Searching sub-stellar objects in DR1-TGAS, effectiveness and efficiency of Gaia’s astrometry

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Abstract

We used 1,477,047 data from DR1-TGAS, in order to analyse the minimum requirements of accuracy, necessary to detect sub-stellar objects in the astrometric measurements of Gaia. We found that the first set of data (DR1) does not have enough accuracy, so sub-stellar objects can not be easily detected. Barely, it would be possible to detect jovian and higher mass objects, with orbital periods over 5 years. We made the calculations of the minimum values of the astrometric angle produced by an orbiting sub-stellar object using a range of different masses. We estimate the efficiency and effectiveness of the DR1-TGAS data in order to detect sub-stellar objects and the minimum accuracy that Gaia would be required to detect these objects using the datasets that the mission will release in the near future.

Keywords: Astrometry and celestial mechanics: astrometry. Astronomical Data bases: miscellaneous, Gaia mission, DR1.

1. Introduction

Only one exoplanet has been discovered by the method of astrometry. It is a jovian giant known as HD 176051 b, discovered in 2010 (Muterspaugh et al., 2010). In addition to this, there is no other record in the literature of new exoplanets discovered using astrometric data.

Some works in the past have addressed the possibility of detecting planets using the astrometric measurements, especially based on those made by Hipparcos mission. Prior to Gaia, the Hipparcos mission was the more precise

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1See in: http://exoplanet.eu/catalogue/
source of astrometric measurements [Perryman, 2008]. Unfortunately the measures of Hipparcos are not sufficiently accurate, and should be supported by other measurements made both on Earth, with the Multichannel Astrometric Photometer MAP (Gatewood et al., 1997), as well as with measures made by space missions such the Full-Sky Astrometric Mapping Explorer FAME (Horner et al., 1999) or the Space Interferometry Mission SIM (Shao et al., 1999). Sadly as we all know, both missions were cancelled by NASA, first FAME was cancelled in 2002, and finally SIM was cancelled in 2010.

Gatewood et al. (2001) work combines observations of Hipparcos and MAP to analyse the \( \rho \) Coronae Borealis system. They found that what appeared to be a planetary companion, it was actually a red dwarf. The accuracy of the astrometric measurement made with MAP confirmed that the mass of the object should be at least 100 times greater than the mass of the sub-stellar companion initially reported by Noyes et al. (1997), which was measured by radial velocity and was of the order of 1.1 \( M_J \). In their work, Gatewood et al. (2001) shows how the measurement of the mass made by astrometry can be many times more precise than that made by the radial velocity. One main conclusion of their work is that only massive objects can actually produce a measurable astrometry signal.

In the work of Han et al. (2001), the Hipparcos data for 30 stars with radial velocity periodic variations was reduced. Their preliminary results were proposed as a guide for the selection of observational objectives for astrometry projects. Their results compare the masses of sub-stellar companions in some systems previously analysed by radial velocity such as Ups And, HD 10687, 70 Vir and 47 UMa. An important conclusion of their work was the need for astrometric instruments of greater precision in a range of 1-2 orders of magnitude higher than Hipparcos. On the other hand, the error in the measure of the mass of sub-stellar companions should be associated with small angles of inclination, which requires better astrometric measurements.

Hipparcos’ astrometric data were also used to estimate the inclination of some planetary systems observed by radial velocity in the work of Pourbaix (2001). A fundamental conclusion of this work is that instruments with a precision of at least 100 \( \mu as \) are required, otherwise, astrometry techniques will not be able to measure the mass of sub-stellar companions. The work of Pourbaix and Arenou (2001) concludes on the same terms that the Hipparcos data is not enough to show if companion candidates could be planets or bodies of stellar nature.

The Gaia mission was launched in December 2013 with the aim of de-
Figure 1: The astrometric angle $\theta$.

termining the accurate position and distance of more than 1 billion stars in the galaxy (Gaia Collaboration et al., 2016b). For almost three years astronomers and planetary scientists around the world were waiting for Gaia to reveal its first set of data, especially the astrometry data, in order to begin the search for signals that allowed us to infer the presence of extrasolar planets. Finally in September 2016, the mission revealed the first set of data (Gaia Collaboration et al., 2016a). This first package (DR1) contains a total of 1,142,679,769 sources, and is divided into three main groups of data: 1) 93,635 shared data with Hipparcos, 2) 1,963,415 data shared with Tycho-2 and Hipparcos, and 3) an additional package of 1,140,622,719 secondary data (Gaia Collaboration et al., 2016a). A detailed description of the astrometry data can be found in Lindegren et al. (2016).

