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Two–colour photometry for 9473 components of close Hipparcos double and multiple stars*

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Abstract. Using observations obtained with the Tycho instrument of the ESA Hipparcos satellite, a two–colour photometry is produced for components of more than $7\,000$ Hipparcos double and multiple stars with angular separations 0.1 to 2.5 arcsec. We publish 9473 components of 5173 systems with separations above 0.3 arcsec. The majority of them did not have Tycho photometry in the Hipparcos catalogue. The magnitudes are derived in the Tycho B_T and V_T passbands, similar to the Johnson passbands. Photometrically resolved components of the binaries with statistically significant trigonometric parallaxes can be put on an HR diagram, the majority of them for the first time.

Key words: stars: binaries: visual – stars: Hertzsprung–Russel (HR) and C-M diagrams – techniques: photometric

1. Introduction

The Hipparcos Double and Multiple Systems Annex (DMSA), as a part of the Hipparcos catalogue, is one of the major products of the ESA Hipparcos astrometric mission (ESA 1997). It comprises by far the most accurate astrometric and photometric information on double and multiple stars detected in various ways. Its Components Solution part contains the results on distinctly resolved components of visual systems, not exhibiting a measurable orbital motion over the 3.5 years duration of the active observation. The DMSA contains $12\,005$ doubles, 182 triples and 8 quadruples, thus adding up to a total of $24\,588$ resolved components.

Although this is not the largest set of multiple systems, the uniformity and high accuracy of data makes DMSA an important tool for binary stars investigations for a long time to come. Besides the astrometric data (positions, proper motions, parallaxes, angular separations and position angles), broad–band Hp magnitudes were given for all components, and the Tycho B_T and V_T magnitudes, somewhat similar to the Johnson magnitudes – for some of them. The B_T and V_T magnitudes were obtained with a separate instrument, Tycho, on board of the Hipparcos satellite resulting in the Tycho-1 Catalogue (ESA 1997, Vol. 4). Only less than half of the systems actually have the two–colour photometry from Tycho-1 in DMSA. There were two reasons for that. Firstly, the angular resolution of the Tycho-1 Catalogue (about 2.0 arcsec) was not matching that of the Hipparcos main instrument (0.1 arcsec). Hence, the majority of close binaries were not resolved in Tycho-1, and a photocentre solution was obtained in the best case. Secondly, some of the Hipparcos double stars were too faint for the Tycho instrument, its limiting magnitude being of the order $V = 11.5$ mag. Components with magnitude differences above 1.0 to 1.5 mag could not be resolved in Tycho-1 either.

It is important to know the colours of both components of a binary for some astrophysical studies. The lack of two–colour photometry in the Hipparcos catalogue for close doubles is a flaw in this respect. In this paper, we present the results of a new photometric solution for close Hipparcos double and triple stars, based on the original (raw) Tycho observational data, but processed in a very different and more advanced way.

Soon after the completion of the Tycho-1 Catalogue (ESA 1997) Høg et al. (1998) decided to carry out a second reduction of the Tycho data, applying a more advanced reduction technique. The photometry presented here is not part of the new *Tycho-2* Catalogue, but it was made possible by the creation of the Identified Counts Data Base (ICDB) for more than 2.5 million stars in the course of the Tycho-2 reprocessing and catalogue construction (Høg et al. 1998, and Høg et al. 2000). The Tycho-2 Catalogue extends the Hipparcos/Tycho reference frame from 1.1 to 2.5 million stars by pushing the limiting magnitude fainter. This improvement of the limiting magnitude by about 0.4 mag was achieved owing to a much better method of data processing, namely *a photon superposition for the whole mission*. The photon superposition also gives better astrometric and photometric values for the fainter half of the original one million stars. Finally, a much better angular resolution was achieved.

The Tycho-2 Catalogue contains a few thousand close double systems with separations down to 0.8 arcsec. Many of them are not given in the Hipparcos catalogue, and some are actually new discoveries. The doubles with separations less than 2.5 arcsec were resolved in a special process, briefly discussed in Høg et al. (2000). It included a full astrometric and photometric solution for the components, based entirely on the Tycho ICDB

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* Based on observations made with the ESA Hipparcos satellite.

dataset. Even though almost half of the stars were in Hipparcos, no external information was used in the solution in any way except for the general instrument calibration.

