ASTROMETRIC INDICATIONS OF BROWN DWARFS BASED ON HIPPARCOS DATA

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ABSTRACT

In order to investigate the standard star solutions of the astrometric parameter determination in the FAST consortium, I developed an algorithm for the detection of astrometric binaries. The application of this algorithm was concentrated on those objects, where the χ^2-test of the astrometric parameter estimation using a single star model was not satisfactory. This method will be outlined in this paper. It is shown, that the accuracy of the Hipparcos observations allows the detection of brown dwarfs as a component of an astrometric binary. A systematic search of low mass companions among the M and K stars in the solar neighbourhood delivered six candidates possibly orbited by a brown dwarf, including Gliese 433.

Key words: space astrometry; astrometric binaries; low mass companions.

1. INTRODUCTION

Searching for low mass companions like brown dwarfs seems to be one of the most exciting tasks in astronomy nowadays. This paper outlines how Hipparcos is able to contribute to this subject.

In order to investigate the standard star solutions, this work was done in the framework of the astrometric parameter determination within the FAST consortium. Details are explained by Kovalevsky (1995). Starting point is a failure of the χ^2-test for a certain number of stars during the estimation of the classical five astrometric parameters (α, δ, μ_α, μ_δ, π). One can assume, that the failure of the χ^2-test is caused by an incorrect star model. Instead of a single star treatment, the objects in question should be handled as astrometric binaries. So, the observations (here the abscissae on the reference great circles) of those stars are disturbed by the existance of a(n) (unseen) companion. This led to the development of an algorithm for the detection of astrometric binaries.

In general, Hipparcos observes the motion of the photocentre in the case of those astrometric binaries. Regarding low mass companions, the magnitude difference between primary and secondary component is larger than 3.5 mag and the photocentre coincides with the primary component. This needs an approval for all stars in question.

The mass of any companion can be derived by a combined spectroscopical and dynamical mass determination using the mass of the primary component M_1 from the mass luminosity relationship. This leads to a favourable error propagation.

2. BASIC IDEA

The algorithm for the detection of astrometric binaries starts with an enlargement of the classical observational equation by terms of the orbital motion. One can accomplish this by the description of the orbital motion using the Thiele Innes constants for the location of the orbit in space and expanding the elliptical coordinates in the orbital plane by Fourier series, see Brouwer & Clemence (1961). This leads to a linear model with the sine and cosine of the mean anomaly as coefficients in a linear observational equation. Here no *a priori* information concerning the orbit is necessary. Due to the mathematical form of the observational equation and due to the small number of measurements, one cannot accomplish the periodogram analysis directly. I vary the period or frequency within reasonable limits, and I estimate the Fourier coefficients as well as the astrometric parameters by a two step least-squares procedure, convolved with the QR decomposition for the computing of the needed proper values Λ_i. After the selection of the best solution by different criteria, one can utilise this solution as starting values of an iterative adjustment (here the Levenberg Marquardt Algorithm) estimating the classical Kepler elements together with the classical astrometric parameters.

Accomplishing this method, one can plot the rms of unit weight versus the frequency I vary. Figure 1 shows this plot for the well known double star: McAlister 65a. The period of the deepest minimum at about 9 mas coincides with the period of the orbit obtained from speckle interferometer measurements of Hartkopf & McAlister (1984). The plot shows some ambiguities which are explained later in this paper.
In contrast the same plot for a confirmed single star in Figure 2. The curve varies at 11 ± 1 mas without any significant peak.

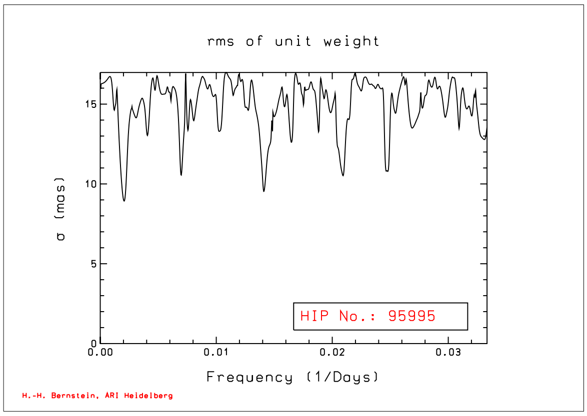

Figure 1. rms of unit weight for McAlister 65a.

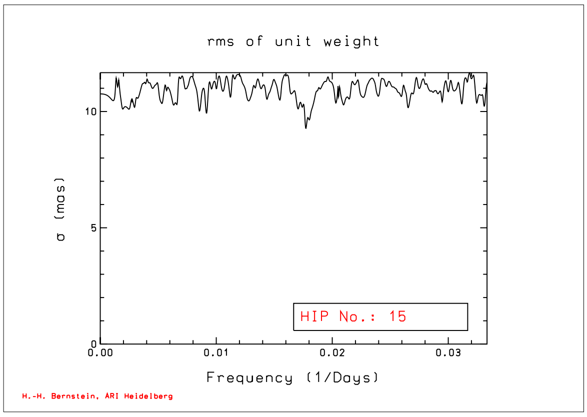

Figure 2. rms of unit weight for HIP 15.

