On the Gaia Exoplanet Discovery Potential

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Astrometry: Blunders

1940’s: Strand, Reuyl & Holmberg (61 Cyg, 70 Oph)
1960’s: Lippincott, Hershey (Lalande 21185)
1960’s-80’s: Van de Kamp (Barnard’s Star)
1980’s: Gatewood (Lalande 21185, again)
2001: Han et al. (some 20 RV planets)
2009: Pravdo & Shaklan (VB10b)

Fig. 1. Barnard’s star: Yearly means, averaging 100 plates and weight 68; time-displacement curves for \( P = 25 \) yr, \( e = 0.75 \), \( T = 1950 \).

mas-precision astrometry is usually not enough for planet detection
Astrometry measures stellar positions and uses them to determine a binary orbit projected onto the plane of the sky. It measures all 7 parameters of the orbit, in multiple systems it derives the relative inclination angles between pairs of orbits, regardless of the actual geometry. Mass is derived given a guess for the primary's.

In analysis, one has to take the proper motion and the stellar parallax into account.

The measured amplitude of the orbital motion (in mas) is:

\[
\Delta \theta = 0.5 \left( \frac{q}{10^{-3}} \right) \left( \frac{a}{5 \text{AU}} \right) \left( \frac{d}{10 \text{pc}} \right)^{-1}
\]
μas Astrometry: Challenges

Two main directions for improvement:

1) Monolithic configurations (optical)
2) Diluted configurations (optical/near IR)

- Narrow-angle, relative astrometry: both from the ground and in space (VLTI/PRIMA,???)
- Global astrometry: only in space (Gaia)

Like RV, it faces:

- technological challenges (achievable precision, ground vs. space, instrument configuration, choice of wavelength, calibrations, etc.)
- astrophysical challenges (noise sources characterization)
- data modeling challenges (orbital fits)

See e.g. Sozzetti (2005, 2010)

<table>
<thead>
<tr>
<th>Source</th>
<th>( \alpha )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jupiter at 1 AU (μas)</td>
<td>100</td>
</tr>
<tr>
<td>Jupiter at 5 AU (μas)</td>
<td>500</td>
</tr>
<tr>
<td>Jupiter at 0.05 AU (μas)</td>
<td>5</td>
</tr>
<tr>
<td>Neptune at 1 AU (μas)</td>
<td>6</td>
</tr>
<tr>
<td>Earth at 1 AU (μas)</td>
<td>0.33</td>
</tr>
<tr>
<td>Parallax (μas)</td>
<td>( 1 \times 10^2 )</td>
</tr>
<tr>
<td>Proper motion (μas yr(^{-1}))</td>
<td>( 5 \times 10^2 )</td>
</tr>
</tbody>
</table>

Note. — A 1 \( M_\odot \) star at 10 pc is assumed.

Sozzetti 2005
Gaia in a nutshell

- ESA mission building on the Hipparcos heritage
- Astrometry, Photometry and Spectroscopy
- Satellite, including the payload, by industry (Astrium, Toulouse), operations by ESA and data processing by scientists (DPAC)
- Launch October 2013
- Science Alerts early on
- First intermediate data release 22 months after launch

Hot Planets and Cool Stars  
Garching-MPE, 16 Nov 2012
Number of FoV crossings per star (5 yr)

Equatorial projection
Gaia vs. Hipparcos

- Magnitude limits:
  - Hipparcos < 12 mag
  - Gaia 6 - 20 mag
- Number of objects: 120,000 => 10^9
- Accuracy: milliarcsec => μarcsec
- Radial velocity: none => 150 million
- Pre-selected => Unbiased survey
It’s Almost Ready!

