The primary objective of Gaia is the Galaxy: to observe the physical characteristics, kinematics and distribution of stars over a large fraction of its volume, with the goal of achieving a full understanding of the MW dynamics and structure, and consequently its formation and history. (Concept and Technology Study Report, ESA-SCI(2000)4)
Gaia in a nutshell

- ESA cornerstone mission building on the Hipparcos heritage
- Satellite & payload by industry management & operations by ESA data processing by scientists (DPAC)
- Launch 19 Dec 2013 with Soyuz from Kourou
- 5 years of operations at L2
- Commissioning completed 18 July 2014
- Data collection: up to 21 million transits per square deg up to end of March

- All sky survey to $R_{\text{lim}} = 20 - 21, \geq 10^9$ sources
- $\mu$as accuracy astrometry (parallaxes, positions, proper motions)
- Optical spectrophotometry (luminosities, astrophysical parameters)
- Spectroscopy to $V = 15-16$ (radial velocities), to $V= 11-12$ (rotation, chemistry)

www.cosmos.esa.int/web/gaia
Payload and Telescope

Two SiC primary mirrors
1.45 \times 0.50 \text{ m}^2 \text{ at } 106.5^\circ

FoV
1.7^\circ \times 0.6^\circ

Rotation axis (6 h)

Basic angle monitoring system

SiC toroidal structure (optical bench)

Combined focal plane (CCDs)

Superposition of two Fields of View (FoV)
Sky Scanning Principle

Spin axis: $45^\circ$ to Sun
Spin/Scan rate: $60$ arcsec/s
Spin period: $6$ hr

FoV-1: $t_0$ & $t_0 + 6$ hr
FoV-2: $t_0 + 106.5m$ & $t_0 + 106.5m + 6$ hr
repeated 10-30 days later

Precession of spin axis around solar direction in 63 days $\Rightarrow$ 29 revolutions in 5 yr

End of mission sky-average number of transits: $\sim 70$
(max $\geq 200$ at $|\beta| = 45^\circ \pm 10^\circ$)

Ecliptic coordinates

Galactic coordinates
The instruments

Slitless spectroscopy on Ca triplet (845–872 nm) Resolution 11,500

R ~ 80 – 20
R ~ 90 – 70
Focal Plane

Total field:
- active area: 0.75 deg²
- CCDs: 14 + 62 + 14 + 12
- each CCD: 4500x1966 px (TDI)
- pixel size = 10 µm x 30 µm
  = 59 mas x 177 mas

Sky mapper:
- detects all objects to 20 mag
- rejects cosmic-ray events
- FoV discrimination

Astrometry:
- total detection noise: 6 e⁻

Photometry:
- spectro-photometer
- blue and red CCDs

Spectroscopy:
- high-resolution spectra
- red CCDs

CCD X time = 4.4 s
Gaia science products: census of ...

Stellar pops in the Galaxy
(based on the Besançon Galaxy model - Robin et al. 2003, 2004)
- Disk: $9.0 \times 10^8$
- Thick disk: $4.3 \times 10^8$
- Spheroid: $2.1 \times 10^7$
- Bulge: $1.7 \times 10^8$

Special objects in the Galaxy
- Solar System bodies ($3 \times 10^5$)
- exoplanets (a few $10^4$)
- binaries & rare stellar types (fast evolutionary phases)
- WDs ($\sim 2 \times 10^5$), BDs ($\sim 5 \times 10^4$)

Outside the Galaxy
- brightest stars in nearby (LG) galaxies
- supernovae and burst sources ($\sim 2 \times 10^4$)
- galaxies ($10^6 - 10^7$)
- QSOs ($\sim 5 \times 10^5$)
- gravitational lensing events:
  $< 10^2$ photometric; a few $10^2$ astrometric

Fundamental Physics
- $\gamma$ to $\sim 5 \times 10^{-7}$ ($10^{-4} - 10^{-5}$ present)
One billion stars in 5D (6D ... 9D) will provide:

in the Galaxy ...
positions & distances, velocity distributions and astrophysical parameters (APs) of all **stellar populations** in the MW to unprecedented accuracy, allowing to:

- map the **spatial and dynamical structure** of bulge, disk(s) and halo(s)
- derive **formation and chemical history** (e.g. accretion and/or interaction events) of the MW & star formation history throughout
- obtain the trigonometric calibration of primary distance indicators (**RR Lyraes, Cepheids**) \(\Rightarrow\) accurate and robust definition of the **cosmic distance scale**

and beyond the Galaxy ...

