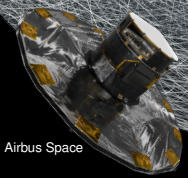
Introduction to Gaia

Anthony Brown

Leiden Observatory, Leiden University

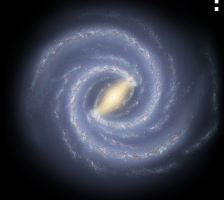
brown@strw.leidenuniv.nl



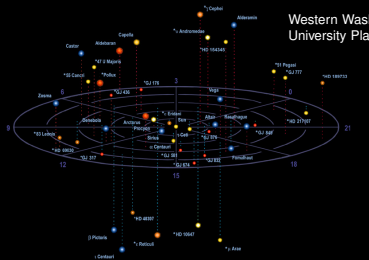
Airbus Space

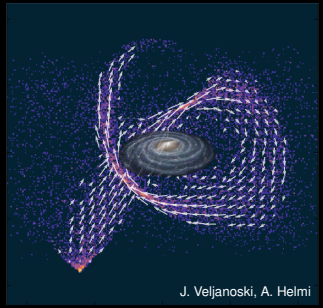
ESA/Gaia/DPAC

?

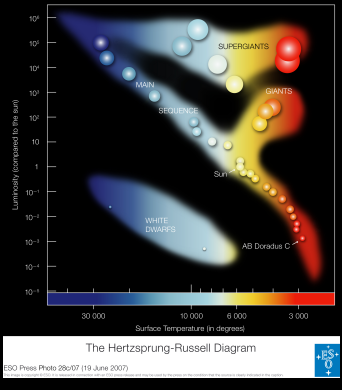


NASA/JPL-Caltech/R. Hurt (SSC)





J. Veljanoski, A. Helmi



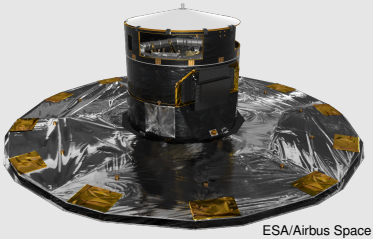
The Hertzsprung-Russell Diagram

ESO Press Photo 28c/07 (19 June 2007)

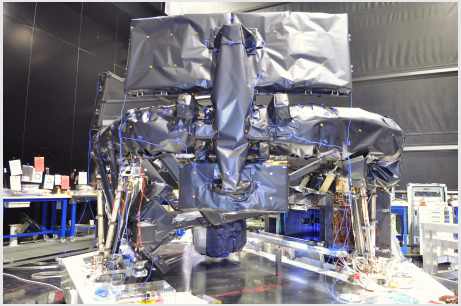
Gaia summary

- Astrometry and spectrophotometry for >1 billion objects
- Radial velocities for >100 million objects
- Survey
  - Complete to $G = 20.7$ ($V = 20$–22)
  - Observing programme: autonomous on-board detection and unbiased
  - Quasi-regular time-sampling over 5 years (~ 70 observations)
- Launch December 2013
- Operational at L2 since July 2014

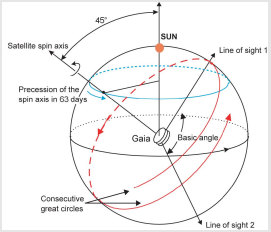
- Gaia end-of-life estimated at early 2025
- Mission extended to end 2022
- With indicative approval to 2025

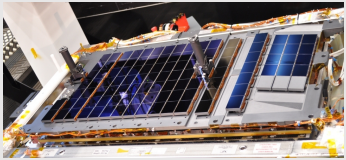


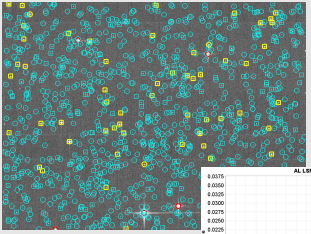
ESA/Airbus Space

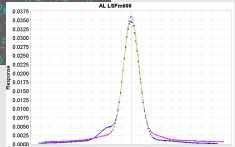


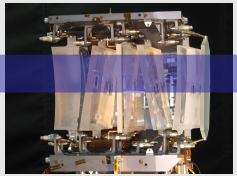
Gaia instruments and measurements

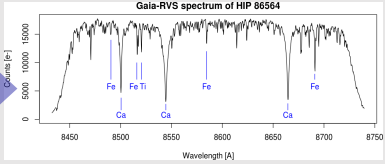


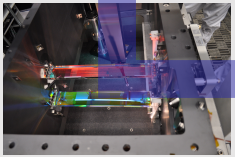


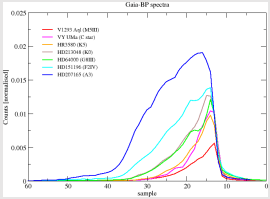


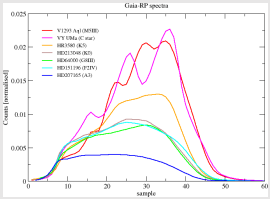






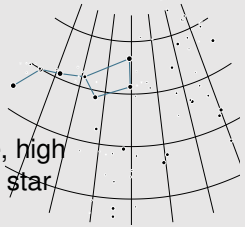


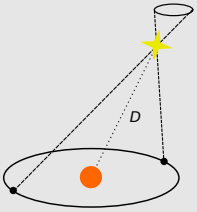




Gaia collects fundamental astronomical data

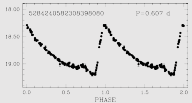
All-sky, complete, high accuracy star atlas

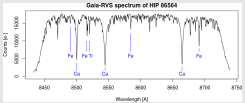


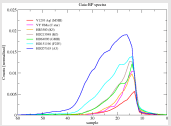


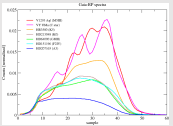
Parallaxes and proper motions

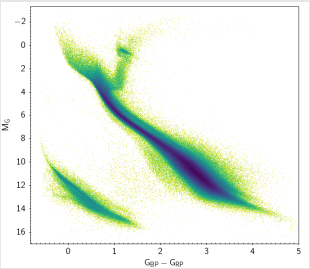
Astrometric, photometric, spectroscopic, radial velocity time series