3. SELECTION CRITERIA

From the data analysing theory, see Grafarend et al. (1979), one can use the following criteria for an optimal solution:

- *min* of the χ^2 or the rms of unit weight [$\sigma_\circ$(*a priori*) = 10 mas],
- *max* the signal-to-noise ratio of the semi-major axis,
- *min* of determinant of the covariance matrix of the unknowns $\prod_i \Lambda_i$,
- *min* of the trace of the covariance matrix of the unknowns $\sum_i \Lambda_i$,
- *min* of the Euclidean norm of the covariance matrix of the residuals,
- *min* of the largest proper value of the covariance matrix of the unknowns.

In addition, one should consider the following conditions:

- the subsequent iterative adjustment must converge to a reasonable solution,
- the mass of the primary component must be larger as the mass of the secondary component; here, the detection of a cold white dwarf is impossible,
- the second harmonic must be smaller than the first harmonic.

4. PROBLEMS

Due to the scanning law and the observing techniques, the abcissae are one dimensional, unevenly spaced observations. The correct peak in the plots must be distinguished from aliasing effects as well as from other order of harmonics; well known effects from the time series analysing. Figure 1 shows an example of these problems.

Due to the small number of observations, the fit of a circle in space could be more appropriate as a fit of an ellipse with full parametrization. Generally, the law of area separates the inclination effect from the effect of ellipticity. Sometimes the time distribution of the Hipparcos measurements does not allow to benefit from this basic fact.

5. THE CAPABILITY OF HIPPARCOS CONCERNING THE DETECTION OF LOW MASS COMPANIONS

Figure 3 plots the mass of a possible companion in solar mass units versus the orbital period. Accepting the Hipparcos accuracy of the position of about 2 mas, the semi-major axis of the orbit of the photocentre a can be fixed of about 6 mas as a 3σ effect. The upper curve is calculated for a sun like star at a distance of 40 pc and the lower curve shows the relationships for a M dwarf at 10 pc.

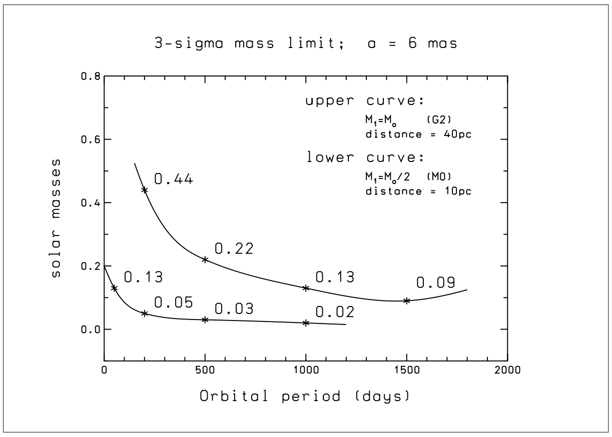

Figure 3. Low mass detection capability.

From Figure 3 one can conclude that the detection of brown dwarfs is possible with Hipparcos, although this kind of data analysis is very close to the sensitivity limit!

HIP 21932 (Gliese 176)
V = 9.948 mag, Sp.T.: M2, $M_1 = 0.39 M_\odot$

π	111.6 ± 6.2 mas
P	463.8 ± 39.1 days
a_1	15.3 ± 5.2 mas
M_2	$0.07 \pm 0.03\ M_\odot$
Ω	$100\overset{\circ}{.}4 \pm 7\overset{\circ}{.}8$
$\imath$	$91\overset{\circ}{.}2 \pm 11\overset{\circ}{.}0$
ω	$352\overset{\circ}{.}6 \pm 17\overset{\circ}{.}4$
$\sigma_\circ$	9.0 mas

HIP 48904 (Gliese 375)
V = 11.265 mag, Sp.T.: M5, $M_1 = 0.22 M_\odot$

π	64.4 ± 2.5 mas
P	294.3 ± 9.5 days
a_1	8.9 ± 3.1 mas
M_2	$0.07 \pm 0.03\ M_\odot$
Ω	$191\overset{\circ}{.}0 \pm 54\overset{\circ}{.}1$
$\imath$	$139\overset{\circ}{.}5 \pm 35\overset{\circ}{.}4$
ω	$10\overset{\circ}{.}3 \pm 49\overset{\circ}{.}3$
$\sigma_\circ$	11.1 mas

