BINARY STAR MASSES FROM HIPPARCOS

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ABSTRACT

The parallaxes from Hipparcos are an important ingredient to derive more accurate masses for known orbital binaries. In order to exploit the parallaxes fully, the orbital elements have to be known to similar precision, and the present work is a first survey of the orbital systems with parallax errors below about 5 per cent. With methods combining the intermediate 'Transit Data' (published in the Hipparcos Catalogue) with the existing ground-based data, we have made solutions that improve both the orbital elements and in some cases also the Hipparcos data. In particular, some systems with only a photocentre position or orbit in the Hipparcos Catalogue can now be 'resolved' and a magnitude-difference estimated. In all, we have made provisional re-derivations of some 130 sets of orbital elements, giving in the end some 45 mass-sum values with an estimated relative accuracy better than 15 per cent. For some 15 short-period systems, a pure astrometric mass ratio has been determined, but for main-sequence systems, sufficiently accurate mass ratios can be estimated from the observed magnitude-differences. This gives finally an observed 'mass-luminosity relation' in good agreement with stellar evolution theory.

Key words: space astrometry; double stars; orbits; masses; mass-luminosity relation.

1. INTRODUCTION

In advance of the general publication of the Hipparcos Catalogue (ESA 1997), members of the reduction consortia have had access to the data for specified research proposals. One obvious application of the Hipparcos parallaxes is for improved mass determinations for visual binaries with known orbits. Because of Kepler's third law $[m_1 + m_2 = (\frac{a}{\pi})^3/P^2]$, the relative mass error is very sensitive to both the parallax-error *and* to the errors in the orbital elements a and P. Interesting mass errors can only be obtained when these are all small, and a bit unexpectedly, the orbit uncertainties turned out to be sometimes the limiting factor. Instead of just 'plugging in' the Hipparcos parallaxes, we have had to rederive most of the orbits. To do this in full detail is a very large undertaking, needing also more ground-based observations, but the 'quick and dirty' methods used here are thought to be a useful first step.

In the selection of stars, we have used rather *ad hoc* lists of known orbits, and then choosing those having a relative parallax-error below about 5 per cent, a period shorter than 250 years, *and* a calculated separation between the components larger than 0.10 arcsec at least during some part of the Hipparcos mission. In this list, there are several systems with no double star solution given in the Hipparcos Catalogue, but which can now (with the aid of external information) be explicitly resolved. Some others have an 'O'-solution in the Hipparcos Catalogue, that is, a photocentre orbit amplitude was determined, while now and again the individual components are resolved. The present methodology works also for multiple stars, as reported in a separate paper (Söderhjelm & Lindegren 1997).

In most cases, only the sum of the masses can be obtained from the Hipparcos astrometry, and mass ratios had to be estimated from the magnitude difference between the components. In some few favourable cases, however, the observable curvature of the motions during the 3-year observation interval of Hipparcos allowed astrometric mass ratios to be determined. In the catalogue, these 'resolved but curved' systems have generally poor solutions, obtained by fitting to an inadequate linear model. Even when the mass ratios are only marginally significant, the present solutions (including the parallaxes) for these systems should therefore be more reliable than the Hipparcos Catalogue ones.

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2. PRINCIPLES FOR THE ORBIT DETERMINATIONS

It is a well-known fact that the visual observations used to derive many of the existing orbits are plagued by observer- and instrument-dependent systematic errors. It is therefore not surprising that the relative positions given in the Hipparcos Catalogue for epoch J1991.25 often differ appreciably from the positions calculated from orbital elements based on visual observations. On the other hand, as reported in the

Hipparcos Catalogue, the systematic differences between speckle interferometric and Hipparcos relative positions are less than some 0.003–0.004 arcsec (3–4 mas), and each of these sources can thus be taken as relatively unbiased. The general idea is then to make the new orbital elements fit as far as possible the Hipparcos plus speckle-interferometry observations. For systems without speckle data, and/or with long periods, the old visual observations are however still crucial. The rule of thumb principle is then to use mainly the visual position angles, while the separations have to be given very low weight.

