The Gaia Mission
A billion star map of the galaxy

Avi Shporer
Sagan Fellow, JPL

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Take Home Message:

Gaia is a game changer in astrophysics and exoplanets
What is the Gaia Mission?

A Multidimensional 1 billion star survey:

- 3D position
  - Sky Position
  - Distance (parallax)

- 3D velocity
  - Proper motion
  - Doppler RV

- Additional "dimensions"
  - Stellar characteristics:
    - $T_{\text{eff}}$
    - log(g)
    - Metallicity
Gaia focal plane

- Astrometric Field (AF), 330-1050 nm, $G \sim 20$ mag
- Spectro-photometry, 62 pix spectroscopy:
  - Blue Photometer (BP), 330-680 nm
  - Red Photometer (RP), 640-1050 nm
- Radial Velocity Spectrometer (RVS), $R=11500$, 847-871 nm, $V \sim 16$ mag
Gaia Performance

Astrometry:

<table>
<thead>
<tr>
<th></th>
<th>B1V</th>
<th>G2V</th>
<th>M6V</th>
</tr>
</thead>
<tbody>
<tr>
<td>V - Ic [mag]</td>
<td>-0.22</td>
<td>0.75</td>
<td>3.85</td>
</tr>
<tr>
<td>Bright stars</td>
<td>5-14 µas (3 mag &lt; V &lt; 12 mag)</td>
<td>5-14 µas (3 mag &lt; V &lt; 12 mag)</td>
<td>5-14 µas (5 mag &lt; V &lt; 14 mag)</td>
</tr>
<tr>
<td>V = 15 mag</td>
<td>26 µas</td>
<td>24 µas</td>
<td>9 µas</td>
</tr>
<tr>
<td>V = 20 mag</td>
<td>600 µas</td>
<td>540 µas</td>
<td>130 µas</td>
</tr>
</tbody>
</table>

Photometry:
Noise level in milli-magnitude

<table>
<thead>
<tr>
<th></th>
<th>B1V</th>
<th>G2V</th>
<th>M6V</th>
</tr>
</thead>
<tbody>
<tr>
<td>G [mag]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>18</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>20</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
</tbody>
</table>

Radial velocity:

<table>
<thead>
<tr>
<th>Spectral type</th>
<th>V [mag]</th>
<th>Radial-velocity error [km s⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1V</td>
<td>7.5</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>11.3</td>
<td>15</td>
</tr>
<tr>
<td>G2V</td>
<td>12.3</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>15.2</td>
<td>15</td>
</tr>
<tr>
<td>K1III-MP (metal-poor)</td>
<td>12.8</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>15.7</td>
<td>15</td>
</tr>
</tbody>
</table>
Gaia Mission Trivia

- Launch: December 2013
- 50-110 epochs in 5 years (2014-2019)
- Possible extended mission: up to 5 years
- 2 x 0.7 m$^2$ rectangular mirrors
- L2 orbit
- Price: 940 M Euro (ESA + member states)
- 106 CCDs, ~1 billion pixels
- Diameter: 3.5 m (10 m with Sun shield)
- Weight: ~2.0 Tons
- FOV: 0.85 x 0.66 deg
- Gaia, not GAIA…
Science with Gaia

Galactic structure

Variable and binary stars

Stellar evolution

Exoplanets

Solar system

Supernovae

Image: ESO/L. Calçada

Image: Richard Powell

Image Credit: High-Z Supernova Search Team, HST, NASA
What can Gaia do for me?!...
Exoplanets with Gaia

Astrometric signal:

\[ \alpha_s = \left( \frac{a_s}{\text{AU}} \right) \left( \frac{d}{\text{pc}} \right)^{-1} \text{arcsec} \]

\[ a_s M_s = a_2 M_2 \]

\[ \alpha_s \approx \left( \frac{M_2}{M_J} \right) \left( \frac{M_s}{M_\odot} \right)^{-1} \left( \frac{a_2}{\text{AU}} \right) \left( \frac{d}{\text{pc}} \right)^{-1} 10^3 \mu\text{as} \]