- QSO detection and definition of rest frame
- structure & stellar population studies in nearby galaxies
Astrometric performance

- **Sky-averaged end-of-mission parallax standard error** in units of μas
- Upper and lower curves show expected variations due to position on the sky, star colour, and bright-star observing conditions (TDI gates, onboard mag-estimation errors etc.)
- The slight upturn of the linear relation in log space starting at ~ 17 mag is mainly caused by straylight

\[
\sigma_{\text{pos}} = 0.74 \sigma_w \\
\sigma_{\mu} = 0.53 \sigma_w
\]

Preliminary results: astrometry

Gaia astrometric positions placed over HST images. Gaia positions from Initial Data Treatment in a routine mode, with a very preliminary attitude determination.

9 new observations of \( Q2237+030 \) and 16 for \( HE0435-1223 \) by end 2015 + improved attitude determination \( \Rightarrow \) much better accuracy

Credits: ESA/Gaia/DPAC/C. Ducourant, J-F. Lecampion (LAB/Observatoire de Bordeaux), A. Krone-Martins (SIM/Universidade de Lisboa, LAB/Observatoire de Bordeaux), L. Galluccio, F. Mignard (Observatoire de la Côte d’Azur, Nice)
Photometric performance

- **Astrophysical parameters (AP)** can be derived using Gaia spectro-photometric data, sometimes in combination with astrometric and spectroscopic data.

- Preliminary internal accuracy (rms residuals) of AP estimates - to be reassessed on real data - on F, G, K, M dwarfs and giants for a wide range of metallicities and interstellar extinctions are (Bailer-Jones+2013, A&A 559, A74):

<table>
<thead>
<tr>
<th></th>
<th>B1V</th>
<th>G2V</th>
<th>M6V</th>
</tr>
</thead>
<tbody>
<tr>
<td>G [mag]</td>
<td>G</td>
<td>BP</td>
<td>RP</td>
</tr>
<tr>
<td>15</td>
<td>1</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>18</td>
<td>2</td>
<td>8</td>
<td>19</td>
</tr>
<tr>
<td>20</td>
<td>6</td>
<td>51</td>
<td>110</td>
</tr>
</tbody>
</table>

The accuracy is a strong function of the parameters themselves, varying by a factor of more than two up or down over this parameter range.

End-of-mission photometric errors, in units of mmag, considering all known instrumental effects including straylight, as well as a 20% science margin.

Figure courtesy C. Jordi & J.-M. Carrasco
Preliminary results: photometry I
RR Lyraes in the LMC

G-band light curves of RRL stars in the LMC observed by Gaia during the Ecliptic Pole scanning (July 2014)

-- Data points from 118 and 96 observations spread over 28 days

-- median uncertainty of measurements ~ 0.02 mag

> 800 measured, including some hundreds new discoveries, with typical average mag G ~ 19.5

Gaia image of the week 5 March 2015
RR LYRAE STARS IN THE LARGE MAGELLANIC CLOUD AS SEEN BY GAIA

I-band light curves obtained by OGLE IV for the same stars

G-band light curves of short period/faint ($G = 18.3-18.7$) Cepheids in the LMC observed by Gaia during the Ecliptic Pole scanning (July 2014)

-- Data points from 31 to 56 observations each star, spread over 32 days

-- median uncertainties of the measurements $\sim 10-15$ mmag

-- Cepheid magnitude distribution peaks at $G \sim 15.5$ mag ($M_v \sim -3$, $P \sim 3-5$ days)

Credits: ESA/Gaia/DPAC/CU5/DPCI/CU7/INAF-OABo/INAF-OACn G. Clementini, V. Ripepi, S. Leccia, L. Eyer, L. Rimoldini, I. Lecoeur-Taibi, N. Mowlavi, D. Evans, Geneva CU7/DPCG and the whole CU7 team. The photometric data reduction was done with the PhotPipe pipeline at DPCI; processing data were received from the IDT pipeline at DPCE.
Spectroscopic performance

**End-of-mission** radial-velocity errors, considering all known instrumental effects including straylight as measured during the in-orbit commissioning phase, as well as a 20% science margin.
Preliminary RVS results at bright end