Neither are the published Hipparcos Catalogue data for these close pairs always optimal. The known orbits were not taken into account in the reductions, and the relative motion between the components was sometimes neglected, sometimes misrepresented by its linear approximation. In other cases, no resolved solution at all was obtained even when the separation is known to have been above the Hipparcos 0.1 arcsec limit. As another main principle for the new orbit determinations, we do not use the final Hipparcos Catalogue results, but start instead from the intermediate 'Transit Data' (see below). These are absolutely calibrated, giving both astrometric and photometric data in the the standard Hipparcos system, and they can be fitted to more complex orbital models than used in the original reductions.

2.1. Hipparcos Transit Data

The (machine-readable) 'Hipparcos Transit Data' are described in Volume 1, Section 2.9 of the Hipparcos Catalogue. They are basically 'rectified Fourier coefficients' $b_1 - b_5$ describing the light-curve as the object transited the modulating grid at some 100 different epochs during the 1990–93 Hipparcos lifetime. For a point source, these five coefficients are redundant, and can be replaced by an intensity and a phase. For a double star, each scan is made in a new direction with a new 'effective' separation between the components, and the b_i-values contain now also information about this varying separation and about the intensities of both components. The key point to note is that the phase of the light-modulation is fixed in the ICRS reference system (to within any multiple of the 1.2 arcsec grid-period), and with a suitable model, we obtain 'absolute' astrometric data. The b_i values are also photometrically calibrated, that is, they give directly the standardized Hp magnitudes for the component stars. For an alternative use of the Transit Data, see also the paper by Quist et al. (1997).

2.2. Input Data and Solution Model

The observational input to the present solutions consists of two different types of data. First, we have the $b_1 - b_5$ Transit Data, together with full information about the scanning geometry, at each of some 100 epochs (1990–1993). This gives absolute position information about each component, and also about e.g. the system parallax. Secondly, we have standard relative double-star observations. Speckle-interferometry observations were taken when available from the WWW-version of the 3rd CHARA Catalogue by Hartkopf et al. (1996a). The speckle data were usually assumed to have 5 mas mean error in each coordinate, but for consistency with the Hipparcos photometry, frequent 180-degree reversals were necessary. For a few short-period binaries, a complete (and very reliable) solution may be had from only speckle plus Hipparcos data. Generally, however, we had to use also some visual data. Recovering and using these old observations is very time-consuming, and as an admittedly crude alternative, the visual observations were sometimes replaced by 'simulated' ones calculated from the orbital elements. This was done only for systems with high-quality 'grade 1' or 'grade 2' orbital elements in the 4th catalogue of orbits of visual binary stars (Worley & Heintz 1983), and any systematic bias on the solutions (compared with using the real data) have not been noted.

The basic model to be fitted is an orbital binary, and the positions of each of the two components are specified by the mass ratio (q), the seven orbital elements $(P, T, a, e, i, \omega, \Omega)$ plus the five astrometric parameters $(\alpha, \delta, \mu_\alpha, \mu_\delta, \pi)$ for the center of mass. To this has to be added the two magnitudes (Hp_i) in the Hipparcos magnitude system, altogether 15 parameters. The mass ratio can in principle only be determined for the few resolved systems showing observable orbit curvature in the 3-year Hipparcos observation interval, and it can otherwise be chosen arbitrarily. The orbital model (with the above two separate types of input data) is implemented in the GaussFit environment (Jefferys et al. 1988), running 'automatically' an iterated least-squares solution with the fitted parameters and their errors as output. The easy implementation has a cost in slow execution and somewhat complicated administration, but for the present application, there has been no need for a more dedicated program.

