Gaia brown dwarfs and binary detections through timing orbits

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Abstract

Duplicity detection may also be done through the analysis of the light curves of variable stars. A light-time effect due to 10 Jupiter mass companions with period > 11 yr may be tested on more than 10^4 stars observed by Gaia.

1 Introduction

Concerning planetary and duplicity detection, what has been mentioned in the GAIA red book is what is related to the astrometric motion and photometric transits, since the epoch radial velocity will not have the required precision, and direct variation measurements of parallax is out of reach.

There is however a lot of stars which may provide some information of long period reflex motion along the line of sight. Consider a variable star with a stable short-period variation, hosting also a longer period planet/brown dwarf/star. Due to the finite speed of light, the epoch of light-curve minima will vary with the reflex motion. Plotting the minima epochs of the light curve as a function of time shows the light-time effect (LITE) or timing orbit, and provides the same orbital elements as the radial velocity curves, namely $P, T, a_1 \sin i, e, \omega_1$. The light arrival time is given by

$$\tau = \frac{a_1 \sin i}{25900} \left[\frac{1 - e^2}{1 + e \cos \nu} \sin(\nu + \omega_1) + e \sin(\omega_1) \right] \tag{1}$$

[Irwin 1952] where ν is the true anomaly, τ is in days (= 173.15 A.U.) and a_1 in Gm. Indeed, this method was used for the first planet detection [Wolszczan & Frail 1992].

We will consider here a 10 Jupiter-mass companion, with a 11 yr period hosted by a one solar mass primary. A 0.05 A.U. distance is roughly covered by the primary during 3 years, neglecting the projection effects. The difference of light-time motion is $0.05 \times 150 \times 10^6$ km/300000 km/s = 25 sec = 0.0003 day.

Measuring times of minima y years after a first observation and still neglecting the projection effects, ($2\pi a_1 y/P$ distance assumed), with a precision σ_T (seconds) on the minimum light epoch, then a planet/BD of mass M_2 (Jupiter mass) and a P (years) long period orbiting a M_1 solar mass star would be detected at a 3σ level if

$$M_2 \, P^{-\frac{1}{3}} M_1^{-\frac{2}{3}} >\approx \sigma_T / y \tag{2}$$

Compared to astrometry, this method allows to probe more distant stars, even those with a unfavourable R.V. precision (Fig. 1). Moreover it is a direct complement to planet transit detection, since it allows to test the presence of another, longer-period companion. An application can be done for HD 209458: the current available precision on transit epochs (0.0001 day, Brown et al., 2001) two years after the first transit would exclude a 10 Jup/11 yr companion. The main difference of the timing method compared to the other methods is that an amateur instrument is almost enough to get a light curve whereas precise astrometric/R.V. observations are less obvious to acquire.

2 How many objects can be tested in Hipparcos

There are 63 stars in Hipparcos with a precision flag 5 on the zero phase of light curves (accuracy of about 0.0001 day). So (in theory) a 3 sigma detection attempt of 10 Jup planets/BD with period > 11 yr could be possible for these stars provided that older or newer ground-based photometric measurements are also available. Concerning astrometry, the wobble size would be 0.05ϖ, so a 3σ detection requires $\sigma_\varpi < 0.017\varpi$ i.e. 619 stars in the Hipparcos Catalogue.

Finding with this method a real case of a brown dwarf companion is of course not obvious. However this method is not that marginal, at least for stellar companions. To find one example the best way was to choose

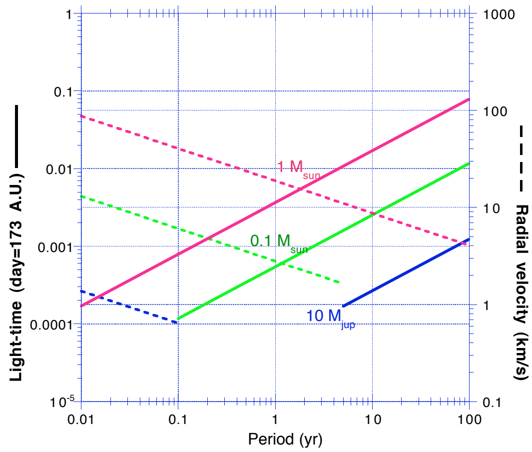

Figure 1: Semi-amplitude for LITE (full lines) and radial velocity (dash) (1 $M_{\rm sun}$ primary, $e = 0, \sin i = 1$ assumed), for different companion masses: 0.01 solar mass (blue), 0.1 (green), 1 (red). Gaia radial velocities will not be sensitive to 10 Jupiter masses, while LITE is present for period above 10 years.

among the stars suspected to have a long-period companion. Simply cross-matching the Hipparcos DMSA/G stars (detected due to an acceleration term in astrometry) with those with a periodic light-curve amounts to 51 stars. Among these, the first star chosen (R CMa, HIP 35487), because it was not too distant, was by chance the appropriate example.

