FINDING PLANETS AND BROWN DWARFS WITH GAIA

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ABSTRACT

The astrometric interferometer satellite GAIA, proposed for ESA's Horizon 2000+ programme, will be able to investigate about half a million stars for Jupiter-sized planetary companions and many more for brown-dwarf companions. Such companions cause non-linear motion of their parent stars on the sky, i.e., they show up as astrometric binaries. GAIA will perform one-dimensional astrometric measurements, much as Hipparcos did, but with a tremendously increased accuracy. It will be a non-trivial problem to derive three-dimensional binary orbits from such data.

We demonstrate, using actual Hipparcos measurements, that this problem can indeed be solved. We sketch the numerical method being used for the discovery of hitherto unsuspected astrometric binaries from the Hipparcos data, and present a few illustrative examples showing that the expected sensitivity is actually reached.

Key words: astrometry; space astrometry; Hipparcos; GAIA; interferometry; extrasolar planets; brown dwarfs

1. INTRODUCTION

The Hipparcos project represented the first step in the acquisition of astrometric data from space. Positions, annual proper motions, and parallaxes have been determined with accuracies in the range 1–2 milliarcsec, and a considerable number of stars are being discovered to be astrometric binaries by their non-constant proper motion. The astrometric signature of an invisible companion is due to the reflex motion of the parent star along a small Kepler ellipse. Up to now, all unseen companions detected by Hipparcos in this way have stellar masses. However, the astrometric sensitivity of Hipparcos is just sufficient to detect possible brown dwarf companions of nearby stars (if such exist). Yet it does not reach the planetary mass range (see Section 2 and Fig. 1.).

GAIA will observe roughly a thousand times more stars than Hipparcos did, and at roughly a hundredfold improvement in sensitivity (Lindegren et al. 1994; Lindegren & Perryman 1995). GAIA will be able to investigate half a million stars for Jupiter-sized planetary companions and many more for brown-dwarf companions, as argued by Casertano et al. (1995). Even planetary objects having only twice the diameter of the earth could be found around roughly 100 nearby stars—if they exist.

The above numbers of candidate stars for the search for planetary companions were derived by Casertano et al. (1995) under the (implicit) assumption of a simple detection method: one-year two-dimensional normal points on the sky are formed from the individual one-dimensional GAIA (or Hipparcos) measurements. Then the deviations of these normal points from an assumed constant proper motion is tested for statistical significance. In their analysis, Casertano et al. considered a companion to be detectable if the semimajor axis of the parent star's reflex ellipse is larger than 3 times the mean error σ_1 of a one-year normal point. This is a very reasonable and conservative estimate.

However, the method of normal points does not fully utilize the information content of the individual satellite measurements. Furthermore, it cannot work properly for periods of less than two years. In the present paper we sketch a more powerful method. Its sensitivity limit is given not by the mean error of one-year normal points, but by the mean errors of the astrometric parameters derived from the entire mission. Furthermore, the method not only *detects* the binarity signature, it also attacks the more difficult problem of deriving orbital parameters.

2. THE DETECTION CAPABILITIES OF HIPPARCOS AND GAIA

Astrometric observations of an unresolved binary trace the motion of the system's centre of light along a Kepler ellipse. If one of the binary components completely dominates the light, then the astrometrically measured semi-major axis a_a is the true semi-major axis a_1 of that component's orbit around the system's centre of mass. If the secondary component contributes some light, then a_a is smaller than a_1, and a_a gets zero in the case of equally bright partners. In no case it is possible to derive the full semi-major axis $a = a_1 + a_2$ of an unresolved binary's orbit from astrometric data alone.

Straightforward error calculus shows that any method which fully utilizes the information content of the one-dimensional Hipparcos (or GAIA) measurements will be able to derive the astrometric semi-major axis a_a with about the same uncertainty as the basic astrometric parameters, viz. position, annual proper motion and parallax. For Hipparcos this means a mean error of the order of 2 mas or better. For GAIA the corresponding value is about 100 times smaller. Consider, as Casertano et al. did, that a binary can be regarded detectable if a_a is at least three times larger than its mean error. This directly leads to a minimum detectable secondary star mass for any assumed combination of primary mass and distance. The thus defined detection limits for Hipparcos are given in Fig. 1, for two representative cases.

Fig. 1 assumes main-sequence stellar partners and $a_a = 6$ mas$= 3\sigma_a$. Over most of the figure, $a_a = a_1$ because the low-mass companions do not contribute to the system's light. The detection limit decreases with increasing orbital period P because for given component masses a_1 grows as $P^{2/3}$. Beyond 1500 days the minimum mass increases slowly because Hipparcos then observes only a part of the astrometric ellipse. At short periods the detection limit increases quite suddenly when the secondary mass approaches that of the primary. The secondary's light contribution then quickly reduces a_a compared to a_1.