3. SOLUTION EXAMPLES

3.1. Kui 37

Kui 37 (= HIP 44248 = CCDM 09007+4147) is a prime example of a complete solution with an astrometric determination of the mass ratio. The whole 22-year period is well covered with speckle observations, and with a semi-major axis above 0.6 arcsec, the orbit curvature is very apparent. The Hipparcos Catalogue solution gives a linear relative motion that is only a poor approximation to the real one, as can be seen in Figure 1. The new solution (including the visual observations listed by Heintz 1967) is given in Table 1, and for the relative orbit, the parameters are seen to agree very well with the ones given by Hartkopf et al. (1996b). The parallax uncertainty dominates the mass error-budget, but at around 6 per cent (cf. Table 3), the mass errors are among the smallest in the present study.

3.2. ADS 1598

For ADS 1598 (= HIP 9480 = CCDM 02020+7054), the period is longer and the curvature imperceptible. Figure 2 shows the observations together with the 'visual' orbit of Heintz (1969), and it is at once apparent that the speckle- (and Hipparcos-) data deviate

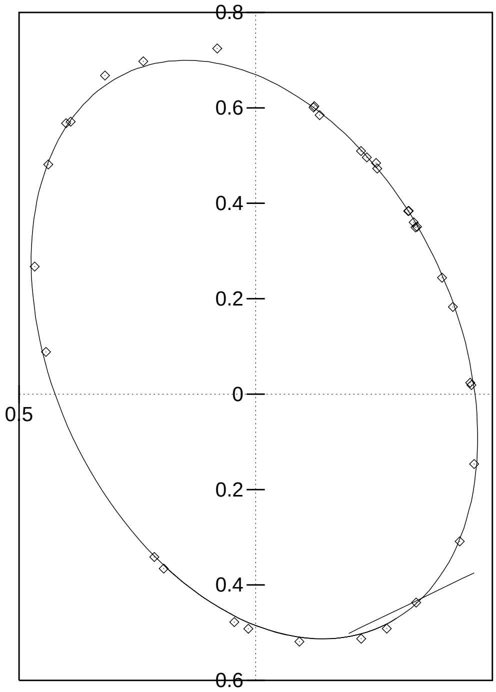

Figure 1. Relative speckle observations of Kui 37, with the derived orbit. The straight line shows the Hipparcos Catalogue data 1990.0–1992.5.

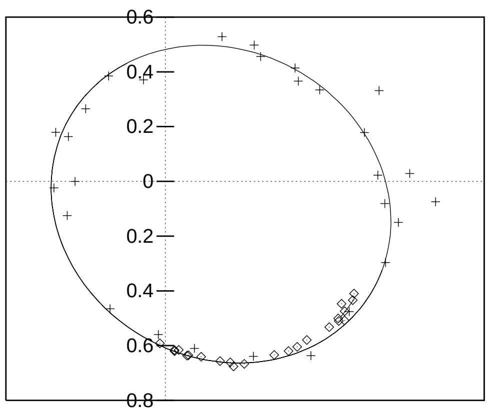

Figure 2. Visual (crosses) and speckle (diamonds) observations of ADS 1598, together with the old orbit. (The Hipparcos Catalogue solution 1990.25–1992.25 is seen as a line coinciding with the speckle data).

systematically. A new orbit (cf. Table 2) fits much better, and this seemingly small correction gives a 17 per cent reduction in the mass sum, showing the importance of even 'minor' orbit adjustments.

3.3. ADS 14893

ADS 14893 (= HIP 105431 = CCDM 21214+1020) has only an unresolved photocentric 'O'-solution in

Table 1. The GaussFit solution for Kui 37 (HIP 44248), compared with the relative orbit solution given by Hartkopf et al. (1996b). The solution parameters x,y are relative to a known reference, and have been subsequently transformed to the center-of-mass α, δ (ICRS, epoch 1991.25).

