The Gaia mission: status, problems, opportunities

M.G. Lattanzi
INAF - Osservatorio Astronomico di Torino
For the Italian participation in the mission
Overview

- Status
- Opportunities
- Problems
Three experiments on board

1. Astrometry (< 20 mag):
   - unbiased and complete to 20 mag ⇒ $10^9$ stars
   - 10 – 25 μarcsec precision at 15 mag
   - scanning satellite with two viewing directions ⇒ global accuracy
   - global astrometric reduction, as for Hipparcos

2. Photometry (< 20 mag):
   - astrophysical diagnostics (spectro-photometry) + chromaticity
   - $T_{\text{eff}}$ to ~200 K, log(g) to 0.2 dex, [Fe/H] to 0.2 dex, extinction, ...

3. Spectroscopy (< 17 mag):
   - slitless spectroscopy of Ca triplet (847 – 874 nm) at $R = 11,500$
   - radial velocities with 15 km s$^{-1}$ precision at 17 mag
   - third component of space motion, perspective acceleration, binaries, chemistry, rotation, ...
Parallax ($\pi$) relative error is the same as relative error in distance ($d$).

The location of an object in astrometry is considered reliable if its error is less than 10%: \[ \frac{\sigma_{\pi}}{\pi} = 0.1 \]
Gaia: the ultimate Milky Way “machine”

- >20 globular clusters
- Many thousands of Cepheids and RR Lyrae
- Mass of galaxy from rotation curve at 15 kpc
- 30 open clusters within 500 pc
- Horizon for detection of Jupiter mass planets (200 pc)
- Proper motions in LMC/SMC individually to 2-3 km/s
- General relativistic light-bending determined to 1 part in 10^8
- Dark matter in disc measured from distances/motions of K giants
- Dynamics of disc, spiral arms, and bulge
- Horizon for proper motions accurate to 1 km/s
- Horizon for distances accurate to 10 per cent
- 1 microarcsec/yr = 300 km/s at z = 0.03 (direct connection to inertial)
Science with Gaia (examples)  
(From the original science case)

- **Stellar astrophysics:**
  - accurate (< 1%) parallax distances to millions of stars
    ⇒ intrinsic properties of stars, test of stellar structure models
  - astrometric detection of (large) planetary companions

- **Galactic astrophysics:**
  - space motions of large, volume-complete samples of stars
    ⇒ galactic potential ⇒ distribution of (dark) matter
  - combined luminosity / colour / velocity data for large samples
    ⇒ history of star formation and how the Galaxy was put together

- **Solar system physics:**
  - about 300,000 asteroids observed
  - about 50 observation epochs per object, 35-1000 μas per epoch
    ⇒ orbit families, dynamical evolution, masses of individual asteroids

- **Reference frame and fundamental physics:**
  - dense and accurate optical frame directly tied to the extragalactic frame
• ESA-only mission (prime EADS Astrium SAS)
• Launcher: Soyuz–Fregat from CSG (Guiana)
• Orbit: L2 Lissajous orbit (1.5 million km from Earth, one-month travel time after launch)
• Lifetime: 5 years (1 year potential extension)
• Ground stations: Cebreros + New Norcia + Malargüe
• Downlink rate: 4 – 8 Mbps (~50 GB day$^{-1}$)
• Only scientific data reduction contracted out to DPAC (European consortium)
Final catalog release expected in late 2021 (2022):

**no proprietary data rights**. Immediate release to community at large.

Intermediate data releases:
starting from ~ 16 months after science verification (4 to 6 months); immediate release as for final catalog

Examples:
- Variability
- “Local” Relativity experiments (GAREQ)
- Spectra of brighter objects
- Astrometry of “nearby” stars (e.g., the new Hipparcos)
- ......
Four intermediate releases before the final data release:

- **Launch+22 months release:**
  - Positions and G magnitudes *for single stars*
  - HTPM: proper motions for Hipparcos stars
- **Launch+28 months release:**
  - 5 parameter astrometric solution *for single stars*
  - Integrated photometry BP/RP
  - Mean radial velocities for brightest stars
- **Launch+40 months release:**
  - Improved estimates of previously released quantities
  - Orbital solutions for binaries with periods between ~2 to 12mo
  - Object classification and astrophysical parameters
  - BP/RP spectra and/or RVS spectra used for the above
- **Launch+65 months release:**
  - Improved estimates of previously released quantities
  - Variable star classification and epoch photometry used
  - Solar System object parameters and epoch observations used
  - Non-single star catalogues (incl. Extrasolar planet candidates)