It appears that this eclipsing binary had indeed been suspected through LITE studies to have a long period ($>$ 91 year!) companion [Radhakrishnan at al. 1984], and epochs of primary minimum were available in the literature. Part of these were obtained with visual photometry, thus quite imprecise.

The Hipparcos acceleration measurement confirms the reality of the third companion. The Fig. 2 shows the orbital motion in the phase space. The orbit has been roughly adjusted only, using all data except R.V. measurements. The light-time curve gave part of the orbital elements, and the Hipparcos data complemented with a proper-motion measurement around 1980 gave the rest. The long-period companion appears to be $\approx 0.5 \pm 0.1$ solar mass [Ribas et al. 2001].

Although detected through astrometry, one may wonder if this binary could have been detected from the Hipparcos photometry too. If the binary period is much larger than the mission duration, an epoch T of minimum light at variability cycle number E, $T = T_0 + P_0 E + \tau$ may be approximated by

$$T = T_0 + P_0 E + g E^2 \qquad (3)$$

where T_0 denotes the first minimum, P_0 is the instantaneous period of the variable, and g is a secular change in period. In practice, g would be in general hidden in the period measurement of the light curve, thus leading to a bias on the computed period, except when a significant curvature is present in the data. In the case shown Fig. 2, the formal period error quoted in the Hipparcos variability annex is about one second, but the systematic error on period due to the LITE is about two seconds.

Using an improved ephemeris for T_0 and P_0 [Ribas et al. 2001], and simple string-length or phase dispersion minimisation programs, Eq. 3 has been solved for g using the Hipparcos Epoch Photometry data. The corresponding effect found during the mission duration, $gE^2_{\rm max} = 0.019 \pm 0.0006$ day, is of the same order as the 0.01 day expected from Fig. 2 (lower left). This implies that the duplicity could have been detected through the photometric "acceleration" term. In this case, we were looking for a LITE, but it should however be noted that period variations may be due to many other causes than LITE, e.g. mass transfer.

3 How many objects could be tested in Gaia

Among the 986 eclipsing binaries in Hipparcos, there are 11 of them with a 0.0001 day precision on zero phase. If we assume the same ratio and 2 million eclipsing binaries for Gaia (from the red book), then the LITE for 10 Jup companions could be tested on a minimum of several 10^4 stars. Another estimation may be done the following way: assuming completeness in the Hipparcos Catalogue up to magnitude 8, i-e an epoch photometry precise at the 0.02 mag level on the average, there are about 38000 stars, and among them 27 variables with a 0.0001 day precision on zero phase. Propagating this ratio to Gaia stars, where all types of stars brighter than $G = 18$ should have an epoch photometry precision better than 0.02 mag, would mean $2\,10^5$ stars where a LITE due to a 10 Jupiter with a 11 year period can be significantly tested.

The difference between these two estimations is that we counted only the eclipsing binaries in the first case. They represent however only a fraction of the objects which can be tested: e.g. 11 eclipsing binaries over 63 stars with a 0.0001 day precision on zero phase in Hipparcos. Indeed, light-time effects detected from ground-based

