story to ever larger audiences. In the future, planetarium audiences can expect a dramatic program based on the search for new worlds that will make the stories related to finding habitable planets even more real to students and parents.

In addition to planet finding, other Astronomy and Physics Division missions and probes will yield the latest chapter in ongoing stories that are the bread-and-butter of museum and planetarium professionals, because these are the stories that visitors want to know about. For example, Constellation-X and the Black Hole Finder Probe will enable museum and planetarium audiences to "travel" to the actual locations of our Galaxy's black holes and to see what happens to matter before it falls into the abyss. The Inflation Probe will help tell the story of what might have come before the Big Bang, and the Dark Energy Probe will help predict the universe's eventual destiny — perennial questions from planetarium audiences. An important part of the public engagement plan will be to provide the nation's planetariums and science museums (both large and small) with images, data, and most importantly, interpretation so that museum professionals can reach a wide audience with age-appropriate stories.

These new views of the universe beyond the visible will perfectly complement one of the important recent educational advances: student access to online or low-cost optical and radio telescopes.

Missions such as LISA will provide a wonderful contribution to technology education, for which there is now growing demand in the classroom (since many states now require technology education) and in science museums (which are increasingly focusing on emerging technologies). LISA's technology is extraordinarily stringent — the equivalent of measuring the distance to the Moon to less than the width of an atom! — yet the underlying principle of interferometry is readily accessible, widely used throughout science and technology, and easy to demonstrate in the classroom.

The Astronomy and Physics Division missions provide some of the best opportunities in all of science to observe the same object in infrared, microwave, visible, ultraviolet, X-ray, and gamma-ray wavelengths and learn what different information is conveyed in each portion of the spectrum — in both visible and "invisible" light. These new views of the universe beyond the visible will perfectly complement one of the important recent educational advances: student access to online or low-cost optical and radio telescopes. For example, students who are investigating the lives of stars using online telescopes will be able to greatly extend their projects using images from Constellation-X and JWST to study the death and birth of stars. Ultimately, public engagement activities will interface with the National Virtual Observatory, providing learners everywhere with access to the images and data returned by the missions, which can catalyze substantial learning.

Adherence to Core Values

In addition to understanding the unique opportunities that missions create, Astronomy and Physics Division public engagement programs also incorporate several important principles that will guide all future work and assure the most effective impact and greatest possible reach:

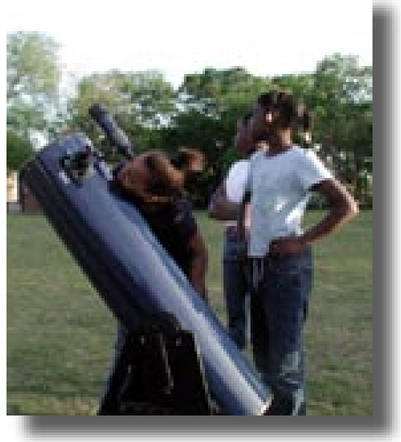
Coherence. Achieve a coherent and coordinated set of programs and products that meets the needs of varied audiences and stakeholders and that mesh seamlessly with NASA's other science themes and education initiatives.

Leverage. Expand public engagement on a large scale by creating sustainable national programs through effective and flexible partnerships with existing organizations.

Scientist participation. Maximize the impact of NASA's programs by fostering the participation of scientists and engineers.

Authentic experiences. Involve students and teachers in real research and expand access to real data.

Diversity. Engage underserved and underutilized groups in ways that genuinely meet mutual needs and interests and that contribute to the pipeline.



Focus on High-Priority Areas

Several areas have been identified for which NASA's educational assets can make a particularly important contribution. Among these are:

- Professional development for preservice and in-service teachers and college instructors.
- Flexible learning tools and experiences that support the learning of scientific inquiry, fundamental concepts in STEM (science, technology, engineering and math), and / or language arts.
- National partnerships with informal education organizations.
- Scientific visualizations, including multimedia and interactive experiences.
- Distance and e-learning.

Examples of innovative programs that address these high-priority areas can be seen in the facing pages of the science chapters of this document.

