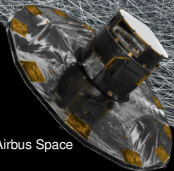




# Introduction to Gaia

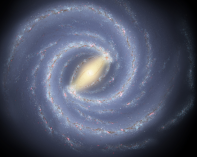
Anthony Brown

Leiden Observatory, Leiden University  
[brown@strw.leidenuniv.nl](mailto:brown@strw.leidenuniv.nl)



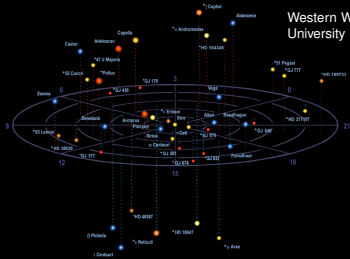
Airbus Space

ESA/Gaia/DPAC

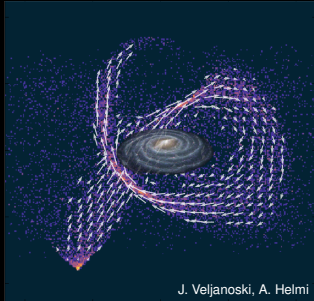


NASA/JPL-Caltech/R. Hurt (SSC)

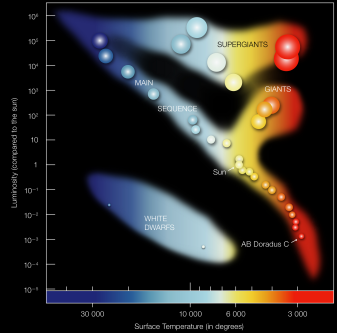
?



Western Washington University Planetarium



J. Veljanoski, A. Helmi



The Hertzsprung-Russell Diagram

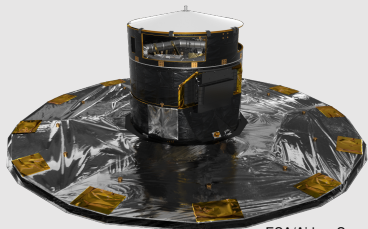
ESO Press Photo 28/07 (19 June 2007)



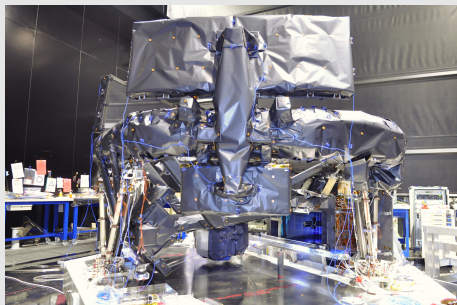


# Gaia summary

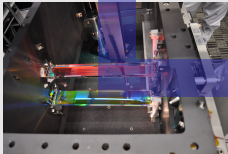
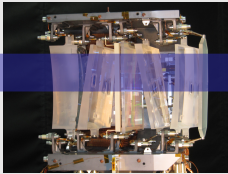
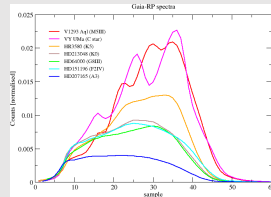
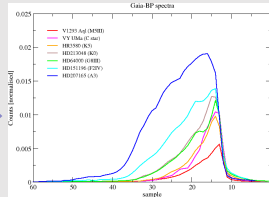
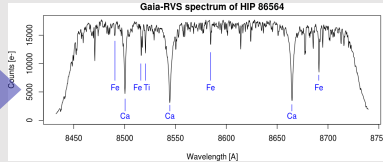
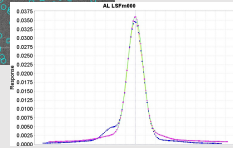
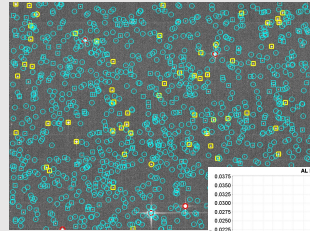
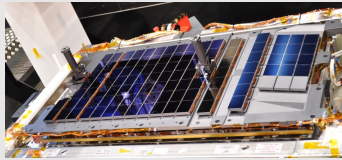
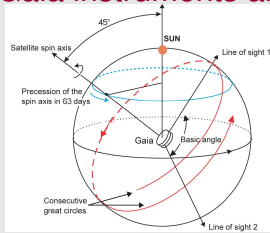
- Astrometry and spectrophotometry for  $> 1$  billion objects
- Radial velocities for  $> 100$  million objects
- Survey
  - ▶ Complete to  $G = 20.7$  ( $V = 20-22$ )
  - ▶ Observing programme: autonomous on-board detection and unbiased
  - ▶ Quasi-regular time-sampling over 5 years ( $\sim 70$  observations)
- 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

