Clueless?

You wonder about hot Jupiter atmospheric dynamics?
You don't understand temperature inversions?
You wanna know more about clouds and chemical composition?
You know nothing about variability?

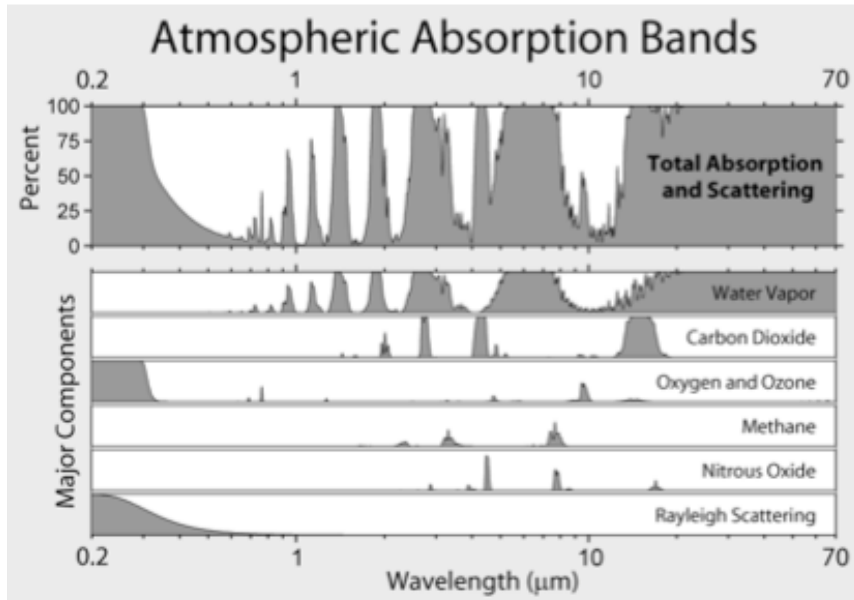
Don't remain clueless!

Get a clue!

Combined Light for Understanding Exoplanets

- CLUE is a stable space spectrophotometer (0.5-7 μm) designed to study known transiting exoplanets with continuous, high-cadence measurements of the combined light from a planet and its host star.
- CLUE relies on well-tested techniques to provide crucial knowledge about an interesting class of planets that cannot be studied in any other way.
- Among its key objectives for the "Exploring New Worlds" program, NASA lists the following:

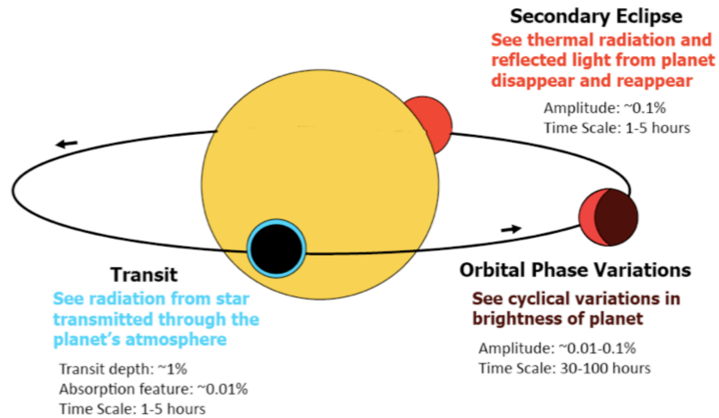
  - *Explore the diversity of other worlds*
  - *Study the formation and evolution of planetary systems*
  - *Search for habitable planets and life*

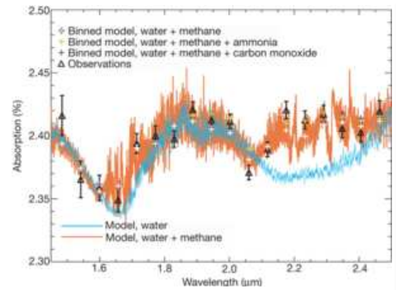


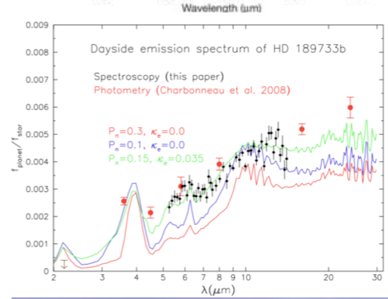
CLUE will make great inroads to each of these key objectives.