Before the first observational results were known, calculations had been made on the real possibilities of detecting exoplanets using the astrometry data from Gaia (Perryman et al., 2014). Based on the signal-noise ratio, Perryman et al. (2014) predicted a very high number of possible detections. At least 21,000 giant planets with masses between 1.0-15.0 $M_J$ with long period could be discovered around stars at distances of up to about $\sim 500$ pc during the nominal period of the mission which is five years. Even the work of Perryman et al. (2014) estimates that between 1,000-1,500 planets could be detected around M dwarfs within a 100 pc distance. The total number of planets at the end of the mission, in about 10 years, could reach 70,000!
We analyse the actual possibilities of finding sub-stellar objects in DR1-TGAS and which is the actual effectiveness and efficiency of the astrometric measurements is this first release. This work is organized as follows. The section 2 is dedicated to explain how the astrometry method works. In section 3 we explain how the DR1-TGAS data is organized and the analysis we have done to it. The section 4 shows our results related to the effectiveness of the astrometric data. Finally in section 5 we discuss our results and the real possibilities of finding sub-stellar objects using DR1-TGAS data.

2. Using astrometry to find planets

In a two body system, like a star-planet system, both orbits their common centre of mass. The star is displaced from the centre of mass by a distance $\varphi$. Viewed from the Earth, this displacement is observed as an angular distance $\theta$ (see Figure 1). The angle $\theta$ is equivalent to the apparent movement of the star over the plane of the sky. This angle can be measured by comparing the changes in the instantaneous position of the star across the time, measured as an astrometric signal. If the measure has the sufficient precision, it is possible to infer the existence of a low-mass object orbiting around the star, i.e. a planet.

From the Newtons’ laws, we can determine the measurement of the astrometric angle $\theta$ as (Quirrenbach, 2010):

$$\theta = \left( \frac{G}{4\pi^2} \right)^{\frac{1}{3}} \left( \frac{M_p}{M_\odot} \right) \left( \frac{M_\star}{M_\odot} \right)^{-\frac{2}{3}} \left( \frac{P}{yr} \right)^{\frac{2}{3}} \left( \frac{d}{pc} \right)^{-1}$$

(1)

Here $G$ is the Cavendish constant, $M_p$ is the mass of the secondary object that disturbs the star of mass $M_\star$, $P$ corresponds to the orbital period of the planet and $d$ is the distance between the measuring instrument (Gaia in our case) and the extrasolar system. This expression for the astrometric angle $\theta$ is independent of the inclination of the orbital plane. This enhances the method of astrometry for the determination of the secondary object mass $M_p$ with respect to other methods, like radial velocity, because it allows us to obtain the precise mass of the object. Usually angle $\theta$ is expressed in microarcsec units ($\mu$as) which are also an indication of the level of accuracy required on the measuring instrument.
Table 1: Astrometric angle in $\mu$as calculated for sub-stellar objects of different masses, with a period of $P=5$ yr, orbiting around low-mass stars, at a distance of 100 pc.

| $M_\ast$ ($M_\odot$) | 1.0  | 10.0  | 20.0  |
|----------------------|------|-------|-------|
| 0.1                  | 129.40 | 1294.03 | 2588.06 |
| 0.4                  | 51.35  | 513.54  | 1027.07 |
| 0.8                  | 32.35  | 323.51  | 647.02  |
| 1.0                  | 27.88  | 278.79  | 557.58  |

3. Gaia Data Release 1 - DR1

3.1. Number of objects and their distances

Our analysis starts with the 2,057,050 objects included in DR1-TGAS, and shared with Hipparcos and Tycho-2 catalogues. Of this total, we discard the objects with negative parallaxes ($\tilde{\omega} < 0$), and with signal-noise ratio $\tilde{\omega}/\sigma_{\tilde{\omega}} < 3$, with which the size of our dataset was reduced to 1,477,047 objects. A similar debugging was done by McDonald et al. (2017) in the determination of the luminosities of this same set of objects. Gaia Collaboration et al. (2016a) used a more demanding signal-noise ratio, $\tilde{\omega}/\sigma_{\tilde{\omega}} < 5$.

