Mem. S.A.It. Vol. 90, 340

Memorie della

Binarity from Gaia DR2 and Hipparcos proper motion anomaly and common proper motion

P. Kervella[1], F. Arenou[2], F. Mignard[3], A. Gallenne[3,4], N. R. Evans[5], and F. Thévenin[3]

[1] LESIA, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, Univ. Paris Diderot, Sorbonne Paris Cité, 5 place Jules Janssen, 92195 Meudon, France
e-mail: pierre.kervella@obspm.fr

[2] GEPI, Observatoire de Paris, Université PSL, CNRS, 5 Place Jules Janssen, 92190 Meudon, France

[3] Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, Lagrange UMR 7293, CS 34229, 06304, Nice Cedex 4, France

[4] European Southern Observatory, Alonso de Córdova 3107, Casilla 19001, Santiago, Chile

[5] Smithsonian Astrophysical Observatory, MS 4, 60 Garden Street, Cambridge, MA 02138, USA

Abstract. Orbiting companions influence the space motion of their parent star through their gravitational field. Using the Hipparcos and *Gaia* DR2 (GDR2) catalogues, we determined the long-term proper motion (PM) of the stars common to these two catalogues. We then searched for a proper motion anomaly (PMa) between the long-term PM vector and the GDR2 (or Hipparcos) measurements, indicative of the presence of a perturbing secondary object. We focused our analysis on classical Cepheids, RR Lyrae stars and the nearby stars located within 50 pc. The PMa allows us to detect orbiting companions, down to planetary mass, or set stringent limits on their presence. Approximately 30% of the tested stars within 50 pc present a PMa signal greater than 3σ. We also estimate that $> 80\%$ of the Cepheids and $\approx 20\%$ of the RR Lyrae stars are members of binary systems. To complement our PMa-based survey, we also searched the GDR2 for common proper motion companions. We used a simple progressive selection algorithm to separate the most probable candidate companions from the unrelated field stars. This revealed a significant number of candidate gravitationally bound systems with wide separations. We identified 27 Cepheids and 7 RR Lyrae stars in spatially resolved binary systems. The PMa opens the possibility to identify long period orbital companions otherwise inaccessible.

Key words. Astrometry – Proper motions – Binaries: general – Stars: variables: Cepheids – Stars: variables: RR Lyrae – Stars: individual: Proxima, ϵ Eri, τ Cet, β Pic

1. Introduction

The binary fraction of nearby stars is largely incomplete, in particular toward the low-mass brown dwarf and long-period exoplanets. It is, however, fundamentally important in the understanding of the stellar and planetary formation and evolution mechanisms. We here report our search for binaries using two complementary techniques: (1) the detection of a proper motion anomaly (PMa) from the comparison of the long-term to short-term proper motion (PM) vectors and (2) the identification of spatially resolved companions that share similar proper motion vectors.

2. Proper motion anomaly as a tracer of binarity

2.1. Principle

The space motion of an isolated single star is at first order linear and uniform, and the photocentre of the system is located at the same position as the centre of mass (we neglect stellar spots or other surface features that may temporarily shift the photocentre). When a secondary orbiting companion is present, both bodies orbit around their centre of mass. When the secondary is faint compared to the primary (e.g., a planet or a compact object), the photocentre of the system coincides with the position of the star. Astrometric observatories like Hipparcos and *Gaia* monitor the position of the photocentre, and therefore trace its apparent displacement around the centre of mass. As a consequence, the presence of a secondary object can be identified from the difference between the long-term PM, considered as the PM of the centre of mass, and the short-term PM. This technique has historically been employed by Bessel (1844) to discover the white dwarf companions of Sirius and Procyon, and more recently by, e.g., Makarov et al. (2008), Brandt (2018) and Brandt et al. (2018).