The present solution is different, because the exact positions of the Hipparcos resolved component are used. An astrometric solution is thus eliminated, making it much simpler than the routine Tycho-2 double star solution.

2. The photometric solution

We will not go into describing the whole complexity and diversity of Tycho in-orbit observations and raw data treatment. Such a description can be found, e.g. in Vol. 4 of the Hipparcos and Tycho Catalogues (ESA 1997). It is only relevant to mention that in the Tycho-2 processing, in contrast to the first processing, all observations of each star are available in a sorted and fully calibrated data base. Each crossing of a programme star produces two series of 31 *photon counts*, separately in the B_T and V_T wavebands, which are the digitized response of the instrument to the flux signal from the star as a function of time. This response is typically expected to consist of a uniform *sky background* and a peak profile due to the transit of the star across the slit. The shape of the peak is described by the so-called slit response function. A sample of 31 consequetive counts corresponds to 0.0517 s in time or 8.72 arcsec in distance projected on the sky in the direction of star motion. The position of a peak relative to the reference central moment contains astrometric information about the star, while its height above the sky background provides photometric datum.

The essence of the second Tycho processing is that the observations are not treated each separately to estimate the one-dimensional instantaneous position and magnitude, but rather all the observations for a given star are taken en masse to derive the mission-average of the parameters. The procedure can be visualized as stacking (or superposition) of all one-dimensional data on top of each other with appropriate weights, and deriving the average values from the combined two-dimensional signal. In computational terms, the estimation task consists of two major intermingling parts, astrometry and photometry, the former being much more complicated and time-consuming than the latter. The astrometric task for visual double stars was yet an order of magnitude more demanding than the routine single star treatment. A sizeable effort brought into the Tycho-2 catalogue some 7000 pairs with separations 0.8 to 2.5 arcsec and differences in magnitude below 2.0 mag. This is to be compared with the Tycho-1 Catalogue, with the angular resolution of about 2.0 arcsec and maximum difference in magnitude 1.0 to 1.5 mag.

The basic idea of the present work is to utilize the very accurate astrometric data of the Hipparcos catalogue (positions, proper motions and parallaxes) as a priori information for a purely photometric solution. With regard to the method used in the Tycho-2 Catalogue production, a new technique is developed, dedicated to Hipparcos close binaries only. Instead of searching for a position which provides the maximum signal for each of the components, we pinpoint the true location of the components in each observation, as deduced from the Hipparcos data, and try to disentangle the two-peaked signal. This is possible because both the coordinate reference system of Tycho and calibration parameters are firmly tied to those of Hipparcos. Not only does it simplify the solution, it also gives more valuable results, since much smaller separations and greater magnitude differences can be handled. In cases of small separations and large magnitude differences, this photometric solution proves remarkably more stable than the routine astrometric solutions of the Tycho-2 processing, even though algorithmically based on the same principles.

We know of three major limitations of the method in use.

1. Unaccounted orbital motion causes a smearing of the component image, so that only part of the star signal will be picked up at the predicted position. Effectively, it will increase the difference in magnitudes, as the primary components move slower and are therefore less smeared, and there is always some "leak" of unaccounted counts from the fainter component to the brighter one. The colour estimation should however not be directly affected.
2. The Hipparcos Double and Multiple System Annex contains many solutions of modest quality and for more than 900 systems alternative solutions are suggested. From this fact alone and also from recent rediscussions of many systems (Falin & Mignard 1999; Fabricius & Makarov 2000) we must expect up to a few hundred wrong solutions, when at the given positions for the secondary or both components there is nothing at all. In that case, most probably, our photometric solution will be rejected as insubstantial (signal to noise ratio too low).
3. The effect of variability of double star components is very hard to predict. Presumably, it is negligible for small and moderate amplitudes of variability, since the derived mean magnitudes are based on typically more than a hundred observations spread over 3.5 years.

The method employed for photometric resolution of doubles is a simplification of the iterative 'cleaning' algorithm used for the routine double star processing in Tycho-2 (Høg et al. 2000). Each iteration includes four principal steps:

- Estimate magnitudes at the position of the primary component
- Subtract the estimated star image from the original counts in each sample
- Estimate magnitudes at the position of the secondary from the remaining (cleaned) counts
- Subtract the estimated image of the secondary from the original counts in each sample.

