Young Stars & Planets Near the Sun
Proceedings IAU Symposium No. 314, 2015
J. H. Kastner, B. Stelzer, & S. A. Metchev, eds.

doi:10.1017/S1743921315006535

Gaia: The Astrometry Revolution

A. Sozzetti[1], M. Bonavita[2], S. Desidera[3], R. Gratton[3] and M. G. Lattanzi[1]

[1]INAF - Osservatorio Astrofisico di Torino - Via Osservatorio 20, I-10025 Pino Torinese (Italy)
email: `sozzetti@oato.inaf.it`
[2]The University of Edinburgh, Royal Observatory, Blackford Hill, Edinburgh EH9 3HJ, UK
[3]INAF - Osservatorio Astronomico di Padova - Vicolo dell'Osservatorio 5, I-35122 Padova (Italy)

Abstract. The power of micro-arcsecond (μas) astrometry is about to be unleashed. ESA's Gaia mission, now headed towards the end of the first year of routine science operations, will soon fulfil its promise for revolutionary science in countless aspects of Galactic astronomy and astrophysics. The potential of Gaia position measurements for important contributions to the astrophysics of planetary systems is huge. We focus here on the expectations for detection and improved characterization of 'young' planetary systems in the neighborhood of the Sun using a combination of Gaia μas astrometry and direct imaging techniques.

Keywords. planetary systems, astrometry, open clusters and associations: general, methods: numerical

1. Introduction

The study of nearby young moving groups (NYMGs) in the vicinity ($d \lesssim 100 - 200$ pc) of the Sun is of particular relevance to improve our understanding of many a key issue related to the early evolutionary stages of stars, circumstellar disks, and planetary systems. NYMGs are excellent laboratories indeed, as their precise and accurate identification, the determination of clean samples of bona-fide members (down to the sub-stellar regime), their origin, age, distance from Earth, and multiplicity properties (see, e.g., the review and contributed papers by Kastner, Mamajek, Pinsonneault, Elliott and Faherty, this volume) are keys to a) provide new insights into the early evolution of low- to intermediate-mass stars (see, e.g., the review and contributed papers by Feiden, Baraffe, Matt and Kraus, this volume), b) shed light on protoplanetary disk sculpting and dispersal (see, e.g., the review papers by Cieza, Birnstiel and Kospal, this volume), and c) globally understand giant and terrestrial planet formation, and the transition region between giant planets and brown dwarfs (see, e.g., the review and contributed papers by Mordasini, Chauvin, Marley, Allers and Youdin, this volume).

While data collected with a variety of techniques over the past two decades has allowed to make significant progress in the field thanks to the identification of hundreds of young nearby stars, the impact of new and future facilities on the study of NYMGs and their members is expected to be revolutionary. Quantum leaps in our knowledge (surprises included!) will come from the next generation of large-scale synoptic surveys in the visible (e.g., http://www.lsst.org/), sub-millimeter and milliter observations (e.g., Wilner, this volume), wide-field spectroscopic surveys at visible wavelengths (e.g., Martell, this volume), and direct imaging surveys in the visible and near-infrared (e.g., Marois, this volume). In this respect, the promise for huge progress in all the above mentioned key areas will soon be achieved when data will become available for ESA's billion star surveyor: Gaia.

2. Gaia: The Dawn of the Age of μas Astrometry

Gaia (http://www.cosmos.esa.int/gaia) is the first experiment set to demonstrate single-epoch measurement accuracies $\sigma_{\mathrm{A}} \approx 20$ μas for bright stars (see, e.g. the review on the mission, including its payload, by de Bruijne *et al.* 2010). The mission is now entering its second year of science operations at L2, after its successful launch in December 2013. Gaia's exquisite astrometric sensitivity will allow to unravel the formation history, evolution, structure, and dynamics of the Milky Way, through measurements of the positions, motions, distances, and astrophysical parameters of the brightest 1,000 million stars in the sky (Perryman *et al.* 2001). At the end of an over six-months long commissioning phase, a number of issues arose, which pose a challenge to data reduction pipelines in order to demonstrate pre-launch performance estimates. First, significant stray light levels were identified. Second, the transmission of the optics slowly degrades with time, as a result of contamination by water ice. Finally, the intrinsic instability of the basic angle which separates the lines of sight of the two telescopes is larger than expected. While a number of additional calibration procedures are being put in place in order to cope with, mitigate, and possibly remove these undesired effects, the impact on the astrometric performance of Gaia is still under evaluation, but the hope is that such complications will still fit within the 20% margin included in pre-launch calculations (for a recent review of the issue, see de Bruijine *et al.* 2015).

