MASSES OF ASTROMETRIC BINARIES*

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ABSTRACT

Among the double stars observed by Hipparcos and solved for their relative and absolute astrometry, the close pairs with an orbital period less than 10 years have a significant non-linear motion of their photocentre over the observation timespan. The amplitude of this motion is related to the size of the relative orbit of the two components and to the difference between the mass and intensity ratio. We present and discuss a specific treatment of the Hipparcos observations of the small sample of astrometric binaries with reliable ground-based orbital parameters. This leads to the determination of the mass ratio with an accuracy of about one per cent and of the masses of the individual components, the accuracy of which is ultimately linked to the quality of the parallax. Out of the 145 systems with ground-based orbits which were investigated in detail, 44 were solved for the scale of the photocentric orbit. For well-known systems, the masses derived from the Hipparcos data are compared to the values found in the literature.

Keywords: Hipparcos; Double stars; Stellar masses.

1. INTRODUCTION

When a Hipparcos target was a single object, the standard astrometric model in the data reduction assumes a uniform rectilinear motion in space relative to the barycentre of the solar system. In this case only five parameters are necessary to describe the full astrometric information embedded in the Hipparcos measurements: the two angular coordinates to specify the coordinate direction at the catalogue epoch (T_0 = J1991.25), the two components of the proper motion used to propagate this position at any other past of future epoch and the parallax, which besides its obvious astrophysical interest, allows determination of the proper direction from the Earth.

In the case of a non-single object the situation becomes more complex and additional parameters are required to model properly the grid observations. For double stars with orbital period much longer than the duration of the Hipparcos mission, the data processing has been adapted to cope with this difficulty and eventually this led to a good decoupling between the relative and absolute astrometry for more than 13 000 binary systems included in the Hipparcos Catalogue. The principles applied to the detection and the astrometry of the double stars have been presented in detail in the literature (Mignard et al. 1992, Mignard et al. 1995, ESA 1997).

For very close binaries with a maximum separation less than few mas, the satellite could not show any photocentric displacement beyond the linear proper motion of the barycentre and the entries were processed in the same way as the single stars. The most interesting cases, as far as the masses are concerned, are to be found in the orbital pairs with significant separation, $\rho > 100$ mas and an orbital period comparable or few times larger than the mission lifetime. In such a case the curved or wavy displacement of the photocentre is significant and can be separated from the proper motion, provided provision for such a motion is made in the astrometric modeling.

Although it is practically impossible to determine the full set of orbital elements only from the Hipparcos observations, it is well known that the photocentric orbit and the relative orbits are similar in shape (see Section 2), differing only by a scale factor which depends only on the mass of the components and on the magnitude difference. Therefore, including this scale factor as an additional unknown allows derivation of the masses of the components as well as the positions, parallax and proper motion.

2. MOTION OF THE BARYCENTRE

The astrometric solution for systems showing significant orbital motion results from a three-level modelling of the proper direction of the sources: (a) the motion of the barycentre is a uniform space motion described by the five basic astrometric parameters; (b) the model for the orbital motion to describe the motion of each of the two sources about their centre of mass; (c) a model specific to Hipparcos to relate the superposition of the signal produced by the primary and the secondary to the observed grid phase, that is to say to the direction ascribed by Hipparcos to this complex source during a grid-crossing. The corresponding point is close to the photocentre, but for projected separations on the grid larger than about 300 mas, one must introduce a different point which has been called by analogy the 'hippacentre' by Martin et al. (1997). While the apparent orbit of the

*Based on observations made with ESA Hipparcos satellite.

Table 1. The set of astrometric binaries for which a ground-based orbit has been used to reprocess the Hipparcos observations and determine the mass of the components. The columns give the Hipparcos identifier, the usual name, the semi-major axis of the relative orbit in mas and the orbital period in years.