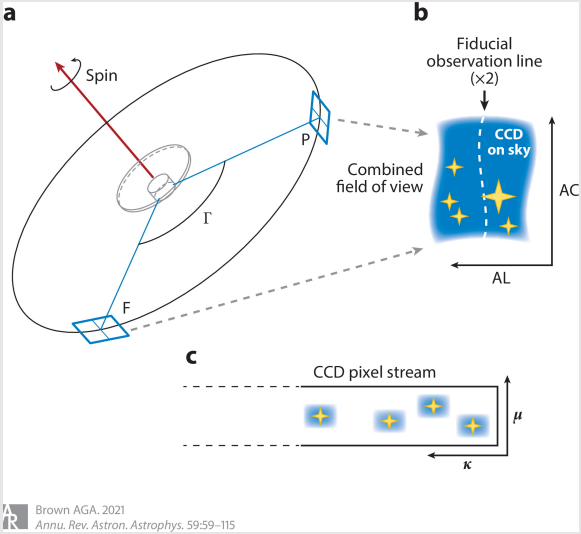






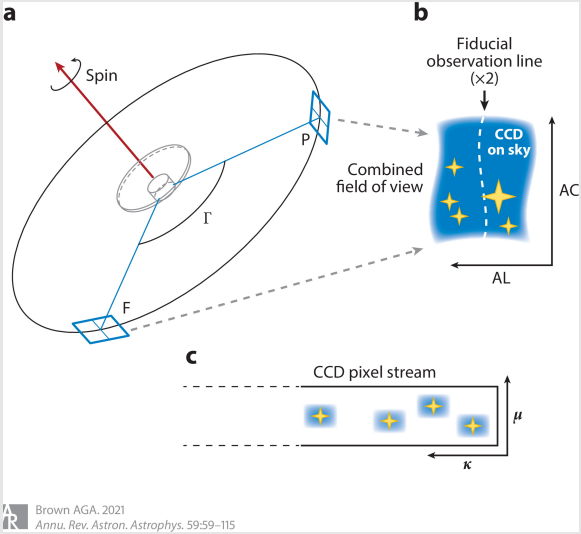
Astrophysical properties

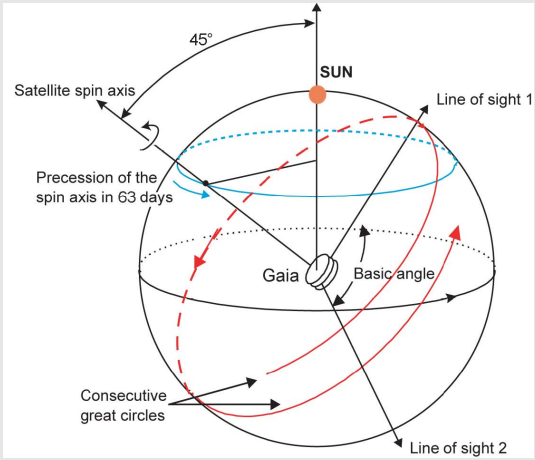
Gaia scanning the sky



Brown AGA. 2021
Annu. Rev. Astron. Astrophys. 59:59–115

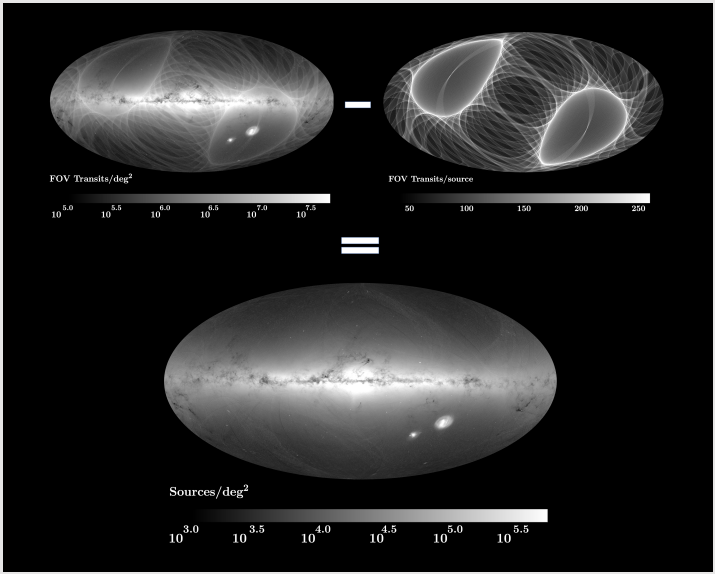
Gaia scanning the sky





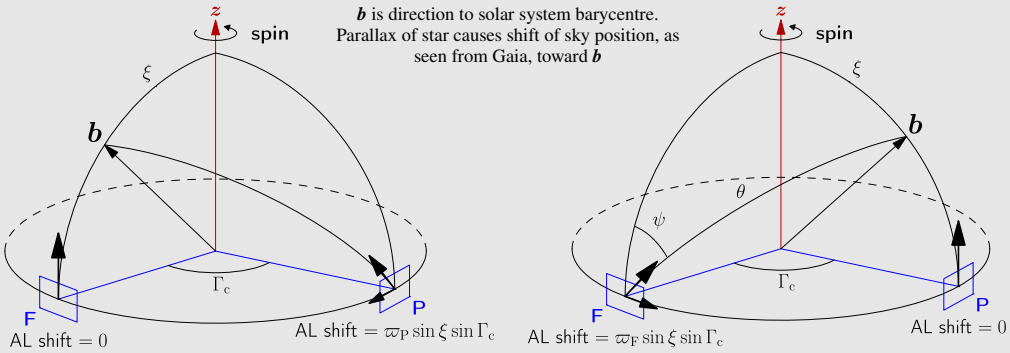
Spin period: 6 hr, Basic angle: 106.5°

Gaia scanning the sky



Credits: F. Mignard, University Côte d'Azur, Observatory of the Côte d'Azur

Why two telescopes?