3. Astrometric Planet Detection within the Gaia Pipeline

High-precision global astrometry with Gaia is poised to enable the detection of planetary-mass companions around stars in the Solar neighborhood. The determination of the astrometric orbits of extrasolar planets will be obtained as part of the non-single star (NSS) treatment within Coordination Unit 4 (Object Processing) of the Gaia Data Processing and Analysis Consortium. CU4 will tackle the NSS problem by attempting to derive, based on the available spectroscopic and photometric Gaia data, spectroscopic and/or eclipsing binary solutions. For astrometry, a cascade of increasingly more complex models will describe the data in terms of solutions containing derivatives of the stellar proper motion, accounting for variability induced motion, all the way to fully Keplerian astrometric orbital solutions, including where appropriate multiple companions. A Development Unit (DU437) has been specifically devoted to the modelling of the astrometric signals produced by planetary systems. The DU is composed of several tasks, which implement multiple robust procedures for (single and multiple) astrometric orbit fitting (such as Markov Chain Monte Carlo and genetic algorithms) and the determination of the degree of dynamical stability of multiple-component systems. This robust approach to orbit modeling is expected to allow coping with the complexities inherent to adjusting large, non-linear models to the data (e.g., Sozzetti 2005, 2014)

4. Planets Around Young Stars: The Gaia Potential

The size of the astrometric perturbation α, espressed in arcsec, induced on the primary of mass M_* by an orbiting planet of M_p (both in $M_\odot$) and with a semi-major axis a_p (in AU) scales with the distance d (in pc), to the observer: $\alpha = (M_p/M_\star) \times (a_p/d)$.

The sensitivity of Gaia astrometry to (single and multiple) giant planetary companions at intermediate separations around bright, nearby, solar-type dwarfs has been the objective of several works in the past (Lattanzi *et al.* 2000; Sozzetti *et al.* 2001; Casertano *et al.* 2008). Those early estimates have been recently revisited and complemented by Sozzetti

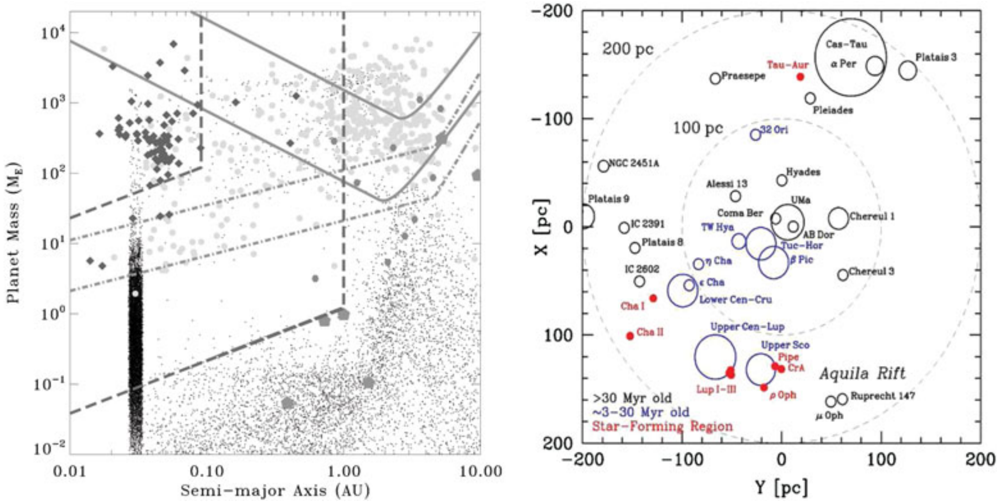

Figure 1. *Left:* Gaia exoplanets discovery space (solid curves) compared to that of Doppler (dashed-dotted lines) and transit (long-dashed curves) techniques. Detectability curves are defined on the basis of a 3-σ criterion for signal detection (see Sozzetti 2010 for details). The upper and lower solid curves are for Gaia astrometry with $\sigma_{\rm A} = 15$ μas, assuming a 1 $M_\odot$ primary at 200 pc and a 0.4 $M_\odot$ M dwarf at 25 pc, respectively, and survey duration set to 5 yr. The light-grey filled circles indicate the inventory of Doppler-detected exoplanets as of May 2010. Transiting systems are shown as dark-grey filled diamonds. Grey hexagons are planets detected by microlensing. Solar System planets are also shown (large grey pentagons). The small black dots represent a theoretical distribution of masses and final orbital semi-major axes (Ida & Lin 2008). *Right:* The closest ($d < 200$ pc) star forming regions and young stellar kinematic groups (image courtesy of E. Mamajek).