HIP	Name	a mas	P yr	HIP	Name	a mas	P yr	HIP	Name	a mas	P yr
171	85 Peg	0.830	26.27	2237	B 1909	0.214	11.25	2762	13 Cet	0.240	6.89
7580	Kui 7	0.318	29.05	12390	ϵ Cet	0.105	2.65	14328	γPer	0.159	14.65
14576	Algol	0.095	1.86	19508	A 2801	0.145	20.00	19719	46 Tau	0.135	7.18
22196	–	0.087	6.81	23170	Hu 1090	0.232	26.00	24608	Capella	0.056	0.28
29850	75 Ori	0.090	9.20	31509	Fin 19	0.295	29.00	38052	Hu 1247	0.200	18.80
39261	53 Cam	0.055	6.64	43671	Fin 316	0.104	7.24	44248	10 Uma	0.647	21.78
45170	81 Cnc	0.116	2.70	54204	χ01 Hya	0.140	7.40	64838	–	0.080	9.05
75695	β Crb	0.203	10.55	80346	GL 623	0.271	3.73	82817	Kui 75	0.218	1.71
83838	c Her	0.112	8.13	84140	Kui 79	0.762	12.95	85141	Rst 3972	0.148	14.73
86032	–	0.483	8.67	87204	–	0.179	20.70	87655	–	0.087	8.92
87895	–	0.085	2.41	89937	χ Dra	0.122	0.77	91394	A 88	0.196	12.18
93574	Fin 357	0.155	14.38	94349	GL 748	0.130	2.30	94739	Rst 4036	0.234	7.61
96683	ϕ Cyg	0.024	1.19	98416	GL 773.3	0.234	9.74	104858	δ Equ	0.245	5.71
105431	A 617	0.102	6.05	107354	κ Peg	0.255	11.56	108431	δ Ind	0.127	6.09
112158	η Peg	0.045	2.24	116849	Mlr 4	0.147	20.75				

Table 2. Same set as in Table 1, showing the Hipparcos results from the standard processing. The labels C, O, G, X refer to the sections of the Double and Multiple Systems Annex in which the solution has been placed. A blank in this column indicates that a single star solution has been adopted.

HIP	π mas	σ_π mas	Hp		HIP	π mas	σ_π mas	Hp		HIP	π mas	σ_π mas	Hp	
171	80.6	3.0	5.874	X	2237	31.0	0.9	6.558	C	2762	47.5	1.1	5.321	C
7580	26.1	0.8	6.355	G	12390	37.0	1.8	4.926	C	14328	12.7	0.7	3.059	O
14576	35.1	0.9	2.097	O	19508	15.9	1.0	7.496		19719	27.0	0.9	5.374	O
22196	14.1	0.9	6.672		23170	12.1	0.9	8.489	C	24608	77.3	0.9	0.239	O
29850	12.9	0.8	5.433		31509	24.8	0.6	6.467	C	38052	26.6	0.8	7.141	C
39261	10.2	0.8	6.076	G	43671	12.5	0.5	5.384	O	44248	60.9	1.3	4.059	C
45170	48.8	0.9	6.626		54204	23.0	0.7	5.009	O	64838	13.4	0.8	6.433	
75695	28.6	0.7	3.737	O	80346	124.3	1.2	10.313	O	82817	174.2	3.9	9.014	C
83838	18.5	0.6	5.484	O	84140	158.2	3.3	9.375	C	85141	15.5	1.2	7.967	G
86032	69.8	0.9	2.126	G	87204	18.8	0.6	7.287	C	87655	14.7	0.8	6.343	G
87895	35.0	0.6	6.454	O	89937	124.1	0.5	3.667	O	91394	4.8	0.9	8.390	
93574	17.6	0.8	5.997	C	94349	98.6	2.7	11.103	O	94739	63.4	2.2	9.446	C
96683	13.0	0.6	4.839	O	98416	40.8	1.4	5.997	C	104858	54.1	0.9	4.593	C
105431	21.5	0.8	6.832	O	107354	28.3	0.9	4.235	C	108431	17.6	0.8	4.478	C
112158	15.2	0.8	3.090	O	116849	14.4	0.8	7.079	C					

photocentre is a scale model of the relative orbit, the orbital path of the hippacentre cannot be deduced from the relative orbit simply by a scale factor.

Let $\boldsymbol{\rho}$ be the radius vector between the primary and the secondary in the sense **PS**. If **G** denotes the centre of mass of the system we have:

$$\mathbf{PG} = \frac{\mathcal{M}_2}{\mathcal{M}}\,\boldsymbol{\rho}, \quad \mathbf{SG} = -\frac{\mathcal{M}_1}{\mathcal{M}}\,\boldsymbol{\rho} \qquad (1)$$

where $\mathcal{M}_1$ and $\mathcal{M}_2$ are the masses of the components and $\mathcal{M} = \mathcal{M}_1 + \mathcal{M}_2$. With the mass ratio $B = \mathcal{M}_2/\mathcal{M}$ and $\beta = I_2/(I_1 + I_2)$ for the intensity ratio, the position of the photocentre **F** with respect to the centre of mass is given by:

$$\mathbf{GF} = (\beta - B)\boldsymbol{\rho} \qquad (2)$$

showing that the photocentric orbit is the same as the relative orbit scaled by $\beta - B$. A similar equation holds for the hippacentre, with a varying scale factor depending on the geometry of the individual observations. The hippacentric orbit is then not proportional to the relative orbit (Martin et al. 1997).