Pathways to the Future for Public Engagement

Astronomy and Physics Division public engagement programs build on and extend an existing educational network of scientists, educators, brokers, and forums that is unprecedented in scope and reach. This network ensures that future efforts will be both cost-effective and highly leveraged.

One key component is the active participation of research scientists and engineers, who provide visualizations, data, artifacts, public lectures, reviews for accuracy, and most importantly, who serve as role models and mentors for the next generation of explorers. Another important element is the active involvement of formal and informal education organizations nationwide, such as the Girl Scouts of the USA, the Night Sky Network of astronomy clubs, the Great Lakes Planetarium Association, and many more. Finally, the network is coordinated by a small number of education forums whose members work with mission scientists and mission educators to develop educational strategies and products — and by regional brokers who partner with educational institutions and regional audiences to ascertain their needs.

The connectivity of this network of scientists, missions, and educational institutions allows NASA's educational assets to enjoy maximum reach and impact. Whether it is high-resolution images from the Chandra X-ray Observatory being distributed to a large number of planetariums, world-class scientists giving public presentations about black holes, or amateur astronomers holding hundreds of NASA sponsored events around the country, the network insures that Astronomy and Physics Division programs achieve the broadest possible reach and impact.

Strategic Leadership

The Astronomy and Physics Division public engagement program is coordinated by a team at the Space Telescope Science Institute and the Harvard-Smithsonian Center for Astrophysics. The team helps provide continuity and direction for the education programs of missions and research scientists, and provides core services such as evaluation of products, entrée to the education research literature, and coordination of effort. Future missions will be able to take advantage of existing partnerships and programs, and it is expected that new programs will relate to the overall goals, program areas, and customer needs identified in this document.

Appendices

A Science and Technology Summaries

B Acronyms, Abbreviations, and Missions

C Contributors

D Sources of Additional Information

E Acknowledgments — Theory Challenges

A 2MASS near-infrared image of the Keyhole Nebula — a breeding ground for some of the hottest and most massive stars known.