*Final Release 3 yrs after end of satellite operations.*
Parallel Initiatives (outside DPAC):

- Developed for ground-based support and preparation for scientific exploitation

Gaia-ESO Survey (GES):
- Spectroscopic survey at VLT
- For supporting MW and stellar population studies

  G. Gilmore, S. Randich (Co-Pis)

**GREAT initiative (ESF, ITN-FP7)**
- Scientific exploitation preparation in all major areas of the Gaia science case.

  N. Walton (PI), G. Clementini (Co-I, for INAF)

**First PRIN INAF entered this year** for the exploitation of Gaia’s early releases

(OAPd – Vallenari PI, OATo – led by Drimmel, OABo – led by Bellazzini)
Mission Essentials
Il Cielo di Gaia

Equatorial projection

Gaia field transits (ICRS) for 5 years

sky average = 80
Mission Challenges
2 off-axis telescopes
1.45 x 0.5 m² aperture
35 m focal length

basic angle = 106.5°

common focal plane, 106 CCDs (1 Gigapixel)
0.93 x 0.42 m²
Multiplexing two FOVs in one

For a spinning and precessing satellite

\[
\sigma^2 = s^2 \sigma^2_{\Delta x} + \sigma^2_{BA}
\]

\[
\delta^2 = \Delta x \delta_s + \delta_{BA}
\]
Gaia focal plane (106 CCDs)

- Detection and FOV discrimination
- Astrometric measurements
- Photometry (dispersed images)
- Radial velocity (dispersed images)

BAM = basic angle monitor, WFS = wavefront sensor
At the micro-arcsec... 

Astrometry and satellite attitude, they both become fully relativistic!
Astrometric solution for Gaia: The problem

• The basic measurement is the "time of observation" for each star’s crossing a CCD
  \( \Rightarrow 10^{12} \) measurements in total

• Unknown parameters to estimate:
  – 5 astrometric parameters per star
  – attitude (celestial orientation) of instrument as function of time
  – instrument calibration parameters (basic angle, CCD positions, etc)
  – possibly additional parameters (incl. PPN-\( \gamma \))
    \( \Rightarrow 5 \times 10^9 \) unknowns in total

• Not all stars are suitable for simple modelling (binaries, etc)
  – a subset of "primary stars" is used for the astrometric solution
  – aim to use at least 100 million primary stars (10% of all)
  – the rest are "secondary stars", can be treated offline
    \( \Rightarrow \) astrometric solution needs \( 5 \times 10^8 \) unknowns
Astrometry and Spectro-photometry have similar measurement principles and, therefore, face similar challenges:

\[ f_{\text{obs}}(u) = \int_0^\infty R(\lambda) \cdot L_\lambda(u - u_0(\lambda)) \cdot S(\lambda) \, d\lambda \]

Photometric model for elementary measurements on focal plane.

\[ I_k = f \int_{k\,(\text{pixel})} L_\lambda(x - x_0) \, dx \]

Astrometric model for elementary measurements on focal plane.

The difference is in the expected (final) errors........
Predicted Errors
(of the ‘as-built’ system)
## End-of-mission photometric errors, in units of milli-magnitude:

<table>
<thead>
<tr>
<th>G [mag]</th>
<th>B1V</th>
<th>G2V</th>
<th>M6V</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>G</td>
<td>BP</td>
<td>RP</td>
</tr>
<tr>
<td>6 - 13</td>
<td>1</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>14</td>
<td>1</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>15</td>
<td>1</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>16</td>
<td>1</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>17</td>
<td>2</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>18</td>
<td>2</td>
<td>7</td>
<td>14</td>
</tr>
<tr>
<td>19</td>
<td>2</td>
<td>13</td>
<td>34</td>
</tr>
<tr>
<td>20</td>
<td>3</td>
<td>29</td>
<td>83</td>
</tr>
</tbody>
</table>