* Gaia Protoflight Payload Module fully integrated

* Spacecraft level assembly starting early 2013 leading to launch in October

* Galileo launch in October 2011 successful and with mechanical loads as anticipated

* Gaia launcher manufacturing started (ahiahi, Soyuz rocket Sz-013!)
Intermediate Data Releases

- 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
1. $6 < G < 12$: bright-star regime (calibration errors, CCD saturation)
2. $12 < G < 20$: photon-noise regime (sky-background and electronic noise at $G \sim 20$ mag)
CCD-level Location Estimation
Fitting Planetary Systems Orbits

• Highly non-linear fitting procedures, with a large number of model parameters (at a minimum, $N_p = 5 + 7 \times n_{pl}$, not counting references)

• Redundancy requirement: $N_{\text{obs}} \gg N_p$

• Global searches (grids, Fourier decomposition, genetic algorithms, Bayesian inference + MCMC) must be coupled to local minimization procedures (e.g., L-M)

• For strongly interacting systems, dynamical fits using N-body codes will be required
Assessing Detections

- Errors on orbital parameters: covariance matrix vs. $\chi^2$ surface mapping vs. bootstrapping procedures

- Confidence in an n-component orbital solution: FAPs, F-tests, MLR tests, statistical properties of the errors on the model parameters, others?

- Importance of consistency checks between different solution algorithms

- Memento lessons learned from RV surveys, with disagreement on orbital solution details, and sometime number of planets!!
Exoplanets in the Gaia DPAC Pipeline
1) $2-3 \, M_J$ planets at $2 < a < 4 \, \text{AU}$ are detectable out to $\sim 200 \, \text{pc}$ around solar analogs.

2) Saturn-mass planets with $1 < a < 4 \, \text{AU}$ are measurable around nearby ($< 25 \, \text{pc}$) M dwarfs.

For Gaia: $\sigma_A \sim 20 \, \mu\text{as}$
How Many Planets will Gaia find?

Star counts (V<13), $F_p(M_p,P)$, Gaia completeness limit

<table>
<thead>
<tr>
<th>$\Delta d$ (pc)</th>
<th>$N_s$</th>
<th>$\Delta a$ (AU)</th>
<th>$\Delta M_p (M_J)$</th>
<th>$N_d$</th>
<th>$N_m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-50</td>
<td>$\sim 10,000$</td>
<td>1.0 - 4.0</td>
<td>1.0 - 13.0</td>
<td>$\sim 1400$</td>
<td>$\sim 700$</td>
</tr>
<tr>
<td>50-100</td>
<td>$\sim 51,000$</td>
<td>1.0 - 4.0</td>
<td>1.5 - 13.0</td>
<td>$\sim 2500$</td>
<td>$\sim 1750$</td>
</tr>
<tr>
<td>100-150</td>
<td>$\sim 114,000$</td>
<td>1.5 - 3.8</td>
<td>2.0 - 13.0</td>
<td>$\sim 2600$</td>
<td>$\sim 1300$</td>
</tr>
<tr>
<td>150-200</td>
<td>$\sim 295,000$</td>
<td>1.4 - 3.4</td>
<td>3.0 - 13.0</td>
<td>$\sim 2150$</td>
<td>$\sim 1050$</td>
</tr>
</tbody>
</table>

Casertano, Lattanzi, Sozzetti et al. 2008

How Many Multiple-Planet Systems will Gaia find?

Star counts (V<13), $F_p(mult,M_p,P)$, Gaia detection limit

<table>
<thead>
<tr>
<th>Case</th>
<th>Number of Systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detection</td>
<td>$\sim 1000$</td>
</tr>
<tr>
<td>Orbits and masses to better than 15-20%  accuracy</td>
<td>$\sim 400 - 500$</td>
</tr>
<tr>
<td>Successfull coplanarity tests</td>
<td>$\sim 150$</td>
</tr>
</tbody>
</table>

Unbiased, magnitude-limited planet census of hundreds of thousands stars
• Gaia & spectroscopic characterization observatories (e.g., EChO)
• Gaia & transit surveys from the ground (e.g., WASP) and in space (CoRoT, Kepler)
• Gaia & direct imaging observatories (e.g., SPHERE/PCS)
• Gaia & RV programs (e.g., HARPS(-N), ESPRESSO, CARMENES, and the likes)
• Gaia & ground-based and space-borne astrometry

**Objectives of study within the GREAT RNP/ITN**

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*Hot Planets and Cool Stars*  
Garching-MPE, 16 Nov 2012
Cool, nearby M dwarfs within a few tens of parsecs from the Sun are now the focus of dedicated experiments in the realm of exoplanets astrophysics.

