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Gaia, non-single stars, brown dwarfs, and exoplanets

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Abstract. In its all-sky survey, Gaia will monitor astrometrically and photometrically millions of main-sequence stars with sufficient sensitivity to brown dwarf companions within a few AUs from their host stars and to transiting brown dwarfs on very short periods, respectively. Furthermore, thousands of ultra-cool dwarfs in the backyard of the Sun will have direct (absolute) distance estimates from Gaia. For these, Gaia astrometry will be of sufficient precision to reveal any orbiting companions with masses as low as that of Jupiter. Gaia observations thus bear the potential for critical contributions to many important questions in brown dwarfs astrophysics: How do they form in isolation and as companions to stars? Can planets form around them? What are their fundamental parameters such as ages, masses, and radii? What is their atmospheric physics? The full legacy potential of Gaia in the realm of brown dwarf science will be realized when combined with other detection and characterization programs, both from the ground and in space.

Key words. stars: low-mass – binaries: close – brown dwarfs – planetary systems – astrometry – surveys

1. Introduction

The age of micro-arcsecond (μas) astrometry has finally dawned upon us. ESA's global astrometry mission Gaia was successfully launched from the Kourou site in French Guyana on December 19, 2013. It is now concluding its commissioning phase after injection in its L2 Lissajous orbit, and will commence science operations in Summer 2014 (for details, see de Bruijne, this volume).

The wealth of high-quality data Gaia will collect in its magnitude-limited ($V \leq 20$ mag) all-sky astrometric survey (complemented by onboard photometric and partial spectroscopic information) is bound to revolutionize our understanding of countless aspects of astronomy and astrophysics within our Milky Way, and beyond (e.g. Perryman et al. 2001). One key element for much improved understanding of star and planetary systems formation and evolution processes will be Gaia's ability to provide astrometric and spectro-photometric information for thousands of ultra-cool (brown) dwarfs in the Solar neighborhood, either directly detected or identified as companions to stars. In this paper I describe the elements of the Gaia Data Processing and Analysis Consortium (DPAC) software chain that will deal with deriving astrometric orbits for non-single stars within the realm of Coordination Unit 4 (Object Processing), with a focus on the strengths and challenges of the chosen approach. I then outline some of the key sci-