This iteration has to be repeated many times to achieve a reasonable degree of convergence at close separations. After the first such iteration, the signal estimated for the primary is always too big, because a substantial part of the counts from the secondary was assigned to the primary through the slit positions crossing both stars. For the same reason, the first estimation

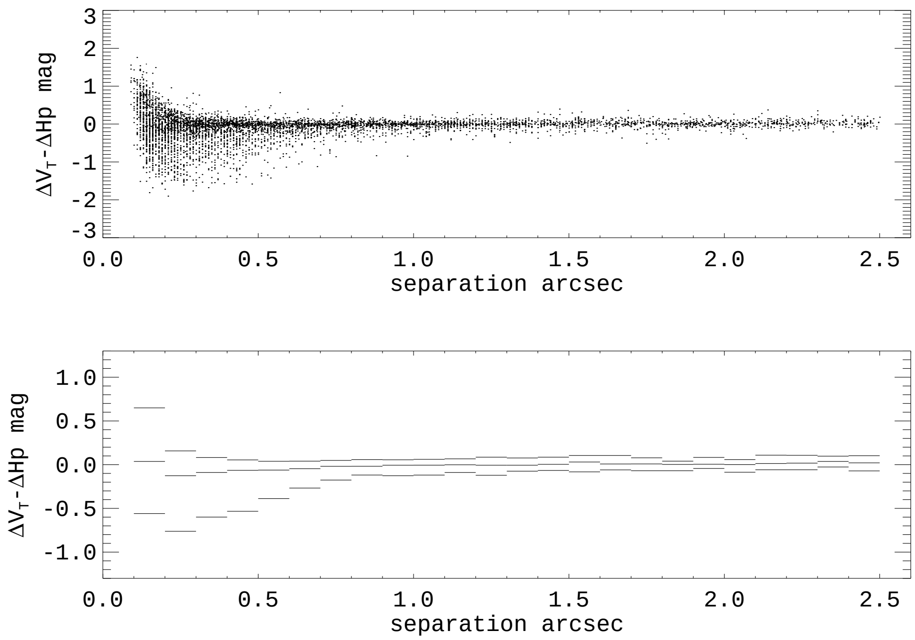

Fig. 1. Comparison of the Hp and V_T magnitude differences between the components of 5634 pairs, as a function of angular separation. The upper panel gives one dot for each pair, while the lower one shows the 15th, 50th (the median) and 85th percentiles for the differences within bins of 0.1 arcsec. Only stars with DMSA quality flags A and B in the field DC5 are included. Only systems with separations above 0.3 arcsec are published.

for the secondary is too faint. In the course of subsequent iterations the secondary component grows in signal, and the primary wanes. This process converges very quickly when the separation is comfortably large (above 0.5 arcsec) and the distribution of scan directions is favourable, i.e. the projected separation is generally large. We found empirically that in most of the cases with separations greater than 0.3 arcsec, a reasonable convergence is achieved after 24 iterations. We refrained from making more iterations in order to avoid too big a 'leak' bias at separations 0.3 to 0.5 arcsec, as discussed in the next section.

3. Results

We included 7547 double and 15 triple stars from the Hipparcos catalogue, confined to a circle of 2.5 arcsec radius centered on the primary component. The positions, proper motions and parallaxes of the components were used in our solution, exactly as they are given in the Double and Multiple Systems Annex (DMSA) of the Hipparcos catalogue. Alternative solutions, sometimes given in the notes to the catalogue, were not used. A certain proportion of Hipparcos astrometric solutions is wrong, and then one of the components, or both, are not at the given positions. In such cases our solution should give a very small signal to noise ratio (SNR) value for the missing components. It is relevant to note, that 14 components have SNRs less than 1.0 in our solution, 537 less than 3.0 and 1419 less than 5.0. Some part of these faint signals could be due to components too faint for Tycho. Still, up to a few percent of the solutions in DMSA can be erroneous. To be on the safe side, we publish only solutions with SNR greater than 5.0 and standard formal errors within 0.1 mag.