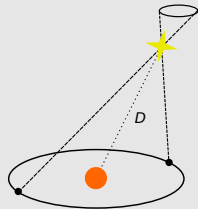
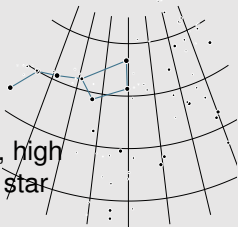


# Gaia instruments and measurements



# Gaia collects fundamental astronomical data

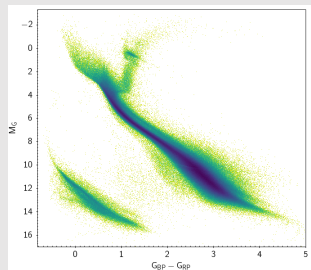
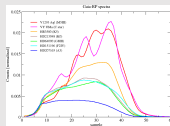
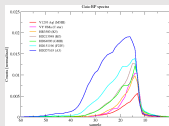
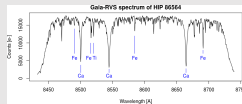
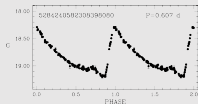
All-sky,  
complete, high  
accuracy star  
atlas



Parallaxes and proper  
motions

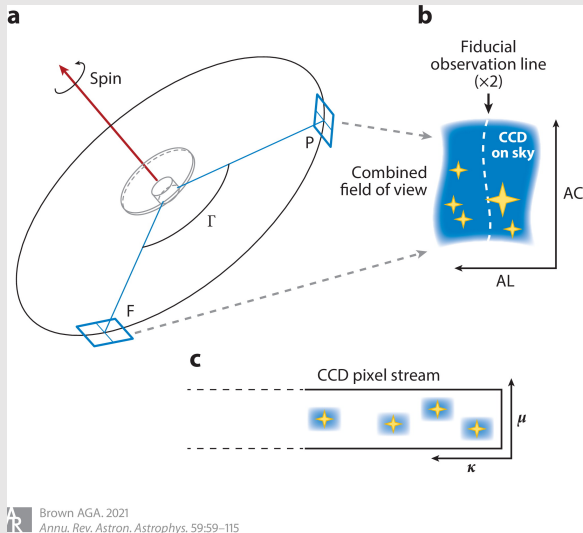


Astrometric,  
photometric,  
spectroscopic,  
radial velocity  
time series



Astrophysical properties

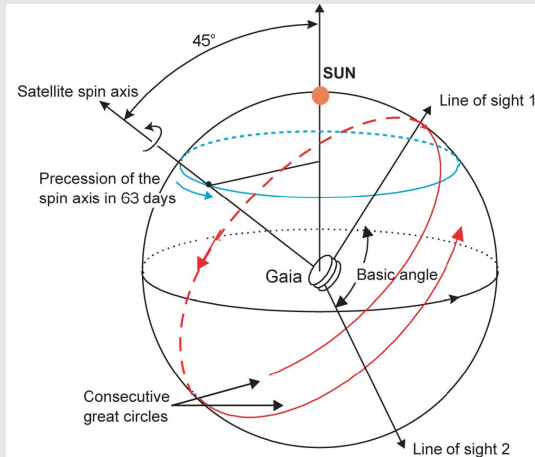
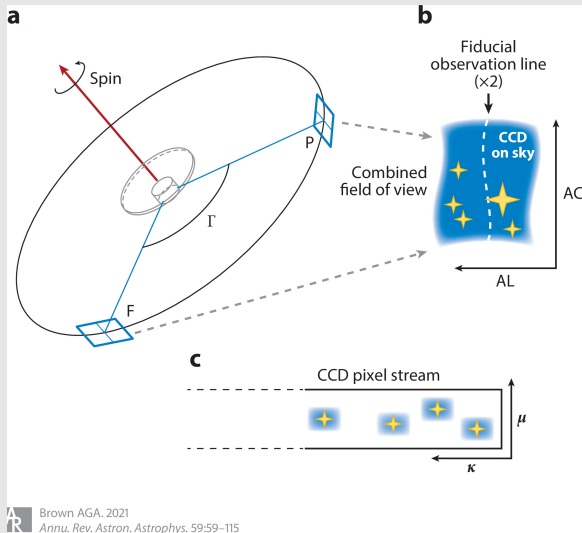
# Gaia scanning the sky



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

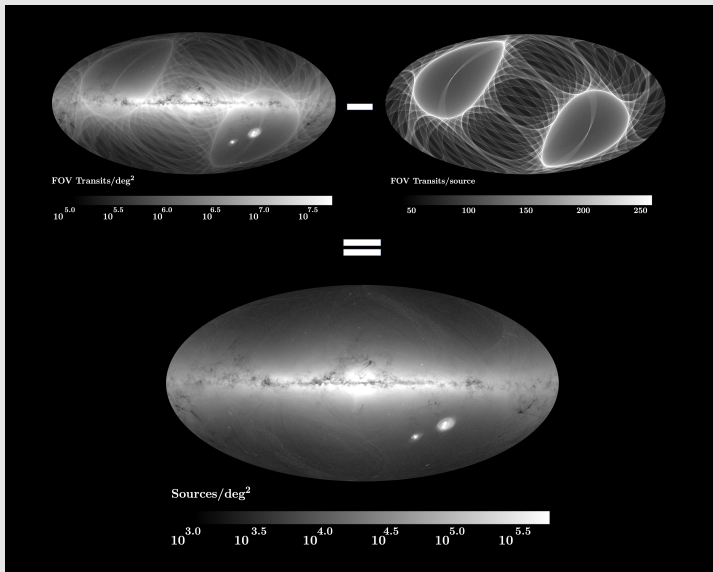


# Gaia scanning the sky



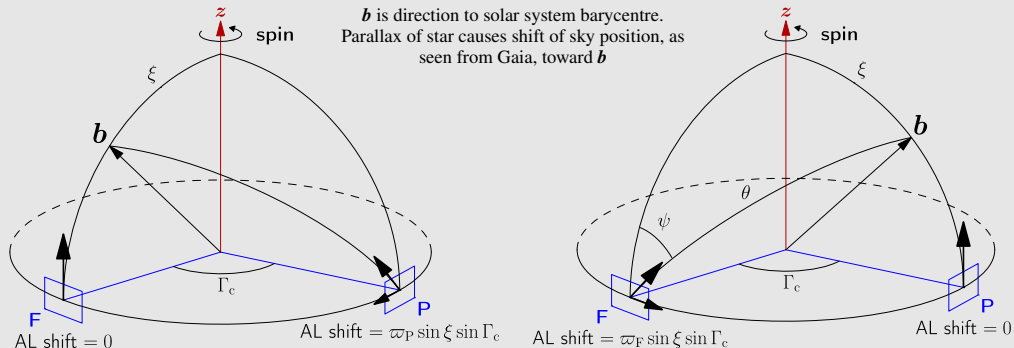
Spin period: 6 hr, Basic angle:  $106.5^\circ$