APPENDIX A
Science Summary

	R&A	Chandra*	LISA	Con-X	IP	DEP	BHFP	BBO	BHI	EUXO	NACT	GLAST	WISE	GALEX*	HST	LUVO	UVOI	SOFIA	Spitzer*	Herschel	JWST	SAFIR	FIRSI	KI	LBTI	Kepler	SIM	TPF-C	TPF-I	LF	PI
Beyond Einstein																															
OBJECTIVE 1																															
Find out what powered the Big Bang																															
Search for gravitational waves from inflation and phase transitions in the Big Bang.	✓		✓		✓			✓																							
Determine the size, shape, and evolution of the universe as a whole.	✓				✓	✓		✓		✓					✓						✓										
Explore the structure of spacetime throughout the universe as a relic of its earliest stages.	✓				✓			✓																							
OBJECTIVE 2																															
Observe how black holes manipulate space, time, and matter																															
Perform a census of black holes throughout the universe.	✓		✓	✓			✓		✓																						
Determine how black holes are formed and how they evolve.	✓	✓	✓	✓			✓		✓																						
Test Einstein's theory of gravity and explore the structure of spacetime near the event horizons of black holes.	✓		✓	✓			✓		✓																						
Observe stars and gas plunging into black holes.	✓	✓	✓	✓			✓		✓	✓	✓	✓																			
OBJECTIVE 3																															
Uncover the nature of the mysterious dark energy pulling the universe apart																															
Determine the mass–energy content of the universe.	✓	✓		✓	✓	✓		✓		✓		✓			✓						✓										
Determine the cosmic evolution of the dark energy pulling the universe apart.	✓			✓	✓	✓		✓							✓						✓										
Origin and Evolution of Cosmic Structure																															
OBJECTIVE 4																															
Understand how primordial fluctuations from the Big Bang grew into the cosmic structure that we observe today																															
Characterize the primordial density fluctuations that seeded the growth of cosmic structure.	✓				✓			✓								✓					✓										
Discover the first galaxies and quasars, investigate their formation mechanisms, and reveal their influence on their environments.	✓	✓	✓		✓	✓				✓			✓		✓	✓			✓	✓	✓	✓						✓			
Determine how baryons and dark matter interact to form galaxies and systems of galaxies.	✓	✓		✓		✓			✓	✓			✓	✓	✓	✓	✓	✓	✓	✓	✓	✓					✓				
Determine how supermassive black holes form and grow, and identify the mechanisms that couple black hole masses to the properties of their galactic hosts.	✓		✓	✓		✓					✓	✓			✓	✓			✓	✓	✓	✓									
Map the distribution, physical state, and enrichment of intergalactic gas.	✓	✓		✓	✓					✓				✓	✓	✓	✓				✓										
Study stellar motions and chemical abundances in the Milky Way Galaxy and its neighbors, to understand the history of their formation and probe the nature of dark matter.	✓														✓	✓	✓	✓			✓	✓	✓				✓				
Origin and Destiny of Stars																															
OBJECTIVE 5																															
Trace the path from interstellar clouds of gas and dust to stars																															
Investigate molecular clouds as cradles of star and planet formation.	✓																	✓	✓	✓	✓	✓									
Study the emergence of stars and stellar systems.	✓	✓		✓									✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓		✓		✓		
OBJECTIVE 6																															
Explore the exotic objects left by dying stars and the creation of the heavy elements essential for planets and life																															
Study the extreme physics at (and beyond!) the ends of normal stellar lives, and understand its application.	✓	✓	✓	✓			✓			✓	✓	✓						✓									✓				
Determine how chemical elements were made and how they are distributed and processed into succeeding generations of stars.	✓	✓		✓						✓		✓		✓	✓	✓		✓			✓	✓	✓								
OBJECTIVE 7																															
Determine how planets form in dense disks of gas and dust around young stars																															
Determine how planets form in dense disks of gas and dust around young stars	✓	✓											✓					✓	✓		✓	✓	✓	✓	✓						
Exploring New Worlds																															
OBJECTIVE 8																															
Study the formation and evolution of planetary systems																															
Study the formation and structure of debris disks in young planetary systems.	✓														✓			✓	✓	✓	✓	✓	✓	✓	✓				✓		
Investigate the properties of young gas-giant planets around other stars.	✓														✓			✓	✓	✓	✓			✓	✓		✓	✓	✓		
Understand the creation and delivery of organics to planets.	✓																	✓	✓	✓	✓	✓	✓					✓			
OBJECTIVE 9																															
Explore the diversity of other worlds																															
Study the architectures and evolution of other planetary systems.	✓																					✓				✓	✓	✓			
Investigate the frequency of giant planets around other stars.	✓																							✓	✓	✓	✓	✓	✓		
Understand the frequency of Earth-sized planets.	✓																									✓	✓	✓	✓		
OBJECTIVE 10																															
Search for habitable planets and life																															
Investigate the properties of gas-giant planets in habitable systems.	✓																				✓					✓	✓	✓	✓		
Characterize the properties of terrestrial planets around other stars.	✓																											✓	✓	✓	✓
Investigate the biosignatures of other worlds.	✓																											✓	✓	✓	✓

