Introduction to Gaia

Anthony Brown
Leiden Observatory, Leiden University
brown@strw.leidenuniv.nl
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
Gaia instruments and measurements

- Why Gaia?
- Instruments
- Survey strategy
- Astrometric data processing
- Gaia DR3
- Data access
- Conclusions
- Literature

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

Why Gaia?  Instruments  Survey strategy  Astrometric data processing  Gaia DR3  Data access  Conclusions  Literature

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
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, \( T_{\text{eff}}, [\text{Fe/H}], \log g, A_0, \) solar system object orbits,

light curves, variable star classification, \ldots

and instrument (calibration) parameters

\{Collection of parameters describing Gaia\}

that best explain the Gaia observations.
Gaia astrometric data processing overview

Astrometric parameters of star + relativistic astrometry model, spacecraft and solar system ephemerides

Find the astrometric parameters that best predict the focal plane observations of sources

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

Why Gaia? Instruments Survey strategy Astrometric data processing Gaia DR3 Data access Conclusions Literature
Gaia astrometric data processing overview

\((\alpha, \delta, \varpi, \mu_\alpha, \mu_\delta, \mu_r)\)

Proper direction
Star position in telescope field of view
Location stellar image

S, G
Astrometric parameters of star + relativistic astrometry model, spacecraft and solar system ephemerides

Find the astrometric parameters that best predict the focal plane observations of sources

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
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, allowing 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.
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
- Position
- Orbit
- Colour/composition details for 60 thousand asteroids
- Brightness
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)
  - 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
Welcome to the Gaia Archive at ESA

Gaia is a European space mission providing astrometry, photometry, and spectroscopy of more than 1000 million stars in the Milky Way. Also data for significant samples of extragalactic and Solar system objects is made available. The Gaia Archive contains deduced positions, parallaxes, proper motions, radial velocities, and brightnesses. Complementary information on multiplicity, photometric variability, and astrophysical parameters is provided for a large fraction of sources.

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.

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

**COMBINE WITH OTHER DATA**
- Pre-computed cross-matches
- Catalogue combination
- Proper-motion corrected cross-match

**PROGRAMMATIC ACCESS**
- Python access: Astroquery
- Command line access: TAP/TAP+
- Command line access: DataLink

**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

**COLLABORATE / USER ACCOUNT**
- Create or update your Gaia user account
- Upload a user table
- Share a user table

**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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Index of /Gaia/

Index of /Gaia/gdr3/

Index of /Gaia/gdr3/gaia_source/

- GaiaSource_000000-003111.csv.gz
- GaiaSource_003112-005263.csv.gz
- GaiaSource_005264-006661.csv.gz
- GaiaSource_006662-007952.csv.gz
- GaiaSource_007953-010234.csv.gz
- GaiaSource_010235-012597.csv.gz
- GaiaSource_012598-014045.csv.gz
- GaiaSource_014046-015369.csv.gz
- GaiaSource_015370-016240.csv.gz
- GaiaSource_016241-017018.csv.gz
- GaiaSource_017019-017658.csv.gz
- GaiaSource_017659-018028.csv.gz
- GaiaSource_018029-018472.csv.gz
- GaiaSource_018473-019161.csv.gz
- GaiaSource_019162-019657.csv.gz
- GaiaSource_019658-020081.csv.gz
- GaiaSource_020082-020493.csv.gz
- GaiaSource_020494-020747.csv.gz
- GaiaSource_020748-020984.csv.gz
- GaiaSource_020985-021233.csv.gz
- GaiaSource_021234-021441.csv.gz
- GaiaSource_021442-021665.csv.gz
- GaiaSource_021666-021919.csv.gz
- GaiaSource_021920-022158.csv.gz
- GaiaSource_022159-022410.csv.gz
- GaiaSource_022411-022698.csv.gz

05-May-2022 07:45  233642769
05-May-2022 08:43  229826558
05-May-2022 09:13  226838638
05-May-2022 10:42  227780596
05-May-2022 07:55  231364710
05-May-2022 09:29  233173214
05-May-2022 10:11  228657814
05-May-2022 07:32  229782980
05-May-2022 08:23  229908320
05-May-2022 10:25  224854608
05-May-2022 09:31  222631212
05-May-2022 10:30  225059250
05-May-2022 09:33  223126665
05-May-2022 10:01  223633783
05-May-2022 09:03  22337592
05-May-2022 09:07  224753956
05-May-2022 09:18  226386218
05-May-2022 10:53  225564998
05-May-2022 07:47  225972898
05-May-2022 08:50  221995518
05-May-2022 08:48  223823485
05-May-2022 10:10  228876997
05-May-2022 08:47  230083311
05-May-2022 08:30  228193616
05-May-2022 08:10  228229994
05-May-2022 10:30  227167345

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Advanced search: Astronomical Data Query Language

Why Gaia?
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Sagan2022 - 2022.07.25 - 28/38
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
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
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&A.58..205H/abstract

- Microarcsecond Astrometry: Science Highlights from Gaia
  https://ui.adsabs.harvard.edu/abs/2021ARA&A.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

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

Galactic 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

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**Astrometry with Gaia**


Relativistic astrometric model for Gaia observations [https://doi.org/10.1086/367593](https://doi.org/10.1086/367593)

Tycho-Gaia Astrometric Solution [https://doi.org/10.1051/0004-6361/201425310](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](http://www.rssd.esa.int/doc_fetch.php?id=3210644)

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

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