- Suppression of zonal (field of view scale) errors by directly bridging angles of $\sim$ 1 radian
- Disentangling of parallaxes of different sources $\rightarrow$ absolute parallax measurements

Gaia data processing in a nutshell

Find the source parameters

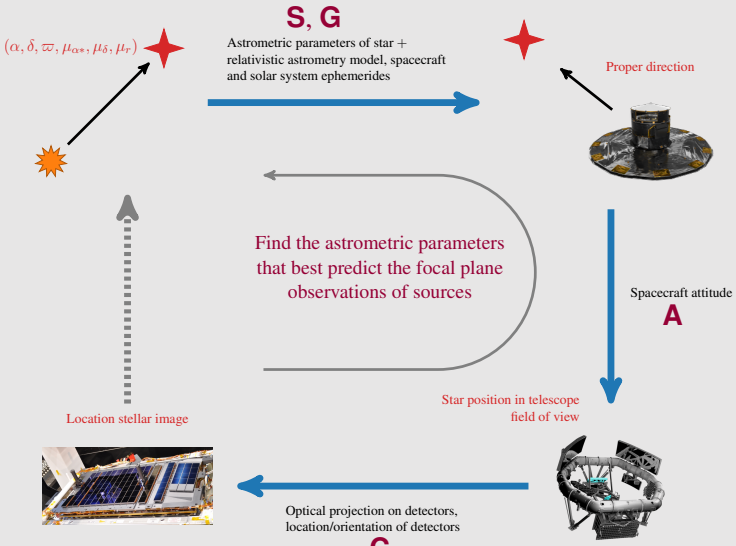
$$\alpha,\ \delta,\ \varpi,\ \mu_{\alpha*},\ \mu_\delta,\ v_{\rm rad},\ \text{orbit parameters multiple stars,}$$
$$G,\ \text{colours,}\ T_{\rm eff},\ [\mathrm{Fe/H}],\ \log g,\ A_0,\ \text{solar system object orbits,}$$
$$\text{light curves,}\ \text{variable star classification,}\ \ldots$$

and instrument (calibration) parameters

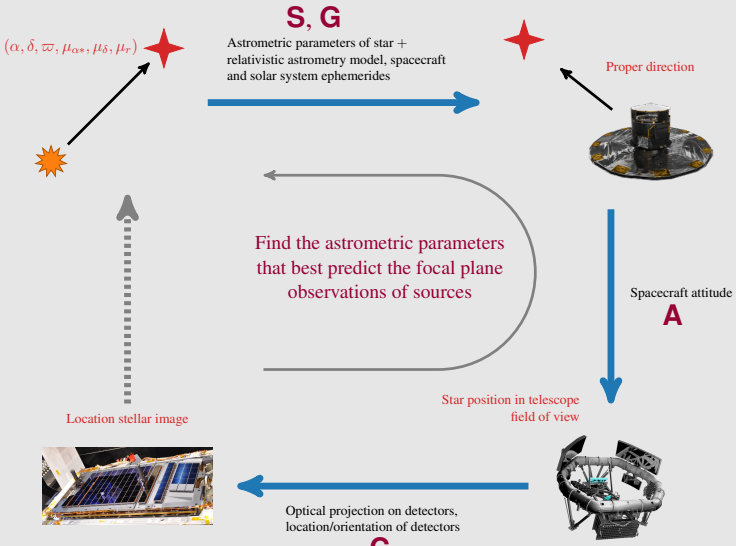
$$\{\text{Collection of parameters describing Gaia}\}$$

that best explain the Gaia observations.

Gaia astrometric data processing overview



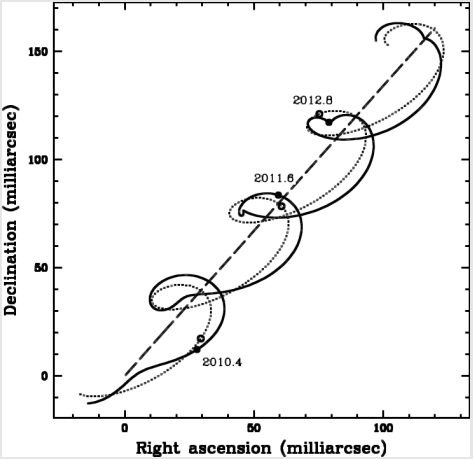
Gaia astrometric data processing overview



Astrometric global iterative solution

- Minimize difference between predicted and observed image locations
  - solve for **C**, **A**, **G** in calibration step
  - solve for **S** in source update step
  - iterate between these steps

Exoplanets for free

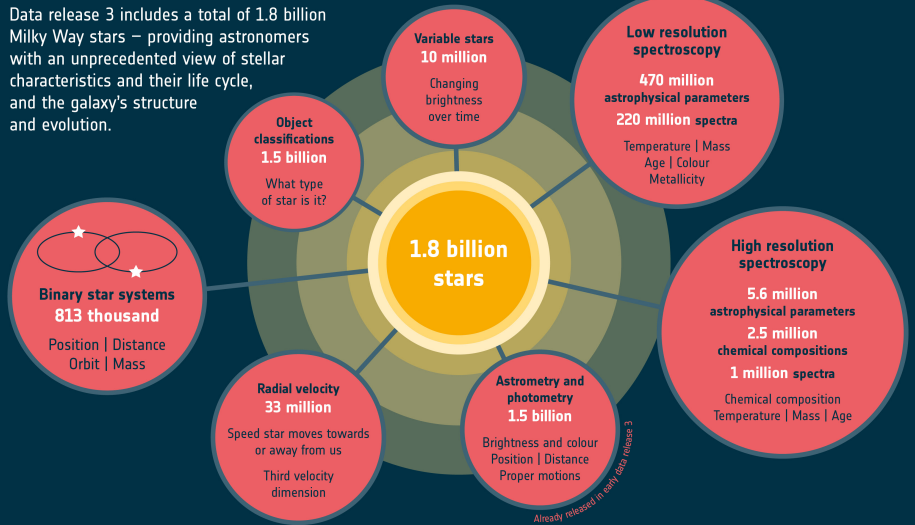


- Determining position, parallax, and proper motion requires repeated measurement of the position of stars on the sky
  - the path on the sky is predicted from a simple model in which stars move at constant velocity along straight lines
- Repeated observations can show deviations from the simple model
  - allows for detection of companions to the stars, including exoplanets
- More later in the week. . .