Figure 2 shows the distribution of distances for our dataset. It is observed that almost 95% of the objects are concentrated in distances up to 1 kpc. 60% of the data are closer than 500 pc. While the astrometric angle $\theta$ decreases with the distance $d$, it is constituted as a border condition for the detectability of sub-stellar objects.

3.2. Error in the position of an object

It is also relevant the determination of uncertainties $\sigma_{\alpha}$ and $\sigma_{\delta}$ in the measurements of the right ascension and declination of the 1,477,047 objects. The accuracy in the measurement of $\theta$ depends on the uncertainty in $\alpha$ and $\delta$ measurements. Figure 3 shows the distribution of both uncertainties, $\sigma_{\alpha}$ (red line) and $\sigma_{\delta}$ (green line). The error in both cases is centred around 200 $\mu$as and 80% of data have error less than 300 $\mu$as.

Figure 4 shows the astrometric angle subtending the semimajor axis of the orbit of the star around the centre of mass, therefore the error on the astrometric angle measurement is determined by the error on the position of the star at each side of the semimajor axis. This means that the astrometric angle measurement should be, at least, greater than the uncertainties in the
location of the star to avoid false positive in exoplanets searching. Normally the measured signal should be, at least, from three to five times the error (Sozzetti et al., 2014).

On the other hand, the distribution of the total uncertainty, $\sigma_\theta$, is the uncertainty on the location of the objects on the plane of the sky, as a result of the combination of right ascension and declination uncertainties. If we consider the errors in spherical coordinates, then the uncertainty $\sigma_\theta$, corresponds to a distance between the points $(\alpha + \sigma_\alpha, \delta + \sigma_\delta)$ and $(\alpha - \sigma_\alpha, \delta - \sigma_\delta)$. The observed object is located at any point within the area forming this spherical square. In a good approximation, the uncertainty on the astrometric angle $\sigma_\theta$ which determinates the length of an arc in spherical coordinates is calculated as follows:

$$\sigma_\theta = \sqrt{(X_1 - X_2)^2 + (Y_1 - Y_2)^2}, \quad (2)$$

It is evident how the error in astrometric angle accumulates around 270
Figure 3: Distribution of the uncertainty $\sigma_{\alpha}$ (right ascension), $\sigma_{\delta}$ (declination) and $\sigma_{\theta}$ (astrometric angle), of the Gaia-Hipparcos 1,477,047 objects.

$\mu$as. More than 80% of the objects have astrometric angle error less than 600 $\mu$as.

3.3. Mass and luminosity of Gaia's stars

Based on the parallax measurements reported in DR1-TGAS and the measurements of the G-band magnitude supplied by Gaia, we proceeded to estimate the stellar masses $M_G$ of each of the objects. For this, we calculate the luminosity $L_G$, which corresponds to an approximation of the actual luminosity, and based on a mass-luminosity relationship, we find finally $M_G$.

These calculations do not take into account the extinction in the measure of the brightness of the stars caused by the interstellar medium. Neither correction of the absolute magnitude is included, from which the bolometric magnitude is obtained. McDonald et al. (2017) concluded in his work that the extinction in most of the objects of DR1-TGAS dataset is very low. On the other hand, Gaia Collaboration et al. (2016a) does not make corrections for the magnitude in the G-band. The work of Jordi et al. (2010) did correction tests for the bolometric magnitude, but these corrections that are less $\sim 0.15$ magnitudes, which is negligible for our purpose.
Additionally, we compared our results with those published by Allende Prieto and Lambert (1999), who calculated the stellar parameters, including the mass, for 17,219 stars in the Hipparcos catalogue within a distance of 100 pc from the Sun. For comparison of the results we take the common data to both catalogs, a total of 12,533 stars. We discard those stars not included in our dataset. Figure 4 shows that the 80% of the stars common to both datasets (12,533 stars), have errors $1 - M_G/M_A$ concentrated between -15% and 5%.

In conclusion, we find that the difference in the results for the stellar masses are negligible for the purposes of our analysis. Figure 5 shows the histogram of magnitudes in G-band, which shows that the stars in our catalogue are between 6 and 13 magnitudes. Figure 6 shows a dispersion diagram of the Gaia’s stellar masses $M_G$ and their distances $d$ in pc.

