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LETTER

Letter to the Editor

The Hipparcos mission: photometric data*

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Abstract. An overview of the Hipparcos and Tycho photometric data is presented, with reference to the main aspects of the data reductions and the overall quality and quantity of the results. The data have been presented in three forms: as mean values in the astrometric catalogues, as epoch photometry, and as interpreted results of the variability analysis, which is also briefly described.

Key words: Hipparcos - Photometry

1. Introduction

The detector signals used for deriving the Hipparcos astrometric data also contained precise information on the intensities of the objects observed. For the main mission this information was contained in both the mean intensity and the modulation amplitude of the signal. In the Tycho experiment, which used the star mapper signal, the information was contained in the peak height of the signal produced by a star passing over the star mapper slits. In the main mission the photometry was obtained using a wide passband, referred to as Hp. The Tycho photometry was obtained in two passbands, B_T and V_T, resembling the B and V passbands of the Johnson system. Reductions of the Hipparcos photometry were carried out by the NDAC and FAST data reduction consortia, with the parallel analysis of the Tycho photometry by the TDAC consortium (with independent checks for some of the results through reductions by the NDAC consortium).

The Hipparcos and Tycho photometry also played (indirectly) an important role in the astrometric reductions, by providing much needed information on duplicity and colours.

The present paper provides a summary of the data reduction methods used (Section 2), the variability analysis (Section 3) and the data products (Section 4). Full descriptions of all these aspects can be found in The Hipparcos and Tycho Catalogues (ESA, 1997), in particular Volume 1, Section 1.3 (description of the photometric data), Volume 3, Chapters 14 and 21 (description of the data reduction methods and the verification of the results), and Volume 4, Chapters 8 and 9 (the Tycho photometric data analysis).

2. The photometric data and their reduction

2.1. The passbands

Approximate response curves for the three passbands, Hp, V_T and B_T, were obtained before the start of the mission using the payload's optical and photomultiplier specifications. The passband responses were refined during the mission using the photometric calibration results. In the case of Hp, the passband changed over the mission due to the darkening of the optics, which affected the blue response of the passband more than the red. The passband was defined for an arbitrary reference time, chosen to be 1 January 1992. The reference passband was obtained through extrapolation of reduction results obtained for data up to October 1991. As a result, the actual passband for 1 January 1992 was not identical to this reference passband. Moreover, there was always a small difference in passband between the two fields of view. The reference passband defines the photometric system, and the closer it was to the actual passband, the smaller the distortions that had to be removed from the actual data by the data reductions. Magnitudes for photometric standards in the resulting photometric system were calculated and used as reference values in the data reductions. Particular emphasis was put on obtaining reliable system calibrations towards the extreme red colours, where no standard stars are available. For this purpose, ground-based photometry and AAVSO moni-

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* Based on observations made with the ESA Hipparcos satellite

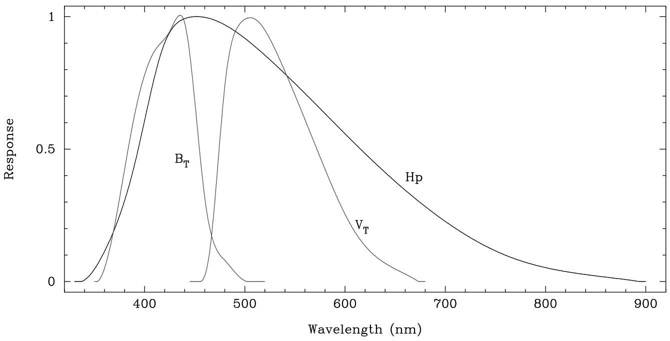

Fig. 1. The Hipparcos (Hp) and Tycho (B_T, V_T) passbands.

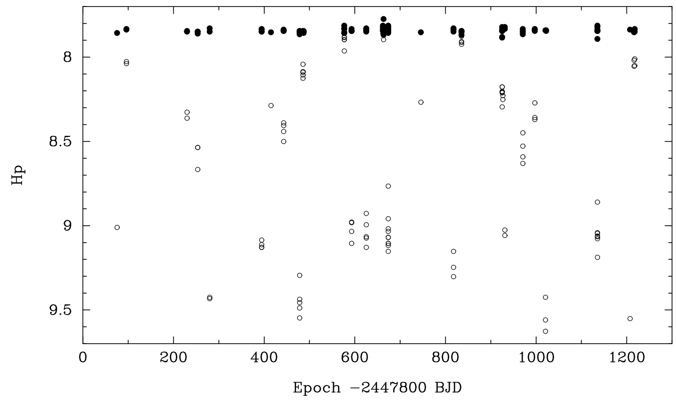

Fig. 2. Hipparcos photometry for a double star. The filled symbols refer to dc magnitudes (not affected by duplicity). The open symbols refer to ac magnitudes, which are affected by duplicity.