The mass limits given in Fig. 1 show that Hipparcos is just able to detect brown dwarf companions for a few hundred nearby stars. The corresponding figure for GAIA looks very similar, but with all masses divided by 100. The 20 Jupiter masses (0.02 $M_\odot$) marked at the lower curve in Fig. 1 thus correspond to a few dozen earth masses in the case of GAIA.

Figure 1. Minimum detectable companion masses from Hipparcos measurements as a function of orbital period for two different assumed primary stars. A low-mass companion is considered detectable if the semi-major axis of the primary's reflex motion is 6 mas, i.e., 3 times the typical measuring accuracy of Hipparcos. The upper curve corresponds to a primary star of 1 $M_\odot$ (i.e., a G2 dwarf) at 40 pc distance, the lower curve to a star of 0.5 $M_\odot$ (i.e., an M0 dwarf) at a distance of 10 pc. The corresponding mass limits achievable by GAIA are smaller by about a factor of 100.

3. NUMERICAL METHODS

This section very superficially sketches the numerical methods used for the detection of unresolved astrometric binaries from Hipparcos data. At the time of writing the methods are still developing, but output data for the final Hipparcos Catalogue will be produced before this text appears in print. A full description of the methods will be given in a forthcoming paper (Bernstein & Bastian 1996). Exactly the same procedures will be applicable to GAIA observations.

3.1. The Problem

The basic task of binary detection looks simple: the standard Hipparcos data reduction fits a single-star model to the observations of unresolved (i.e., pointlike) stars in a standard least-squares adjustment (see Lindegren 1989, Bernstein 1994). The model contains position, annual parallax and (constant!) proper motion as free parameters. If this model is correct then the normalized residuals of the individual observations after the parameter adjustment should possess a normal distribution. The sum of their squares (called χ^2 in the following) should have a standard chi-square distribution. This means that the values of χ^2 for individual stars should cluster around the individual degrees of freedom $f = n_{\rm obs} - 5$, where $n_{\rm obs}$ is the number of one-dimensional astrometric measurements for the particular star. Any significant excess of χ^2 over f signifies either an astrometric binary or else the chance occurrence of one or more bad measurements.

In actual Hipparcos data reductions a simple function of χ^2 is used as diagnostic quantity instead of χ^2. It is the a-posteriori mean error of unit weight σ_0 and defined as $\sigma_0 = 10\sqrt{\chi^2/f}$ mas. This quantity is displayed in Figs 2–6 (to be discussed in Section 4 below). Its target value is 10 mas. The typical degree of freedom in Hipparcos single-star reductions is $f = 25$, i.e., $n_{\rm obs} = 30$. Under these conditions $\sigma_0 = 13.3$ mas corresponds to the 1-percent significance limit for excessive χ^2. Any star having σ_0 above this value may be considered as candidate astrometric binary.

Astrometric orbit parameters cannot be derived from Hipparcos (or GAIA) data by a straightforward least-squares adjustment, for several reasons. In principle, one would like to derive the full set of seven Keplerian elements $a_a, P, e, i, \omega, \Omega, T_0$. The occurrence of angular unknowns i, ω, Ω (and T_0) makes the problem so non-linear that convergence critically depends on good starting values. The 'obvious' starting value, namely the single-star solution corresponding to $a_a = 0$ does not lead to any binary solution at all: with $a_a = 0$ all derivatives in the design matrix of the least-squares adjustment are zero. To search a 7-dimensional parameter space of starting values is impractical on computing-time grounds, and furthermore it would lead to a multitude of spurious solutions. Therefore it is necessary to look for ways to either reduce the parameter space to be searched for starting values, or else to reformulate the problem so that it becomes a linear one. Our method does a combination of both.

3.2. The Solution

There is a well-known linear formulation of a restricted problem: four Thiele-Innes constants parameterize a binary obit if the period P is known and the eccentricity e is zero. The observable astrometric displacement on the sky due to such an orbit is a linear function of these four parameters. So, if we could assume circular orbits we would have a linear problem in 4 unknowns. One of the other three unknowns (e) would have become fixed, one (T_0) would have lost its significance, and only one, namely the period P, would remain to be searched for a starting value. However, at the relevant periods of a hundred days and more, most of the known binary orbits have considerable eccentricities. So this is not a complete solution of our problem.

In case of eccentric orbits the Thiele-Innes constants essentially describe the first harmonic of the periodic astrometric motion on the sphere. The second harmonic contains the necessary information about e and T_0. In our forthcoming paper (Bernstein & Bastian 1996) we shall show how a set of two parameters u, v in addition to the Thiele-Innes constants can be constructed which represent the second harmonic and give a linear problem in 6 unknowns. Thus, without going into details, our method for the detection of astrometric binaries and the derivation of orbital parameters can be sketched as follows:

(1) select candidate stars from the results of standard Hiparcos data reductions. The selection criteria are that the star must appear pointlike to Hipparcos, but at the same time have an excessive σ_0, as discussed above.