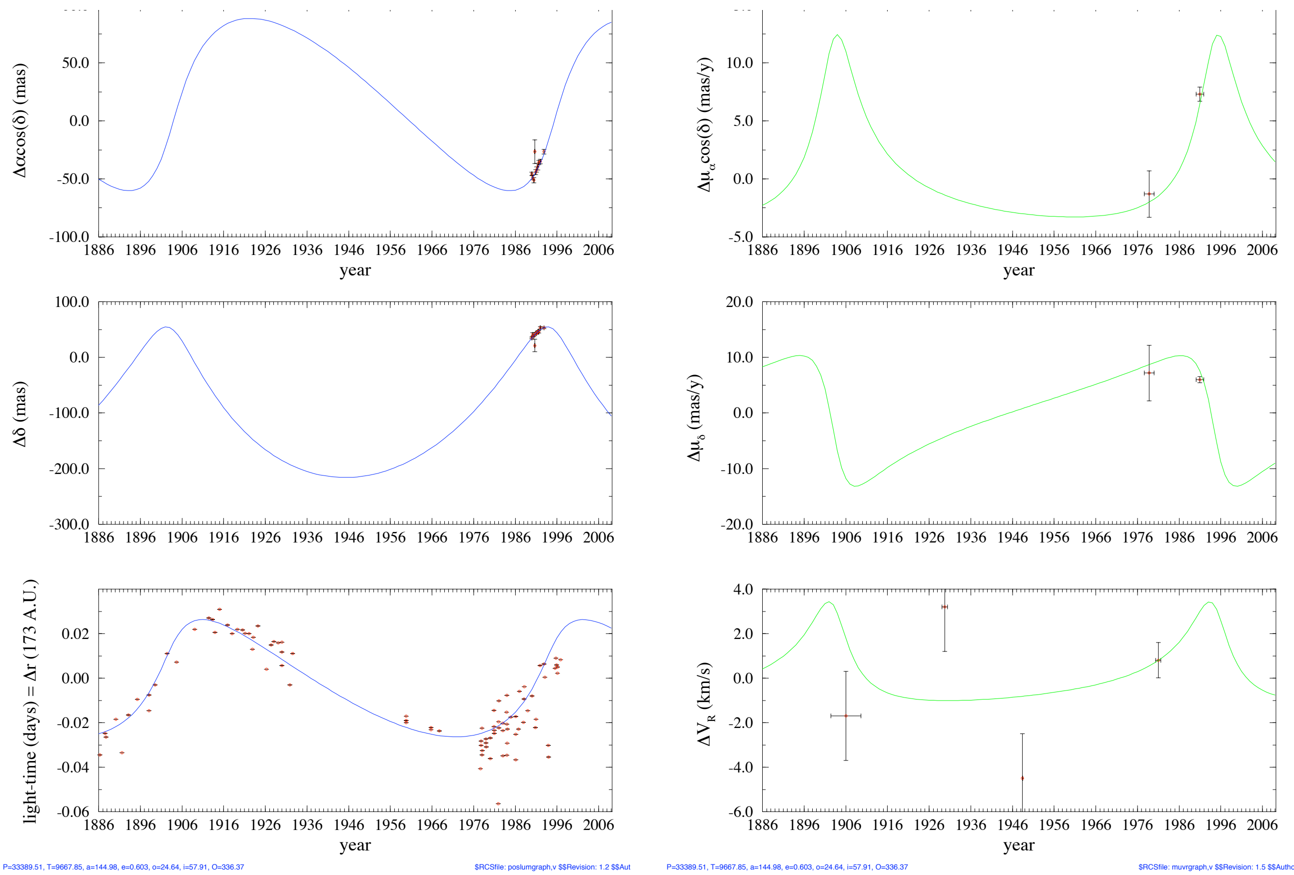

Figure 2: Example of a third companion detected by a light-time effect (lower left), and also detected by the Hipparcos astrometry (top and middle): some normal points for the positional residuals (left), proper motion (right). The variation of proper motion in right ascension explains why the acceleration had been detected during the Hipparcos mission. The RV points (bottom right) come from Simbad, and are shown for completude only (the systemic velocity is not known, so the measurements have been arbitrarily shifted, and the error bars have been roughly estimated).

studies also concern non-eclipsing binaries, e.g. the RR Lyrae TU UMa [Wade et al. 1999] or the β Cepheids β Cep, σ Sco and BW Vul [Pigulski 1993] and obtaining masses for these stars would be very valuable. In fact, what we need is just a "clock in orbit" where the clock precision depends on the shape of the light curve and on the number of measurements.

In general Gaia will hardly detect by itself a LITE, due to the uneven photometric sampling and the small number of measurements, and past or future complementary observations will often be needed in order to prove a Keplerian motion. However, current ground-based experiments about μ-lensing already provide millions of light curves. If a compilation of these light-curves is done in advance, using the same time scale as Gaia, then long periods may be detectable.

The detection confirmation would be easier for more massive (stellar) secondaries, since Gaia astrometry will be able to detect accelerations due to a period of several centuries up to several hundreds of pc. In the data reduction, when an orbital motion due to a third body is detected through astrometry for a variable star, a correction may have to be taken into account in the light-curve analysis in order to get an unbiased variability period. Also, in order to make the most efficient use of the light curves, the photometric data should be preserved at the highest time resolution level (i.e. better than 1 second) in all the CCDs of the focal plane.

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References

[Brown et al. 2001] Brown T.M., et al., 2001, astro-ph/0101336

[Irwin 1952] Irwin J., 1952, ApJ 116, 211

[Pigulski 1993] Pigulski, 1993, A&A 274, 269

[Radhakrishnan at al. 1984] Radhakrishnan K. R. et al., 1984, Ap&SS 99, 229R
[Ribas et al. 2001] Ribas I., et al., 2001, in preparation
[Wade et al. 1999] Wade R.A., et al., 1999, AJ 118, 2442
[Wolszczan & Frail 1992] Wolszczan A., Frail D. A., 1992, Nature 355, 145