# 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

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

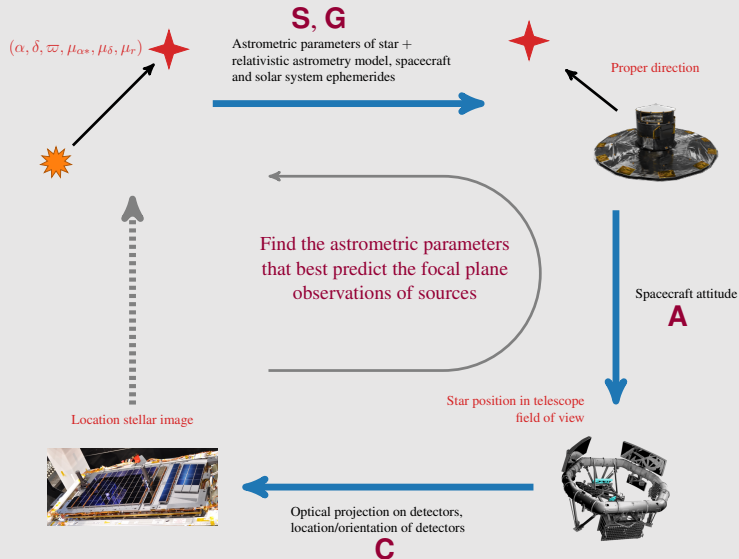
and instrument (calibration) parameters

{Collection of parameters describing Gaia}

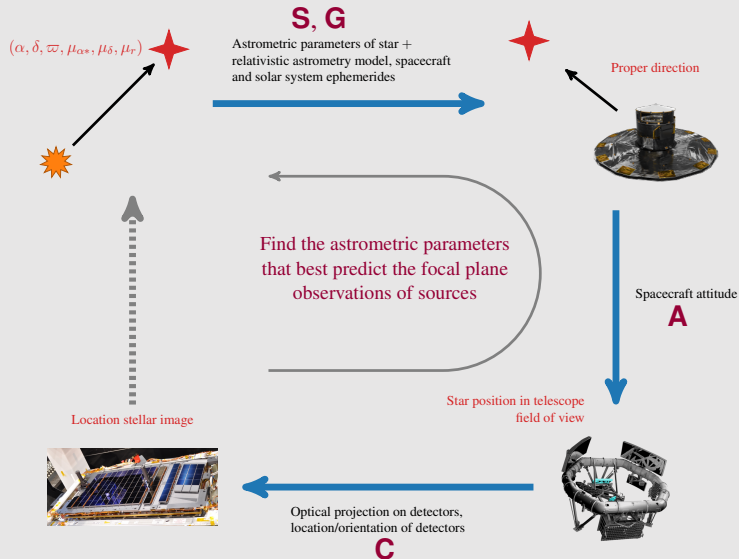
that best explain the Gaia observations.



# Gaia astrometric data processing overview



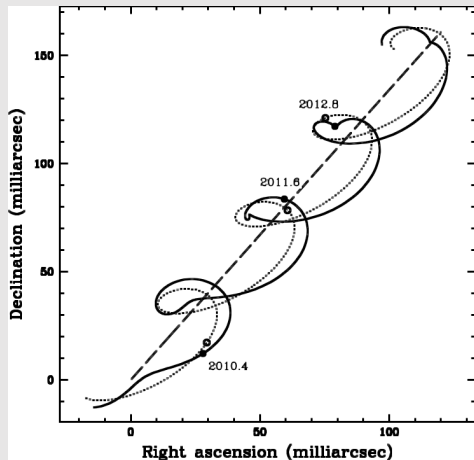
# Gaia astrometric data processing overview