(2) perform a period search, i.e., solve the linear 6-parameter problem for a dense grid of trial periods.

(3) select the 'best-fit' period (if any) from the many trial solutions. This selection is done on the basis of several criteria. The most basic one is the decrease of σ_0 with respect to the standard single-star solution. In the rest of the present paper we shall refer to this criterion only.

(4) refine the period determination and parameter estimation within a narrow range around the 'best-fit' trial solution, using additional numerical and statistical tools.

(5) assess the statistical significance, astrophysical plausibility and possible ambiguities of the selected 'best-fit' solution. Compare with alternative solutions.

3.3. Difficulties and Caveats

Our method unavoidably possesses the usual problems of any period search procedure. On one hand, it is impossible to determine periods which are much longer than the total time interval spanned by the individual satellite measurements. For both Hipparcos and GAIA this limit is somewhere between 5 and 10 years, depending on the particular value of a_a. The astrometric effect of orbits with longer periods is still detectable, of course; it shows up as a time derivative of the proper motion. But the value of the period, and thus of all other orbital parameters, can no longer be determined.

On the other hand there is the usual problem of aliasing. The Hipparcos (and also GAIA) measurements of any individual star are not too numerous and, moreover, they are badly distributed in time. Thus one may expect a complicated pattern of alias periods which in many cases will make a decision on the correct period impossible. This, however, is not a property of our method, but of the problem it treats. There is no way to avoid the period search in the treatment of new binary orbits, no matter whether the observational material is astrometric, spectroscopic or photometric. The aliasing problem limits the effective range of period determinations on the short-period side. The limit is somewhere around 2 months, both for GAIA and Hipparcos. Any true period below this limit may show up as a long-period alias, and vice versa.

Third, our method determines the first and second harmonic of the periodic motion on the sphere as largely independent parameters. Thus it can happen that the size of the second harmonic corresponds to an eccentricity $e > 1$. Such solutions must then be discarded as astronomically implausible. In fact, this happens quite regularly. Consider a circular orbit, with no second harmonic at all. Whenever our period search uses twice the true period of the orbit as its trial period it will find zero first harmonic and a very big second harmonic. Ways to either avoid this situation or else to recognize and eliminate such cases will be described in Bernstein & Bastian (1996). The effect is nicely visible in Figs 2–6, to be discussed in Section 4 below.

As a caveat of a very different nature we remind the readers of the difference between a_a and a_1 or $a_1 + a_2$ discussed at the start of Section 2. As a consequence of this it will generally not be possible to derive stellar masses (for unresolved binaries) from Hipparcos or GAIA measurements alone. The addition of evidence from either radial velocities or speckle interferometry immediately removes the indeterminacy, however. Such external data from spectroscopy or imaging will of course also be able to remove the ambiguities due to alias periods and the indeterminacy of very long periods discussed above.

Figure 2. Result of the period search for the known spectroscopic binary HIC 95995. The a-posteriori mean error of unit weight σ_0 from trial orbit solutions is plotted versus the inverse of the trial period. Values of σ_0 approaching the horizontal line at 10 mas indicate good model fits. The best fit is found for the a priori known spectroscopic period of about 500 days. For more explanations see Section 4.1.

4. A FEW ILLUSTRATIVE RESULTS

Our methods are being trained and verified on well-known spectroscopic and/or speckle-interferometric binary orbits. Formal error calculus inherent to the adjustment procedure says that the astrometric semi-major axis a_a can frequently be determined with a mean error of the order of 2 mas, as expected. The agreement with speckle data and spectroscopic orbits confirms the internal error estimates, both for a_a and for the other orbital parameters.

4.1 Two Known Binaries

Fig. 2 illustrates the result of the period search for the known spectroscopic binary HIC 95995 (the abbreviation HIC denotes the Hipparcos Input Catalogue). The binary nature of this star produces only a mild astrometric disturbance, giving $\sigma_0 \simeq 16$ mas in the single-star model solution. Hipparcos yielded a comparably large number of measurements for HIC 95995 which are well distributed in time. Therefore the orbit could be very well determined although a_a is only about 6 mas. The known spectroscopic period of about 500 days is confirmed, and a_a is determined with a mean error of about 1 mas.

The thin curve in Fig. 2 displays the values of σ_0 from the 6-parameter orbit solutions for a few hundred trial periods between 30 and 30000 days. The abscissa of Fig. 2 is the inverse of the trial period. The target value of σ_0 for a perfect model fit is denoted by the horizontal line at 10 mas. The short vertical line at lower left denotes the 'best-fit' period selected from the displayed data. Two strong aliases at 0.014 days^{-1} and 0.021 days^{-1} (corresponding to periods of about 70 and 50 days, respectively) are obvious.