Parameter	[unit]	solution(m.e.)	Hartkopf et al.
P	[yr]	21.80(0.04)	21.78(0.02)
T	[AD]	1993.75(0.07)	1993.72(0.02)
a	[arcsec]	0.644(0.002)	0.647(0.001)
e		0.154(0.002)	0.151(0.001)
i	[deg]	131.5(0.3)	131.3(0.1)
ω	[deg]	33.2(0.9)	33.5(0.4)
Ω	[deg]	204.8(0.4)	204.4(0.2)
x	[mas]	95.9(4.7)	
y	[mas]	20.3(5.7)	
α	[deg]	135.1614118	
δ	[deg]	41.7833930	
$\mu_{\alpha *}$	[mas/yr]	−435.7(1.8)	
μ_δ	[mas/yr]	−246.4(1.2)	
π	[mas]	61.50(1.01)	
Hp_1	[mag]	4.180(0.001)	
Hp_2	[mag]	6.519(0.007)	
q		0.76(0.04)	

the Hipparcos Catalogue [α = 11.7(1.4) mas], although the speckle-observations show a separation well above 0.1 arcsec in an eccentric 6-year orbit. There were some convergence problems in the combined solution, but running successive solutions with fixed eccentricity we found a definite global minimum at about $e = 0.87(0.02)$. The low mass ratio $q = 0.44(0.12)$ is very reasonable if the spectroscopic binary noticed by West (1976) is identified with the visual primary component. The mass sum is about 2.4(0.4) $M_\odot$ which can at least marginally be distributed in three component stars.

In satisfying agreement with the 'O'-solution, the present a, q and Δm predict a photocentric semi-major axis about 11 mas through the well-known relation $\alpha = a(\mu - \beta)$, with $\mu = q/(1+q)$ and $\beta = 10^{-0.4\Delta m}/(1 + 10^{-0.4\Delta m})$.

4. MASS RESULTS

The new solutions give 'new' parallaxes, and it is of course interesting to compare with the standard Hipparcos Catalogue values. For the 15 systems with astrometric q-determinations, the Hipparcos Catalogue model was certainly inadequate, and the new parallaxes should be better. Table 3 shows however that the differences are surprisingly small. Only for the extreme case of Kui 75, the 1.7-year period has made for an erroneous Hipparcos Catalogue parallax. (The present value agrees perfectly with previous ground-based determinations). For the systems with little observed orbital curvature, the Hipparcos Catalogue model was correct, and as expected, the old and new parallaxes do not differ systematically (Figure 3). Because the Hipparcos Catalogue values are careful combinations from the work of the independent reduction consortia NDAC and FAST, while

Table 2. The GaussFit solution for ADS 1598 (HIP 9480), compared with the relative orbit solution given by Heintz (1969). The low inclination makes the node uncertain, but the position angle of periastron $\varpi = \omega + \Omega$ is still well-defined. The solution parameters x,y are relative to a known reference, and have been subsequently transformed to the center-of-mass α, δ (ICRS, epoch 1991.25).

Parameter	[unit]	solution(m.e.)	Heintz
P	[yr]	60.54(0.17)	60.44
T	[AD]	1964.73(0.27)	1964.78
a	[arcsec]	0.621(0.004)	0.653
e		0.358(0.008)	0.345
i	[deg]	17.3(3.0)	22.8
ω	[deg]	24.0(9.7)	4.5
Ω	[deg]	44.1(8.5)	64.2
x	[mas]	–293.4(0.9)	
y	[mas]	582.2(0.9)	
α	[deg]	30.48949748	
δ	[deg]	70.90698184	
$\mu_{\alpha *}$	[mas/yr]	–69.3(0.7)	
μ_δ	[mas/yr]	7.0(0.6)	
π	[mas]	27.22(0.70)	
Hp_1	[mag]	4.687(0.001)	
Hp_2	[mag]	6.828(0.004)	
q		1.00(assumed)	