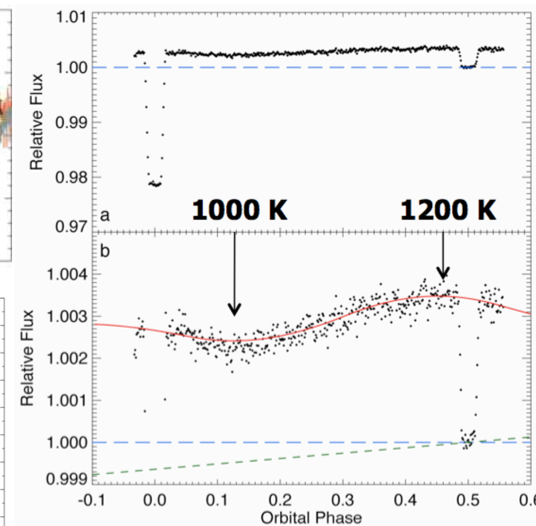
Explore the diversity of other worlds

- characterize the upper atmospheres of planets with transmission spectroscopy
- study atmospheric dynamics and chemistry with full orbit phase curves
- obtain day-side planetary emission spectra and constrain albedos from secondary eclipse measurements
- simultaneous broad wavelength coverage to probe atmospheric weather at different pressures
- detangle true exoplanet signals (IR) from stellar variability (optical)



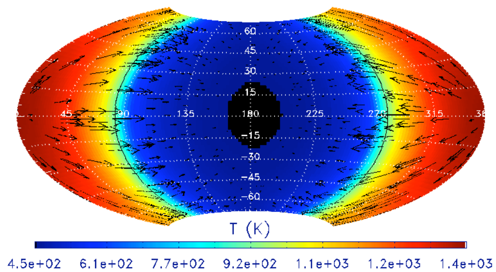


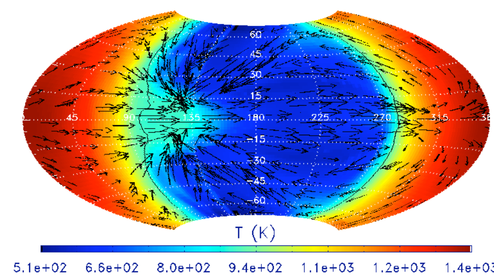


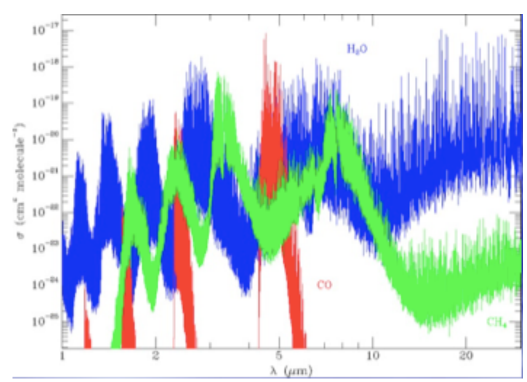


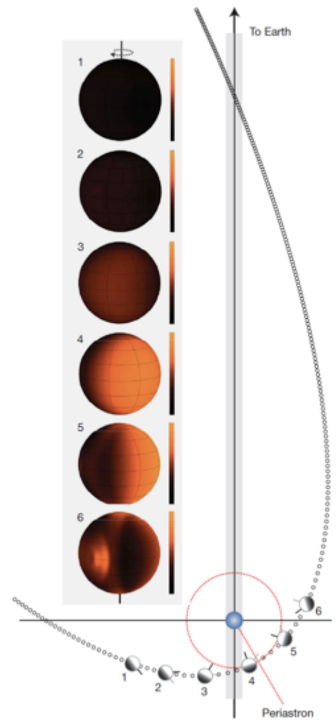
Study the formation and evolution of planetary systems