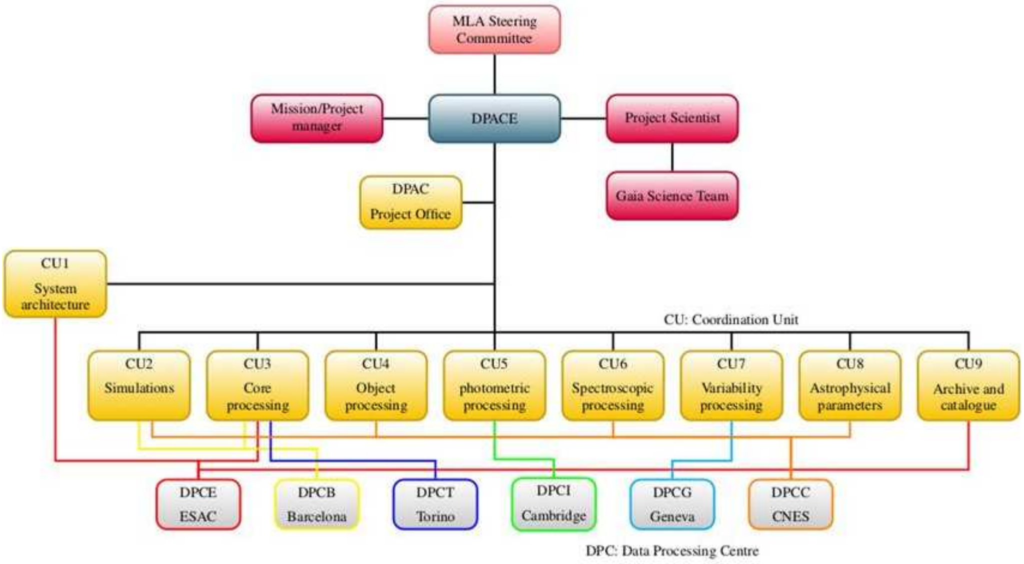

Fig. 1. Overall structure of the Gaia Data Processing and Analysis Consortium (DPAC) from `http://www.cosmos.esa.int/web/gaia/dpac/consortium`. This large pan-European team of expert scientists and software developers is responsible for the processing of Gaia's data with the final objective of producing the Gaia Catalogue. DPAC is composed of more than 450 members from over 20 countries.

ence topics that might be addressed using the potential harvest of astrometrically detected brown-dwarf companions to normal stars and planetary-mass companions to brown dwarfs.

2. Gaia non-single-star processing

Fig. 1 provides an overview of the DPAC structure, built around specialized sub-units known as Coordination Units (CUs). Each CU is responsible for developing the scientific algorithms and software corresponding to a particular sub-system of the overall Gaia data processing system. The software developed by the CUs is run by one of the data processing centres (DPCs). These centers host the computing hardware and provide software engineering expertise to support the CU software development work. Each DPC supports at least one CU. In particular, CU4 will further process any ill-behaved objects that might not be described simply in terms of a five-parameter astrometric model by CU3's Astrometric Global Iterative Solution (AGIS. See e.g. Lindegren et al. 2012), that might be found photometrically and/or spectroscopically variable by CU5 and CU6 and or recognized as potentially eclipsing systems by CU7. Such objects include Non-Single Stars (NSS), Solar System Objects (SSO), and Extended Objects (EO).

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. As 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 (particularly for the case of extrasolar planetary systems) multiple companions. It is worth underlining that for the most complex models, involving a large number of adjustable parameters many of which nonlinear, the assessment of their reliability and robustness (including meaningful error estimates on the fitted quantities) will be a nontrivial task, particularly in the limit of astrometric signals comparable in size to Gaia's