Overview of Gaia Data Release 3

MILKY WAY STARS

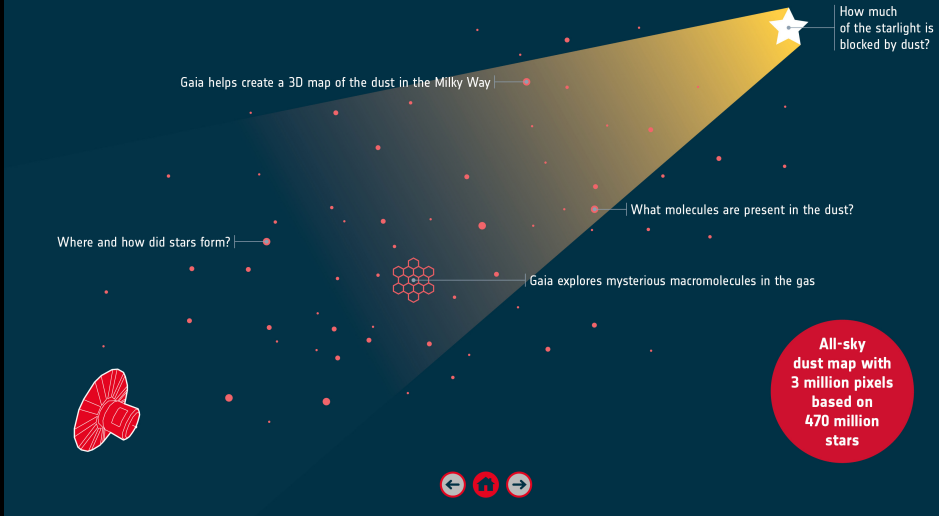
Data release 3 includes a total of 1.8 billion Milky Way stars – providing astronomers with an unprecedented view of stellar characteristics and their life cycle, and the galaxy's structure and evolution.



WHAT'S IN BETWEEN STARS

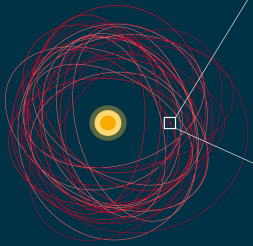
esa

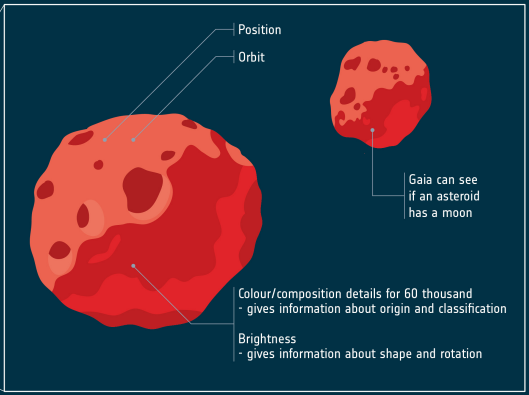
ESA's Gaia not only maps the stars in our galaxy, but also what is in between the stars.
This is called the interstellar medium, consisting mostly of dust and gas.



SOLAR SYSTEM

ESA's Gaia data release 3 is providing vital information about the Solar System's asteroid population, which is essential to investigate the origin of our Solar System.





156 thousand asteroids

Near-Earth asteroids | Main belt asteroids
Mars crossers | Jupiter trojans
Centaurs | Trans-Neptunian Objects

Additionally, Gaia observed:

31 moons of Mars, Jupiter, Saturn, Uranus and Neptune

OUTSIDE OUR GALAXY

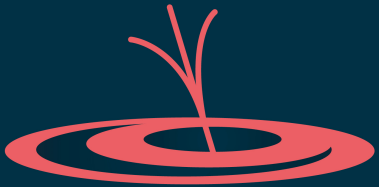
Unlike other missions that target specific objects, ESA's Gaia is a survey mission. This means that while surveying the entire sky multiple times, it is bound to see objects outside the Milky Way as well, such as quasars and other galaxies. Gaia's data release 3 provides astronomers with details on a few million extragalactic objects.

1.9 million quasars

Supermassive black holes accreting matter

Redshift | Brightness | Colour

Host galaxy detected for 60 thousand quasars



2.9 million galaxies

Brightness | Colour

Star formation history | Shape

Accessing the Gaia data through the ESA archive

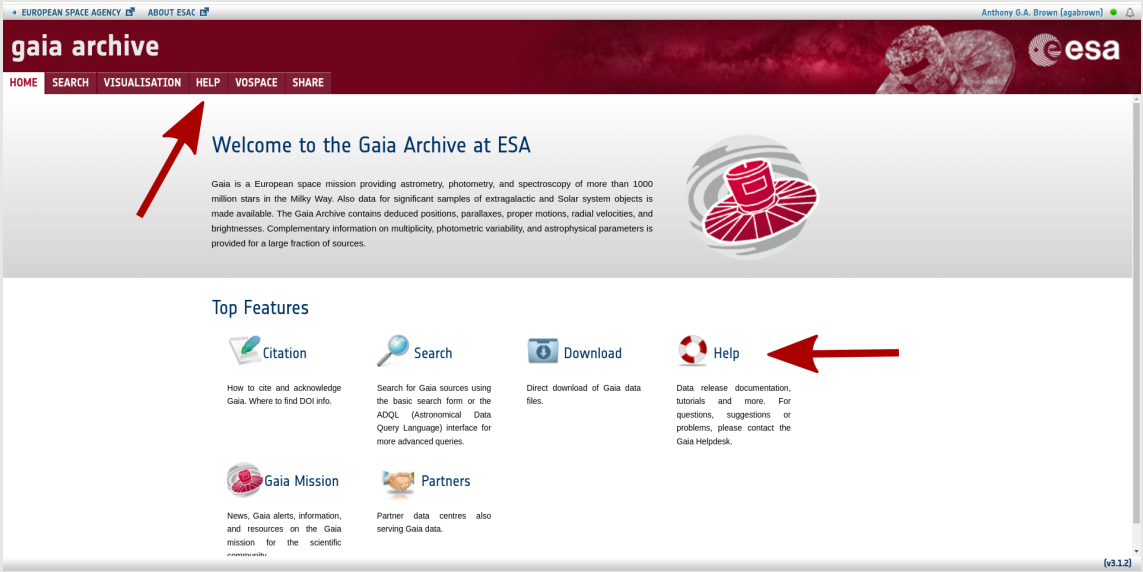
Slides based on presentation by Jos de Bruijne
More details: https://doi.org/10.5281/zenodo.6826703