- characterize the energy budget of exoplanets to probe their formation and evolution
- perform detailed modeling of CO, CO_2, CH_4, H_2O to estimate C/O abundances and constrain planets' evolutionary histories
- study the nature of aerosols in planetary atmospheres
- understand the variability of exoplanetary atmospheric properties (aerosols, temperature profiles, chemistry):
  - \+ on orbital timescales
  - \+ between multiple orbits







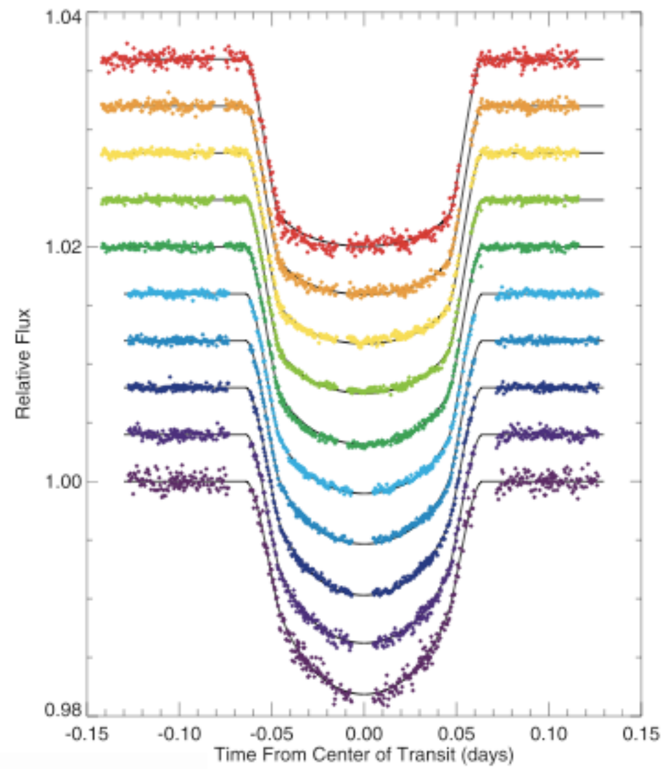


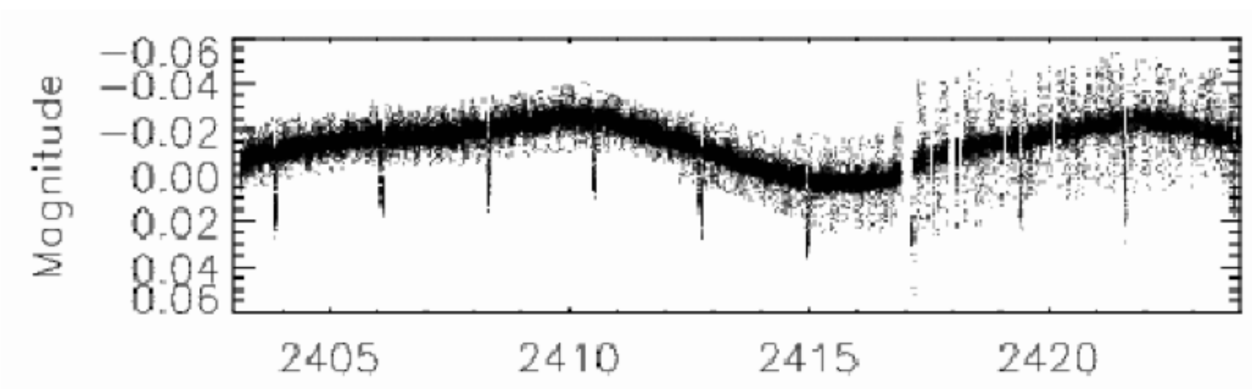
Search for habitable planets and life

- search for exomoons and coplanar planets that could harbor life

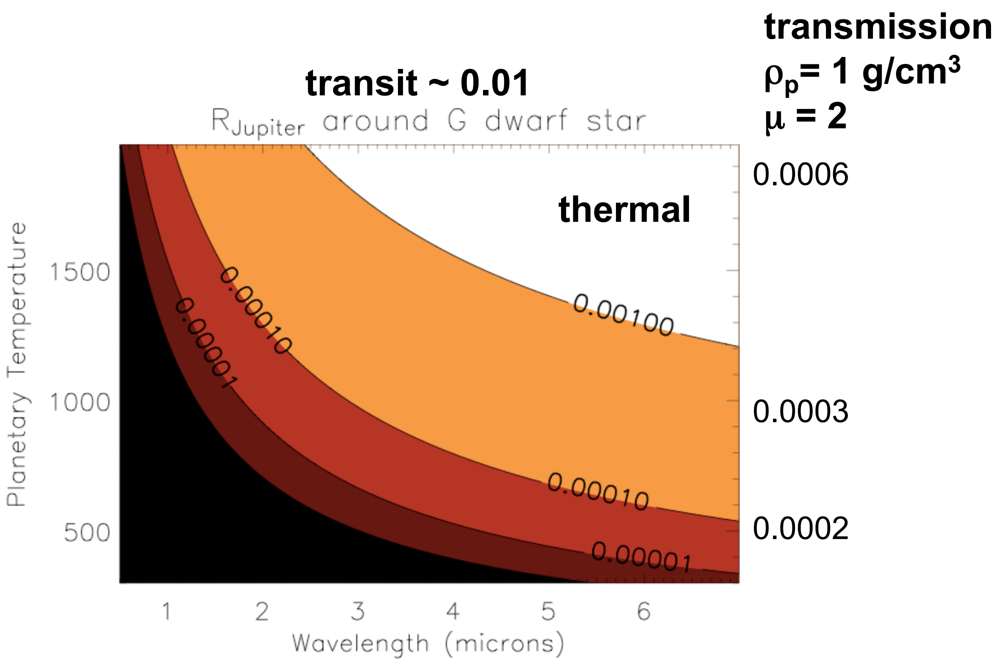
- improve our understanding of exoplanet stellar hosts (spots, limb-darkening)

- refine parameters of transiting exoplanets, including those in the habitable zone, by tracking and removing the effects of starspots and stellar variability