Two-colour photometry of binary stars, especially with separations below 1.0 arcsec, remains largely a "terra incognita" for observational astronomy. The existing on-ground data are too scarce and imprecise to be used for verification of the present results. The Hipparcos catalogue provides magnitudes in just one passband, Hp, which is much broader than either of the B_T and V_T (see Fig. 1.3.1 in Vol. I, ESA 1997). The relation between Hp and V_T magnitudes is not known, but obviously it is colour-dependent. This dependence would dominate a direct comparison of Hp and V_T magnitudes, but a comparison of magnitude differences between the components is less sensitive to colour variations, at least for pairs of main sequence stars of not too different magnitudes. Fig. 1 gives such a comparison for 5634 pairs with Tycho SNRs greater than 5.0 and photometric errors within 0.1 mag. Only Hipparcos solutions of 'good' and 'fair' quality (flags A and B) are included.

The figure shows that the majority of our solutions are in good agreement with the Hipparcos photometry at separations above 0.7 arcsec. With smaller separations, two systematic effects are apparent. Firstly, the distribution of residuals becomes strongly lopsided, with an increasing proportion of Tycho components less different in magnitude than those of Hipparcos. Secondly, down at separation 0.25 arcsec, the number of pairs where Tycho finds a more drastic difference in magnitudes than Hipparcos, starts to increase sharply. Trying to determine the origin of these two systematic effects is largely a guesswork. It is impossible to estimate the quality of the Hipparcos photometry at small angular separations. One can only see that formal standard errors as large as 0.3 to 0.5 mag are given sometimes for ΔHp for fairly bright stars which might be an indication of uncertainties. Mason et al. (1999) could not resolve by speckle interferometry up to 70 percent of Hipparcos doubles at separations below 0.2 arcsec which might be a clue that the real Δm are substantially larger than given in Hipparcos. However, it is more likely that the first effect, i.e. the pronounced skewness of the error distribution at separations below 0.7 arcsec is a manifestation of a Tycho photometric bias. The FWHM value for the Tycho slit response function (i.e., one-dimensional image

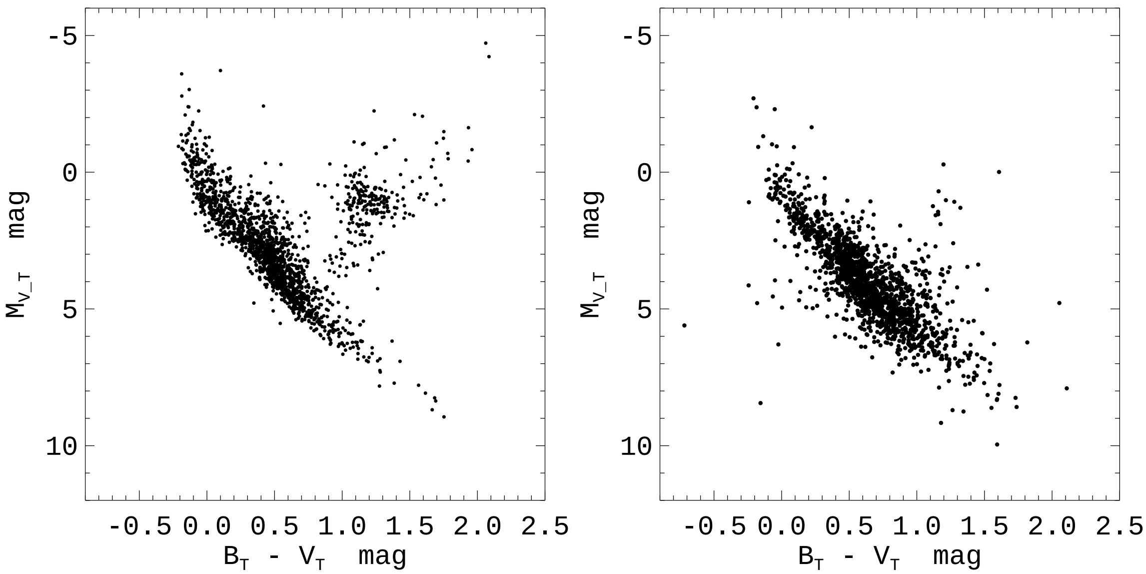

Fig. 2. Observational HR diagrams for 1697 primary components (left panel) and 1699 secondary components of double and triple systems (right panel) with statistically significant Hipparcos parallaxes ($\pi/\sigma_\pi > 4.0$) and angular separations 0.30 to 2.5 arcsec. The sample is restricted to systems with $max(\sigma_{B_T}, \sigma_{V_T}) < 0.1$ mag.