4. Effectiveness and efficiency in DR1-TGAS data

Based on DR1-TGAS data, and in the stellar masses estimated in the previous section, we can calculate the minimum orbital period of the star around the barycentre of the system caused by the presence of a sub-stellar
object. We will assume a minimum mass of the sub-stellar object $M_{\text{obj}}$, and a minimum astrometric angle $\theta$ equal to a signal-noise ratio $SNR \geq 3$, this is to ensure reliability in the detectability of the sub-stellar object.

$$SNR = \frac{\theta}{\sigma_{\theta}} \geq 3.$$  \hfill (3)

Hence, the minimum value of $\theta$ is,

$$\theta_{\text{min}} = 3\sigma_{\theta},$$ \hfill (4)

therefore, from Eq. (3) we will obtain the minimum detection period,

$$P_{\text{min}} \approx 1.27 \times 10^{-3} M_G \left(\frac{\sigma_d}{M_p}\right)^{3/2} \text{ yr.}$$ \hfill (5)

4.1. Efficiency and effectiveness indicators

It is worth mentioning that, for multiple sub-stellar objects systems, the measurements of astrometry correspond to a composition of the effects produced for each of the objects (Butkevich, 2017, Sect. 5). We will assume
that each of the stars houses only one object of mass $M_{\text{obj}}$, whose effect on stellar displacement predominates over the possible effect of others hypothetical objects in the system (Ranalli et al., 2017, Sect. 1). We define three indicators:

- **Nominal Efficiency (NE):** We define $N_{\text{nom}}$ as the number of stars with a minimum detectable period calculated using eq. 5 and that contains objects of mass $M_{\text{obj}}$, and which could be detected with the nominal precision of Gaia (Perryman et al., 2014). Then, the nominal efficiency will be the ratio between $N_{\text{nom}}$ and the total number of stars $N$ in our data set,

$$NE = \frac{N_{\text{nom}}}{N}. \quad (6)$$

The minimum detectable periods that we used to calculated $N_{\text{nom}}$ are 5 and 10 years respectively (see table 2).
Figure 7: Minimum period for sub stellar objects detection in function of the distance (pc) and of the $M_G$ for all stars of our dataset. Each point represents a particular object of our dataset of 1,477,047 stars according to its mass $M_G$ and the distance it is located. The contour lines, referenced with the upper right colour bar, indicate the minimum orbital period that the system of each particular star must have in order for a planet of mass $M_{obj}$ to be detectable. The lower right colour bar indicates that the highest star density of our dataset is between 200 and 500 pc (yellow points). The top figure shows that only a small set of stars are able to find a planet of the mass of Jupiter with the accuracy of DR1 and considering a minimum orbital period of 5 years. The middle panel moves the contour lines to the right increasing the efficiency for the detection of objects with $M_{obj} = 10 M_J$, and the bottom figure shows the contour lines displaced further to the right which shows that sub-stellar objects with $M_{obj} = 15 M_J$ could be more detectable, however, the higher density of stars are beyond our reach to find sub-stellar objects there.
• **DR1 Efficiency (DE):** This is the ratio between the number of stars that contain objects of mass $M_{\text{obj}}$, which could be detected with the precision of the first release of Gaia (DR1), $N_{\text{DR1}}$, and the total number of stars in our dataset,

$$DE = \frac{N_{\text{DR1}}}{N}$$  \hspace{1cm} (7)

• **Effectiveness (Eff):** It is the ratio between DE and NE, and indicates the effectiveness of Gaia for the detection of sub-stellar objects. This indicator shows us the percentage of success of the mission based on the nominal accuracy, and is not affected by the actual existence of objects orbiting the stars in the dataset,

$$E_{\text{ff}} = \frac{NE}{DE}$$  \hspace{1cm} (8)

Both, NE and DE were calculated using Eq. 5 for each object in the dataset, depending on: 1) its respective G-mass, 2) its distance, 3) its particular nominal precision, which varies according to the visual magnitude in the G-band, and 4) its particular observational precision obtained from DR1, which was estimated as the square root of the sum of the squares of the uncertainties in right ascension and declination.