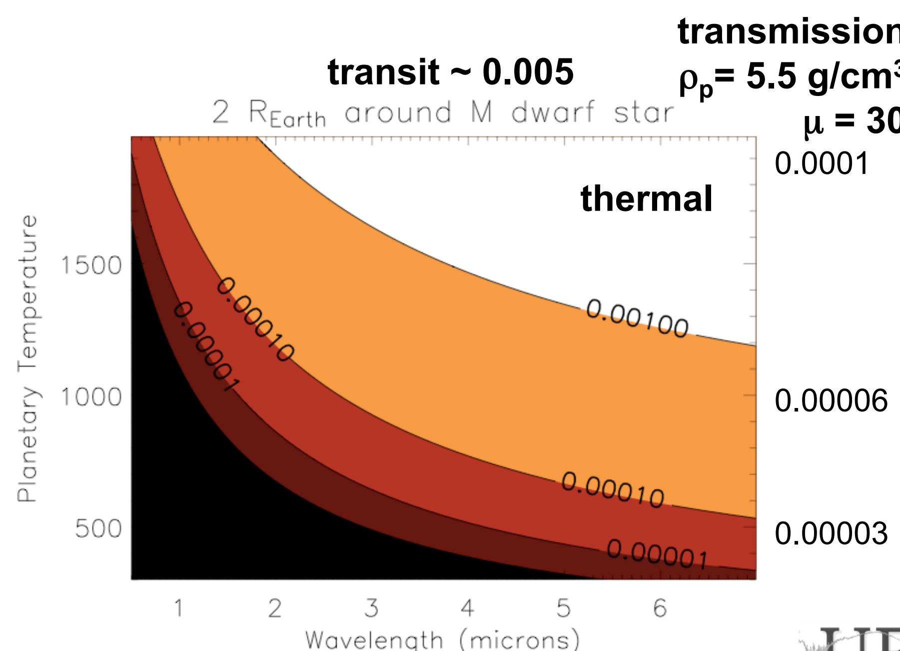




Search for habitable planets and life



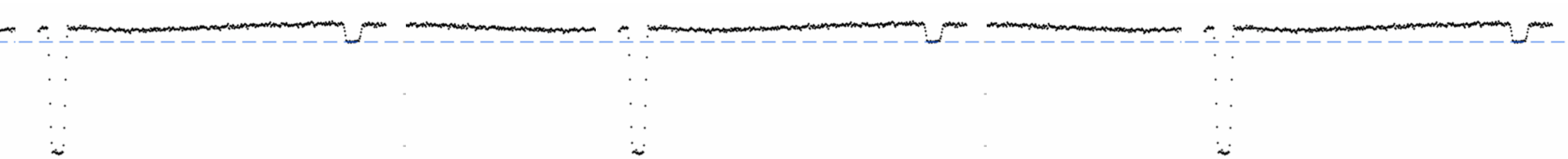
CLUE will observe a broad range of transiting exoplanets of a variety of sizes with a variety temperatures, from hot Jupiters to hot "super Earths"



- **transit contrast ratio**
  $\sim (r_p/r_*)^2$
- **thermal contrast ratio**
  $\sim (r_p/r_*)^2 \times B(T_p)/B(T_*)$
- **transmission contrast ratio**
  $\sim 10Hr_p/r_*^2 \propto T/(\rho_p \mu\, r_*^2)$

Observing strategy

- Spend ~100hr continuously on target
  - Allows for full orbit coverage of planets with period < 4 days
  - Spend the next few hours for data transfer (needs to move the telescope)
  - Observing cadence ~1 data point per minute
- Come back ~5 times on each target to monitor variability
  - Total time per target ~ 600h including overheads
  - 3 yr mission lifetime as a baseline → 40+ targets
- Choice of targets
  - First focus on the 10 brightest transiting planets (K<10)
  - Then include non-transiting planets
  - Go for Neptune-mass planets and super-Earths if available



Telescope and instrument concept

- Wavelength
  - 0.5-1.0 micron visible detector
  - 1.0-7.0 micron doped $HgCd_xTe_{1-x}$ with cryo-cooler
- Size
  - 1 m standard on-axis telescope
- Sensitivity
  - K = 12 mag (most targets brighter than K=10 mag)
- Resolution (spectral and angular)
  - R ~ 200-300 to fit into single order spectrum on chip
- Thermal Requirements
  - 60 K passive cooling for bus
  - 30 K cryo-cooler for detector array
- Duration
  - 3 yrs nominal + 3 yrs extended
  - More depending on orbit trailing

Detector details

- Larger detector than Spitzer, slightly larger telescope
- Instrument modeled after Spitzer IRS adapted for near IR
  - R ~ 300 from 1.0-7.0 micron
  - No moving parts in the IR detector, multiple uses are made of the same detector array
- Detectors (pixel size, noise, windowing, etc)
  - 1k x 1k $HgCd_xTe_{1-x}$ detector, wavelength 1.0 – 7.0 micron
    - Spectrum fills one strip of the detector
    - Read only 1 strip (or 2 if calibration star)
    - Peak-up guiding arrays on another part of detector
  - Read noise 16 electrons/60 s integration
  - Pixel size ~ 75 mas (2 pixels per PSF at 1μm)
- Possibility to add a filter wheel with additional capabilities on the visible side
  - Polarizers, neutral densities, etc