## 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

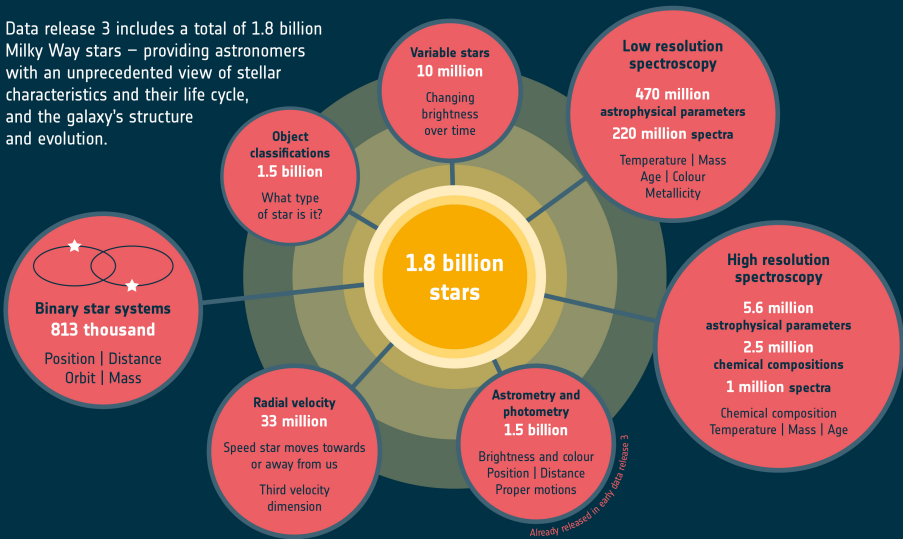


- Determining position, parallax, and proper motion requires repeated measurement of the position of stars on the sky
  - ▶ the path on the sky is predicted from a simple model in which stars move at constant velocity along straight lines
- Repeated observations can show deviations from the simple model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

# Overview of Gaia Data Release 3

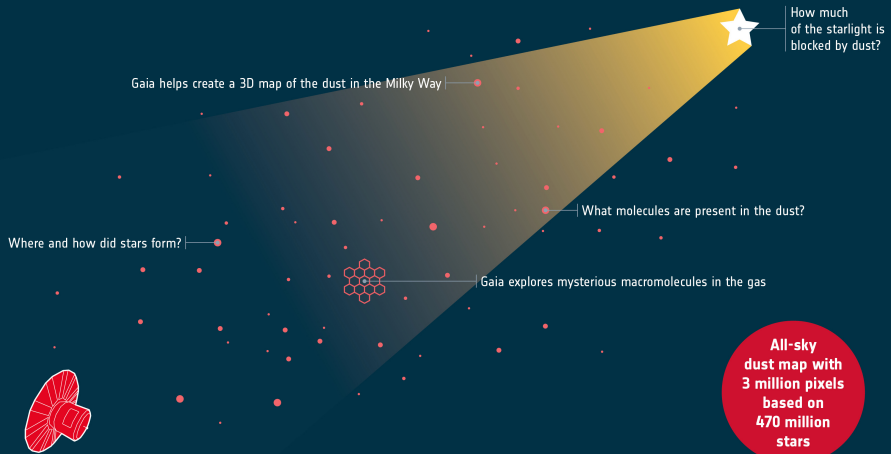


Data release 3 includes a total of 1.8 billion Milky Way stars – providing astronomers with an unprecedented view of stellar characteristics and their life cycle, and the galaxy's structure and evolution.