Figure courtesy O. Marchal & D. Katz
Data processing & distribution

- Data Processing and Analysis Consortium (DPAC): ≥ 450 people from 20 European countries and ESA
- No proprietary data rights
- Science alerts (e.g. SNe) data released immediately
- Final catalogue ~ 2020-22
- Intermediate data releases:
  - **GDR1: Mid-2016** Positions + G magnitude (~ 90% sky, single stars)
    Includes more often scanned Ecliptic Pole regions (~ 1 deg)
    Hundred Thousand Proper Motions (HTPM Hipparcos-Gaia, ~ 50 μas/yr)
  - **GDR2: Early 2017** radial velocities for bright stars, two-band photometry, and full astrometry (α, δ, ω, μα, μδ, ) where available

Two more intermediate releases (2017/18 and 2018/19) TBD
**Stellar populations of the MW**

Some selected **kinematic tracers**: $\sigma_{\text{vel}}$ = velocity dispersion of MW component

<table>
<thead>
<tr>
<th>MW component</th>
<th>Tracer</th>
<th>Mv mag</th>
<th>Av mag</th>
<th>D kpc</th>
<th>V mag</th>
<th>$\sigma_{\text{vel}}$ km/s</th>
<th>Gaia $\sigma_\mu$ μas/yr - km/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulge</td>
<td>gM (M0III)</td>
<td>-1</td>
<td>5</td>
<td>8</td>
<td>18.5</td>
<td>100</td>
<td>67 – 2.5</td>
</tr>
<tr>
<td></td>
<td>HB (A5V)</td>
<td>+0.5</td>
<td>5</td>
<td>8</td>
<td>20</td>
<td>100</td>
<td>324 – 12</td>
</tr>
<tr>
<td></td>
<td>MS-TO (G2V)</td>
<td>+4.5</td>
<td>2</td>
<td>5</td>
<td>20</td>
<td>100</td>
<td>290 – 6.9</td>
</tr>
<tr>
<td>Thin disk warp</td>
<td>gK (K3III)</td>
<td>0</td>
<td>2</td>
<td>10</td>
<td>17</td>
<td>10-20</td>
<td>33 – 1.6</td>
</tr>
<tr>
<td></td>
<td>gM (M0III)</td>
<td>-1</td>
<td>2</td>
<td>10</td>
<td>16</td>
<td>10-20</td>
<td>20 - 0.9</td>
</tr>
<tr>
<td>Thick disk</td>
<td>gK (K3III)</td>
<td>0</td>
<td>2</td>
<td>8</td>
<td>16.5</td>
<td>50-60</td>
<td>25 – 1.0</td>
</tr>
<tr>
<td></td>
<td>HB (A5V)</td>
<td>+0.5</td>
<td>0</td>
<td>8</td>
<td>17</td>
<td>50-60</td>
<td>39 – 1.5</td>
</tr>
<tr>
<td></td>
<td>gK (K3III)</td>
<td>0</td>
<td>0</td>
<td>15</td>
<td>18</td>
<td>30</td>
<td>59 - 4.2</td>
</tr>
<tr>
<td></td>
<td>HB (A5V)</td>
<td>+0.5</td>
<td>2</td>
<td>15</td>
<td>18.5</td>
<td>30</td>
<td>100 – 7.1</td>
</tr>
<tr>
<td>Spiral arms</td>
<td>Cepheids (F8)</td>
<td>- 3</td>
<td>5</td>
<td>10</td>
<td>17</td>
<td>10-20</td>
<td>37 – 1.8</td>
</tr>
<tr>
<td></td>
<td>SgB (B0I)</td>
<td>- 5</td>
<td>5</td>
<td>10</td>
<td>15</td>
<td>10-20</td>
<td>14 - 0.7</td>
</tr>
<tr>
<td></td>
<td>SgM (M7III)</td>
<td>- 5</td>
<td>5</td>
<td>10</td>
<td>15</td>
<td>10-20</td>
<td>4 - 0.2</td>
</tr>
<tr>
<td>Inner</td>
<td>gK (K3III)</td>
<td>- 1</td>
<td>0</td>
<td>10</td>
<td>14</td>
<td>100</td>
<td>8 - 0.4</td>
</tr>
<tr>
<td>Halo</td>
<td>HB (A5V)</td>
<td>+0.5</td>
<td>0</td>
<td>10</td>
<td>15.5</td>
<td>100</td>
<td>18 - 0.9</td>
</tr>
<tr>
<td></td>
<td>MS-TO (G2V)</td>
<td>+4.5</td>
<td>0</td>
<td>10</td>
<td>19.5</td>
<td>100</td>
<td>193 – 9.1</td>
</tr>
<tr>
<td>Outer</td>
<td>gK (K3III)</td>
<td>-1</td>
<td>0</td>
<td>30</td>
<td>16.5</td>
<td>100</td>
<td>25 – 3.6</td>
</tr>
<tr>
<td></td>
<td>HB (A5V)</td>
<td>+0.5</td>
<td>0</td>
<td>30</td>
<td>18</td>
<td>100</td>
<td>71 - 10</td>
</tr>
</tbody>
</table>
The disk: open clusters