How to access the Gaia DR3 data at ESA

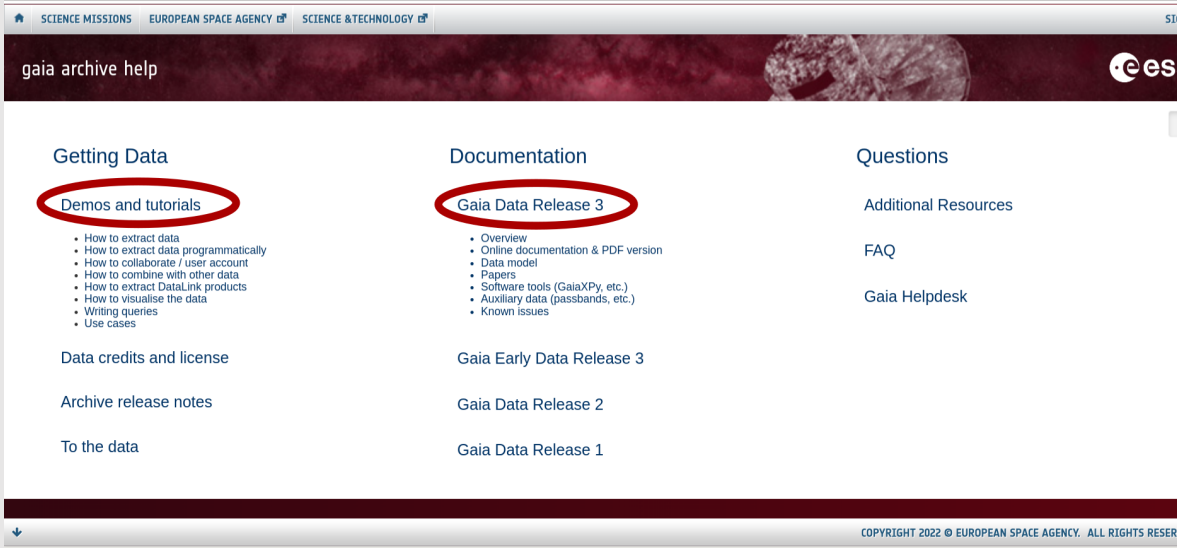
- Python astroquery.gaia package (hands-on session today)
- Command line interface (e.g., curl)
- Virtual Observatory cone-search service (e.g., from within Topcat)
- Bulk download repository ($\sim$ 10 TB of compressed ECSV files, including tutorial for cone search)
- Gaia ESA Archive (GEA) web interface (archives.esac.esa.int/gaia)
  - Basic form, for single sources and short lists of objects as well as cone searches
  - Advanced (ADQL) form, for 'all functionality', including DataLink access
  - Visualisation, for bulk data (Moitinho et al. 2017)
  - Help, includes tutorials, Python notebooks, FAQs, example queries (use cases), etc.
- ESA Sky
- Official partner and affiliated data centres

Gaia ESA archive

Gaia ESA archive



Gaia ESA archive: help landing page



Gaia ESA archive: demos and tutorials

- EXTRACT DATA
- PROGRAMMATIC ACCESS
- COLLABORATE / USER ACCOUNT
- COMBINE WITH OTHER DATA
- DATALINK PRODUCTS
- VISUALISATION
- WRITING QUERIES
- USE CASES

EXTRACT DATA

- Graphical User Interface
- Search for a single source
- Search for a list of sources
- Advanced (ADQL) tab
- Advanced ADQL features
- Tutorial: Bulk download

PROGRAMMATIC ACCESS

- Python access: Astroquery
- Command line access: TAP/TAP+
- Command line access: DataLink

COLLABORATE / USER ACCOUNT

- Create or update your Gaia user account
- Upload a user table
- Share a user table

COMBINE WITH OTHER DATA

- Pre-computed cross-matches
- Catalogue combination
- Proper-motion corrected cross-match

DATALINK PRODUCTS

- DataLink Service
- DataLink: Access from the Archive web interface
- DataLink products serialization
- DataLink: Python access
- Tutorial - Programmatic download of large datasets through DataLink

VISUALISATION

- Gaia Archive Visualisation Service

WRITING QUERIES

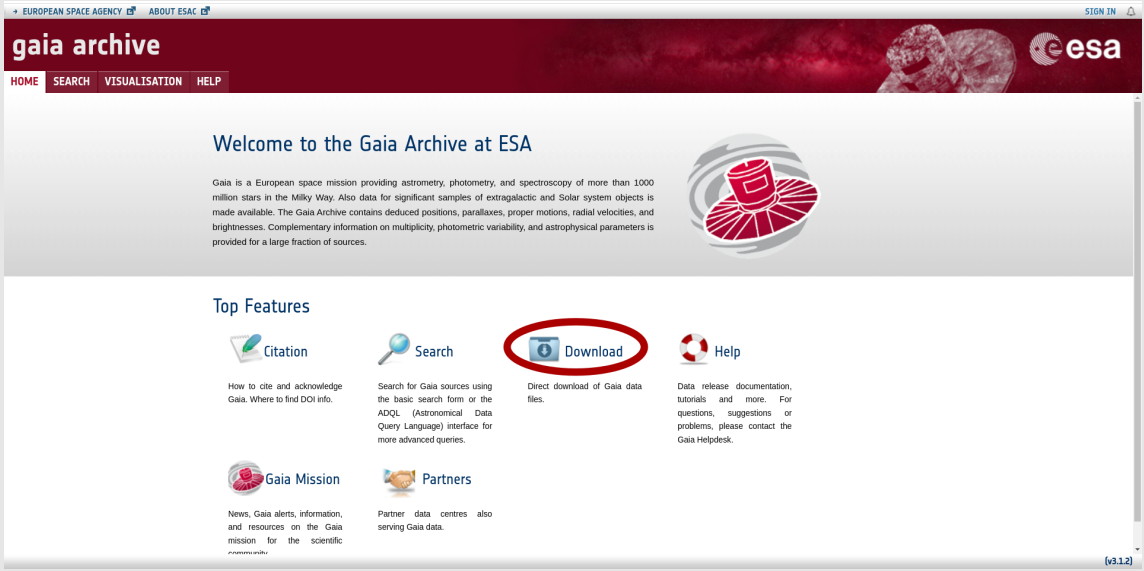
- Query examples
- Query speed booster
- ADQL syntax
- Epoch Propagation
- Gaia Collaboration queries