Choose orbit

- Need for high spacecraft stability (thermal, vibrations, etc)
  - Earth-trailing and L2 are the possible choices
  - Also avoids thermal stray light from the Earth
  - Earth-trailing selected as baseline (well tested with Spitzer, Kepler)

- Data transfer rate similar to Spitzer and Kepler

Data volume, rate, downlink time

- **Standard Mode – read out and downlink a single 1024 x 32 strip**
- **Each frame (32 b/pix, plus overhead, compressed 2x) = 72kB**
- **Total data in one obs: 0.5 Gb**
  - **100 hrs of data at 60-s cadence**
  - **~10 hrs at 6-s cadence**
  - **Storage capability ~10Gb**
- **Earth-trailing orbit: downlink rate decreases as mission continues, CLUE trails further (see table)**
- **Double Mode – read out and downlink two 1024 x 32 strips**
- **Changes in cadence will affect downlink time.**

Year of Mission	X-band Downlink Rate (kB/s)	Downlink time (mins. / 100 hrs.)
0.5	1500	5
1	375	18
1.5	167	41
2	94	73
2.5	60	115
3	42	165

Calculate pointing requirements

- PSF is largest at 7 μm: λ/D = 1 arcsec
  - Chosen slit width w = 2 arcsec

- Required PSF stability: 1/10th of a PSF size for flux stability
  - PSF size at 1 μm: 150 mas → ~10 mas stability

- Pointing control ~ 100 mas with instrument's star tracker
- Pointing stability ~ 10 mas with instrument's star tracker

Select spacecraft bus

- 1 m telescope (passively cooled) – 150 kg, 75 W
- Vis and IR Spectrometer – 40 kg, 30 W each → 80 kg, 60 W

- Total payload mass + 42% contingency: 325 kg

- Total required power + 42% contingency: 193 W

- SPACECRAFT C (dry bus mass: 600kg)
  - Payload mass limit: 650 kg
  - Payload power limit: 730 W
  - Science data downlink: 320 Mbps
  - Mission design lifetime = 5 years

Determine launch mass

Telescope	-	150 kg
Bus	-	600 kg
Instruments	-	80 kg
Propellant	-	15 kg
Margin	-	370 kg
TOTAL	-	**1250 kg**

Select launch vehicle

- Total launch mass
  - 1250 kg with margin
- Orbit
  - Earth trailing (L2 can be considered as well)
- **Launch vehicle L/V B**
  - Capacity: 3,485 kg
  - Launch vehicle margin: 2,000+ kg
    - Sharing the launcher fairing may be considered
- Cost: **$136M**

Describe major risks

- Low technological risk
  - Proven detector technologies HgCdTe 1k x 1k detector
  - Technology orbit tested
    - Spitzer for HgCdTe detectors
    - HST, Kepler for visible cameras
- No cryogenic liquid reduces complexity and increases lifetime
- Orbital thermal stability and data downlink rates demonstrated by Spitzer
- Demonstrated capability to remove residual telescope jitter with ground-based de-correlation techniques (Spitzer)

- Below guideline margins

Estimate total mission cost

- Telescope: 50M$ (passively cooled 1-m on-axis telescope)
- Bus: 125M$ (Spacecraft C)
- Instrument:
  - 30M$ for visible spectrometer
  - 20M$ for visible spectrometer
  - 50M$ for cryocooler
- Development / science costs: ~130M$
- Launch vehicle: 136M$ (L/V B)
- Operations: 45M$ (3 yr operation baseline)
- Reserves: 130M$

- TOTAL: 710M$ with reserves
  - Well within ExoPlanet Probe mission (650-800M$)

The CLUE team

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