We examined the PMa of Cepheids and RR Lyrae stars (Kervella et al. 2019a) and of the nearby stars located within 50 pc from the Sun (Kervella et al. 2019c) using the Hipparcos catalogue (van Leeuwen 2007, hereafter 'Hip2', see also Perryman et al. 1997) and *Gaia*'s second data release (GDR2; Gaia Collaboration et al. 2016, 2018). Figure 1 shows the principle of the determination of the PMa. We first determined the long-term PM from the difference between the Hip2 and GDR2 positions. Subtracting this two-dimensional vector from the PM vectors measured by each of the two missions gives us two PMa vectors $\Delta\boldsymbol{\mu}_{\mathrm{H}}$ and $\Delta\boldsymbol{\mu}_{\mathrm{G2}}$. Neglecting the photometric contribution from the secondary, the $\Delta\boldsymbol{\mu}$ vectors represent the velocity of the primary around the centre of mass of the system at the mean epoch of the measurement (1991.25 for Hip2, 2015.5 for GDR2).

However, two factors bias this velocity estimate: (1) the time smearing due to the astrometric measurement window and (2) the time base for the determination of the long-term proper motion. Both have the effect to decrease the apparent velocity anomaly, biasing it below its true instantaneous value and therefore reducing the sensitivity in terms of companion mass. Regarding point (1), considering for instance the measurement window of GDR2 (668 days), the sensitivity to companions orbiting with a period shorter than $\approx$ 2 years is significantly decreased by the time averaging in the GDR2 catalogue. The individual epoch astrometry measurements are expected to become available at the end of the mission, which will remove this limitation. Regarding point (2), the determination of the long-term PM vector from the difference in position between the Hip2 and GDR2 measurements also introduces a bias. For very long orbital periods (longer than a century, or about 4× the Hip2-GDR2 time base of 24.25 years), the determination of the μ_{HG} vector is biased by the orbital displacement. Part of the orbital motion is subtracted from the instantaneous PM vectors in the computation of the $\Delta\boldsymbol{\mu}$ vectors. Further details on these two sensitivity limitations can be found in Kervella et al. (2019a). Their overall effect is a degradation of the sensitivity to companions for orbital periods outside of the 2 – 100 years range.

2.2. Application to Cepheids and RR Lyrae

As they are intermediate mass stars ($\approx$ 5 to 10 $M_{\odot}$), classical Cepheids are known to host a high fraction of binary and multiple stars (Evans et al. 2013, 2015). From a survey of the PMa of 254 Galactic Cepheids, Kervella et al. (2019c) found that 57 stars exhibit a PMa at a level of more than 3σ. Taking into account the decreasing sensitivity with distance and other completion biases, this implies that >80% of Cepheids are members of binary or

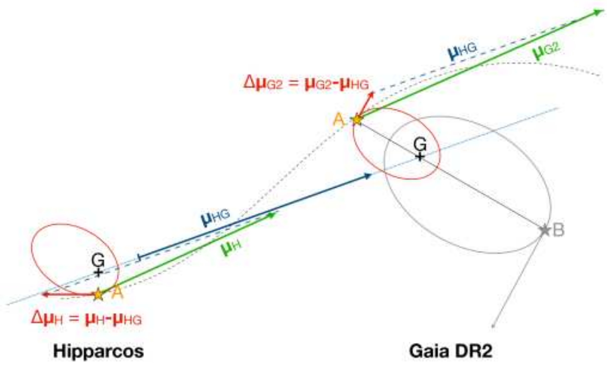

Fig. 1. Principle of the determination of the proper motion anomaly $\Delta\mu_H$ (at Hipparcos epoch) and $\Delta\mu_{G2}$ (at *Gaia* epoch). $\Delta\mu_{HG}$ is the long term proper motion determined from the Hipparcos and *Gaia* positions. We consider here the case of a companion with a negligible photometric contribution compared to the primary.