et al. (2014) and Perryman *et al.* (2014), who used improved (pre-commissioning) knowledge of the astrometric error budget and extended the studies to encompass a wider range of primary spectral types and limiting target magnitudes ($G = 20$ mag). The global figures on which all the above works converge speak of several thousands (possibly $\sim 10^4$) astrometrically detectable giant planets in the separation range $0.5 \leqslant a \leqslant 4.5$ AU from their parent stars (see Figure 1, left panel). The overall all-sky reservoir of stars around which Gaia will be sensitive to planetary-mass companions thus exceeds 10^6.

As for the population of young stars near the Sun ($d < 200$ pc), there exist of order twenty or so nearby star-forming regions, young associations, open clusters and moving groups (see Figure 1, right panel) with ages in the approximate range $1 - 100$ Myr (Mamajek, this volume; see also Zuckerman & Song 2004, and references therein, and López-Santiago *et al.* 2006, and references therein). The likely number of bright ($V < 13 - 14$ mag) members is on the order of 10^3 (Mamajek, private communication). All these stars will be observed by Gaia with enough astrometric sensitivity to massive giant planets ($M_p \gtrsim 2$ M_J) orbiting at $2-4$ AU. The possibility of detecting giant planets still forming in the protoplanetary disk would constitute fundamental observational evidence to validate the proposed theoretical models of giant planet formation. It will also probe the transition region between giant planets and brown dwarfs (e.g., Helled *et al.* 2014, and references therein) in a regime of orbital separation that would uniquely complement near- and mid-infrared imaging surveys (e.g., Burrows 2005, and references therein) for direct detection of young, bright, wide-separation ($a > 30 - 100$ AU) giant planets, such as those presently carried out by SPHERE (Beuzit *et al.* 2006) and GPI (Macintosh *et al.* 2014), and in the near future by JWST. The above is just one example of the broad range

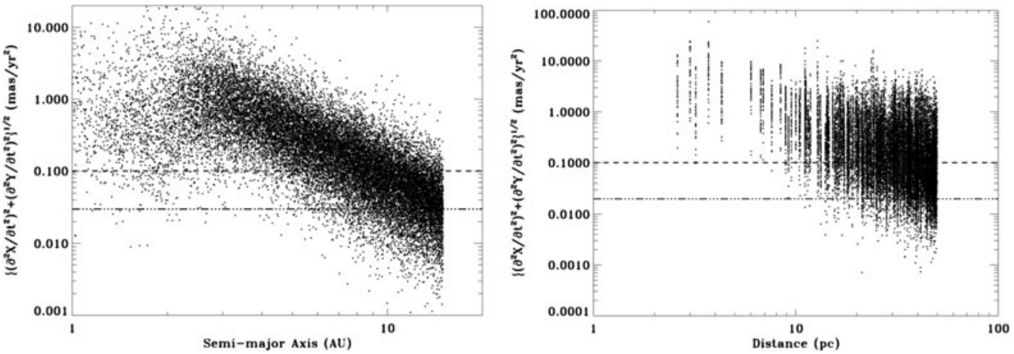

Figure 2. *Left:* Accelerations in the stellar motion induced by $1 - 70\ M_J$ orbiting companions at orbital separations $a < 15$ AU detected by SPHERE around a sample of > 400 targets of the GTO program with $V < 12$ mag and $d < 50$ pc. Dashed and dashed-dotted lines indicate 3-$\sigma_{\rm A}$ detection limits with Gaia at mid-mission (2.5 yr) and at mission end (5 yr). Only 5% of the accelerations in Gaia astrometry go undetected at the end of the mission, with a high degree of completeness (99%) for $a < 7$ AU. *Right:* The same quantity expressed as a function of the distance of the systems from the Sun.

of applications to exoplanets science in which Gaia data will act as an ideal complement to (and in synergy with) many ongoing and future observing programs devoted to the indirect and direct detection and characterization of planetary systems, both from the ground and in space (Sozzetti 2015).