$\sigma_{\text{pcal}} = 30$ milli-mag at CCD-level
### End-of-mission radial-velocity robust formal errors $\sigma_{v\text{rad}}$ [km s$^{-1}$]

<table>
<thead>
<tr>
<th>$V$</th>
<th>B1V</th>
<th>G2V</th>
<th>K1III - MP</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>12</td>
<td>8.5</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>V = 13</td>
<td>21</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>V = 14</td>
<td>-</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>V = 16</td>
<td>-</td>
<td>7.8</td>
<td>5</td>
</tr>
<tr>
<td>V = 17</td>
<td>-</td>
<td>20</td>
<td>13.3</td>
</tr>
</tbody>
</table>

Astrophysical Parameters predicted accuracy (CU8):  
>>For zero extinction stars:  
Teff accuracy 0.3% at G=15 and 4% at G=20  
[Fe/H] ~ 0.1-0.4 dex for stars G< 18.5  
log g ~ 0.1-0.4 dex for stars G<18.5  
>>as extinction varies:  
[Fe/H] ~0.3-0.5 dex at G=15  
log g ~ 0.3-0.5 dex at G=15  
Teff and Av 3-4% accuracy, but strong degeneracy
End-of-life astrometric performance

<table>
<thead>
<tr>
<th>$\mu$as</th>
<th>B1V</th>
<th>G2V</th>
<th>M6V</th>
</tr>
</thead>
<tbody>
<tr>
<td>V &lt; 10 mag</td>
<td>&lt; 7</td>
<td>8.4</td>
<td>&lt; 7</td>
</tr>
<tr>
<td>V = 15 mag</td>
<td>&lt; 25</td>
<td>26.3</td>
<td>&lt; 24</td>
</tr>
<tr>
<td>V = 20 mag</td>
<td>&lt; 300</td>
<td>328.7</td>
<td>&lt; 300</td>
</tr>
</tbody>
</table>

Sky-averaged **parallax** standard error in micro-seconds-of-arc ($\mu$as)

Very little or nothing of comparable quality is available for external comparisons!

$\sigma \approx \sqrt{\frac{720}{\text{worse, on average, at the single CCD-level transit}}}$
Gaia Data Processing and Analysis Consortium (DPAC)

Formed 2006 in response to an "Announcement of Opportunity" issued by ESA

Consists of individual persons organized in an ad hoc structure

Currently (Feb 2009) 396 members

22 funding agencies

6 data processing centres
AVU: the astrometric verification unit within CU3 includes its own DPC (DPCT)
Astrometric Verification Unit (AVU)@DPCT

- Up to 2 million primaries in house (at DPCT) as trial (optimization) runs
- Up to 100 million primaries at CINECA (via DPCT) supercomputer center on the new IBM BLUE GENE Q [10,000 computing nodes (16 processing elements each)]

AVU is a unique (only) tool to validate the astrometry of Gaia at all levels down to the quality of the all-sky astrometric reconstruction (to $\geq 10$ μas, depending on magnitude) expected for the final catalog.
The last CU to join DPAC was CU9. This was done through a special call by ESA.

One proposal was submitted in January 2013 after a 1-year DPAC preparatory study (the GAP initiative) and recently approved by ESA SPC).

CU9 deals with the Gaia Archive preparation that will be released to the community at large and includes exploitation tools (Data Access).

The Italian contribution is coordinated by the Gaia Team @ ASDC (Marrese, Giuffrida, Marinoni, and IT support team)
**Contribution to CU3**
Core Processing@ESAC
- Initial Source catalog
- Object naming and observations threading (**OATo**)

**Contribution to CU4**
Object Processing@CNES
- Minor planets identification (**OAFi**) and Phot. Classification (**OATo**)
- Exoplanets identifications and characterization (**OATo**)

**Contribution to CU5**
Photpipe@Cambridge
- Absolute flux calibration and monitoring (**OABo**)
- Crowded fields (**OARm, OATe, ASDC-Gaia team**)