*Operational missions

Technology Summary

	LISA	TPF-C	Con-X	DEP	BHFP	IP	TPF-I	SAFIR	LUVO	Life Finder	FIRSI	Planet Imager	UVOI	NACT	EUXO	BHI	BBO
Telescopes																	
Optics and Mirrors																	
Lightweight X-ray			✓		✓										✓	✓	
Mass fabrication techniques			✓				✓			✓		✓	✓		✓		
Coatings		✓	✓	✓			✓		✓	✓		✓	✓		✓		
High smoothness	✓	✓							✓	✓		✓	✓			✓	✓
Lightweight mirror panels							✓	✓	✓	✓	✓	✓	✓				
Metrology and Structures																	
Precision deployable structures		✓					✓		✓	✓		✓					
Cryogenic structure stability	✓						✓	✓		✓	✓	✓					✓
Cold large apertures							✓	✓		✓	✓	✓					
Wavefront Control																	
Active surface control		✓					✓		✓	✓	✓	✓	✓		✓		
Cryogenic delay and wavefront compensation							✓			✓	✓	✓					
Detectors																	
Gamma-ray to X-ray																	
X-ray calorimeter arrays			✓												✓	✓	
X-ray CCDs			✓												✓	✓	
Hard X-ray/gamma-ray detectors			✓		✓									✓	✓	✓	
UV, Optical, and Near-IR																	
SWIR focal plane arrays				✓			✓			✓		✓					
Optical CCDs		✓		✓					✓	✓		✓	✓				
UV CCDs									✓				✓				
Far-IR to Radio																	
Quantum-limited heterodyne								✓			✓						
FIR/mm bolometer arrays						✓		✓			✓						
Superconducting multiplexers			✓			✓		✓			✓					✓	
LWIR focal plane arrays								✓			✓						
Coolers and Thermal Control																	
Cooling to 0.05–0.30 K																	
Continuous 100 mK coolers			✓			✓		✓			✓				✓	✓	
Heat switches			✓			✓		✓			✓				✓	✓	
Cooling to 4–6 K																	
Advanced active cooler, 6 K @ >30mW			✓			✓	✓	✓		✓	✓	✓			✓	✓	
Microvibration control			✓			✓	✓	✓		✓	✓	✓			✓		
Passive Cooling																	
Large deployable sunshields		✓				✓	✓	✓	✓	✓	✓	✓					
Low-temperature passive designs	✓			✓		✓	✓	✓		✓	✓	✓	✓				✓
Thermal Stability																	
Precision structural stability		✓					✓		✓	✓		✓	✓				
Distributed Spacecraft																	
Formation Flying																	
Formation-control algorithms							✓				✓	✓	✓			✓	✓
Micronewton thrusters	✓						✓				✓	✓	✓			✓	✓
Laser metrology	✓						✓				✓	✓	✓			✓	✓
High-precision/low-drift gyros											✓	✓	✓			✓	✓
Metrology and Navigation																	
Intersatellite ranging							✓				✓	✓	✓			✓	✓
Relative navigation							✓				✓	✓	✓			✓	✓
Formation-alignment sensors	✓						✓				✓	✓	✓			✓	
Microarcsecond star tracker	✓						✓				✓	✓	✓			✓	

APPENDIX B

Acronyms, Abbreviations & Missions

A

AASC	Astronomy and Astrophysics Survey Committee
ACE	Advanced Composition Explorer
ACS	Advanced Camera for Surveys (HST)
ACTDP	Advanced Cryocooler Technology Development Program
ADR	adiabatic demagnetization refrigerator
AGN	active galactic nuclei
Archeops	International balloon experiment
ASAP	After-School Astronomy Project
ASIC	application-specific integrated circuit
ASM	All-Sky Monitor
Astro-E2	Japan–U.S. mission (now Suzaku)
ATC	Advanced Technology Center (Lockheed Martin)

B

BeppoSAX	Beppo Satellite per Astronomia X mission (Italy–Netherlands)
BBO	Big Bang Observer (Beyond Einstein Vision Mission)
BOOMERANG	Balloon Observations of Millimetric Extragalactic Radiation and Geophysics
BHFP	Black Hole Finder Probe (Einstein Probe)
BHI	Black Hole Imager (Beyond Einstein Vision Mission)

C

Chandra X-ray Observatory	Operational mission
CAPER	Conceptual Astronomy and Physics Education Research
CCD	charge-coupled device
CDM	cold dark matter
CGRO	Compton Gamma-Ray Observatory
CHIPS	Cosmic Hot Interstellar Plasma Spectrometer
CMB	cosmic microwave background
CNES	Centre National d'Etudes Spatiales
COBE	Cosmic Background Explorer
COMPTEL	Imaging Compton Telescope (CGRO)
Con-X	Constellation-X (Beyond Einstein Great Observatory)
COROT	Convection, Rotation, and Planetary Transits (CNES mission)
COS	Cosmic Origins Spectrograph (HST)
CPU	Committee on the Physics of the Universe
CSO	Caltech Submillimeter Observatory
CZT	cadmium-zinc-telluride

D

DEP	Dark Energy Probe (Einstein Probe; also known as Joint Dark Energy Mission, NASA–DOE)
DIB	diffuse interstellar bands
DM	deformable mirror
DoD	Department of Defense
DOE	Department of Energy