USE CASES

- ICRF2 sources (DR1)
- Cluster Analysis GUI (DR2)
- Cluster Analysis Python (DR2)
- White Dwarfs Exploration (DR2)
- On the use of Gaia parallaxes
- Variable sources (DR1)

Includes Jupyter notebooks

Gaia ESA archive



Bulk download respository (http://cdn.gea.esac.esa.int/Gaia/)

Index of /Gaia/

../
gdr1/
gdr2/
gdr3/
gedr3/

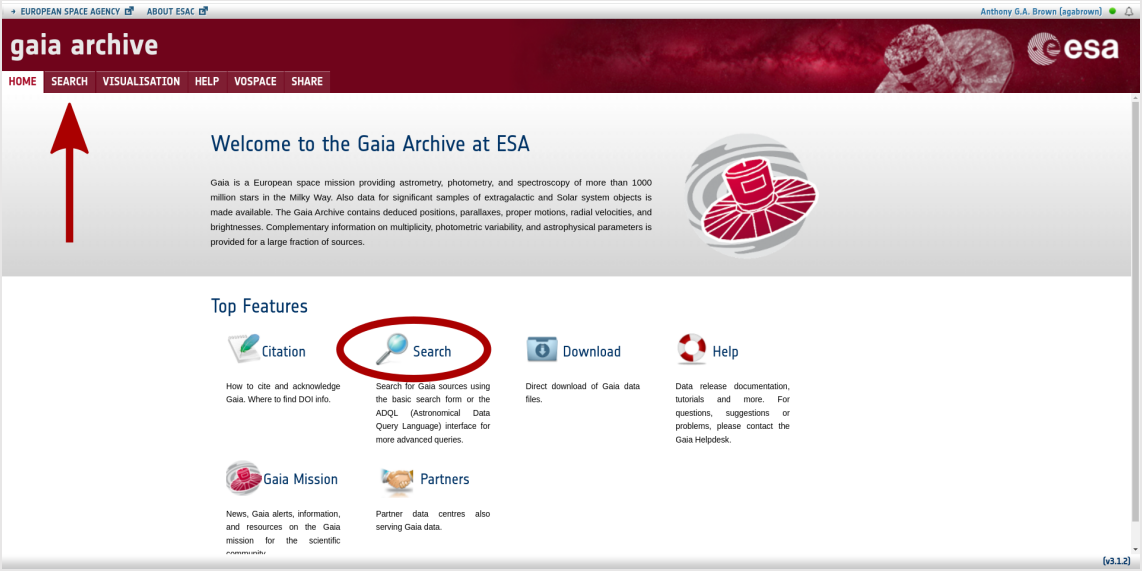
Index of /Gaia/gdr3/

../
Astrophysical_parameters/
Auxiliary/
Cross-match/
Extra-galactic/
Non-single_stars/
Performance_verification/
Photometry/
Reference_frame/
Science_alerts/
Simulation/
Solar_system/
Spectroscopy/
Variability/
gaia_source/
_catalogue_sizes.txt
_citation.txt
_disclaimer.txt
_readme.txt