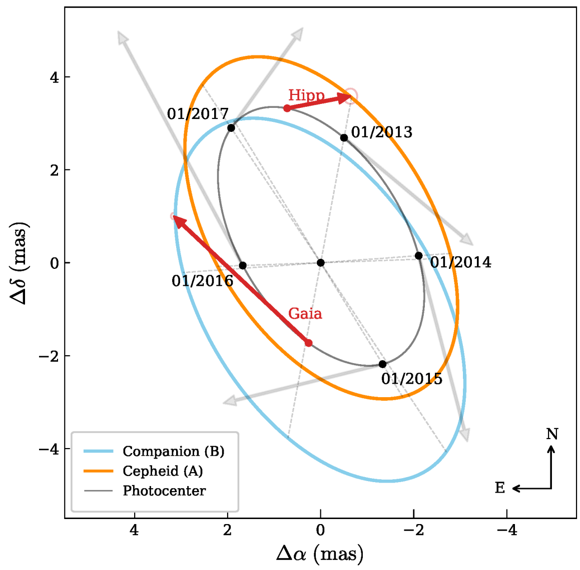

Fig. 2. Orbits of V1334 Cyg A (orange ellipse) and its companion B (light blue) around their common centre of mass from Gallenne et al. (2018). The virtual orbit of the photocentre of the system is shown as a grey ellipse. The measured tangential velocity vector (proper motion anomaly) is represented at the Hipparcos and *Gaia* epochs (figure from Kervella et al. 2019c).

multiple systems. For the stars that are known to be binaries from radial velocimetry, the determination of the PMa vectors opens up the possibility to resolve the inclination degeneracy ($\sin i$ term), as demonstrated by Kervella et al. (2019c) for the short period Cepheid V1334 Cyg (Fig. 2).

RR Lyrae stars (RRLs) are evolved, short period ($P \approx 0.5$ d) pulsating stars with sub-solar masses. A large number of RRLs is known, in particular in the Galaxy and its globular clusters. Like Cepheids, they are used as standard candles for distance determinations. Until recently, there was very little evidence for the existence of RRLs in binary systems, as only one case has been convincingly identified from spectroscopy: TU UMa (Liška et al. 2016). From the survey of the PMa of 198 RRLs, Kervella et al. (2019c) detected 13 stars showing a significant PMa at a more than 3σ level (TU UMa exhibits the strongest signal of the sample). The minimum binarity fraction among RRLs is therefore estimated to 7%, with a probable overall frequency of stellar mass companions around 20%.

2.3. Binarity fraction of stars within 50 pc

A survey of the PMa on the 6741 stars located within 50 pc from the Sun and present in both the Hip2 and GDR2 catalogues is presented by Kervella et al. (2019a). This sample is close to complete for stars more massive than the Sun, but due to the limited sensitivity of Hipparcos, a large fraction of the less massive red dwarfs is missing. The overall completeness compared to the total number of objects present in the GDR2 with $\varpi > 20$ mas is 9%. The distribution of the detected PMa as a function of the star mass, and the corresponding binarity fraction, are presented in Fig. 3. A fraction of 30.6% of the stars exhibits a PMa at a level of more than 3σ. The binarity fraction increases for higher mass stars above $2\,M_{\odot}$. It also presents a steep increase for very low mass stars ($m < 0.35\,M_{\odot}$). This effect is caused by the fact that the red dwarfs of the sample are located at very short distances, due primarily to the limited sensitivity of Hipparcos. The sensitivity of the PMa, that depends linearly on the distance, is therefore very high and goes down to the brown dwarf and planetary regime. This allows for the detection of a larger number of very low mass companions than for more massive stars of the sample.

When considering a larger sample of $\approx$ 116 000 stars covering 99% of the full Hip2 catalogue, Kervella et al. (2019a) identified a fraction of 26.9% of the stars with a PMa signal larger than 3σ. This sample is however less homogeneous in terms of completeness and sensitivity than the 50 pc sample.