E

EGRET	Energetic Gamma-Ray Experiment Telescope (CGRO)
ESA	European Space Agency
ESO	European Southern Observatory
EOS-Aura	Earth Observing System Aura
EUVE	Extreme Ultraviolet Explorer (Operational mission)
EUXO	Early Universe X-ray Observer

F

FIR	far-infrared
FIRSI	Far-Infrared and Submillimeter Interferometer
FOV	field of view
FUSE	Far-Ultraviolet Spectroscopic Explorer (Operational mission)

G

GALEX	Galaxy Evolution Explorer (Operational mission)
Gaia	European Space Agency mission
GLAST	Gamma-ray Large-Area Space Telescope (NASA–DOE and France–Italy–Japan–Sweden mission)
GOODS	Great Observatories Origins Deep Survey
GP-B	Gravity Probe B
GRACE	Gravity Recovery and Climate Experiment
GRB	gamma-ray burst

H

HAWC	High-resolution Airborne Wide-bandwidth Camera (SOFIA)
Herschel Space Observatory	European Space Agency mission
HETE-II	High-Energy Transient Explorer-II
Hipparcos	ESA astrometry mission (completed)
HIRES	High-Resolution Echelle Spectrometer (Keck)
HRC	High-Resolution Camera (Chandra)
HST	Hubble Space Telescope (Operational mission)
HUDF	Hubble Ultra-Deep Field
HXT	Hard X-ray Telescope (Con-X)
HZ	habitable zone

I

IGERT	Integrated Graduate Education and Research Traineeship
IGM	intergalactic medium
IMP-8	Interplanetary Monitoring Platform-8
IP	Inflation Probe (Einstein Probe)
IR	infrared
IRAS	Infrared Astronomical Satellite
IRS	Infrared Spectrograph (Spitzer)
ISAS	Institute of Space and Astronautical Studies (Japan; part of JAXA)

ISM	interstellar medium
IRTF	Infrared Telescope Facility
ISO	Infrared Space Observatory (ESA)

J

JAXA	Japan Aerospace Exploration Agency
JDEM	Joint Dark Energy Mission (Einstein probe; also known as Dark Energy Probe; NASA–DOE)
J-PEX	Joint Astrophysical Plasmadynamic Experiment
JWST	James Webb Space Telescope

K

KI	Keck Interferometer (Navigator program mission)
Kepler	Discovery program mission
KID	kinetic inductance detector

L

LBTI	Large Binocular Telescope Interferometer (Navigator program)
Life Finder	Vision Mission
LIGO	Laser Interferometer Gravitational-wave Observatory
LISA	Laser Interferometer Space Antenna (Beyond Einstein Great Observatory)
LTSA	Long-Term Space Astrophysics
LUVO	Large ultraviolet/optical observatory (Vision Mission)
LWIR	long-wavelength infrared

M

MAXIMA	Millimeter Anisotropy Experiment Imaging Array
MCP	microchannel plate
MHD	magnetohydrodynamic
MIDEX	Medium-Class Explorer
MIRI	Mid-Infrared Instrument
MMS	Magnetospheric Multiscale mission
MSC	Michelson Science Center
MUX	multiplexer

N

NACT	Nuclear Astrophysics Compton Telescope
NASA	National Aeronautics and Space Administration
NEAT	Near-Earth Asteroid Tracking
NMP-EO1	New Millennium Program–Earth Observing 1
NRC	National Research Council
NSF	National Science Foundation
NuSTAR	Nuclear Spectroscopic Telescope Array
NVO	National Virtual Observatory

P

PI	Planet Imager (Vision Mission)
Planck Surveyor	ESA–NASA mission
PTI	Palomar Testbed Interferometer

R

R&A	Research and Analysis
RBSE	Research-Based Science Education
RHESSI	Reuven Ramatry High-Energy Solar Spectroscopic Imager
ROSAT	Roentgen Observatory Satellite (Germany–U.S.–U.K.)
ROTSE	Robotic Optical Transient Search Experiment
RXTE	Rossi X-ray Timing Explorer (Operational mission)