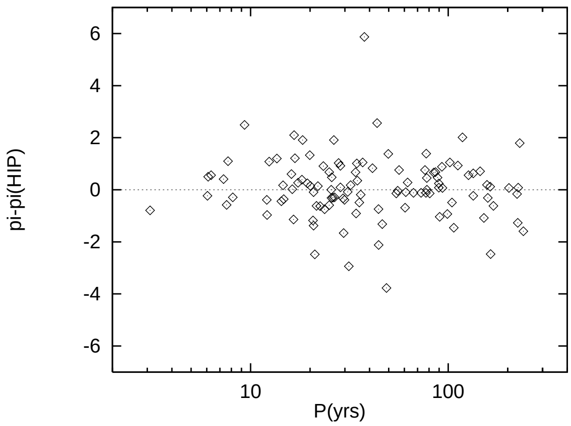

Figure 3. The differences between the present and the Hipparcos Catalogue parallaxes for 117 systems with no observable orbit curvature.

the Transit Data are in principle 'NDAC only', we have based the mass determinations in this case on the Hipparcos Catalogue parallaxes.

The three interesting parameters for determination of mass sums are a, P and π, together with their formal uncertainties. From the mean errors, we calculated 'orbit' (a^3/P^2) and 'parallax' error contributions, which were quadratically added to give the total uncertainty in the calculated mass sums. To allow for remaining systematic errors, the 'orbit' error was conservatively increased by a factor 2 (or even 3 with 'simulated' observations) whenever the solution relied mostly on visual observations.

For comparisons with stellar models, one needs the individual masses for the two stars in a system. The required mass ratios could only seldom be determined directly from the astrometry, but for most main-sequence systems, they were estimated from the photometry as described below.

4.1. Astrometric Mass Ratios

In Table 3 are given the most important results for the 15 systems with well-determined astrometric mass ratios. It is interesting to note that two or three of the q-values are significantly above unity, indicating that the secondary (fainter) component is more massive than the primary and thus probably an unresolved binary. (In the case of κ Peg, *both* visual components are known to be spectroscopic binaries).

4.2. Photometric Mass Ratios

For main-sequence systems, a mass ratio can be estimated from the magnitude-difference between the components. The main problem is the lack of individual colours (generally unobservable at sub-arcsecond separation) for the component stars. What is available is a mean $V-I$ colour, the absolute magnitudes, plus some clues from the combined spectrum. Using the theoretical results for stellar evolution, we have tried to put each system on an isochrone and then determined the mass ratio from the luminosity ratio.

A useful set of isochrones for standard ($Z = 0.02$) stellar models is given by Bertelli et al. (1994). They give the data in e.g. $M_V/(V-I)$, which can easily be transformed (using the calibration relations given in the Hipparcos Catalogue, Volume 1, Section 1.3) to the observed Hp(abs)/(V−I) coordinates. For the low-mass extension below $0.6M_\odot$, we have used the models by VandenBerg et al. (1983), but the transformations from $M_{\rm bol}/\log T_e$ are then uncertain, and the low-mass curve is mostly illustrative.

For each binary, the absolute magnitude and the colour of the primary are approximately known, and a search finds an isochrone passing close to the primary. The known Δm along this isochrone gives the secondary colour, and thus a more accurate correction from mean to primary $V-I$. The loop is repeated and the primary and secondary masses along the isochrone give the mass ratio. Stars definitely above the main sequence are excluded (as probably giants or non-singles), while those below are deemed more likely to have poor colours than to be true subdwarfs. They were therefore simply shifted in colour back to the ZAMS, and the masses evaluated along young isochrones. [The present scheme for q-determination has been compared with a less elaborate formulation (Söderhjelm 1997). The differences are small, and the photometric mass ratios derived should not be greatly in error].

5. THE MASS LUMINOSITY DIAGRAM

As described schematically above, a number of mass values are finally obtained, with the main uncertainty

Table 3. Partial solution results (mean errors in parentheses) and corresponding calculated masses for the systems with astrometrically determined q-values.