For bright stars:
- single measurement \( \sigma_{\text{fov}} \approx 30 \mu\text{as} \),
- parallax \( \sigma_\omega \approx 10 \mu\text{as} \)
\[
\alpha_s \approx \left( \frac{M_2}{M_J} \right) \left( \frac{M_s}{M_\odot} \right)^{-1} \left( \frac{a_2}{\text{AU}} \right) \left( \frac{d}{\text{pc}} \right)^{-1} 10^3 \mu\text{as}
\]

Unknown distances assumed to be 1,000 pc
Circle radius proportional to planet mass  

Perryman et al. 2014
\[ \alpha_s \approx \left( \frac{M_2}{M_\text{J}} \right) \left( \frac{M_s}{M_\odot} \right)^{-1} \left( \frac{a_2}{\text{AU}} \right) \left( \frac{d}{\text{pc}} \right)^{-1} 10^3 \mu\text{as} \]
ABSTRACT

We provide a revised assessment of the number of exoplanets that should be discovered by Gaia astrometry, extending previous studies to a broader range of spectral types, distances, and magnitudes. Our assessment is based on a large representative sample of host stars from the TRILEGAL Galaxy population synthesis model, recent estimates of the exoplanet frequency distributions as a function of stellar type, and detailed simulation of the Gaia observations using the updated instrument performance and scanning law. We use two approaches to estimate detectable planetary systems: one based on the signal-to-noise ratio of the astrometric signature per field crossing, easily reproducible and allowing comparisons with previous estimates, and a new and more robust metric based on orbit fitting to the simulated satellite data. With some plausible assumptions on planet occurrences, we find that some 21,000 (±6000) high-mass (≈1−15 \textit{M}_J) long-period planets should be discovered out to distances of ≈500 pc for the nominal 5 yr mission (including at least 1000–1500 around M dwarfs out to 100 pc), rising to some 70,000 (±20,000) for a 10 yr mission. We indicate some of the expected features of this exoplanet population, amongst them ≈25–50 intermediate-period (P ≈ 2–3 yr) transiting systems.
Simulated detections:

- Number of detected exoplanets in the mass range $M_p (M_J)$.
- Number of detected exoplanets in the semi-major axis range $a$ (AU).
- Number of detected exoplanets in the eccentricity range $e$.

**Astrometric exoplanet detection with Gaia**

“Astrometric exoplanet detection with Gaia”


Simulated detections:

Simulated population:

NASA Exoplanet Archive

Planet mass
Exoplanet hunting with Gaia

• Accurate mass: no $M_p$ and $\sin(i)$ degeneracy

• Wide range of host star properties:
  ‣ Mass, Metallicity, Evolutionary stage

• Transit:
  ‣ Astrometrically predicted

Astrometry you use, mass and inclination degeneracy no more!
Gaia contributions to exoplanet science

• Stellar characterization:
  ‣ Improved known planet hosts parameters
    ➞ Re-calculate known planet properties
  ‣ Future targets for transit surveys

• Astrometric companions to known planetary systems

• Brown dwarf companions
  ‣ Wide range in host star parameters
Astronomy in the 2020’s

Emerging (synergetic) science

“The whole is larger than the sum of its parts”
Emerging (synergetic) science

“The whole is larger than the sum of its parts”
Simulating Gaia data for bright stars
Courtesy Michael Perryman et al.