### 4.2. Effectiveness and efficiency for Allendes’ stars

We applied our effectiveness and efficiency indicators to 12,533 stars included in the work of [Allende Prieto and Lambert (1999)](https://example.com), in order to evaluate the actual accuracy of Gaia using well-known established masses. Table 2 shows that with the nominal precision indicated by [Perryman et al. (2014)](https://example.com) and considering that the mission time is 5 years it is possible to find 6,664 objects with $M_{\text{obj}} = 1.0M_J$, assuming that in these stars they have planets of the mass of Jupiter that are responsible for the movement of the star around the centre of mass. This 6,664 objects corresponds to 53.172% of the stars in the Allendes’ catalogue. With the accuracy of DR1 that percentage drops to 0%, and therefore the effectiveness to find planets of the Jupiter masses is 0%. In the same way, it is possible to find 12,532 objects with $M_{\text{obj}} = 10.0M_J$ that corresponds to 99.992% of the stars in the Allendes’ catalogue (assuming, again, that these stars have planets with 10 times the mass of Jupiter that are responsible of the movement of the star around the
centre of mass). With the accuracy of DR1, that percentage drops to 11.7% and the corresponding effectiveness is 11.746%, and so on for the rest of the objects.

Down in table 2 we show the same indicators applied to the 1,477,047 stars in our dataset. We can see that the effectiveness is less than 1% for all the masses if considering that the time of operation of Gaia will be 5 years. If we consider that the operating time extends to 10 years, the effectiveness to find objects that have 15 times the mass of Jupiter increases to 1.333% (that corresponds to 19,191 objects) and the effectiveness to find objects that have 20 times the mass of Jupiter increases to 2.421% (that corresponds to 35,660 objects). We applied the effectiveness and efficiency, keeping in mind that the mass of the stars corresponds to our estimation $M_G$, which according to Figure 4 is a good approximation. It should be noted that the effectiveness applied to the stars of Allende is much higher than the effectiveness applied to the stars of our catalogue because all the stars of Allende are located at a distance of less than 100 parsec.

4.3. Effectiveness and efficiency including planetary mass percentiles

We take into account the bulk distribution of planetary masses observed. We used 1330 data measurements of $M_P$ taken from the exoplanet catalogue\footnote{http://exoplanet.eu/}, including measurements made by radial velocity ($M_P \sin(i)$) and masses measured directly by other exoplanets detection methods like imaging, microlensing, transits and TTV. With this bulk data we calculated percentiles for planetary masses detectable with Gaia (see table 3). We see that 50.977% of the measured exoplanetary masses have values less than the 1.0$M_J$ and they are virtually impossible to detect for Gaia. If we include this percentiles into the effectiveness indicator, then the probability of detecting an exoplanet using Gaia’s astrometry is reduced. The new value of the effectiveness is shown in the last column of table 2. Although the planetary mass distribution function keep being unknown, observational evidence (Ho and Turner, 2011) and statistical approximations (Jiang et al., 2007), point to the fact that small masses are the most common among the planets.

4.4. The top ten objects in DR1-TGAS

Table 4 shows the candidate stars that are located less than 10 pc and that could contain objects of mass $M_{obj}$ and with a minimum orbital period
Table 2: Results for efficiency and effectiveness of DR1-TGAS data, for minimum periods of 5 and 10 years respectively for Allendes’ masses (up) and for masses in our dataset (down).

| Object | Objs (NE) | NE | Objs (DE) | DE | Eff | Eff Mp |
|--------|----------|----|-----------|----|-----|--------|
| Allendes’ catalogue (12,533 stars) | | | | | | |
| Period 5 years | | | | | | |
| 1 Jup | 6664 | 53.172% | 0 | | 0.000% | 0.000% |
| 5 Jup | 12513 | 99.840% | 1 | 0.008% | 0.008% |
| 10 Jup | 12528 | 99.960% | 271 | 2.162% | 2.163% |
| 15 Jup | 12532 | 99.992% | 1215 | 9.694% | 9.695% |
| 20 Jup | 12532 | 99.992% | 2791 | 22.269% | 22.271% |
| Period 10 years | | | | | | |
| 1 Jup | 11799 | 94.143% | 0 | | 0.000% | 0.000% |
| 5 Jup | 12525 | 99.936% | 84 | 0.670% | 0.671% |
| 10 Jup | 12532 | 99.992% | 1472 | 11.745% | 11.746% |
| 15 Jup | 12533 | 100% | 4163 | 33.216% | 33.216% |
| 20 Jup | 12533 | 100% | 7026 | 56.060% | 56.060% |
| Our dataset (1,477,047 stars) | | | | | | |
| Period 5 years | | | | | | |
| 1 Jup | 30005 | 2.031% | 12 | | 0.001% | 0.040% |
| 5 Jup | 552554 | 37.409% | 595 | 0.040% | 0.108% |
| 10 Jup | 1032432 | 69.898% | 2880 | 0.195% | 0.279% |
| 15 Jup | 1270598 | 86.023% | 7125 | 0.482% | 0.561% |
| 20 Jup | 1392728 | 94.291% | 13212 | 0.894% | 0.949% |
| Period 10 years | | | | | | |
| 1 Jup | 79778 | 5.401% | 33 | | 0.002% | 0.041% |
| 5 Jup | 876900 | 59.368% | 1660 | | 0.112% | 0.189% |
| 10 Jup | 1298613 | 87.899% | 8091 | | 0.548% | 0.623% |
| 15 Jup | 1439411 | 97.452% | 19191 | | 1.299% | 1.333% |
| 20 Jup | 1472704 | 99.706% | 35660 | | 2.414% | 2.421% |