HIP	Ident	CCDM	Hp_1	Δm	q	π [mas]	$\pi_{\rm HIP}$	P	a	$M_1/M_\odot$	$M_2/M_\odot$
2237	B 1909	00284−2020	7.27	0.07	1.03(0.10)	33.39(1.01)	31.01(0.87)	11.34	0.200	0.82(0.09)	0.85(0.09)
2762	ADS 490	00352−0336	5.61	1.26	0.64(0.08)	47.73(1.21)	47.51(1.15)	6.89	0.234	1.49(0.26)	1.00(0.18)
12390	Fin 312	02396−1152	5.36	0.76	0.85(0.08)	40.59(1.25)	36.99(1.76)	2.65	0.107	1.41(0.19)	1.19(0.16)
19719	ADS 3064	04136+0743	5.76	0.91	0.95(0.12)	27.41(0.93)	27.04(0.90)	7.20	0.134	1.16(0.15)	1.10(0.14)
20087	51 Tau	04184+2135	5.87	2.03	0.76(0.10)	18.23(0.86)	18.25(0.82)	11.32	0.133	1.72(0.27)	1.31(0.22)
22550	ADS 3475	04512+1104	7.51	0.21	0.85(0.15)	20.22(1.13)	20.15(1.14)	16.27	0.188	1.64(0.32)	1.40(0.28)
38052	ADS 6354	07480+6018	7.71	0.39	0.76(0.13)	25.41(0.89)	26.60(0.83)	18.76	0.228	1.17(0.18)	0.89(0.15)
44248	Kui 37	09007+4147	4.18	2.34	0.76(0.04)	61.50(1.01)	60.86(1.30)	21.80	0.644	1.37(0.08)	1.04(0.06)
45170	Fin 347	09123+1459	7.28	0.20	0.93(0.14)	49.60(1.02)	48.83(0.92)	2.70	0.118	0.96(0.13)	0.89(0.13)
47479	B 780	09407−5759	5.95	0.37	1.29(0.24)	15.23(0.60)	14.85(0.69)	10.64	0.125	2.13(0.53)	2.75(0.66)
82817	Kui 75	16555−0820	9.70	0.12	1.56(0.15)	154.93(1.98)	174.23(3.90)	1.72	0.229	0.43(0.04)	0.67(0.06)
84140	Kui 79	17121+4540	9.93	0.42	0.96(0.03)	156.82(1.50)	158.17(3.26)	12.95	0.781	0.37(0.02)	0.36(0.02)
98416	Ho 276	19598−0957	6.23	1.54	0.81(0.13)	41.60(1.63)	40.75(1.35)	9.74	0.239	1.10(0.21)	0.89(0.17)
104858	δ Equ	21145+1001	5.31	0.08	0.93(0.05)	53.91(1.04)	54.11(0.85)	5.70	0.233	1.29(0.11)	1.20(0.10)
107354	κ Peg	21446+2539	4.97	0.04	1.82(0.20)	27.48(0.87)	28.34(0.88)	11.60	0.238	1.71(0.23)	3.12(0.37)