NGC 2099 - Kalirai et al. 2001  
d=1.4 kpc  
age=0.5 Gy

NGC 2401 - Baume et al. 2006  
d=6.3 kpc  
age=25 My

Be 29 - Tosi et al. 2004  
d=22 kpc  
age=3.5 Gy

All the MW open clusters will be observed by Gaia
The distance scale: **Galactic RR Lyraes**

**GEOS database photometry:**

\[ M_V = 0.52 \ (\sim [\text{Fe/H}] = -1.5 \ \text{dex}) \]

\[ V-I = 0.50 \]

\[ \langle V \rangle = \left( V_{\text{max}} + V_{\text{min}} \right) / 2 \]

Zero reddening

\[ \Rightarrow \ \text{Individual end-of-mission} \]

\[ \sigma_\pi / \pi \ \text{estimates} \]

<table>
<thead>
<tr>
<th>n. stars</th>
<th>( \sigma_\pi / \pi )</th>
<th>D(kpc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(~ 5 % \ (\sim 340) )</td>
<td>( \leq 1% )</td>
<td>( \leq 2 )</td>
</tr>
<tr>
<td>(~ 15 % \ (\sim 1000) )</td>
<td>( \leq 5% )</td>
<td>( \leq 4 )</td>
</tr>
<tr>
<td>(~ 26 % \ (\sim 1750) )</td>
<td>( \leq 10% )</td>
<td>( \leq 6 )</td>
</tr>
<tr>
<td>(~ 43 % \ (\sim 2900) )</td>
<td>( \leq 20% )</td>
<td>( \leq 8 )</td>
</tr>
<tr>
<td>(~ 60 % \ (\sim 4000) )</td>
<td>( \leq 30% )</td>
<td>( \leq 10 )</td>
</tr>
</tbody>
</table>

**Expected from Gaia**

\(~ 15-40 \ 10^3 \) bulge

\(~ 70 \times 10^3 \) halo

\(~ > 25 \times 10^3 \) LMC

(Eyer & Cuypers, 2000)
The distance scale: Galactic Cepheids

Only ≤ 1000 Galactic Cepheids are known - most are located in the Solar neighbourhood
~ 400 Galactic Cepheids from David Dunlap Observatory DB ➔ photometry, reddening, distance, magnitude

Gaia predicted accuracy
≤ 1% for 145 stars (35%)
≤ 2% for 290 stars (70%)
≤ 4% for 390 stars (95%)

Presently, there are only ~ 250 Cepheids with parallax & photometry ➔ ~ 100 with σ_π ≤ 1 mas (Hipparcos) - 10 with HST parallax

Estimated MW Cepheids for Gaia: 2-9 x 10^3 (Eyer & Cuypers, 2000; Windmark 2011)

➔ direct (trigonometric) calibration of local standard candles for the cosmological distance scale
Case 1: globular clusters

**Simulation tool**

Produce a full 3-D synthetic cluster at dynamical equilibrium

Assign magnitudes to all stars from appropriate stellar models: old & metal-poor

Place it at a given distance

Add reddening and contamination by field stars [from a Galactic model: Besançon]

Simulate the process of Gaia observation [end of mission] including crowding

Pancino, Bellazzini, Marinoni 2013, MemSAIt, 84, 83
### Astrometry: systemic motion

**Easy cluster**  \( M_v = -7.6 \)

- \( \mu_{RA/Dec} = 5000 \mu\text{as/yr} = 118 \text{ km/s} \)
- Distance = 5 kpc

With (de)blends (16838):
- \( \mu_{RA} = 4998.7 \pm 0.8 \mu\text{as/yr} \)
- \( \mu_{Dec} = 5000.2 \pm 0.7 \mu\text{as/yr} \)
- \( \pi = 199.7 \pm 0.7 \mu\text{as} \)
- \( D = 5.007 \pm 0.007 \text{ kpc} \)

**Difficult cluster**

- \( \mu_{RA/Dec} = 5000 \mu\text{as/yr} = 237 \text{ km/s} \)
- Distance = 10 kpc