Table 1. First few lines of the published photometric catalogue for components of Hipparcos double and multiple stars.

25	2	A	6.894	0.004				7.94	0.01	6.89	0.01	98.8
25	2	B	7.551	0.007	A	0.463	315.8	8.06	0.01	7.47	0.01	81.8
50	2	A	6.674	0.003				7.29	0.01	6.63	0.01	140.3
50	2	B	9.962	0.057	A	1.700	324.8	10.96	0.03	9.85	0.02	16.0
110	2	A	9.202	0.011				10.01	0.02	9.16	0.01	21.8
110	2	B	9.843	0.019	A	1.200	176.3	10.80	0.04	9.89	0.02	12.3

of a point source) is about 0.9 arcsec. Components of a double star at separation 0.7 arcsec and shorter begin to overlap even at favourable slit position angles. Some 'leak' of the signal from the brighter component to the fainter, decreasing the difference in magnitude, may occur if the real slit responce function is broader and therefore higher at the wings than the assumed one. Too little signal is subtracted then in each iteration at the wings of the brighter component, which enhances the fainter companion. This surmise is corroborated by the fact that the skewness grows with increasing ΔHp for pairs with separations between 0.25 and 0.7 arcsec.

From this consideration, we publish only systems with separations greater than 0.3 arcsec. The user is cautioned when using solutions with separations less than 0.7 arcsec, where ΔV_T, and perhaps ΔB_T may have a negative error down to 0.5 mag. It is not known how this error affects the colours $B_T - V_T$.

As many of the Hipparcos doubles have statistically reliable trigonometric parallaxes, an HR diagram can be constructed with the determined Tycho magnitudes. Such a diagram for systems with a relative parallax error $\sigma_\pi/\pi < 0.25$ is shown in Fig. 2, separately for the primary (left part) and secondary (right part) components. Most of the primaries belong to the main sequence, ranging from OB stars to M dwarfs. The subgiant branch, with a clear gap from the main sequence, and the red giants clump are also well populated, extending in a broad plume to the redder colours and brighter absolute magnitudes. There are two conspicuous M type supergiants, and a few subdwarfs lying below the rather clearly outlined ZAMS lower bound. Giants are relatively rare among the secondaries, as should be expected. The most curious feature is a dozen secondaries by far bluer and fainter than the main sequence stars. If they are not blunders, their position on the diagram indicates their being hot subdwarfs, more likely the cooler, hydrogen-rich sdB stars. Two of these stars have already been reported (Makarov & Fabricius 1999) as candidate hot subdwarfs in visual binaries with a realistic possibility to determine their masses from the orbital motion. Only one such object was previously known for sure (HD 113001B) which is also confirmed by our data. Most of the other candidates are coupled with much brighter and rather blue main sequence and subgiant stars, which makes it impossible to resolve them spectroscopically from ground, but it must be possible with the HST STIS instrument.

Table 1 shows the first 6 lines of the published catalogue. Each system is represented by 1, 2, 3 or 4 lines, each corresponding to one component. The following data are given for a component, in the left to right order: the Hipparcos identification number, the number of components into which this Hipparcos star is photometrically resolved in this catalogue, a one-letter component designation from Hipparcos DMSA (Component Solutions), Hp magnitude and its standard formal error, reference component designation letter, separation in arcsec and position angle in degrees with respect to the reference component, observed B_T magnitude and its standard formal error, observed V_T magnitude and its standard formal error, and the signal to noise ratio. The fields for the relative astrometric data are left blank for primary components. All together 9473 components in 5173 systems are published. All solutions with photometric errors not larger than 0.11 mag and signal to noise ratio values above 4.0. Components with separations below 0.3 arcsec are not included. Surviving single components (881) are also published, because presumably their photometric data are more accurate than photocentre magnitudes. More information and a description of the format can be found in the ReadMe file, which supplements the catalogue deposited at CDS, Strasbourg, and available through Internet.

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