S

SAFIR	Single-Aperture Far-Infrared mission
SDSS	Sloan Digital Sky Survey
SED	spectral energy distribution
SHARC-2	Submillimeter High Angular Resolution Camera-2 (CSO)
SIM	Space Interferometry Mission –PlanetQuest (Navigator progran
SMEX	Small Explorer
SOFIA	Stratospheric Observatory for Infrared Astronomy
SOHO	Solar and Heliospheric Observatory (Operational mission)
SPIRE	Spectral and Photometric Imaging Receiver (Herschel)
Spitzer Space Telescope	Operational mission
SQUID	superconducting quantum interference device
STEM	science, technology, engineering, and mathematics
STIS	Space Telescope Imaging Spectrograph (HST)
Suzaku	Formerly Astro-E2 (Japan–U.S. mission)
SWIR	short-wavelength infrared
Swift	Operational mission
SXT	Spectroscopy X-ray Telescope (Con-X)

T

TES	transition-edge sensor
TPF-C	Terrestrial Planet Finder Coronagraph (Navigator program mission)
TPF-I	Terrestrial Planet Finder Interferometer (Navigator program mission)
TRACE	Transition Region and Coronal Explorer
TRL	technology readiness level

U

UARS	Upper Atmosphere Research Satellite
UIR	unidentified infrared bands
UVOI	Ultraviolet Optical Interferometer

V

VLA	Very Large Array
VLBA	Very Long Baseline Array
VLT	Very Large Telescope (ESO)
VLTI	Very Large Telescope Interferometer (ESO)

W

WFC3	Wide-Field Camera 3
WISE	Wide-field Infrared Survey Explorer
WMAP	Wilkinson Microwave Anisotropy Probe (Operational mission)

X

XMM-Newton	X-ray Multi-Mirror–Newton (ESA mission)

APPENDIX C

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APPENDIX D

Sources of Additional Information

Key Sources

National Aeronautics and Space Administration
http://www.nasa.gov/

NASA's Science Mission Directorate
http://science.hq.nasa.gov/

Space Science Advisory Committee (SScAC)
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APPENDIX E

Acknowledgments–Theory Challenges

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Courtesy of Geoff Bryden.

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Courtesy of Phil Armitage.

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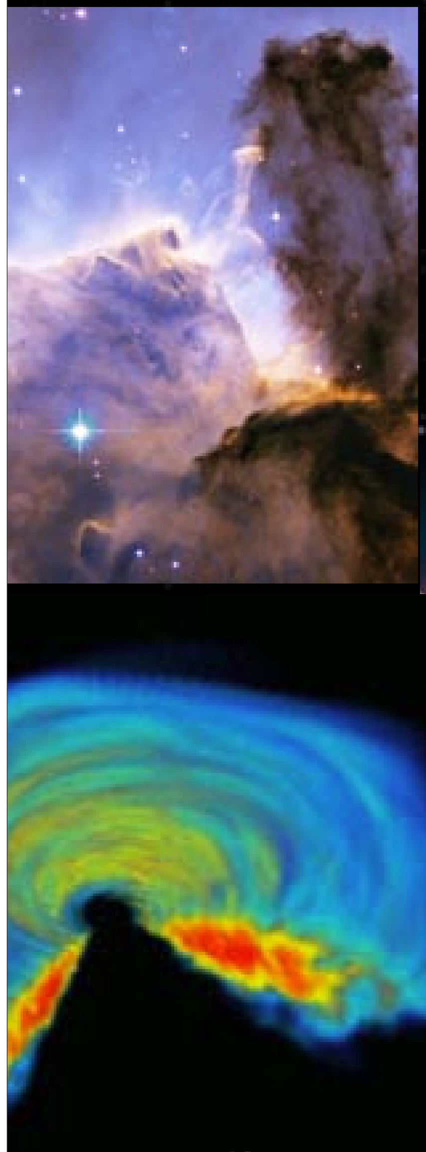
Courtesy of Victoria Meadows, Infrared Processing and Analysis Center, California Institute of Technology; and Jim Kasting, Penn State.

Visualization of an Accretion Disk Orbiting a Black Hole
Courtesy of J. F. Hawley, U. Virginia.

When we try to pick out anything by itself, we find it is tied to everything else in the universe.

—John Muir



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