HIP 53767 (Gliese 408)
V = 10.034 mag, Sp.T.: M3, $M_1 = 0.33 M_\odot$

π	149.4 ± 2.5 mas
P	250.1 ± 11.4 days
a_1	8.2 ± 3.4 mas
M_2	$0.04 \pm 0.02\ M_\odot$
Ω	$286\overset{\circ}{.}9 \pm 6\overset{\circ}{.}8$
$\imath$	$102\overset{\circ}{.}7 \pm 15\overset{\circ}{.}6$
ω	$60\overset{\circ}{.}4 \pm 28\overset{\circ}{.}5$
$\sigma_\circ$	12.9 mas

HIP 91699 (G 206-40)
V = 11.270 mag, Sp.T.: M4, $M_1 = 0.27 M_\odot$

π	88.2 ± 2.5 mas
P	258.6 ± 8.9 days
a_1	10.5 ± 3.0 mas
M_2	$0.07 \pm 0.03\ M_\odot$
Ω	$10\overset{\circ}{.}8 \pm 20\overset{\circ}{.}4$
$\imath$	$103\overset{\circ}{.}2 \pm 13\overset{\circ}{.}0$
ω	$166\overset{\circ}{.}9 \pm 16\overset{\circ}{.}7$
$\sigma_\circ$	10.4 mas

HIP 73184 (Gliese 570A)
V = 5.723 mag, Sp.T.: K4V, $M_1 = 0.70 M_\odot$

π	171.7 ± 1.3 mas
P	33.3 ± 0.3 days
a_1	3.4 ± 0.9 mas
M_2	$0.06 \pm 0.02\ M_\odot$
Ω	$31\overset{\circ}{.}5 \pm 18\overset{\circ}{.}2$
$\imath$	$89\overset{\circ}{.}4 \pm 29\overset{\circ}{.}8$
ω	$62\overset{\circ}{.}0 \pm 12\overset{\circ}{.}8$
$\sigma_\circ$	9.2 mas

HIP 56528 (Gliese 433)
V = 9.811 mag, Sp.T.: M0V, $M_1 = 0.50 M_\odot$

π	109.8 ± 2.1 mas
P	523.6 ± 36.9 days
a_1	6.9 ± 2.2 mas
M_2	$0.03 \pm 0.01\ M_\odot$
Ω	$351\overset{\circ}{.}0 \pm 22\overset{\circ}{.}8$
$\imath$	$63\overset{\circ}{.}3 \pm 20\overset{\circ}{.}5$
ω	$321\overset{\circ}{.}9 \pm 15\overset{\circ}{.}9$
$\sigma_\circ$	10.3 mas

6. OBJECT REQUIREMENTS

In order to get a list of candidates to have low mass companions, I select those stars which show $\sigma_\circ$(standard solution) $\geq$ 15 mas. And from this subset I extract a new subset of nearby stars with $\pi \geq$ 50 mas. And among these stars I focused on the spectral types M and K with some exceptions on G.

7. HIPPARCOS RESULTS

From the final subset of stars in question, one gets the following list of candidates orbited by a low mass companion. The object data are taken from the Hipparcos Input Catalogue and the framed values come from the Hipparcos data analysis (fit of all parameters).

The plot of the rms of unit weight for Gliese 433 differs significantly from a correponding plot of a single star. Since the σ(standard solution) is larger than 15 mas, the fit of a double star model delivers a remarkable improvement, but however, Figure 4 shows no convincing peak. We have local minima at 560, 220 and 140 days, the minimum at 35 days is a well known artifact. The double star character of Gliese

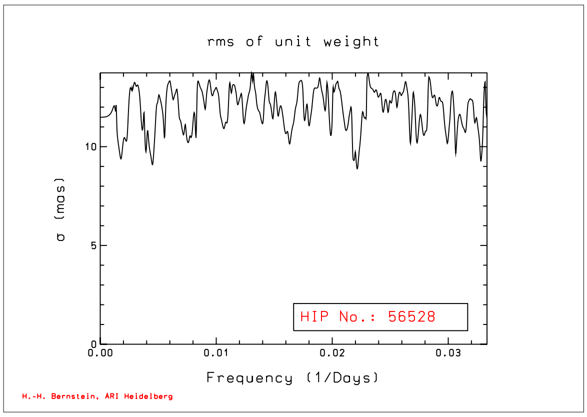

Figure 4. rms of unit weight for Gliese 433.

433 becomes much more evident, in Figure 5, where the signal-to-noise ratio of the semi-major axis is plotted. Here a remarkable effect of 3.8 at 560 days is obvious. In addition the general variance in Figure 6 shows the deepest minimum at 560 days. So I expect the best double star solution at a period of about 560 days. The data analysis of Gliese 433 yields, that a very low mass companion is orbiting this nearby M dwarf. Note that the spectral type and mass (here, like an upper limit) of the primary component given in the accompanying table is from the current version of the catalogue of nearby stars.