**Contribution to CU7**
Variability Processing @ Geneva
- Cepheids, RR Lyrae, Solar-like, … (**OABo, OACt, OANa**)

**Contribution to CU8**
Astrophysical characterisation@CNES
- Stellar parameters (**OACt, OAPd**)
- Interstellar absorption (**OATo**)

SAIt2013, Bologna
The Gaia mission - MGL
7 mag 13
The Italian contribution to DPAC is (numerically) first with that of France at approx. 18-19% of the total effort: ~ 25 FTE/yr of staff personnel (spread over just more than 60 colleagues!!) + 12 FTE/yr of contract personnel

Parallel initiatives:
- GES (S. Randich)
- GREAT (G. Clementini)
- ASDC Gaia’s team (P. Marrese)

Randich is Member of the GST, Vallenari is DPAC Deputy Chair

Coordination Group
- C. Cacciari (OABo; CU5, CU7)
- A. Lanzafame (OACt; CU7, CU8, CU3)
- A. Piersimoni (OATE; CU5)
- L. Pulone (OARm; CU5)
- V. Ripepi (OANA; CU7)
- A. Vallenari (OAPd; CU8)
The launch vehicle configuration which will be used for Gaia was qualified by the Galileo IOV-M1 launch in October 2011.

The launch vehicle assigned to Gaia is Sz 013 (Soyuz 2.1.b three stages) and 133-01 for the Fregat MT upper stage. This means that the manufacturing has started.

The launcher adaptor is ready and its fit check with the Service Module is planned in September.

The activities for the Launch Campaign preparation are ongoing.

G. Sarri | MOC-CU3_13-14.6.2012_Gaia | Slide 9
Launch date: 20 Nov 2013

DPAC has been given a schedule for a launch on Sep 29 (possibly Sep 19)
✓ Status

☐ Opportunities

☐ Problems
Deviations from GR to $3 \times 10^{-7}$ detectable: presence of residual scalar field from within the Solar System? (Vecchiato, Lattanzi et al 2003)

Circular velocity-metallicity relation in the Galaxy Thick Disk

$\langle V_\phi \rangle$ vs. $[\text{Fe/H}] : 50 \pm 5 \text{ km/s /dex}$

$(\Lambda) \text{CDM}$ prediction for the Galactic halo. Structure in phase space: true?

First detection of light deflection by Jupiter’s quadrupole ($J_2$)
(MGL 2012, MemSAIt, vol.83 No.3)
Gaia: a unique opportunity for physics and astronomy, possibly a new beginning for MW studies and Local Cosmology.

Large potential for unexpected discoveries

The Gaia legacy: delivering the catalog/archive will not be the end of the story. A treasury DB, like a space instrument but with a much longer ‘lifetime’ (!), will await at DPCT for full exploitation and leaving laboratory (new theories and/or new reduction methods to try, data mining, space science and space engineering research) for many decades to follow. All of that will be available through ASDC (data access and exploitation of catalogs for astrophysics) and DPCT (MDB investigations and reprocessing/recalibration capabilities).
Following initial investment for operational HW (early 2013, current contract), which will provide 250 TB of DB storage, system will grow to 1 PB; Oracle-based DBMS, through INAF-Oracle Italia special agreement; High speed connection to ESAC and CINECA (provided by ASI);

- Pipeline processing of AVU systems throughout DPAC operations (5+3 years since launch)
- Host copy of the Mission Data Base (MDB)
- Extended reprocessing capability from MDB and catalog extraction beyond final catalog release (**strategic legacy**).

- **A unique space-like instrument made possible by ASI for the INAF community to continue to exploit!!**
The Gaia mission - MGL

World community

Italian very own contribution to the world community

National OPPORTUNITY

CINECA

ASDC: data access

DPCT: raw data preservation and recalibration capabilities

CU9 – Public archive

DPAC

SAIt2013, Bologna
✓ Status

✓ Opportunities

❑ Problems
Gaia is on the launch pad........

• ASI has a long term commitment through MLA, but tied, by necessity, to the mission.....

• The Gaia INAF community is coming through with what it can do for its own Institute, including long term commitments

• I think it is now time for the Institute to do something for Gaia and its legacy.........a long term view for the use of a space facility that will ‘last’, unique, for decades to come!
For more info on the Gaia program go to:

http://www.rssd.esa.int/gaia