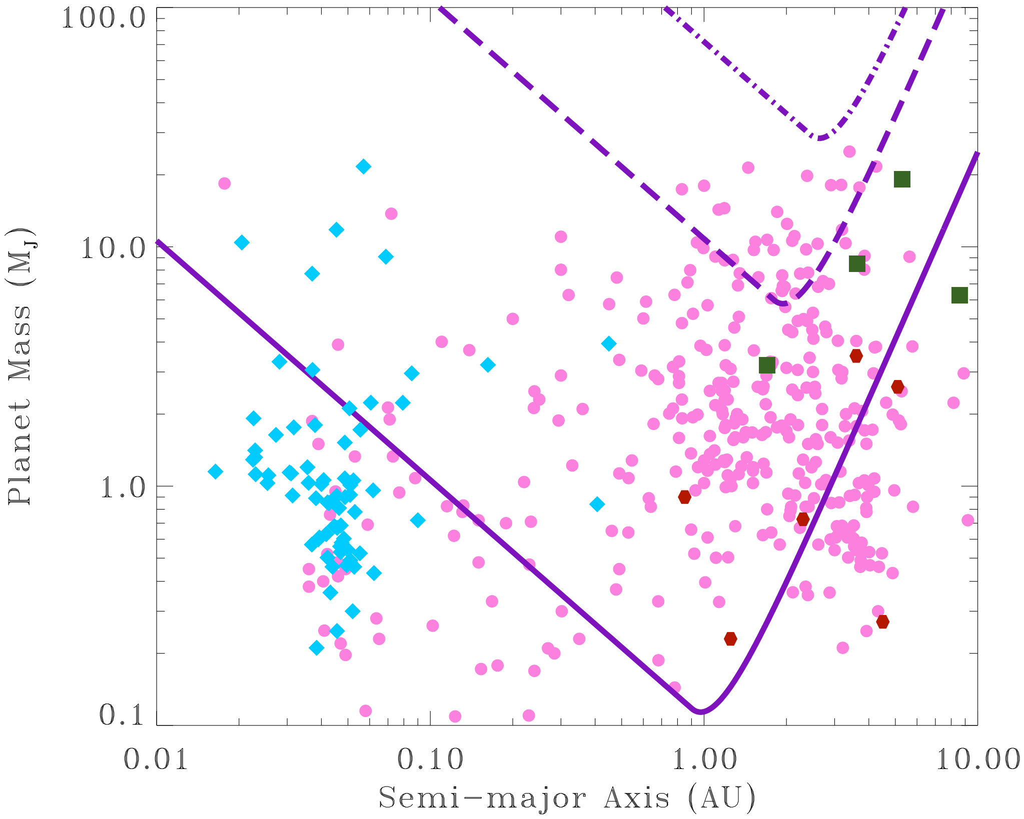

Fig. 2. Gaia brown dwarfs discovery space (purple curves). Detectability curves are defined on the basis of a 3-σ criterion for signal detection (see Sozzetti 2010 for details). The upper dashed-dotted and center dashed curves are for Gaia astrometry with $\sigma_A = 120$ μas, assuming a 0.8-$M_\odot$ primary at 300 pc and for $\sigma_A = 400$ μas, assuming a 0.2-$M_\odot$ primary at 30 pc, respectively. The lower solid curve is for $\sigma_A = 500$ μas, assuming a 0.050-$M_\odot$ primary at 2 pc (appropriate for Luhman 16A). The survey duration is set to 5 yr. The pink filled circles indicate a representative samples of Doppler-detected exoplanets. Transiting systems are shown as light-blue filled diamonds. Red hexagons are planets detected by microlensing. Planets detected with the timing technique are also shown as green squares.

single-measurement uncertainties and/or limited redundancy in the number of observations with respect to the model parameters (see, e.g., Sozzetti 2012).

3. Gaia sensitivity estimates

In the recent past, Casertano et al. (2008), Sozzetti et al. (2014) and Dzigan & Zucker (2012) have quantified the sensitivity of Gaia astrometry and photometry to giant planetary companions at intermediate and very short separations (respectively) around F-G-K-M-type dwarfs. They found that Gaia should provide a sample of maybe 10^4 new astrometrically detected giant planets and a few thousands transiting hot Jupiters. The results of the above mentioned works can be used to extrapolate the Gaia yield of brown dwarf (BD) companions to main-sequence stars with any orbit orientation in space. For BDs bright enough to be directly detected by Gaia, their masses being in the substellar regime ($M \approx 10-80\ M_J$), the sensitivity of Gaia measurements might also enable detection of very low-mass companions around this sample.

3.1. Gaia photometry: eclipsing BDs

Brown dwarfs have radii that vary by only 10-15% over the range of possible masses, and they all roughly have the same radius as Jupiter. This is a result of the dominant equation of state for their interiors (classical ionic Coulomb pressure + partial electron degeneracy pressure. See e.g., Basri & Brown 2006). The expected Gaia per-transit photometric standard errors are on the order of 0.001 mag for stars with magnitudes $G \leq 13$ mag, and still in the 0.003-0.005 mag range at $G = 16$ mag (Jordi et al. 2010). Detection of transiting Jupiter-sized objects (such as BDs) around solar-type (or later-type) stars is thus relatively easy, as the corresponding transit depths are on the order of 0.01 mag or more. The detection limits for close-in (a few days of period) Jupiter-sized companions identified by Dzigan & Zucker (2012) thus apply directly to the potential sample of transiting BDs found with Gaia photometry. The most serious limitation is naturally the low-cadence of Gaia observations, however mitigated at least in part by the sheer numbers (millions) of stars potentially available for transit detection.