Due to the 3σ-effects I asked for a confirmation of this result: the 2D IR speckle interferometer observations at ESO SHARP on the NTT (Leinert & Woitas, MPIA Heidelberg, private communication 1997) confirms that Gliese 433 has a very faint companion!

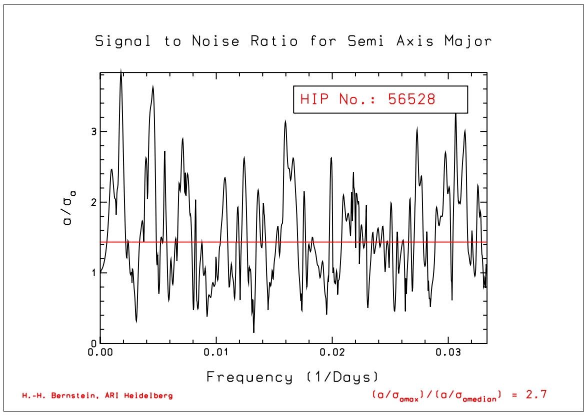

Figure 5. Signal-to-noise ratio of the semi-major axis for Gliese 433.

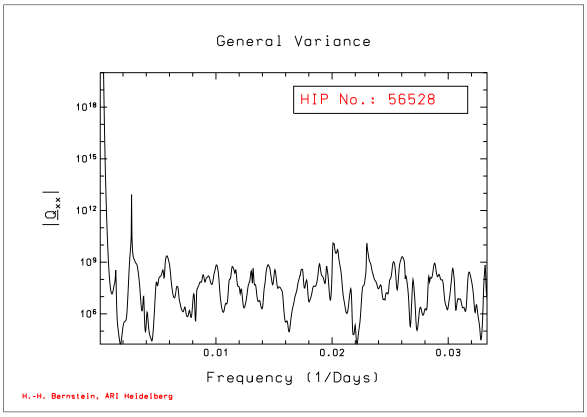

Figure 6. General variance of Gliese 433.

From these observations we get the separation ρ, the position angle Θ and the luminosity difference at T=49911 JD: $\rho_T = 0''.087 \pm 0''.009$, $\Theta_T = 317^\circ.8 \pm 0^\circ.7$ and $\Delta K \approx 3.6$ mag which results in V(companion) ≈ 17.1 mag. Predicted from Hipparcos data we get: $\rho_T = 0''.083 \pm 0''.035$ and $\Theta_T = 327^\circ.5$. The predicted values from Hipparcos shows very good agreement with the 2D IR speckle interferometer observation.

Figure 7 shows these observations in the context of the mass-luminosity-age diagram, where the IR luminosity (at K) is plotted versus the mass in solar mass units. The solid lines in this plot shows the 10 Gyr, 1 Gyr and 0.1 Gyr age isochrones from the theoretical calculations. The dotted lines indicates the critical zone of the brown dwarf detection. The horizontal dashed line shows the 2D IR speckle interferometer observation and the vertical dashed line gives the Hipparcos result. Due to the observational errors, the vertical dashed line could be shifted to 0.06 and the horizontal dashed line could be moved to $M_K = 11$, which is in reasonable agreement with the theoretical age calculations for main sequence stars.

One can conclude, that the Hipparcos data analysis led to the detection of a very faint IR companion, possibly a brown dwarf!

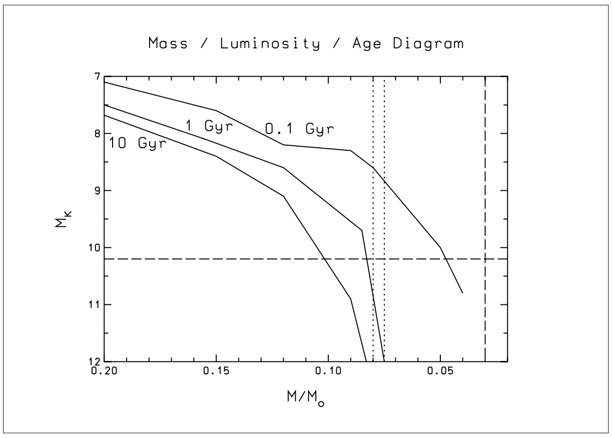

Figure 7. Mass-luminosity-age diagram [using Henry & McCarthy(1993)].

ACKNOWLEDGEMENTS

The author is indepted to Dr. U. Bastian for very fruitful discussions and for some astrophysical advice. Our contributions to the data reduction activities for the ESA Space Astrometry Mission Hipparcos were financially supported by BMBF/DARA under project No. 50OO90020.

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