GAIA AND THE ASTEROID POPULATION: A REVOLUTION ON EARTH, COMING FROM SPACE

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Gaia ID card

- It is a **ESA cornerstone scientific mission**:
  - ESA: building, operation
  - Scientific community: data reduction
  - No instrument PI; no proprietary period

- **Astrometry**:
  - $10^9$ stars, $V<20$
  - 25 μas at $V \sim 15$
  - uniform sky coverage (70-100 obs./source)

- **Physical observations**:
  - Spectro-photometry
  - Radial velocities, hi-res spectra ($V<16.5$)

- **5 years of observations**
  (nominal mission started in July 2014)

- Positioned around L2

- automated selection of sources, on input catalog

- Self-monitored, onboard metrology

- Heritage of Hipparcos
Gaia in the history of astrometry
Two SiC primary mirrors
1.45 × 0.50 m², F = 35 m

SiC toroidal structure

Focal axis (6 h)

LOS 2

106°.5

Combined focal plane (CCDs)

M4: beam combiner

Figure courtesy EADS-Astrium
Sunshield deployment test – Oct. 2011
December 19, 2013
The scanning law

Rotation axis movement

Sun trajectory, 4 months

Spin axis trajectory, 4 months

Scan path in 4 days

Scan path

Spin axis trajectory
4 days

Spin axis

4 rotations/day

45°
1 pixel 60 x 180 mas

106 CCDs (4.5 x 2 kpix) = 1 Gpixel

SM1-2

AF1 - 9

BP

RP

RVS

WFS

BAM

WFS

BAM

courtesy F. Mignard, OCA

FOV1

FOV2

0s 10.6 15.5 30.1 49.5 56.3 64.1

0s 5.8 10.7 25.3 44.7 51.5 59.3

420 mm 0.69°
The Astrometric Global Iterative Solution (AGIS)

- Simultaneous all-sky solution of positions, parallaxes, proper motions, physical parameters (e.g. color) and instrument calibration parameters

- Link to ICRS by VLBI sources directly observed by Gaia

—> All aspects of the data reduction are deeply connected
Gaia as Micro-meteorite detector

Corrective torques applied to recover spacecraft attitude after a meteoroid strike (Perseid activity peak).
The strengths of Gaia

• Astrometry:
  • Accurately measure relative positions at large angles —> no zonal error
  • Measure time instead of positions (and control very accurately the transformation)
  • Average the signal over several 10,000s pixels (good for photometry too)

• Spectro-photometry
  • provide colors and low-resolution spectra (—> classification) for all sources

• Radial velocities
  • Add the 3rd dimension of motions in the Galaxy

+ automated source detection on board
Gaia does not produce images

- (Except for testing in a special mode)
- Operates in TDI mode (line period 1 ms)
- Small windows read from the CCD around the sources
- 2D windows are binned across scan —> 1 D data sample (typ. 6 pixels)
- on board lossless compression

- Fundamental measurement: crossing time of a fiducial line on the CCD by the brightness peak of a source

\[ \sim 0.38 \text{ as} \]

\[ \sim 1 \text{ as} \]
Gaia produces unusual epoch astrometry

- In the along scan direction the typical accuracy is a small fraction of a pixel (~1 mas)
- Across scan it is of the order of a pixel (~100 mas)
- When rotated to (RA, dec) this results in highly correlated uncertainties
- This is not (very) relevant for stars
- It is fundamental for asteroids! Pay attention to the covariance matrix
The Data Processing and Analysis Consortium - since 2007

DPAC participating countries
October 2013
450 members

Including:
BR
CA
DZ
ESA
IL
US
Gaia data - when?