2.4. Planetary companions

For several stars that are known to host exoplanets, Kervella et al. (2019a) detected the PMa induced by the orbital motion of the planet. Several known exoplanet star hosts show a PMa signal (e.g., ϵ Eri, ϵ Ind and β Pic) that opens up the possibility to determine the planetary mass. The signature of a possible planet of a few Jovian masses orbiting τ Ceti has also been detected. When we know the orbital period of the planet, it is possible to estimate its mass from its astrometric PMa. The example of the possible mass range for the companion of β Pic is shown in Fig. 4. The range of possible companion mass and orbital radius (m_2, r) explaining the observed $\Delta\mu_{\rm H}$ PMa from Hip2 are shown with the green curve and shaded green uncertainty domain. The mass and orbital period of β Pic b determined by Snellen & Brown (2018) and Dupuy et al. (2019) are shown with red symbols. The orange vertical line marks the orbital radius whose period corresponds to the Hip2 time window ($\delta t_{\rm H} = 1227$ d). The permitted (m_2, r) domain for short-period planets from existing radial velocity searches is shaded in pink. The orbital radii corresponding to periods of $P_{\rm orb} = 1$ to 400 years are indicated with pink vertical marks.

The accuracy of the GDR2 proper motions, combined with the long-term PM vectors from the Hip2-GDR2 positions, gives access to the detection of tangential velocity anomalies at a median accuracy of $\sigma(\Delta v_{\rm tan}) = 1.0$ m/s per parsec of distance. This remarkable accuracy is comparable, for the nearest stars, to the level of radial velocity accuracy achieved by high resolution spectrographs optimised for planet detection. The astrometric detection of very low mass companions down to approximately Neptune's mass for the nearest stars (Proxima, Barnard's star...) is already accessible. Radial velocimetry (focusing on planets with orbital periods of a few years) and ultra precise *Gaia* astrometry (for long period planets up to several decades) are particularly complementary.

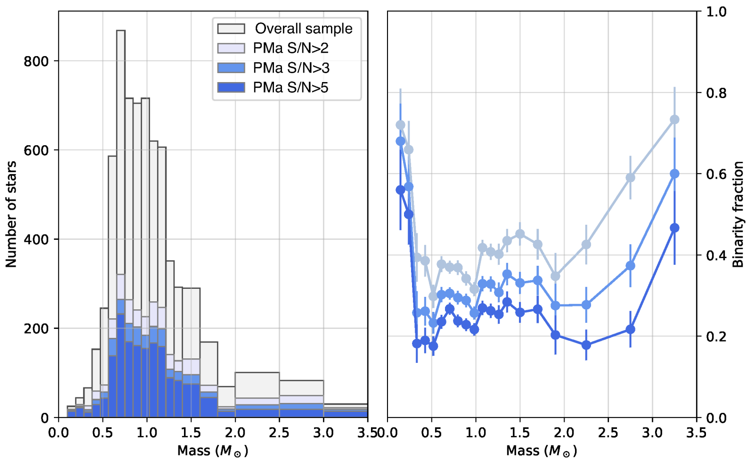

Fig. 3. *Left:* Number of stars within 50 pc showing a PMa Δ_{G2}, with thresholds in signal-to-noise ratio of 2, 3, and 5 (light blue, medium blue and dark blue histograms, respectively) as a function of the primary star mass m_1. *Right:* Binarity fraction as a function of the primary star mass. The binaries detected considering thresholds of Δ_{G2} = 2, 3, and 5 are represented with light blue, medium blue, and dark blue lines, respectively (figure from Kervella et al. 2019a).