The thick, generally smoother curve shows the corresponding results from 4-parameter orbit solutions, using only the Thiele-Innes constants, i.e., assuming circular orbits. The two smaller aliases at about 0.007 days^{-1} and 0.012 days^{-1} do not show up in this curve. This fact signifies that they belong to the class of second-harmonic aliases discussed in the third paragraph of Section 3.3.

Figure 3. Result of the period search for a known spectroscopic binary, for which two different orbital periods can be found in the literature. The longer period is confirmed by Hipparcos (vertical line at lower left), while there is no signal at all at the other candidate period (short vertical line at upper left).

Fig. 3 is an analogous display for HIC 82020. This also is an *a priori* known spectroscopic binary, but two different values of the orbital period can be found in the spectroscopic literature: 363 days and 1386 days.

The astrometric data of Hipparcos produce a very nice fit at about 1300 days (thus confirming the longer period, vertical line at lower left), but no fit at all at the alternative period of about 1 year (short vertical line at upper left). The astrometric orbit of this star is much larger than that of HIC 95995; a_a is of the order of 35 mas. Therefore the values of σ_0 at non-fit periods are much larger than in Fig. 2.

Three strong aliases can be seen, all of which give much worse fits to the data than the period of 1300 days. The left-most of the three is the second-harmonic alias of the central one. The two strongest aliases—besides giving a worse fit than the 1300-days period—can be eliminated on astrophysical grounds for this star. They both would imply a mass of the secondary star which is higher than the mass of the spectroscopically visible main-sequence star of spectral type F2. Such a massive secondary should dominate the light of the system—unless it were a neutron star or black hole.

4.2 A Disturbed Single Star

HIC 34115, like the spectroscopic binary HIC 95995 above, produced $\sigma_0 \simeq 16$ mas in the single-star data reduction. In the case of this star the period search did not yield any good fit (Fig. 4). So it must be considered a single star, with some of its Hipparcos observations affected by unduly large accidental errors. Obviously the 'best-fit' period selected by the software (vertical line) does not indicate a good fit at all.

Figure 4. Unsuccessful period search for a star with excessive σ_0. The unduly large scatter of the individual Hipparcos measurements for this object is obviously not caused by duplicity.

HIC 34115 is a mild case of a disturbed single star. There are much more severe cases, which still do not yield significant binary solutions. However, it is clear that the occurrence of several bad measurements among only 20 or 25 good ones might occasionally mimick a binary orbit. Thus it will be highly worthwhile to do spectroscopic follow-up observations on as many Hipparcos (and GAIA) astrometric binary candidates as possible.

4.3 Two Newly-Discovered Astrometric Binaries

A considerable number of hitherto unsuspected astrometric binaries is being found from Hipparcos observations. Figs 5 and 6 announce the discovery of two such systems. The first example, HIC 2, is a K3 dwarf star exhibiting an astrometric orbit with a period of about 550 days and $a_a \simeq 14 \pm 2.5$ mas. The prominent alias at about 30 days (far right in Fig. 5) can be excluded as the true period since it would result in a highly unreasonable companion mass.

Figure 5. An astrometric binary newly discovered from Hipparcos measurements and treated with the methods discussed in Section 3. For details see text.

Figure 6. A second example of an astrometric binary discovered by Hipparcos. For details see text.

The second example, HIC 5496, also is a nearby K dwarf. It exhibits a 400-day orbit with an a_a of about 20 mas (± 2.5 mas). None of the aliases give a reasonably good fit to the data, so that the 400-day period looks quite trustworthy. These results indicate that the unseen companion is a fairly late M dwarf.

As a side remark we would like to encourage ground-based observers to attempt a spectroscopic confirmation of these two astrometric binaries, even before the final Hipparcos results are released in early 1997. The amplitude of the variations in radial velocity should be of the order of one or a few km/s in both cases. Speckle interferometry measurements may also be tried, but are less likely to produce a positive result for these two stars.

5. CONCLUSIONS

The astrometric signature of binarity for GAIA is absolutely analogous to that for Hipparcos, albeit on a hundredfold higher level of sensitivity. Therefore the same mathematics and the same numerical methods are applicable. Thus, by demonstrating a method to detect and analyse astrometric binaries at the expected accuracy level for Hipparcos, we immediately do the same for GAIA. In other words, the very deep and rigorous census of our galactic neigbourhood for brown dwarfs and heavy planets expected from GAIA is not only possible in principle, but also in practice.

REFERENCES

Bernstein, H.-H., 1994, *Astron. Astrophys.*, 283, 293

Casertano, S., Lattanzi, M., Perryman, M.A.C., 1995, ESA SP–379, this volume

Lindegren, L., 1989, in: The Hipparcos Mission, ESA SP-1111, Vol III, 171