3.2. Gaia astrometry: BDs companions to stars

The astrometric detection of giant planetary companions ($M \approx 1\ M_J$) around main-sequence stars takes full advantage of Gaia's limiting positional precision of $\sigma_{\rm A} \simeq 15-20\ \mu$as achieved uniformly for bright objects with $G \leq 13$ mag (e.g., Sozzetti et al. 2014). The masses of BDs can be almost a factor of 10 larger than the most massive objects defined as planets ($M \approx 10\ M_J$) based on simple mass-thresholds (e.g., Oppenheimer et al. 2000). Their detection in Gaia astrometry can thus be achieved allowing for comparatively larger values of $\sigma_{\rm A}$, depending on the actual combination of target mass, distance, and apparent brightness at G-band. The regions above the upper and center curves of Fig. 2 show the discovery space in the mass-orbital separation diagram for two representative systems. One thus infers that BD detection with Gaia can be achieved around a much larger stellar sample ($10^6 - 10^7$ objects) than available for giant planet discovery, depending on spectral type.

3.3. Gaia astrometry: planetary companions to BDs

At the presently envisioned faint-end limit ($G = 20$ mag) of the Gaia survey, a few thousands isolated BDs will be directly observed by Gaia (see de Bruijne this volume, and references therein). The typical per-measurement precision in Gaia astrometry for these very faint objects will be on the order of 500-700 μas. However, the combination of very low masses of BDs and their being found in the close vicinity of the Sun ($d < 20 - 30$ pc) due to their intrinsic low luminosity will allow Gaia to detect orbiting very low-mass secondaries around this sample, if present in the orbital separation range to which Gaia is most sensitive. The lower curve of Fig. 2 shows the Gaia sensitivity limits in mass and separation for companions orbiting Luhman 16 (Luhman 2013), a well-studied BD binary (the closest known BD and the third closest system to the Sun). One of the components appears to host an intermediate-separation low-mass (possibly planetary) companion (Boffin et al. 2014). As one can see, if present, the companion would be clearly detectable in Gaia astrometry, that would also easily identify around which of the two components the object is actually orbiting.

4. Discussion

The detection with Gaia of brown dwarfs in the three categories mentioned in the previous Section will pave the way to important advances in our comprehension of many issues in connection with the formation and evolution processes of stars and sub-stellar objects (BDs and planets). We highlight here some of the most relevant ones.

4.1. The BD - giant planet connection

The physical properties of BDs and giant planets are expected to bear important elements of similarity, in terms of mass, temperature, gravity, but also substantial differences, in terms of atmospheric chemistry, mechanisms of cloud formation, and general interpretation of spectral features (e.g., Madhusudhan et al. 2014). Close-in, strongly irradiated BDs and gas giant planets found in transit by Gaia could bring statistically significant samples to improve the overall understanding of these two partially overlapping classes of astrophysical objects. In particular, data from the CoRoT and Kepler missions allow us to infer that the occurrence rate of close-in ($P \lesssim 5$ days) BDs is at least one order of magnitude lower than that of hot Jupiters (Moutou et al. 2013, and references therein). A simple extrapolation from the expected numbers of transiting hot-Jupiters uncovered by Gaia (Dzigan & Zucker 2012, see also Dzigan, this volume) around stars with $G \leq 16$ mag would indicate that on the order of a few hundred transiting BD candidates might be identified in Gaia photometry. While follow-up efforts for mass confirmation with precision radial velocities (RVs) will still suffer some difficulties due to the typical faintness of the primaries (the bulk of detections expected to be at $G > 14$ mag), these will definitely not be severe given the range of BD masses and thus expected RV signals in the ballpark of at least a few km/s (see also Bouchy this volume).