5. On the Synergy Between Gaia Astrometry and Direct Imaging

The new generation of high-contrast imaging devices (SPHERE, GPI) is primarily sensitive to young giant planets at wide separations. Mass estimates of any detected companion heavily rely on structural and evolutionary models, that carry in turn large uncertainties, particularly in the age estimates. Dynamical mass constraints are highly desirable, but difficult to obtain. Doppler techniques could help in principle, but a) the amplitudes of the radial velocity (RV) signals decrease with orbital period, and b) young stars are trouble (due to rotation and activity). For astrometry, the amplitude of the signature increases with a, while youth and stellar activity are not an issue for positional measurements with Gaia-like precision. It is thus worthwhile to investigate in detail the extents of the synergy between Gaia data and high-contrast imaging programs. We focus here in particular on the effectiveness of the combination of SPHERE/VLT direct detections of wide-separation giant planets with Gaia determinations of accelerations in the stellar motion due to the orbiting companions. The aim of this study, which details will be presented in a forthcoming publication (Bonavita *et al.* 2015, in preparation) is to provide improved constraints on the orbital architecture and mass, thereby helping in the modeling and interpretation of giant planets' phase functions and light curves.

5.1. *Simulation Setup*

The stellar sample used is composed of 439 $V < 12$ mag stars with an age cut-off at $t < 0.5$ Gyr and within 50 pc drawn from the SPHERE GTO sample. Synthetic planet populations (1 companion per star) are instead generated with mass and semi-major axis following the distributions from Cumming *et al.* (2008), extrapolated to 70 M_J and 15 AU, and with the other orbital parameters randomly drawn from uniform distributions bracketed by their natural boundaries. Then, a large Monte Carlo simulation is run

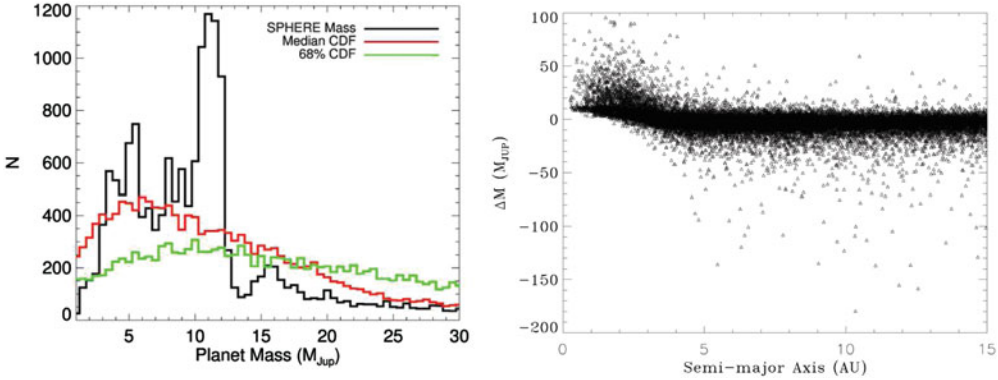

Figure 3. *Left:* Comparison between the distribution of the nominal companion masses based on SPHERE imaging and the median and 68.3% credibile intervals of the cumulative distribution function of the mass of the companions based on Gaia measurements of accelerations in the astrometry of the primaries and the angular separation at a single epoch from SPHERE. *Right:* Difference between median mass estimate from Gaia astrometry and the SPHERE value as a function of orbital separation.

using the MESS code (Bonavita *et al.* 2012) to identify a statistically significant sample of directly detected systems using up-to-date SPHERE detection limits (Zurlo *et al.* 2014). Next, Gaia-like simulations of the directly imaged systems are generated, using a setup described in Sozzetti *et al.* (2014). Astrometric detection of the companions is based on significant deviations from a five-parameter, single-star model, following which acceleration terms in the stellar motion are included in the model to account for curvature effects in the residuals. Finally, the methodology described in e.g. Torres (1999) is adopted to compute the cumulative distribution function (CDF) of companion masses inferred by Gaia astrometry that are compatible with the allowed range of orientations and eccentricities, and with separation estimates from SPHERE.

5.2. *Preliminary Results*

Figure 2 shows the magnitude of the acceleration terms (espressed in mas yr^{-2}) estimated by Gaia astrometry for the companions directly imaged by SPHERE as a function of the orbital separation (left panel) and system distance from the Sun (right panel). Only $\approx$ 10% of the curvature signals are deemed not significant based on a time baseline spanning the nominal 5-yr duration of the Gaia mission. For $a < 7$ AU, the completeness levels are higher than 99%. Similar sensitivity limits apply to systems within $\sim$ 25 pc and to companions with masses larger than $\approx 10\ M_J$ (plot not shown).