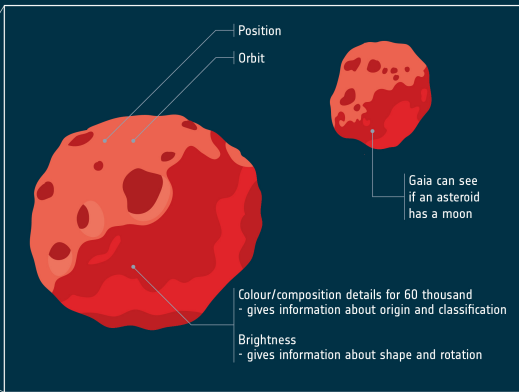
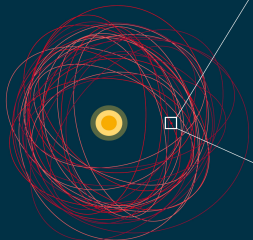


Already released in early data release 3

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.



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:



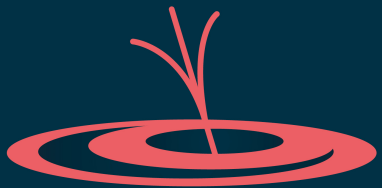
31 moons of Mars, Jupiter, Saturn, Uranus and Neptune



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](#) (~ 10 TB of compressed ECSV files, including [tutorial for cone search](#))
- [Gaia ESA Archive \(GEA\) web interface](#) ([archives.esac.esa.int/gaia](http://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 archive

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### Welcome to the Gaia Archive at ESA

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Save jobs and tables  
Share tables  
Extended time-out  
and quota

### Top Features



#### Citation

How to cite and acknowledge Gaia. Where to find DOI info.



#### Search

Search for Gaia sources using the basic search form or the ADQL (Astronomical Data Query Language) interface for more advanced queries.



#### Download

Direct download of Gaia data files.



#### Help

Data release documentation, tutorials and more. For questions, suggestions or problems, please contact the Gaia Helpdesk.



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News, Gaia alerts, information, and resources on the Gaia mission for the scientific community.



#### Partners

Partner data centres also serving Gaia data.

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# Gaia ESA archive: help landing page

## Getting Data

### Demos and tutorials

- How to extract data
- How to extract data programmatically
- How to collaborate / user account
- How to combine with other data
- How to extract DataLink products
- How to visualise the data
- Writing queries
- Use cases

Data credits and license

Archive release notes

To the data

## Documentation

### Gaia Data Release 3

- Overview
- Online documentation & PDF version
- Data model
- Papers
- Software tools (GaiaXPy, etc.)
- Auxiliary data (passbands, etc.)
- Known issues

Gaia Early Data Release 3

Gaia Data Release 2

Gaia Data Release 1

## Questions

Additional Resources

FAQ

Gaia Helpdesk



# 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

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[readme.txt](#)

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<a href="#">GaiaSource_003112-005263.csv.gz</a>	05-May-2022	08:43	229826558
<a href="#">GaiaSource_005264-006601.csv.gz</a>	05-May-2022	09:13	226838638
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<a href="#">GaiaSource_022411-022698.csv.gz</a>	05-May-2022	10:30	227167343



## gaia archive

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# Advanced search: Astronomical Data Query Language

EUROPEAN SPACE AGENCY ABOUT ESAC Anthony G.A. Brown [agabrown]

## gaia archive

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Basic **Advanced (ADQL)** Query Results

gaia Job name:

Query examples

1

Ctrl+Space for query autocompletion

[Reset Form](#) [Submit](#)

Status	Job	Creation date	Num. rows	Size	
<input checked="" type="checkbox"/>	<input type="checkbox"/> FGKMGoldenSample	10-Jul-2022, 15:09:12	3273041	482 MB	
<input checked="" type="checkbox"/>	<input type="checkbox"/> OBAGoldenSample	10-Jul-2022, 14:49:26	3023388	353 MB	
<input checked="" type="checkbox"/>	<input type="checkbox"/> RVSSampleSelection	20-Jun-2022, 17:47:07	999645	46 MB	
<input checked="" type="checkbox"/>	<input type="checkbox"/> VariTransits	20-Jun-2022, 12:25:00	214	8 KB	
<input checked="" type="checkbox"/>	<input type="checkbox"/> exoplanets_dr3_aps	20-Jun-2022, 12:22:54	4292	687 KB	
<input checked="" type="checkbox"/>	<input type="checkbox"/> exoplanet_archive_dr3	20-Jun-2022, 12:17:13	4999	661 KB	
<input checked="" type="checkbox"/>	<input type="checkbox"/> exoplanets gaia	20-Jun-2022, 12:16:37		1 KB	