Table 3: $M_P \sin i$ percentiles for exoplanets masses.

| $M_{Obj}$ (Percentile) | Percentage | Actual detectable fraction |
|-------------------------|------------|----------------------------|
| 1 Jupiter               | 50.977%    | 49.023%                    |
| 5 Jupiter               | 83.609%    | 16.391%                    |
| 10 Jupiter              | 92.180%    | 7.820%                     |
| 15 Jupiter              | 95.188%    | 4.812%                     |
| 20 Jupiter              | 96.541%    | 3.459%                     |
$P_{\text{min}}$. Here we show the best targets to search for exoplanets in DR1-TGAS data, according to our efficiency and effectiveness calculations.

- **HIP 57367** (GJ 440). On this white dwarf, distanced at 4.634 pc, is possible the detection of objects starting from a 1 Saturn mass, with a minimum orbital period of 3.469 year and with DR1-TGAS accuracy. This is the best candidate according to our results.

- **HIP 82809** (Wolf 629) This is a binary star distanced at 6.506 pc that may host detectable objects if they have a minimum mass of 1 $M_J$.

- **HIP 106440** (HD 204961) This high proper-motion star hosts two confirmed planets, but a third planet was predicted by Satyal et al. (2017). With the DR1-TGAS accuracy it is possible the detection of objects with masses above 1 $M_J$ and periods of 4.706 yr.

- **HIP 93873** (Ross 730). On this high proper-motion star it could be detected objects above 1 $M_J$ and with a minimum period of 4.793 yr.

- **HIP 1475** (GJ 15A) This flare star have a candidate companion identified by Tanner et al. (2010) using direct imaging. Around this star DR1-TGAS could provide signals only if the object have at least 1 $M_J$ and a period of 3.591 yr.

- **HIP 80824** (BD-12 4523) On this BY draconis variable star a Jovian exoplanet orbiting could be detected with a minimum period of 3.293 yr.

- **HIP 23512** (LP 776-46) This high proper-motion star was included in the work of Bozhinova et al. (2015), who studied the stellar parameters of the M-dwarf in order to detect low-mass planets. With the current Gaia’s accuracy it could be detected Jovian planets orbiting this star with a minimum period of 3.781 yr. Considering that this star is only 9.265 pc away, could be detected planets with masses less than 1 $M_J$ with a slight improvement in the accuracy of Gaia-TGAS for nearby stars.

- **HIP 91768** (HD 173739) This star is located at a distance of 3.527 pc and was included in the work of Léger et al. (2015) who did present an analytic model to estimate the capabilities of space missions dedicated
to the search for bio-signatures in the atmospheres of rocky planets located in the habitable zone of nearby stars. With the current accuracy it could be detected Jovian planets with a minimum period of 2.972 yr.

- **HIP 29295 (GJ 229)** On this flare star could be detected Jovian planets of minimum period 3.579 yr. This star was included in the work of Newton et al. (2016) who analyzed the impact of stellar rotation on the detectability of habitable planets around M-dwarfs.

- **HIP 57544 (GJ 445)** This is another flare star, distanced at 5.225 pc. It is possible to detect objects starting from a $1 \, M_J$, with a minimum orbital period of 4.121 yr.