Equation 2 is the basic relationship used in the analysis of the Hipparcos data to transfer the observed direction of the photocentre to the barycentre of the orbital system. If the relative orbit is known, we can compute $\boldsymbol{\rho}(t)$ at the time of every observation and determine its projection on the reduction great circle to determine the respective abscissae of the primary and secondary. However the observation is directly related to the photocentre (we neglect the difference with the hippacentre here; a more extensive treatment will appear in Martin & Mignard, 1998).

To get the abscissa difference between the centre of mass and the photocentre, we need know the mass and intensity ratios. As the factor $\beta - B$ is usually poorly known, we included it as an additional unknown to the general astrometric model, so that the abscissas on the reference great circles were fitted to a model with six unknowns $f(l,\, b,\, \pi,\, \mu_l,\, \mu_b,\, \beta - B)$. Quite often Δm is available, and from the scale factor one can deduce the mass ratio B.

As mentioned earlier, for separations larger than about 300 mas, the hippacentre and the photocentre are not identical. In this fortunate situation, since the scale factor is not constant, the observation model is more general with seven independent unknowns, $g(l,\, b,\, \pi,\, \mu_l,\, \mu_b,\, \beta, B)$, which means that the mass and intensity ratios can be solved for from the observations. Obviously there is no clear distinction as to when to use a six- or seven-parameter model. The two models were consistently applied and a numerical criterion determined whether the seven-parameter model was too close to a rank-deficient system to be accepted (Martin & Mignard, 1998).

3. SOURCES OF ORBITS

According to the investigation of Martin et al. (1997), the good candidates must have an orbital period smaller than or equal to 30 years and an angular separation as large as possible. These two requirements are more or less contradictory, unless the systems are at very small distance from the Sun. The orbits were first selected from four different and largely overlapping sources: (a) a file of orbits maintained at the Observatory of Nice and communicated by P. Morel and P. Couteau. It includes 905 orbits of 800 systems; (b) a similar file from the Royal Observatory of Belgium (J. Dommanget), built on the same rules as the previous one, containing 864 orbits relative to 838 systems; (c) the Fourth Catalogue of Orbits of Visual Binary Stars (Worley et al. 1983), including 928 orbits for 847 systems; (d) finally, an extensive bibliographical search updated the information contained in the previous files or found new orbits recently published, usually from speckle observations.

Altogether, after the application of several selection criteria, this yields a set of 242 orbits linked to 145 objects observed by Hipparcos. A solution was attempted for all these systems which ended up with 43 conclusive results. These systems are listed in Table 1. For the sake of comparison with the Hipparcos solution we provide also in Table 2 the parallaxes found in the standard processing of the Hipparcos data. The reference to the DMSA annex (labels C, G, O, X) informs on the kind of modeling adopted in the Hipparcos processing: a 'C' means that a double star with fixed components has been adopted and a uniform motion of the barycentre, a 'G' tells us that a significant departure to a uniform proper motion has been detected while with an 'O', some orbital parameters have been fitted to the data. The 'X' solutions are considered as non reliable because the residuals were not compatible with the abscissa formal errors.

4. EXAMPLES OF SOLUTIONS

The results in term of mass ratios, parallaxes and component masses are listed in Table 3. For the sake of simplicity only the solutions derived from the six-parameter model have been considered here, with a magnitude difference adopted from the Hipparcos photometric solution of the double stars or from the ground in a few cases. The parallaxes differ slightly from the values adopted in the Hipparcos Catalogue (Table 2) because the modelling of the orbital motion is more sophisticated now. One may note that the standard error of the parallax is in general smaller with this new modelling. Discussion of these solutions will be given by Martin & Mignard (1998).

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Table 3. Result of the determination of the masses for 43 orbital systems. The parallaxes refer to the solution with the simple modelling of the scale of the photocentric orbit. All the solutions listed correspond to the six-parameter model and a magnitude difference has been adopted either from the Hipparcos data or from published photometry.