Download format:  [Apply jobs filter](#)  Select all jobs  Delete selected jobs

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(v3.1.2)

# Advanced search: Astronomical Data Query Language

## gaia archive



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Basic **Advanced (ADQL)** Query Results

gaia

Other

- Gaia Data Release 1
- Gaia Data Release 2
- Gaia Data Release 3
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  - gaiadr3.gaia\_source\_lite
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  - Auxiliary
  - Cross match
  - Extra-galactic
  - Non-single stars
  - Performance verification
  - Reference frame
  - Science alerts
  - Simulation
  - Solar system
  - Spectroscopy
  - Variability
- Gaia Early Data Release 3
- User tables

Job name:

Query examples

```
1 select fgkm.*, gaia.ra, gaia.dec, gaia.parallax, gaia.pmra, gaia.pmdec,
2 gaia.pmra_error, gaia.pmdec_error, gaia.parallax_error,
3 gaia.pmra_pmdec_corr, gaia.parallax_pmra_corr, gaia.parallax_pmdec_corr,
4 gaia.radial_velocity, gaia.radial_velocity_error, gaia.rv_template_teff, gaia.grvs_mag,
5 gaia.phot_g_mean_mag, gaia.bp_rp, gaia.bp_g, gaia.g_rp, ap.abp_gspphot, ap.arp_gspphot
6 from gaiadr3.gaia_source as gaia
7 join gaiadr3.gold_sample_fgkm_stars as fgkm
8 using (source_id)
9 join gaiadr3.astrophysical_parameters as ap
10 using (source_id)
```

Ctrl+Space for query autocompletion

Reset Form

Submit

Status	Job	Creation date	Num. rows	Size	
✓ <input type="checkbox"/>	FGKMGoldenSample	10-Jul-2022, 15:09:12	3273041	482 MB	
✓ <input type="checkbox"/>	OBAGoldenSample	10-Jul-2022, 14:49:26	3023388	353 MB	
✓ <input type="checkbox"/>	RVSSampleSelection	20-Jun-2022, 17:47:07	999645	46 MB	
✓ <input type="checkbox"/>	VariTransits	20-Jun-2022, 12:25:00	214	8 KB	
✓ <input type="checkbox"/>	exoplanets_dr3_aps	20-Jun-2022, 12:22:54	4292	687 KB	
✓ <input type="checkbox"/>	exoplanet_archive_dr3	20-Jun-2022, 12:17:13	4999	661 KB	
✓ <input type="checkbox"/>	exoplanets gaia	20-Jun-2022, 12:16:37		1 KB	

1-20 of 37

Download format: VOTable

Apply jobs filter

Select all jobs

Delete selected jobs

# Advanced search: Astronomical Data Query Language

## gaia archive



HOME SEARCH VISUALISATION HELP VOSPACE SHARE

Basic **Advanced (ADQL)** Query Results

gaia

- Auxiliary
- Cross match
- Extra-galactic
- Non-single stars
- Performance verification

- gaiadr3.binary\_masses
- gaiadr3.gold\_sample\_carb
- gaiadr3.gold\_sample\_fgkm