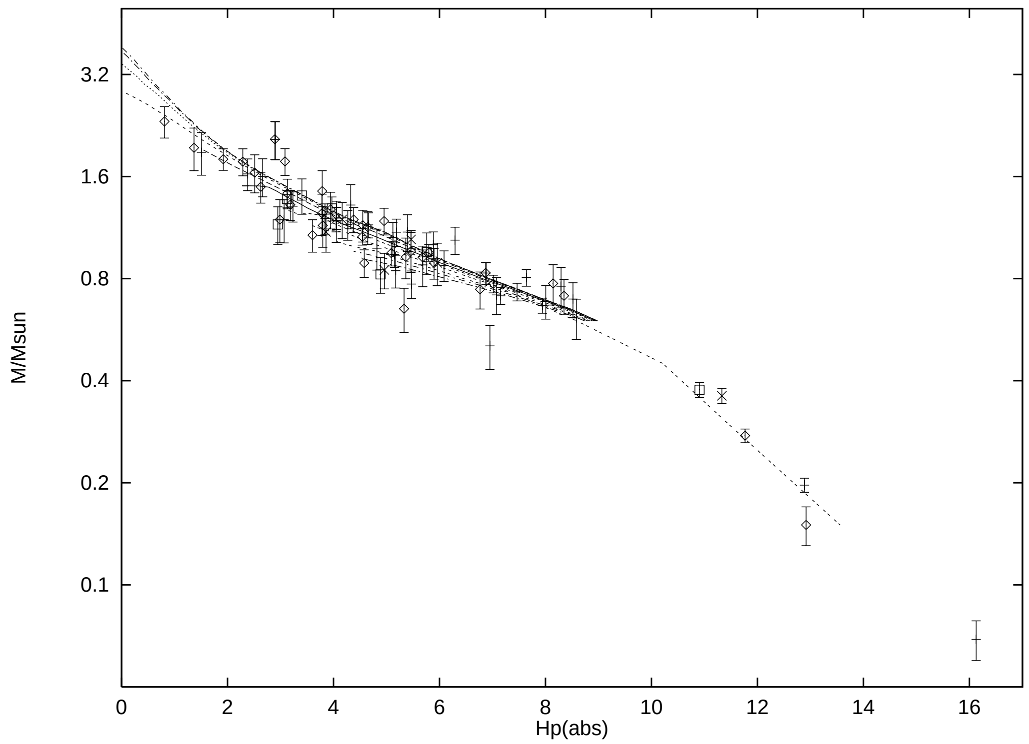

Figure 4. The 'mass-luminosity' plot for all masses with an uncertainty below 15 per cent. Known triples and non-main sequence systems excluded.

still from the fundamental mass sums. With known triples and non main-sequence systems excluded, the masses can be plotted versus the absolute Hp magnitudes, giving in principle a 'mass-luminosity diagram'. In Figure 4, all masses with an estimated error below 15 per cent are plotted together with the Bertelli isochrones, and apart from a few outliers, the fit is very satisfactory. Some of the 'high-mass' points are very likely triples, while at least some of the 'low-mass' outliers may be metal-poor subdwarfs. The low-mass 'isochrone' is only qualitative but seems also in reasonable agreement with the few observed points. (The two lowest masses are for Ross 614, where the secondary at $Hp = 14.2$ is only indirectly observable through the size of the photocentre orbit versus the full semi-major axis).

A final vindication that the new orbit-determinations have indeed reduced the error-contribution from the orbits can be obtained if one compares the M/L-diagram in Figure 4 (skipping the isochrones and error-bars) with a similar one constructed with 'old' orbits plus Hipparcos Catalogue parallaxes. These new diagrams are shown as Figures 5 and 6, and it

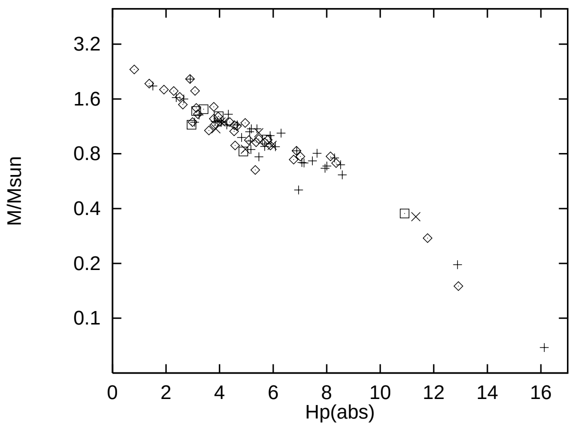

Figure 5. The 'mass-luminosity' plot for all masses with an uncertainty below 15 per cent. (The data are identical to those in Figure 4).