- $G < 7$ mag
- $0.5 < M_2 < 15 M_J$
- 5-year mission
- 0.1” resolution

Reflected-light low-res spectrum of planets with measured mass
Take Home Message:

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Data release schedule:

**Mid-2016:** Positions, G magnitude.

**Early 2017:** RV, photometry, astrometry.
The Gaia Mission

A billion star map of the galaxy

Resources:
Perryman et al. 2014
Sozzetti et al. 2014
Sozzetti 2011
sci.esa.int/gaia
cosmos.esa.int/web/gaia/
blogs.esa.int/gaia
gai.ub.edu/Twiki/bin/view/GREATITNFC/

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Extra Slides
$\alpha_s \approx \left( \frac{M_2}{M_J} \right) \left( \frac{M_0}{M_\odot} \right)^{-1} \left( \frac{a_2}{AU} \right) \left( \frac{d}{pc} \right)^{-1} 10^3 \mu\text{as}$

$0.4 \, M_\odot \ @ \ 25 \, \text{pc}$

Sozzetti 2011
Primary mirrors for the Astro telescopes
Beam combination optics
Astro focal plane
Primary mirror for Spectro
Spectro focal plane
Basic angle monitoring system
Focal plane assembly radiator

Schematic figure of the Gaia payload
Gaia Data Releases (Pre-commissioning)

- Intermediate Data Release Scenario agreed with inputs from Data Release Policy and DPAC Operations Plan
  - Science Alerts as soon as possible
  - L+22m positions, G-magnitudes, proper motions to Hipparcos stars, ecliptic pole data
  - L+28m + first 5 parameter astrometric results, bright star radial velocities, integrated BP/RP photometry
  - L+40m + BP/RP data, some RVS spectra, astrophysical parameters, orbital solutions for short period binaries
  - L+65m + variability, solar system objects

Post-Commissioning: First data release expected by mid-2016
WFIRST Coronagraph

- 400 - 1000 nm
- $10^{-9}$ contrast
- 0.1 arcsec @ 400 nm
- IFS: R~70

$$6 \times 10^{-8} \left( \frac{R_2}{R_J} \right)^2 \left( \frac{a_2}{\text{AU}} \right)^{-2}$$

- Gas and ice giant planets in reflected light
- Characterize planetary atmospheres
- Test technology for future terrestrial planet imaging mission
## WFIRST-2.4 coronagraph

<table>
<thead>
<tr>
<th>Bandpass</th>
<th>400-1000 nm</th>
<th>Measured sequentially in five 18% bands</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner Working Angle</td>
<td>100 mas</td>
<td>at 400 nm, 3λ/D driven by challenging pupil</td>
</tr>
<tr>
<td></td>
<td>250 mas</td>
<td>at 1 μm</td>
</tr>
<tr>
<td>Outer Working Angle</td>
<td>1 arcsec</td>
<td>at 400 nm, limited by 64x64 DM</td>
</tr>
<tr>
<td></td>
<td>2.5 arcsec</td>
<td>at 1 μm</td>
</tr>
<tr>
<td>Detection Limit</td>
<td>Contrast=10^{-9}</td>
<td>Cold Jupiters. Deeper contrast looks unlikely due to pupil shape and extreme stability requirements.</td>
</tr>
<tr>
<td>Spectral Resolution</td>
<td>70</td>
<td>With IFS</td>
</tr>
<tr>
<td>IFS Spatial Sampling</td>
<td>17 mas</td>
<td>This is Nyquist for λ = 400 nm</td>
</tr>
</tbody>
</table>

**Table 3-3: Key coronagraph instrument characteristics**
Precursor Observations

- LBT-I observations of dust around nearby stars will greatly leverage WFIRST-AFTA disk imaging
  - LBT-I gives total area & mass, adding WFIRST-AFTA gives grain reflectance/albedo
- More ground-based radial velocity (RV) measurements are needed; masses of planets are critical for understanding WFIRST-AFTA spectra
  - Working to evaluate completeness of specific WFIRST-AFTA candidate stars
- Coronagraph science would benefit greatly from having more known RV planets with measured masses ($m \sin i$) by launch date:
  - A list of known planets will make WFIRST-AFTA much more efficient for detection and characterization
  - RV investments are valuable now for WFIRST: orbits and masses take years
- GAIA astrometry mission will also provide masses in addition to RV
Gaia 2D stellar density sky map (not an image!)