4.2. Characterizing the BD desert

The differences in giant planet and BD occurrence rates extend to a wide range of orbital separations. In particular, intermediate-separation ($a < 3-4$ AU) BD companions to solar-type stars appear rare ($< 1\%$) when compared to the fraction of giant planet hosting stars at similar separations ($\sim 7\%$). At wider separations ($\approx 20-1000$ AU) this number rises to $2-3\%$ (for a review, see Ma & Ge 2014, and references therein). The paucity of close-in BD companions to solar-type dwarfs is usually referred to as the 'brown dwarf desert'. Furthermore, the statistical properties of BDs at intermediate separations from RV surveys allow us to infer the existence of a particularly 'dry' region at short periods and medium masses (Ma & Ge 2014), with low- and high-mass BDs exhibiting significantly different eccentricity distributions.

All the above results bear relevant insights to improve our understanding of the different formation mechanisms for BDs (and their relative role), in connection to those of stars and planets. Nevertheless, the findings still suffer from small-number statistics. For example, $1-\sigma$ errors on BD occurrence rates from Doppler surveys have present-day best-case uncertainties of 30% (some 60 objects known to-date). Based on the Gaia sensitivity thresholds for astrometric detection of BD companions to relatively bright ($G \lesssim 16$ mag) F-G-K-M stars and the BD fraction inferred from RV data (a 10^4-fold increase in the target sample) one then expects 1000s of detections in Gaia astrometry. Gaia thus has the potential to completely characterize the BD desert, with fine-structure studies of its dependence on stellar properties such as mass and metallicity. The wealth of Gaia data on BD companions to stars will thus allow us to probe effectively possible differences in BD formation mechanisms at intermediate separations (see also Parker, this volume).

4.3. Planet formation around BDs

Observations of accretion disks around young BDs (e.g., Ricci et al. 2012) have led to the speculation that they may form planetary systems similar to normal stars. Microlensing surveys have provided the first evidence of the existence of planetary-mass objects around BDs. Most of the detections have occurred for planetary companions to BDs at relatively large separations (Chauvin et al. 2004; Todorov et al. 2010), thus leaving room for formation mechanisms analogous to stellar binaries for such systems. There is however one recent notable exception (Han et al. 2013) that provides initial observational support to the hypothesis that planet formation processes may not stop around sub-stellar mass primaries.

Clearly, additional theoretical work is needed to explore the viability of planet formation in BD protoplanetary disks, either by the gravitational instability or core accretion mechanism. For this, it is essential to find more binaries with BD hosts in wide ranges of mass ratios and separations. In this respect, we have seen how Gaia will be capable of detecting a few thousands BDs of all ages (and up to a factor of 4 more if a limiting $G = 21$ mag is achieved, see de Bruijne this volume), with sufficient astrometric sensitivity to giant planets orbiting within $2-3$ AUs. Gaia astrometric measurements of directly detected BDs thus bear the potential to provide a fundamental observational test of planet formation around ultra-cool dwarfs.

5. Conclusions

Gaia astrometry and photometry are set to provide very 'cool' results in the realm of ultracool (brown) dwarfs in the Solar neighborhood. The wealth of Gaia data will 1) allow to pin down their occurrence rates as companions to normal stars at short and intermediate separations with outstanding statistical resolution (in bins of both primary and secondary masses), 2) enable measurements of their radii for those found transiting the disk of their hosts, 3) deliver exquisitely precise direct distance estimates and detailed spectral characterization for those directly detected (see de Bruijne this volume, Sarro this volume), and 4) provide the first-ever statistically robust estimates of giant planet frequencies around them.

The power of the Gaia legacy in brown dwarfs astrophysics is even better understood when seen as an element of synergy with other ground-based and space-borne programs to address many key questions related to the formation of brown dwarfs, their fundamental parameters (mass, radius, age), their atmospheric physics and chemistry, the likelihood that they might host planetary systems, and those unforeseen aspects that still need to be unveiled (see for example contributions to this proceedings volume by Bochanski, Bouchy, Dzigan, Faherty, Joergens, Kirkpatrick, and Sahlmann).

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