With this analysis we are not ensuring that sub-stellar objects will be found around these stars, but we believe that given Gaia’s observational capability, these would be the best candidates to search among the astrometry data. We know that as the mission releases new results, it is expected that its accuracy will improve, which will facilitate the search for objects. We believe that some stars on our list could be feasible for analysis in search of exoplanets.

5. Discussion and conclusions

The precision of DR1-TGAS is $\sim 200 \mu as$ for right ascension and declination, and $\sim 280 \mu as$ for parallax respectively. The astrometric angle that describe a star at 100 pc of distance moving around the centre of mass of the system, and with a period of 5 years, indicates that the accuracy of DR1 is not enough to detect objects of mass $M_{obj} = 1.0 \, M_J$ (see table 1). An object of mass $M_{obj} = 10 \, M_J$ will be detectable if it orbits stars of $M_* < 0.4 \, M_\odot$. An object of 20 $M_J$ will be detectable if it orbits stars of less than $1.0 \, M_\odot$. That is, the accuracy of DR1-TGAS only allows the detection of giant sub-stellar objects that orbit low mass stars.

Although you must be aware of the preliminary character of this first release, it is undoubted that the precision of the measures faces a great challenge, as they must be improved by a factor of 10 for the search of Jovian planets in a radius of 100 pc and periods of 5 years (see Table 1), if you go up to 500 pc, the factor increases up to 50.

According to our results in table 2 and for a minimum detectable period of 10 years, if we consider a mission duration of 10 years, we could find
Table 4: List of Gaias' stars that are located less than 10 pc with alleged objects of mass $M_{obj}$ and with a measurable minimum orbital period $P_{min}$.