With deblends (3513):
- \( \mu_{RA} = 4993 \pm 3 \mu\text{as/yr} \)
- \( \mu_{Dec} = 4994 \pm 3 \mu\text{as/yr} \)
- \( \pi = 101.2 \pm 1.4 \mu\text{as} \)
- \( D = 9.997 \pm 0.017 \text{ kpc} \)

**Tens of GCs with \( D \leq 10 \text{ kpc} \)**

**Orbits:** find out groups from common progenitors

Credits: Elena Pancino (INAF-OABo)
Case 2: dwarf spheroidal galaxy Draco

\[ M_V = -9.0 \quad \mu_{V,0} = 25.0 \text{ mag/arcsec}^2 \quad D = 93 \text{ kpc} \]

\[ 2^\circ \times 2^\circ \text{ CFHT photometry from Segall et al 2007} \]

After statistical decontamination \( \Rightarrow \) 750 RGB stars with \( V \leq 20 \)

Courtesy Michele Bellazzini, OABo
To each of the 750 Draco member stars observable by Gaia I associate:

- A realistic SYSTEMIC tangential motion (amplitudes from HST estimates)
- A realistic velocity dispersion (9.1 km/s, assuming isotropy)
- Observational errors from de Bruijne’s model
- To simulate non-perfect knowledge of individual observational errors a Gaussian component of amplitude 10% is added to the error

For each star observed by Gaia I obtain realistic:

PMRA ± ePMRA & PMDE ± ePMDE
Case 2: dwarf spheroidal galaxy Draco

Maximum Likelihood estimate of systemic proper motion and velocity dispersion using a simple gaussian model. In input PMRA ± ePMRA & PMDE ± ePMDE

State of the art systemic PM with HST: uncertainty = 0.063 mas/yr (Pryor et al. 2015)

<table>
<thead>
<tr>
<th>N./M_v</th>
<th>Error inaccuracy</th>
<th>TRUE &lt;PMRA&gt;</th>
<th>Measured &lt;PMRA&gt;</th>
<th>TRUE &lt;PMDE&gt;</th>
<th>Measured &lt;PMDE&gt;</th>
<th>TRUE σ</th>
<th>Measured σ</th>
<th>Gaia/HST</th>
</tr>
</thead>
<tbody>
<tr>
<td>750/-9.0 in mas/yr</td>
<td>10%</td>
<td>0.177</td>
<td>0.175 ±0.0033</td>
<td>-0.221</td>
<td>-0.217 ±0.0031</td>
<td>0.0206</td>
<td>0.0210 ±0.0054</td>
<td>~19</td>
</tr>
<tr>
<td>750/-9.0 in km/s</td>
<td>10%</td>
<td>78.0</td>
<td>77.1 ±1.4</td>
<td>97.4</td>
<td>-95.6 ±1.4</td>
<td>9.1</td>
<td>9.2 ±2.4</td>
<td></td>
</tr>
<tr>
<td>75/-6.5 in mas/yr</td>
<td>10%</td>
<td>0.177</td>
<td>0.172 ±0.0119</td>
<td>-0.221</td>
<td>-0.217 ±0.0093</td>
<td>0.0206</td>
<td>0.0420 ±0.0156</td>
<td>~6</td>
</tr>
<tr>
<td>10/-4.3 in mas/yr</td>
<td>10%</td>
<td>0.177</td>
<td>0.180 ±0.030</td>
<td>-0.221</td>
<td>-0.185 ±0.030</td>
<td>0.0206</td>
<td>------</td>
<td>~2</td>
</tr>
</tbody>
</table>
Summary – Conclusions

□ In the Galaxy Gaia will provide the distances, velocity distributions and APs of all stellar populations to unprecedented accuracy as far as 10 kpc (and beyond), allowing to:
   - map the spatial and dynamical structure of the MW components
   - identify merger debris, streams etc. (evidence of accretion and/or interaction events), and derive the MW formation and chemical history
   - derive the star formation history throughout the Galaxy
   - obtain the trigonometric calibration of primary distance indicators ➔ a definitive and robust definition of the cosmic distance scale

□ Comparable astrometric accuracy may be achieved by other present (future) space- & ground-based facilities, but on small areas of the sky

□ Several surveys (especially the high-resolution spectroscopic ones, see talk by Carlos Allende-Prieto) will be very important: none will provide all-sky coverage, but all will contribute to complement and extend the scientific potential of the Gaia data
more information on Gaia at

http://www.cosmos.esa.int/web/gaia