The left panel of Figure 3 shows the comparison between the nominal value of the companion mass as derived from the SPHERE observations (based on inferences from theoretical models) and the median and $1-\sigma$ confidence intervals of the mass CDF as obtained from the combination of detections of curvature in Gaia astrometry and a measurement of the projected separation from SPHERE (a model-independent estimate). Both the latter metrics tend to overestimate the mass of the companion with respect to the one inferred from the models. The systematic effect is likely due to the need (given the range of orbital separations) to fit the Gaia observations with improved descriptions of the curvature effects, such as time derivatives of the accelerations. In the right panel of Figure 3 we show instead how the effect reverses when orbital periods become comparable to the timespan of the observations: In these cases a full orbital model should instead be fitted to the observations.

6. Summary

The Gaia mission is bound to set the standards in high-precision astrometry for the next decade. Gaia's defining role in the exoplanet arena will be its ability to provide a large compilation of new, high-accuracy astrometric orbits of giant planets, unbiased across all spectral types, along with exquisitely precise parallaxes. There exists a huge synergy potential between Gaia and ongoing and planned exoplanet detection and (atmospheric) characterization programs, both from the ground and in space, for much improved understanding of many aspects of the formation, physical and dynamical evolution of planetary systems. We have started gauging the effectiveness of the combination of Gaia astrometry and SPHERE high-contrast imaging for constraining masses of directly-imaged companions around young stars in the solar neighborhood, as a means to reduce inherent degeneracies and uncertainties in model predictions. Our preliminary findings indicate that accelerations in Gaia astrometry for stars with companions detected by SPHERE will be easy to spot. We have identified a potential reference metric (the mass CDF) for the assessment of the quality of actual mass estimates without relying on model assumptions. Future work will focus on a) quantifying the uncertainties in companion mass estimates when other elements of information (e.g., the system age) are factored in, and b) determining the possible improvements in mass determinations when detection of orbital motion is obtained in both Gaia and SPHERE data.

Acknowledgements

It is a great pleasure to acknowledge the SOC and LOC of IAU Symposium 314 for organizing a top-class event, spanning a wide range of topics connected to the astrophysics of young stars and their planets. This work has been funded in part by ASI under contract to INAF 2014-025-R.0 (Gaia Mission: The Italian Participation to DPAC).

References

Beuzit, J.-L., *et al.* 2006, *The Messenger*, 125, 29
Bonavita, M., *et al.* 2012, *A&A*, 537, A67
Burrows, A. 2005, *Nature*, 433, 261
Casertano, S., Lattanzi, M. G., Sozzetti, A., *et al.* 2008, *A&A*, 482, 699
Cumming, A., *et al.* 2008, *PASP*, 120, 531
de Bruijne, J., Kohley, R., & Prusti, T. 2010, *Proc. SPIE*, 7731, id. 77311C
de Bruijne, J., Rygl, K., & Antoja, T. 2015, *EAS Pub. Ser.*, in press (arXiv:1502.00791)
Helled, R., *et al.* 2014, *Protostars and Planets VI*, University of Arizona Press, Tucson, 643
Lattanzi, M. G., Spagna, A., Sozzetti, A., *et al.* 2000, *MNRAS*, 317, 211
López-Santiago, J., *et al.* 2006, *ApJ*, 643, 1160
Macintosh, B., *et al.* 2014, *PNAS*, 111, 12661
Perryman, M. A. C., *et al.* 2001, *A&A*, 369, 339
Perryman, M. A. C., Hartman, J., Bakos, G. Á., *et al.* 2014, *ApJ*, 797, 14
Sozzetti, A., Casertano, S., Lattanzi, M. G., *et al.* 2001, *A&A*, 373, L21
Sozzetti, A. 2005, *PASP*, 117, 1021
Sozzetti, A. 2010, *EAS Pub. Ser.*, 42, 55
Sozzetti, A. 2014, *Mem. SAIt*, 85, 643
Sozzetti, A. 2015, *EAS Pub. Ser.*, in press (arXiv:1502.03575)
Sozzetti, A., Giacobbe, P., Lattanzi, M. G., *et al.* 2014, *MNRAS*, 437, 497
Torres, G. 1999, *PASP*, 111, 169
Zuckerman, B. & Song, I. 2004, *ARA&A*, 42, 685
Zurlo, A., *et al.* 2014, *A&A*, 572, A85