| Id          | Distance (pc) | $M_{obj}$  | $P_{min}$ (yr) | Id          | Distance (pc) | $M_{obj}$  | $P_{min}$ (yr) |
|-------------|---------------|------------|----------------|-------------|---------------|------------|----------------|
| HIP 101180  | 8.056         | 10 Jupiter | 0.433          | HIP 5020    | 6.906         | 10 Jupiter | 0.320          |
| HIP 102409  | 9.792         | 10 Jupiter | 0.574          | HIP 5360    | 9.120         | 10 Jupiter | 1.346          |
| HIP 103096  | 7.034         | 10 Jupiter | 0.442          | HIP 56452   | 9.561         | 10 Jupiter | 1.013          |
| HIP 105900  | 3.982         | 15 Jupiter | 0.241          | HIP 56528   | 9.126         | 15 Jupiter | 0.546          |
| HIP 106440  | 4.972         | 15 Jupiter | 0.140          | HIP 57087   | 9.749         | 15 Jupiter | 0.292          |
| HIP 109388  | 8.830         | 10 Jupiter | 0.496          | HIP 57367   | 4.634         | 1 Saturn   | 3.469          |
| HIP 111802  | 8.875         | 10 Jupiter | 0.270          | HIP 57544   | 5.225         | 1 Jupiter  | 4.121          |
| HIP 113020  | 4.672         | 10 Jupiter | 0.458          | HIP 57548   | 3.381         | 1 Jupiter  | 1.571          |
| HIP 113229  | 8.605         | 10 Jupiter | 0.153          | HIP 57802   | 8.773         | 10 Jupiter | 0.202          |
| HIP 113576  | 8.194         | 15 Jupiter | 0.476          | HIP 62452   | 8.056         | 10 Jupiter | 0.398          |
| HIP 114733  | 9.141         | 15 Jupiter | 0.193          | HIP 66906   | 9.116         | 15 Jupiter | 0.216          |
| HIP 120005  | 6.291         | 15 Jupiter | 0.359          | HIP 71253   | 6.284         | 10 Jupiter | 0.399          |
| HIP 14101   | 6.734         | 15 Jupiter | 0.664          | HIP 74995   | 6.303         | 1 Jupiter  | 4.547          |
| HIP 1475    | 3.562         | 1 Jupiter  | 3.591          | HIP 76074   | 5.926         | 10 Jupiter | 0.237          |
| HIP 21088   | 5.509         | 10 Jupiter | 0.269          | HIP 7751    | 8.097         | 10 Jupiter | 1.370          |
| HIP 21553   | 9.878         | 10 Jupiter | 2.181          | HIP 80459   | 6.490         | 10 Jupiter | 0.500          |
| HIP 21932   | 9.405         | 15 Jupiter | 0.920          | HIP 80824   | 4.305         | 1 Jupiter  | 3.203          |
| HIP 23512   | 9.265         | 1 Jupiter  | 3.784          | HIP 82003   | 9.844         | 10 Jupiter | 0.399          |
| HIP 23932   | 9.357         | 10 Jupiter | 0.754          | HIP 82809   | 6.506         | 1 Jupiter  | 2.459          |
| HIP 25878   | 5.647         | 10 Jupiter | 0.721          | HIP 85295   | 7.736         | 10 Jupiter | 0.270          |
| HIP 29277   | 9.383         | 10 Jupiter | 0.507          | HIP 86057   | 9.925         | 10 Jupiter | 2.148          |
| HIP 29295   | 5.792         | 1 Jupiter  | 3.579          | HIP 86162   | 4.545         | 10 Jupiter | 0.217          |
| HIP 31292   | 8.832         | 10 Jupiter | 0.826          | HIP 91768   | 3.527         | 1 Jupiter  | 2.972          |
| HIP 31293   | 8.843         | 10 Jupiter | 0.355          | HIP 93873   | 8.815         | 1 Jupiter  | 4.793          |
| HIP 33226   | 5.546         | 10 Jupiter | 0.462          | HIP 93873   | 8.815         | 10 Jupiter | 0.217          |
| HIP 33499   | 7.899         | 10 Jupiter | 0.608          | HIP 93873   | 8.815         | 10 Jupiter | 0.217          |
| HIP 40501   | 8.926         | 10 Jupiter | 1.178          | HIP 93899   | 8.867         | 10 Jupiter | 0.218          |
| HIP 46655   | 9.998         | 10 Jupiter | 0.608          | HIP 94761   | 5.902         | 10 Jupiter | 0.119          |
| HIP 47103   | 9.399         | 10 Jupiter | 0.928          | HIP 96100   | 5.760         | 10 Jupiter | 0.098          |
| HIP 47425   | 9.615         | 10 Jupiter | 0.402          | HIP 99701   | 6.164         | 10 Jupiter | 0.394          |
| HIP 47780   | 9.450         | 15 Jupiter | 0.219          | HIP 10081-1 | 8.292         | 10 Jupiter | 1.306          |
| HIP 4856    | 8.240         | 10 Jupiter | 0.335          | TYC 3980-1081-1 | 8.292 | 10 Jupiter | 1.306          |
| HIP 4872    | 9.849         | 10 Jupiter | 0.589          | TYC 3980-1081-1 | 8.292 | 10 Jupiter | 1.306          |
sub-stellar objects of mass $M_{\text{obj}} = 10 \, M_J$ in the 88% of the stars of our dataset, this is, assuming, of course, that all the stars in our dataset could host objects with this mass, and that the precision in the measurements of position is equal to the nominal precision. However, with the accuracy of DR1, the percentage of sub-stellar objects of mass $M_{\text{obj}} = 10 \, M_J$ that we would find is reduced to only 0.5%. It should be noted that the use of Gaias’ astrometry for the search of sub-stellar objects requires that all observations made during the mission have, at least, the same minimum required precision.

Therefore, if Gaias’ operating time increases to 10 years, and the nominal precision in the position measurements is achieved in the fifth year of operation, then we would have 5 years of observations with the nominal precision, and according to table 2 for a minimum period of 5 years, we could find sub-stellar objects of mass $M_{\text{obj}} = 10 \, M_J$ in the 70% of the stars of our dataset, again, assuming that all the stars of our dataset host objects of mass $M_{\text{obj}} = 10 \, M_J$.

The present analysis shows us the magnitude of the challenge that is assumed for the Gaia project in order to minimize uncertainty in the measurements of the position of the stars, since the precision of the data in the DR1-TGAS only offer possibility of detecting a few massive objects with periods above 5 years and that orbits dwarf stars at a distance of up to 100 pc.

Acknowledgements

We thank the referee for the valuable insights and comments, all of them have been included in the final version of the text. FACom - SEAP group is supported by Estrategia de Sostenibilidad 2016-2017, Vicerectoría de Investigación - UdeA. This work has made use of data from the European Space Agency (ESA) mission Gaia (https://www.cosmos.esa.int/gaia), processed by the Gaia Data Processing and Analysis Consortium (DPAC, https://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.

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