GDR1: star positions + Tycho-Gaia Astrometric Solution

- 40 mas
- Sept. 2016

GDR2: star positions + parallaxes + proper motions
- 10 mas
- Apr. 2018
- 2 mas

Final release
- 2022
GDR1: brightness accuracy

This plot shows the distribution of the estimated uncertainties on the weighted mean G-band photometry as a function of magnitude. The colours indicate the density of data points, from low (red) to high (blue) on a logarithmic scale. Credits: ESA/Gaia/DPAC
GDR1: parallax accuracy (TGAS)
GDR1: position errors

Right ascension error medians

Declination error medians
Gaia Archive

Welcome to the Gaia Archive

Gaia is an ambitious mission to chart a three-dimensional map of our Galaxy, the Milky Way, in the process revealing the composition, formation and evolution of the Galaxy. Gaia will provide unprecedented positional and radial velocity measurements with the accuracies needed to produce a stereoscopic and dramatic census of about one billion stars in our Galaxy and throughout the Local Group. This amounts to about 1% of the Galactic stellar population.

If you use public Gaia DR1 data in your paper, please take note of our guide on how to acknowledge and cite Gaia DR1.

Top Features

- Search
- Download
- Statistics

Query for Gaia sources using an AQL (Astronomical Query Language) - Language Interface in an asynchronous mode (LINES).

https://gea.esac.esa.int/archive/
The Solar System and Gaia
What Gaia observes

• What Gaia observes = all small objects at $V < 20.5$
  – 350,000 asteroids ($>700,000$ known today)
  – comets, TNOs
  – small planetary satellites

• Why we are interested
  – small bodies record the history of the Solar System
  – very poorly known properties:
    • a few 1000s spectra, 10s masses, 100k sizes, ~400 shapes
Where Gaia observes

~70 observations per object

- Discovery space:
  - Low elongations (~45-60°)
  - Inner Earth Objects (~unknown)
  - Other NEOs
  - Some MBAs
What Gaia observes: how big

- NEA
- MBO
- Jupiter Trojans
- Kuiper Belt

Graph showing distance at observation (au) vs. diameter (km) for NEA, MBO, Jupiter Trojans, and Kuiper Belt, with Gaia (V = 20) lines at A = 0.05 and A = 0.15.
Gaia single-epoch astrometric accuracy

final attitude and calibration, single FoV (9 positions) transit, point-like source

<table>
<thead>
<tr>
<th>Type</th>
<th>Name</th>
<th>Number of measurement</th>
<th>Percentage of accepted measurement</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>CCD</td>
<td>79,569,190</td>
<td>99.49%</td>
<td>0.388 arcsec</td>
</tr>
<tr>
<td>S</td>
<td>Wise</td>
<td>1,526,466</td>
<td>99.86%</td>
<td>0.583 arcsec</td>
</tr>
<tr>
<td>S</td>
<td>Hubble Space Telescope</td>
<td>867</td>
<td>96.54%</td>
<td>0.585 arcsec</td>
</tr>
<tr>
<td>S</td>
<td>Spitzer</td>
<td>48</td>
<td>33.33%</td>
<td>1.673 arcsec</td>
</tr>
</tbody>
</table>

Observations in the AstDys service (Univ. Pisa)

random errors + systematic
Photometric accuracy

 Epoch transit accuracies

(courtesy D. Evans)
Low-resolution spectroscopy

$= \sim 25$ bands
Science goals for the end of the mission

- Complete the sample (discoveries)
- Orbits: X 100 improvement
- Precession: Gen. Relativity tests
- 100 masses from close encounters
- Diameter ~1000 asteroids
- Composition, taxonomy
- Shape, pole, rotation period
From data reduction...to scientific exploitation

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Ground-based follow-up
- Search for binaries
- Asteroid occultations
- Re-processing of “old” astrometry

- More sizes, masses, densities

Asteroid families
- Differentiation signatures
- Collisional evolution
## Our knowledge – before and after Gaia