HIP	π	σ_π	Δm	$\sigma_{\Delta m}$	M	σ_M	M_1	σ_{M_1}	M_2	σ_{M_2}
	mas	mas	mag	mag	$M_\odot$	$M_\odot$	$M_\odot$	$M_\odot$	$M_\odot$	$M_\odot$
171	82.16	1.27	3.200	0.15	1.494	0.069	0.701	0.063	0.793	0.065
2237	30.24	0.98	0.060	0.15	2.800	0.272	1.492	0.153	1.308	0.136
2762	46.74	0.97	0.750	0.15	2.852	0.425	1.425	0.258	1.427	0.258
7580	26.22	1.08	0.411	0.15	2.112	0.282	0.890	0.139	1.222	0.178
12390	38.70	1.07	0.060	0.15	2.876	0.258	1.886	0.171	0.990	0.092
14328	13.67	0.85	1.567	0.15	7.332	1.368	5.036	0.951	2.295	0.453
14576	34.77	0.74	3.030	0.15	5.812	0.373	4.302	0.281	1.510	0.110
19508	16.00	1.05	0.100	0.15	1.861	0.366	1.036	0.209	0.824	0.168
19719	26.11	0.96	0.150	0.15	2.712	0.303	1.086	0.133	1.626	0.190
22196	13.38	5.93	0.010	0.15	5.928	1.489	3.061	0.775	2.867	0.727
24608	77.13	0.94	0.154	0.05	4.839	0.177	2.412	0.124	2.427	0.125
29850	12.90	1.06	0.150	0.15	4.048	1.004	2.115	0.554	1.933	0.511
31509	23.92	0.63	0.400	0.15	2.230	0.176	1.006	0.160	1.224	0.169
38052	26.20	0.93	0.100	0.15	1.765	0.190	1.096	0.162	0.669	0.133
39261	10.56	0.79	0.050	0.15	3.271	0.801	0.502	0.301	2.769	0.732
43671	12.01	0.64	0.010	0.15	12.390	1.980	9.406	1.595	2.982	0.715
44248	61.61	1.13	2.080	0.15	2.445	0.135	1.473	0.102	0.972	0.081
45170	48.24	1.02	0.400	0.15	1.908	0.153	1.072	0.087	0.836	0.068
54204	23.01	0.86	0.100	0.15	4.113	0.461	2.225	0.261	1.888	0.226
64838	12.92	0.95	0.010	0.15	2.869	0.684	1.616	0.422	1.253	0.345
75695	27.48	0.82	1.600	0.12	3.632	0.334	1.963	0.193	1.668	0.168
80346	125.56	1.63	5.500	0.79	0.723	0.252	0.590	0.206	0.132	0.047
82817	159.70	2.98	0.180	0.15	0.865	0.048	0.354	0.021	0.511	0.029
83838	18.22	0.72	0.130	0.15	3.496	0.415	2.041	0.246	1.455	0.178
84140	152.20	1.82	0.380	0.15	0.748	0.027	0.404	0.020	0.344	0.018
85141	15.00	1.21	0.010	0.15	4.454	1.148	1.511	0.470	2.943	0.802
86032	69.09	1.01	3.500	0.15	4.710	0.760	3.875	0.631	0.835	0.157
87204	18.99	0.69	0.010	0.15	1.948	0.220	0.834	0.153	1.114	0.174
87655	15.66	0.81	0.200	0.15	2.175	0.361	1.653	0.289	0.522	0.126
87895	35.04	0.88	2.822	0.30	2.455	0.253	1.509	0.167	0.946	0.115
89937	123.93	0.47	2.023	0.39	1.617	0.044	0.884	0.072	0.733	0.071
91394	19.66	1.06	0.130	0.15	2.892	0.468	1.932	0.360	0.960	0.237
93574	17.20	0.61	0.010	0.15	3.539	0.377	1.594	0.176	1.945	0.212
94349	97.70	4.63	2.700	0.15	0.445	0.063	0.302	0.045	0.144	0.025
94739	62.76	1.96	0.010	0.15	0.895	0.084	0.556	0.079	0.339	0.067
96683	14.13	0.58	0.300	0.20	3.346	0.445	1.648	0.277	1.697	0.283
98416	39.20	1.53	0.010	0.15	2.247	0.266	1.758	0.306	0.489	0.232
104858	54.69	1.00	0.290	0.15	2.759	0.151	1.670	0.108	1.089	0.083
105431	20.73	0.97	0.100	0.15	3.255	0.457	2.089	0.298	1.165	0.173
107354	28.63	0.92	0.400	0.15	4.173	0.412	1.799	0.188	2.374	0.243
108431	17.68	0.94	0.100	0.15	4.945	0.789	2.156	0.536	2.789	0.605
112158	16.48	0.98	3.703	0.15	4.072	0.727	2.773	0.498	1.299	0.238
116849	13.96	0.96	0.300	0.15	2.723	0.563	1.257	0.326	1.466	0.361