- source\_id
- teff\_gspphot
- logg\_gspphot
- mh\_gspphot
- ag\_gspphot

**ebpmnrj** Name: logg\_gspphot  
**alphafe\_c** Description: Surface gravity from GSP-Phot Aeneas best library using BP/RP spectra  
Click here for more information  
**teff\_gsp**  
**logg\_gsp** Units:  $\log(\text{cm.s}^{-2})$   
**mh\_gsp** Utype:  
**radius\_fle** Ucd: phys.gravity  
**lum\_flam** Data type: float  
**mass\_fla** Indexed: Yes  
**age\_flam**

Job name:

Query examples

```
1 select fgkm.*, gaia.ra, gaia.dec, gaia.parallax, gaia.pmra, gaia.pmdec,
2 gaia.pmra_error, gaia.pmdec_error, gaia.parallax_error,
3 gaia.pmra_pmdec_corr, gaia.parallax_pmra_corr, gaia.parallax_pmdec_corr,
4 gaia.radial_velocity, gaia.radial_velocity_error, gaia.rv_template_teff, gaia.grvs_mag,
5 gaia.phot_g_mean_mag, gaia.bp_rp, gaia.bp_g, gaia.g_rp, ap.abp_gspphot, ap.arp_gspphot
6 from gaiadr3.gaia_source as gaia
7 join gaiadr3.gold_sample_fgkm_stars as fgkm
8 using (source_id)
9 join gaiadr3.astrophysical_parameters as ap
10 using (source_id)
```

Ctrl+Space for query autocompletion

Reset Form

Submit

Status	Job	Creation date	Num. rows	Size	
<input checked="" type="checkbox"/>	FGKMGoldenSample	10-Jul-2022, 15:09:12	3273041	482 MB	
<input checked="" type="checkbox"/>	OBAGoldenSample	10-Jul-2022, 14:49:26	3023388	353 MB	
<input type="checkbox"/>	RVSSampleSelection	20-Jun-2022, 17:47:07	999645	46 MB	
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<input type="checkbox"/>	exoplanets gaia	20-Jun-2022, 12:16:37		1 KB	

Download format:

Apply jobs filter

Select all jobs

Delete selected jobs

# 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

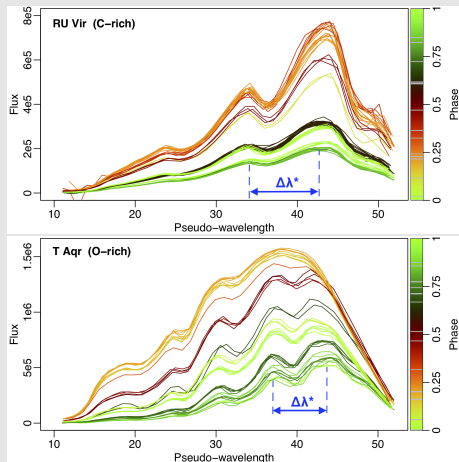
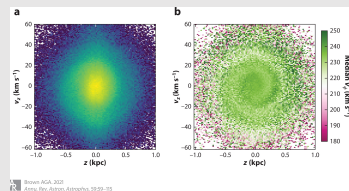
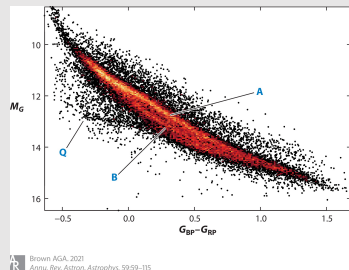


Image credits: ESA/Gaia/DPAC, Mowlavi et al.

# 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 occultation 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:](https://ui.adsabs.harvard.edu/abs/2020ARA%26A..58..205H/abstract)

[//ui.adsabs.harvard.edu/abs/2020ARA%26A..58..205H/abstract](https://ui.adsabs.harvard.edu/abs/2020ARA%26A..58..205H/abstract)

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

[//ui.adsabs.harvard.edu/abs/2021ARA%26A..59...59B/abstract](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>

<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- $\mu$ as astrometry options

[http://www.rssd.esa.int/doc\\_fetch.php?id=3210644](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>