<table>
<thead>
<tr>
<th>Property</th>
<th>today</th>
<th>Gaia</th>
</tr>
</thead>
<tbody>
<tr>
<td>astrometry</td>
<td>~ 0&quot;5</td>
<td>0&quot;005</td>
</tr>
<tr>
<td>ephemeris precision</td>
<td>50-200 mas</td>
<td>&gt; 20 times better</td>
</tr>
<tr>
<td>shape, pole</td>
<td>500</td>
<td>~100,000</td>
</tr>
<tr>
<td>rotation period</td>
<td>4000</td>
<td>~100,000</td>
</tr>
<tr>
<td>satellites</td>
<td>~ 50 (MBA)</td>
<td>1000s ?</td>
</tr>
<tr>
<td>spectral type</td>
<td>~ 1000</td>
<td>~200,000</td>
</tr>
<tr>
<td>mass, σ &lt; 50%</td>
<td>~ 50</td>
<td>150</td>
</tr>
<tr>
<td>size</td>
<td>100,000</td>
<td>~1000</td>
</tr>
</tbody>
</table>
Solar System in DPAC Coordination Unit 4

**Manager:** D. Pourbaix (Univ. Brussels)
**Deputy:** P. Tanga (OCA, France)

- DU450 Management
- DU451 Auxiliary data
- DU452 Identification of known objects
- DU453 CCD processing
- DU454 Astrometric reduction
- DU455 Object threading
- DU456 Orbital inversion
- DU457 Global Effects on Dynamics
- DU458 Physical parameters
- DU459 Ground-based observations
- DU460 Simulation
CU4: two pipelines for the science goals

**Daily processing**
- Processing of « new » asteroids
- Per-object, on 48h time frames
- Preliminary astrometry (OGA1)
- Preliminary calibration

**Long–term processing**
- All sources
- Best calibrations, best astrometric model
- Take into account shape and motion
- Devoted to obtain the best possible final output of the mission

- ground-based alert network
- epoch astrometry refined orbits dynamical and physical parameters
Diffusion of asteroid alerts

From the Gaia-FUN-SSO web site

http://gaiafunssso.imcce.fr

Footprints of areas to search for (in red) and the field of view (in blue, 15x15 arcmin²) of your device (OHP). You can change your device and its parameters in your settings.
First confirmation of an asteroid alert

- Orbit computation from Gaia and from the ground (OHP, France)
- Observations on Dec. 29 (Gaia - 4 transits) and Jan. 3-4 (OHP, 2 nights)
- resulting uncertainty $\sigma_{a}^{-3}$
Looking forward to long-term processing: asteroid orbits by Gaia ONLY - accuracy
But we don’t have asteroid astrometry by Gaia, yet!

So, what can we do?

Exploit the stars in GDR1!
Re-calibration of ground-based astrometry

- Asteroid observations from the Ground-Based Optical Tracking of Gaia (GBOT)
  - VST - Paranal
  - Liverpool robotic - Canary Isl.
- Several 10s asteroids observed each night
- Data reduction with PPMXL and Gaia DR1
- Typical sequence: 10 images over ~15 minutes, once
PPMXL calibration
Gaia GDR1 calibration

1132 - GBOT GDR1 residuals

O-C RA (mas)

O-C DEC (mas)

-20          +20

-20        +20
Potential “impactor” NEA 2016EK85

- Discovered by GBOT (8 observations by VST, 20 by LT, March 9-10, 2016)
- On the impact risk list with low probability for Feb. 22, 2102
- New observations from Mauna Kea (March 16, 2016) rule out impact
- If GDR1 were available, the object would have never been on the risk list
The revolution in astrometry

• ...does not come for free!
• Tools must be ready to handle accuracy ~100 X better
• An appropriate, careful weighting of the observations is necessary

• A factor 10 X improvement is accessible with GDR1
• More to come...!
Stellar occultations: potential with Gaia

- predictions based on GDR1 available since end 09/2015

The duration of the occultation can be transformed into a chord length.
Typ. AL accuracy of the occultation \( \sim 0.1-0.2 \text{ s} = 1 - 3 \text{ km} \)
Occultations: science case