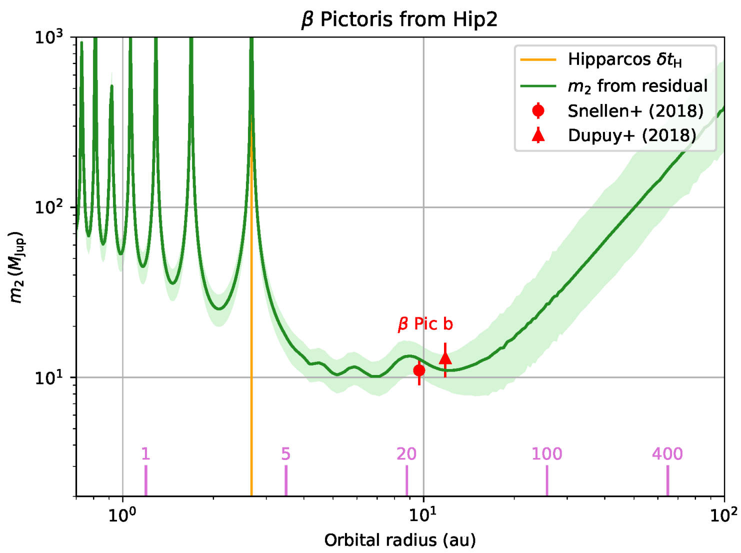

Fig. 4. Range of possible masses for the planet β Pic b, considering the Hip2 proper motion anomaly (figure from Kervella et al. (2019a), see Sect. 2.4 for details).

3. Common proper motion companions

For visual pairs of stars resolved by the *Gaia* telescope, the comparison of their PM and parallax makes it possible to determine if they are potentially bound gravitationally. Kervella et al. (2019b) searched the GDR2 catalogue for resolved companions of a set of 456 classical Cepheids and 789 RR Lyrae stars. The candidate companions were selected based on three criteria: 1) the similarity of their parallax with that of the target, 2) their tangential differential velocity), 3) their projected linear separation. They were tested to determine whether they are possibly bound gravitationally, by comparing the differential tangential velocity dv_{tan} with the escape velocity v_{esc} at their projected separation. We underline that this is in general not an absolute demonstration of the gravitational link, as due to projection effect, the distance between the source and its companion is generally a lower limit.

The companions detected for the Cepheid TV CMa and the RRL SS Oct are presented in Fig. 5. The target position is shown with a magenta + symbol, and the tested field stars are represented with cyan × symbols. The bound candidate companions are indicated with a yellow star symbol. The GDR2 proper motion vector $\boldsymbol{\mu}_{\mathbf{DR2}}$ is shown in magenta for each target star. The mean proper motion vector of the target $\boldsymbol{\mu}_{\mathbf{HG}}$ estimated from the Hip2 and GDR2 positions is also displayed in cyan, when available. We note in Fig. 5 that the Cepheid TV CMa exhibits a significant PMa, as shown by the divergence of its GDR2 PM vector $\boldsymbol{\mu}_{\mathbf{G2}}$ and long-term PM vector $\boldsymbol{\mu}_{\mathbf{HG}}$. Further details are presented in Kervella et al. (2019b).

Overall, high probability gravitationally bound candidates were identified for 27 Cepheids, and 7 for RR Lyrae stars. Part of the Cepheid companions were already known (e.g., those of Polaris and δ Cep), while the bound candidate companions of RRLs are all new discoveries.

4. Conclusion

The detection of binary systems using the combination of Hipparcos and *Gaia* astrometry (positions and proper motions) has demonstrated a strong potential. Thanks to the long time baseline between the Hipparcos and *Gaia* missions, the mean long-term PM vector of the stars common to Hip2 and GDR2 is known with an extraordinary accuracy. The difference between this vector and the *Gaia* epoch measurement (the PMa) revealed that approximately 1/3 of the Hipparcos stars are members of binary or multiple systems (Kervella et al. 2019a). The astrometric signatures of companions of planetary mass were identified around several nearby stars (e.g., β Pic, τ Cet, ϵ Eri...). A survey of the PMa of classical Cepheids showed that members of this important class are almost always members of multiple systems. The discovery of companions of RRLs, both from PMa (Kervella et al. 2019c) and from common proper motion (Kervella et al. 2019b) resolved the long-standing mystery of the absence of RRLs in multiple systems.

The coming *Gaia* data releases will further improve the position, PM vector and parallax accuracy, and provide individual transit measurements (only average positions are present in the GDR2). This will enable the determination of the full orbital parameters for a large number of binary and multiple systems, down to exoplanet companions for the nearest stars.