**WHY?**

* Shifting theoretical paradigms in light of new observations

* Improved understanding of the observational opportunities for planet detection and characterization provided by this sample.

**WHAT CAN Gaia CONTRIBUTE?**

* Gaia, in its all-sky survey, will deliver precision astrometry for a magnitude-limited sample of M dwarfs, providing an inventory of cool nearby stars with a much higher degree of completeness (particularly for late sub-types) with respect to currently available catalogs.
SIMULATION SCHEME


2) Updated Gaia scanning law. $T=5$ yr nominal mission duration

3) Up-to-date error model as a function of Gaia $G$-band mag (inclusive of gate scheme for 20% of bright [$G<12$] stars). Single-measurement errors are typically $\sigma_m \sim 100 \mu$as

4) Actual list of targets: 3150 M dwarfs (0.09-0.6 $M_{\text{SUN}}$) within 33 pc from the Sun from the LSPM-North Catalog (Lépine 2005, AJ, 130, 1680), with average $G \sim 14.0$ mag and $M_* \sim 0.3 \, M_{\text{SUN}}$

5) 1 $M_{\text{JUP}}$ companions, orbital periods $P < 3T$, moderate eccentricities ($e<0.6$), all other orbital elements uniformly distributed within their respective ranges
Determining Giant Planets Orbits (1)

Fractional Error (%) vs Orbital Period (yr)

- d < 33 pc
- d < 15 pc
- G < 12
How Many Giants?

- Present-day estimates from RV surveys imply $f_p \sim 3-4\%$ (within 3 AU)
- Gaia could identify $\sim 100$ giant planets around this sample, an order-of-magnitude increase
- For approximately 50% of them, accurate orbit reconstruction will be possible
- The sample size is such that $f_p$ will be put on much more solid statistical grounds
- Very important synergy with present (e.g., HARPS@ESO), starting (e.g., HARPS-N@TNG), and upcoming (ESPRESSO@VLT) RV surveys
For quasi-edge-on orbits, $i$ is measured to $\sim 3\%$.

Gaia may find hundreds of giant planets around M dwarfs (and thousands around F-G-K dwarfs). Some may be transiting!

Obvious synergy with ground-based transit work!
For well-sampled orbits (P<T), $\Delta \rho < 0.01$ AU/yr and $\Delta \theta < 2$ deg/yr (Over an order of magnitude better than HST/FGS predictions for $\varepsilon$ Eri!)
Assuming $\Phi(\beta)$ of a Lambert sphere, typically $\Delta \beta \sim$ several deg, $\Delta \Phi(\beta) \sim 0.1$
For $0.3 < a < 3.0$ AU, uncertainties in the emergent flux will typically be 10-15%.

Potential synergy with direct imaging, reflected light and atmospheric characterization measurements.
Re-Calibrating the Hosts

• ALL parallaxes of this M dwarf sample released formally around mid-2016 (not to mention the improvement in completeness levels down to V=20!)

• For a typical target with V~14 at d~ 20 pc, expect $\sigma(\pi)/\pi<0.1\%$

• Re-calibrate absolute luminosities

• Derive trigonometric gravities to $\sim 0.03$ dex

• Re-determine the stellar radii to $<3\%$

• Great synergy with ongoing (MEarth), starting (APACHE), and upcoming (NGTS) ground-based surveys, as well as space-based observatories (e.g., EChO)
The Message
(take it home!)

- **Providing the largest catalogue of ‘new’ astrometric orbits & masses of extrasolar planets and superbly accurate parallaxes is Gaia’s defining role in the exoplanet arena.**

- **The synergies between Gaia and ongoing and planned exoplanet detection and (atmospheric) characterization programs from the ground and in space are potentially huge**

- This was a snippet of the Gaia potential on the sample of nearby low-mass M dwarfs

- Gaia’s ‘first’ release: L+22m (Summer 2015)

- Gaia’s ‘first’ major release: L+28m (Beginning of 2016)

- Gaia’s ‘first’ complete catalog release: L+40m (Early 2017)