- Determine asteroid sizes, shapes
  - discriminate among spin pole solutions
  - calibrate indirect size determination methods (thermo-physical modeling)
  - complement photometric inversion ("KOALA")
  - the only efficient method for TNO size determination
- Measure binary systems
  - separations, primary/secondary size → mass, density (!!)
- Detect thin atmospheres
  - on Pluto, large satellites (Titan), TNOs
Pluto and Charon from *daily astrometric calibration* (~70 mas)

motion around barycenter ~100 mas
photocenter wobbling ~10 mas
variations linked to albedo changes ~?~

from the ground - 19 years

Benedetti-Rossi et al. 2014
Example - Prediction of stellar occultations: Pluto

NOMAD1 0688-0855872

18 July 2016
(~24 h before event)

Pluto + star

19 July 2016
(occultation night)

Pluto’s motion in one day

NOMAD1 0688-0855872 star

Observatory Valle d’Aosta, Saint Barthélémy, July 19, 2016

Courtesy: B. Sicardy, LESIA, Obs. de Paris
Example - Prediction of stellar occultations: Pluto

The July 19, 2016 Pluto occultation
our prediction as of early July
Example - Prediction of stellar occultations: Pluto

The July 19, 2016 Pluto occultation, prediction using the GAIA star position (and estimation of its pm), plus the New Horizons-updated ephemeris.

Gaia “GDR0”!
Example - Prediction of stellar occultations: Pluto

The July 19, 2016 Pluto occultation post-occultation reconstructed path (what really happened)

shadow center
shadow northern limit
shadow southern limit

green dots: sites involved in the campaign (not all got data!)
Example - Prediction of stellar occultations: Pluto

Sicardy et al. (2003)
Sicardy et al. (2016)
Dias Oliveira et al. (2015)
Yelle & Elliot (1997)

Capacity: B. Sicardy, LESIA, Obs. de Paris

(B. Sicardy, presented at DPS 2016)
TNO detections

- 30 TNOs (in theory) below the V=20.5 threshold
- accuracy per transit probably 2-3 mas (along scan)
- example of time distribution:
At 1.4 AU, 1 km ~1 mas 

~ size limit of Gaia in the Main Belt

Tanga & Delbo’ 2007

~1000 objets

~100 objets

practical limit

Uncertainty / apparent size at opposition

Cumulative number of asteroids

Diameter (km)

100.0

10.0

1.0

1.0

0.1

0.1

0

10

100

1000

10000

100000

1000000

10000000

100000000

1000000000
Impact of Gaia on stellar occultations

• Predictions possible (in principle) for ~1 billion stars
  • in practice: limited by delta-mag
• Path width = uncertainty at D ~ 5-15 km
• Many 10s events observable per night from any site for V < 15 (star)

• New tools to be developed
  • not a task for humans!
  • accurate prediction at ~100 m level on the ground
  • introduction of a probabilistic description of the results
Occultation astrometry: a new approach

- Is it possible to calculate optimized asteroid orbits from occultations ONLY?

- Well-observed occultations can be very accurate astrometric positions for asteroids
  - at the level of the stellar astrometry
  - ...but possible *before* and *after* Gaia
Dream becoming true: the *occultation astrometry of asteroids*

![Graph showing orbit accuracy vs. occultation accuracy](image)

F. Spoto, OCA
Occultation residuals

- Asteroid 105 Artemis
Selection for the Gaia Data Release 2 (Apr. 2018)

- Last version (January 8):
  - no transit loss for the included asteroids
  - asteroids with less than 9 transits are excluded
  - 13,400 planets (195,000 transits)

F. Mignard, OCA
Conclusions

• Gaia data are delivering the expected resolution
  • stellar data already interesting for Solar System science
• Big potential in asteroid data: sensitivity to shape/satellites, subtle dynamical effects
• “old” approaches are being renovated: asteroid occultations is the example of excellence
Thank you!