Acknowledgements. This work has made use of data from the European Space Agency (ESA) mission *Gaia* (`http://www.cosmos.esa.int/gaia`), processed by the *Gaia* Data Processing and Analysis Consortium (DPAC, `http://www.cosmos.esa.int/web/gaia/dpac/consortium`). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the *Gaia* Multilateral Agreement. The authors acknowledge the support of the French Agence Nationale de la Recherche (ANR), under grant ANR-15-CE31-0012-01 (project UnlockCepheids). The research leading to these results has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation program (grant agreement No. 695099). This research made use of Astropy[1], a community-developed core Python package for Astronomy. We used the SIMBAD and VIZIER databases and catalogue access tool at the CDS, Strasbourg (France), and NASA's Astrophysics Data System Bibliographic Services. The Digitized Sky Surveys were produced at the Space Telescope Science Institute under U.S. Government grant NAG W-2166. The images of these surveys are based on photographic data obtained using the Oschin Schmidt Telescope on Palomar Mountain and the UK Schmidt Telescope. The plates were

[1] Available at `http://www.astropy.org/`

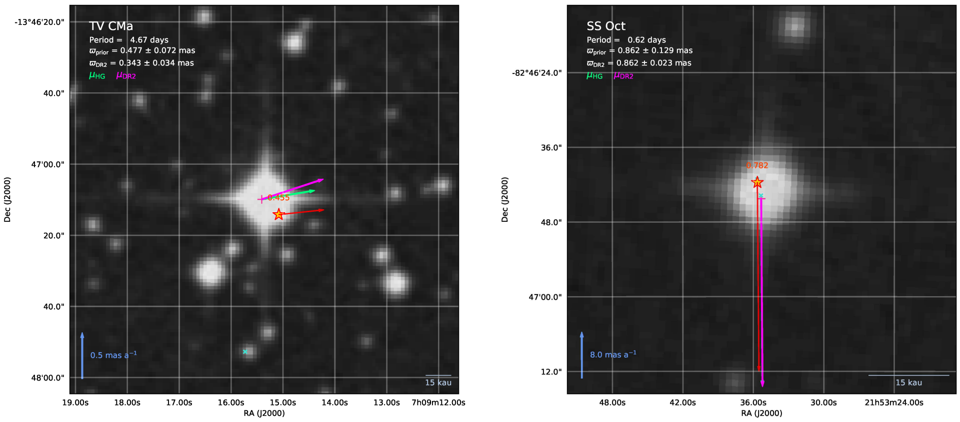

Fig. 5. Resolved companions of the Cepheid TV CMa (left panel) and the RR Lyrae star SS Oct (right panel) (figures taken from Kervella et al. 2019b).

processed into the present compressed digital form with the permission of these institutions.

References

Bessel, F. W. 1844, MNRAS, 6, 136
Brandt, T. D. 2018, ApJS, 239, 31
Brandt, T. D., Dupuy, T., & Bowler, B. P. 2018, arXiv: 1811.07285
Dupuy, T. J., et al. 2019, ApJ, 871, L4
Evans, N. R., Berdnikov, L., Lauer, J., et al. 2015, AJ, 150, 13
Evans, N. R., Bond, H. E., Schaefer, G. H., et al. 2013, AJ, 146, 93
Gaia Collaboration, Brown, A. G. A., Vallenari, A., et al. 2018, A&A, 616, A1
Gaia Collaboration, Prusti, T., de Bruijne, J. H. J., et al. 2016, A&A, 595, A1
Gallenne, A., Kervella, P., Evans, N. R., et al. 2018, ApJ, 867, 121
Kervella, P., et al. 2019a, A&A, 623, A72
Kervella, P., Gallenne, A., Evans, N. R., et al. 2019b, A&A, 623, A117
Kervella, P., Gallenne, A., Remage Evans, N., et al. 2019c, A&A, 623, A116
Liška, J., et al. 2016, A&A, 589, A94
Makarov, V. V., Zacharias, N., & Hennessy, G. S. 2008, ApJ, 687, 566
Perryman, M. A. C., Lindegren, L., Kovalevsky, J., et al. 1997, A&A, 323, L49
Snellen, I. A. G. & Brown, A. G. A. 2018, Nature Astronomy, 2, 883
van Leeuwen, F., 2007, Hipparcos, the New Reduction of the Raw Data (Springer), ASSL, 350