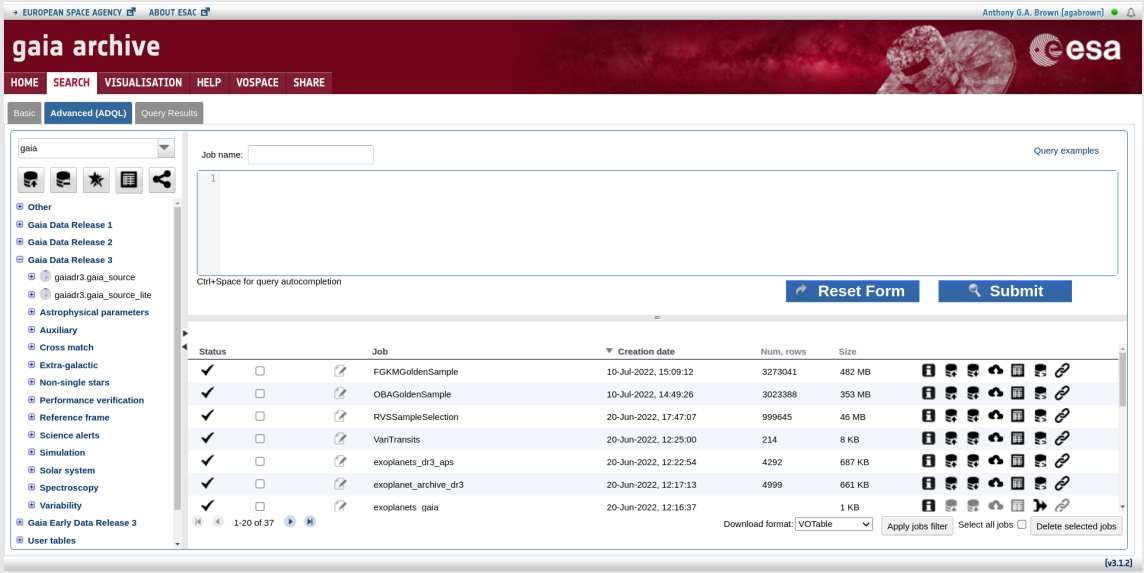
Index of /Gaia/gdr3/gaia_source/

../		
GaiaSource_000000-003111.csv.gz	05-May-2022 07:45	233642769
GaiaSource_003112-005263.csv.gz	05-May-2022 08:43	229826558
GaiaSource_005264-006601.csv.gz	05-May-2022 09:13	226838638
GaiaSource_006602-007952.csv.gz	05-May-2022 10:42	227780596
GaiaSource_007953-010234.csv.gz	05-May-2022 07:55	231384710
GaiaSource_010235-012597.csv.gz	05-May-2022 09:29	233173214
GaiaSource_012598-014045.csv.gz	05-May-2022 10:11	228657814
GaiaSource_014046-015369.csv.gz	05-May-2022 07:32	229702988
GaiaSource_015370-016240.csv.gz	05-May-2022 08:23	229908320
GaiaSource_016241-017018.csv.gz	05-May-2022 10:25	224859723
GaiaSource_017019-017658.csv.gz	05-May-2022 09:31	222631212
GaiaSource_017659-018028.csv.gz	05-May-2022 10:30	225059250
GaiaSource_018029-018472.csv.gz	05-May-2022 09:33	223120665
GaiaSource_018473-019161.csv.gz	05-May-2022 10:01	223633783
GaiaSource_019162-019657.csv.gz	05-May-2022 09:03	223379592
GaiaSource_019658-020091.csv.gz	05-May-2022 09:07	224753956
GaiaSource_020092-020493.csv.gz	05-May-2022 09:18	226386218
GaiaSource_020494-020747.csv.gz	05-May-2022 10:53	230564098
GaiaSource_020748-020984.csv.gz	05-May-2022 07:47	229702898
GaiaSource_020985-021233.csv.gz	05-May-2022 08:50	221995518
GaiaSource_021234-021441.csv.gz	05-May-2022 08:48	223823485
GaiaSource_021442-021665.csv.gz	05-May-2022 10:10	228076997
GaiaSource_021666-021919.csv.gz	05-May-2022 08:47	233003311
GaiaSource_021920-022158.csv.gz	05-May-2022 08:30	228103016
GaiaSource_022159-022410.csv.gz	05-May-2022 08:10	228229994
GaiaSource_022411-022698.csv.gz	05-May-2022 10:30	22716734[illegible]

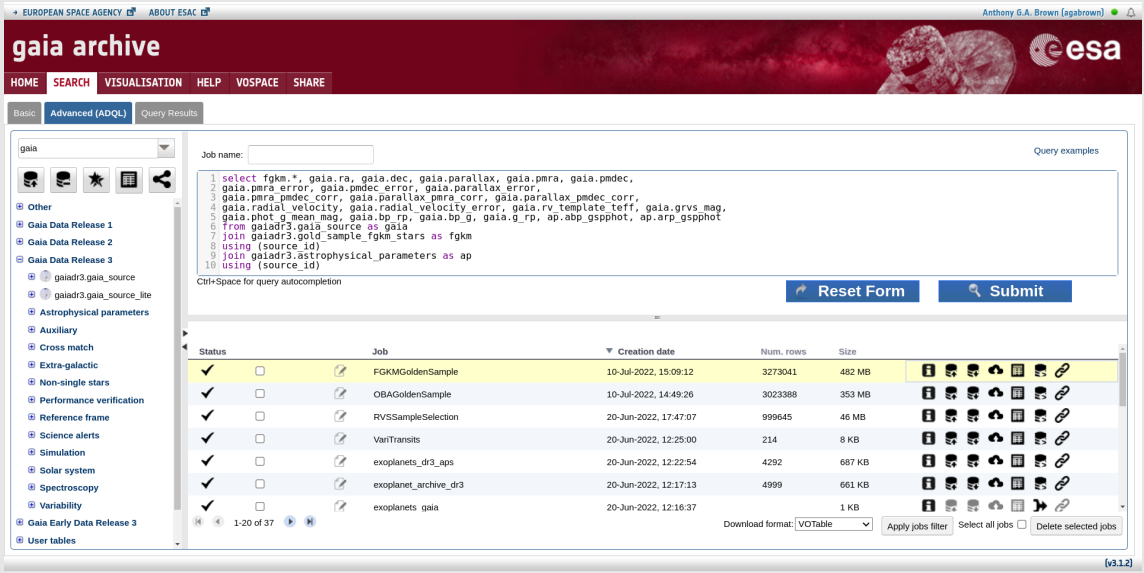
Gaia ESA archive



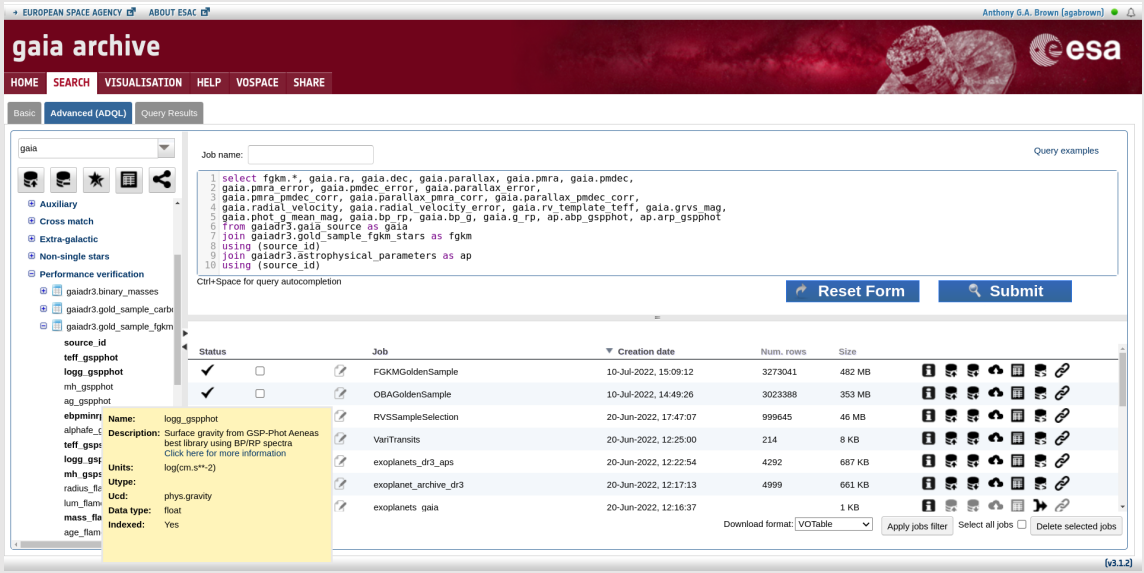
Advanced search: Astronomical Data Query Language