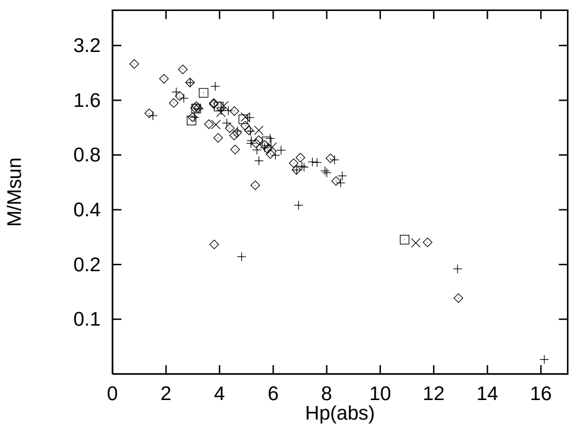

Figure 6. The 'mass-luminosity' plot for the same systems as in Figures 4 and 5. The Hipparcos parallaxes are still used, but together with old orbit data.

is at once apparent that the spread of the masses around some mean relation is smaller with the new orbits.

6. CONCLUSIONS

For the present, astrophysically interesting masses (with relative errors below some 15 per cent) can be derived only for rather few well-observed visual binaries. Except for an accurate (Hipparcos) parallax, one needs a relative orbit defined accurately by unbiased (normally speckle interferometric) observations, and only some 45 systems of this sort have been found in the present study. One bottleneck is in the ground-based observations (especially for southern hemisphere systems), and with 10 more years of speckle-work, the sample will be much larger. On the same time-scale, some of the new binaries with separations of the order of 0.1–0.2 arcsec discovered by Hipparcos may have their orbits determined, but again only after continued systematic (speckle) observations. The general method combining Hipparcos Transit File data with ground-based observations is readily used for such future rediscussions.

Turning back to the diagram in Figure 4, the tentative conclusion is that the observed masses seem to be in good agreement with the stellar evolution models. One cannot expect a narrow 'mass-luminosity relation' because of age and abundance-differences in the random near-star sample. Also, the number of hierarchical triples with a spectroscopic pair in one of the visual components may be higher than generally realized, giving points in the M/L-diagram with too high masses. Finally, as stated in the introduction, the present mass determinations are not 'final', and some further error-reduction can be expected with more optimized solutions.

ACKNOWLEDGMENTS

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REFERENCES

Bertelli G., Bressan, A., Chiosi, C., Fagotto, P., Nasi, E., 1994, A&ASS, 106, 275

ESA, 1997, The Hipparcos and Tycho Catalogues, ESA SP–1200

Hartkopf W.I., McAlister, H.A., Mason, B.D., 1995, CHARA Contr. No. 4

Hartkopf W.I., Mason, B.D., McAlister, H.A., 1996, Astron. J., 111, 370

Heintz, W.D., 1967, Veröff. Sternw. München, 7, 31

Heintz, W.D., 1969, A&A, 1, 249

Jefferys, W.H., Fitzpatrick, M.J., McArthur, B.E., McCartney, J.E., 1988, GaussFit user's manual, University of Texas, Austin

Quist, C.F., Lindegren, L., Söderhjelm, S., 1997, ESA SP–402, this volume

Söderhjelm, S., 1997, Proc. International workshop on multiple stars and celestial mechanics, Santiago de Compostela, Kluwer

Söderhjelm, S., Lindegren, L., 1997, ESA SP–402, this volume

VandenBerg, D.A., Hartwick, F.D.A., Dawson, P., Alexander, D.R., 1983, ApJ, 266, 747

West, F.R., 1976, ApJ, 205, 194

Worley, C.E., Heintz, W.D., 1983, Publ. USNO Vol. 24, No. 7