Advanced search: Astronomical Data Query Language



Advanced search: Astronomical Data Query Language



Gaia Data Release 4

- 66 months input data; publication not before end 2025
- Gain in precision wrt Gaia DR3: $\times 1.4$ for parallaxes, $\times 2.8$ for proper motions
- Foreseen data products
  - Full astrometric, photometric, and radial-velocity catalogues
  - All variable-star and non-single-star solutions
  - Source classifications; multiple astrophysical parameters for stars, unresolved binaries, galaxies, and quasars
  - Catalogue of binaries and exo-planets
  - Source environment analysis results
  - Astrometry+photometry for selected crowded fields
  - Gravitationally lensed QSO candidates
  - Solar system: astrometry, orbits, reflectance spectra, taxonomy
  - Time series data for all sources, including astrometry, photometry, radial velocities, BP/RP/RVS spectra
- Gaia DR5 based on 10 years of data

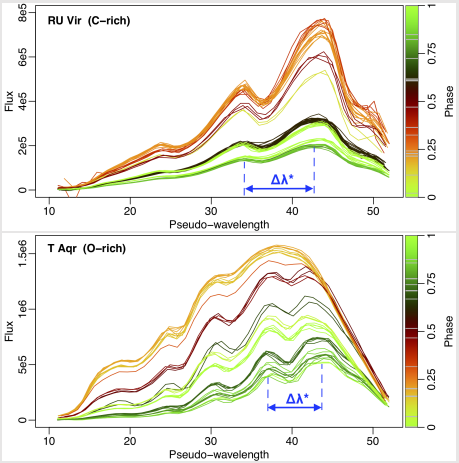
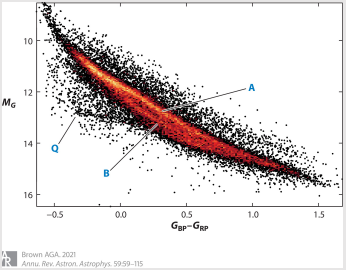
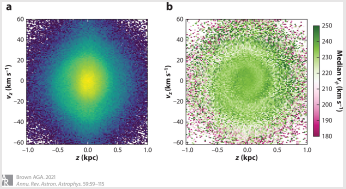


Image credits: ESA/Gaia/DPAC, Mowlavi et al.

The impact of Gaia

- Gaia is revolutionizing astronomy through a vast set of **easily available fundamental data**
- Definitive demonstration of the **power of an all-sky, high spatial resolution, high astrometric and photometric accuracy survey**
- **Dense sampling of Galactic phase space** at high astrometric,photometric,and radial velocity precisions
  - uncovering subtle features in phase space and the observational HR diagram
  - enabling Galactoseismology
- The celestial reference frame provided by **Gaia enables the accurate astrometric and photometric calibration of past, current, and future sky surveys**
- Accurate star map with parallaxes and proper motions allows for **vast improvements in stellar occulation campaigns**
  - shape measurements of Kuiper-belt objects at < 1 km resolution, limits on atmospheres
  - enhanced spacecraft navigation and mission planning





Gaia data is brought to you by

Entry points to Gaia literature

Reviews on micro-arcsecond astrometry and Gaia DR2 science results

Streams, Substructures, and the Early History of the Milky Way https://ui.adsabs.harvard.edu/abs/2020ARA%26A..58..205H/abstract

Microarcsecond Astrometry: Science Highlights from Gaia https://ui.adsabs.harvard.edu/abs/2021ARA%26A..59...59B/abstract

Entry points to Gaia literature

Gaia data releases, data processing and validation

Gaia (E)DR3 papers https://www.cosmos.esa.int/web/gaia/edr3-papers and https://www.cosmos.esa.int/web/gaia/dr3-papers

Gaia DR1 A&A special issue
https://www.aanda.org/component/toc/?task=topic&id=641

Gaia DR2 A&A special issue
https://www.aanda.org/component/toc/?task=topic&id=922

Gaia EDR3 A&A special issue
https://www.aanda.org/component/toc/?task=topic&id=1342

Gaia DR3 A&A special issue
https://www.aanda.org/component/toc/?task=topic&id=1641

Gaia Celestial Reference Frame 3 https://ui.adsabs.harvard.edu/abs/2022arXiv220412574G/abstract

Documentation http://gea.esac.esa.int/archive/documentation/index.html

Entry points to Gaia literature

Mission, spacecraft, payload, data processing and validation

Gaia presentation Science case and mission description in 2001
https://doi.org/10.1051/0004-6361:20010085

Mission, instruments, and data processing overview
https://doi.org/10.1051/0004-6361/201629272

RVS detailed description https://doi.org/10.1051/0004-6361/201832763

On-board detection capabilities https://doi.org/10.1051/0004-6361/201424018

In-orbit CCD performance https://doi.org/10.1051/0004-6361/201628990

Entry points to Gaia literature

Description of Gaia data products, mostly pre-launch

Gaia broad-band photometry https://doi.org/10.1051/0004-6361/201015441

Astrophysical parameters https://doi.org/10.1051/0004-6361/201322344

Astrophysics from RVS https://doi.org/10.1051/0004-6361/201425030

Double and multiple stars http://dx.doi.org/10.1063/1.3597594

Variable stars https://doi.org/10.1051/eas/1567012

Solar system https://doi.org/10.1016/j.pss.2012.03.007 and
https://doi.org/10.1016/j.pss.2015.11.009

Galaxy morphology with Gaia https://doi.org/10.1051/0004-6361/201219697

Source environment analysis https://doi.org/10.1007/s10686-011-9240-7

Transient astronomy https://doi.org/10.1098/rsta.2012.0239

Simulated Gaia data https://doi.org/10.1051/0004-6361/201118646 and
https://doi.org/10.1051/0004-6361/201423636

Entry points to Gaia literature

Astrometry with Gaia

Astrometric Global Iterative Solution https://www.aanda.org/articles/aa/abs/2012/02/aa17905-11/aa17905-11.html

Relativistic astrometric model for Gaia observations https://doi.org/10.1086/367593

Tycho-Gaia Astrometric Solution https://doi.org/10.1051/0004-6361/201425310

Beyond Gaia

White paper on sub-μas astrometry options http://www.rssd.esa.int/doc_fetch.php?id=3210644

Study report on GaiaNIR http://sci.esa.int/jump.cfm?oid=60028

White paper on GaiaNIR https://ui.adsabs.harvard.edu/abs/2021ExA....51..783H/abstract