toring (contemporaneous with the Hipparcos observations) were obtained for a selection of Mira variables. These data were used to produce a number of reference points for different colours and at different epochs, from which the red response of Hp passband was reconstructed as a function of time. This reconstructed response was applied *a posteriori* and is referred to as the 'ageing correction'. The final passbands are shown in Fig. 1. The magnitude scales were chosen such that $Hp = V_T = V_J$ and $B_T = B_J$ at $B - V = 0$.

2.2. The main mission photometric reductions

The Hp photometry was derived from the same signal as the astrometric data, i.e. from the measurements by the image dissector tube photomultiplier of the light of stellar images, modulated by a grid of transparent lines in the focal plane of the instrument. The light was sampled at 1200 Hz, and almost eight sampling periods covered the crossing of a single slit line. This modulated signal was accurately represented by a simple 5-parameter model:

$$E(N_k) = I_k = I_b + I_s\big[1 + M_1 \cos(p_k + g_1) + M_2 \cos 2(p_k + g_1 + g_2)\big], \quad (1)$$

where p_k is the local reference phase of the modulating grid as defined by the grid-period, the local scan-velocity, and the time of the observation. (M_1, g_1) and (M_2, g_2) are the modulation coefficients and relative signal phases for the first and second harmonic respectively and I_s and I_b are the intensities of the star and the background. The background signal was, under normal conditions (away from the radiation belt crossings), equivalent to the signal of a 14 mag star. I_k is the estimated value of N_k, the observed photon count over the integration time. The Hp photometry was primarily obtained from I_s, using elaborate methods for background correction I_b. This part of the photometry is generally referred to as the $Hp_{\rm dc}$ photometry. The photometry obtained from $I_s M_1$ and $I_s M_2$ was also fully reduced, but is of lower accuracy (with an average value for M_1 of 0.7, the estimated errors on these photometric data are about 2 times larger than on the dc photometry). This part of the photometry was referred to as the $Hp_{\rm ac}$ photometry. As the modulation of the signal could be disturbed by the presence of other images in the detector field (a 30 arcsec diameter instantaneous field of view), the comparisons between the ac and dc magnitudes provide indications of such disturbances. Figure 2 shows data for a star which are affected by duplicity according to the geometry of the transit.

The data reductions were developed and carried out independently by CERGA (Grasse) for the FAST consortium and by RGO (Cambridge) for the NDAC consortium. The reductions involved the calibration of the detector response as a function of the position in the field of view and as a function of colour. The colour part of the calibrations was replaced *a posteriori* with the results obtained from the passband calibration, taking at the same time better care of the calibrations for the extreme red stars, something that was not possible for the standard reductions due to the complete absence of constant stars among those with very red colours. Here, 'very red colours' refers to stars with $(V - I)$ ranging from 2 to 9.

The colour-dependent coefficient evolved over the mission, reflecting the changes to the passband as a result of darkening of the main detector optics due to radiation damage. As a result, stars that were reduced using a $(V - I)$ colour different from its true value will show a drift in the Hp magnitude as a function of time. Similarly, variable stars with strong colour variations have been reduced with a single representative colour. The Hp magnitudes for these stars may still be improved upon. The mechanism for corrections to the Hp magnitudes on the basis of colour improvements are described in detail in Volume 3, Chapter 14, and briefly in Volume 1, Section 1.3. In the final colour corrections a pseudo-colour, based on the Cousins $(V-I)$ index, was used to provide much improved resolution of stars of different luminosity classes and temperatures.

The calibrations were performed on data accumulated over $32/15$ s intervals. The amount of integration time actually spent on an individual star within that interval depended on the magnitude of the star and the competition for observing time from other stars. This means that accuracies as given for epoch photometry data for one and the same star can differ significantly,

Table 1. Standard errors on transit and median magnitudes

mag	<Transit error>		<Error on median>			
	Hp_{dc}	Hp_{ac}	Hp_{dc}	Hp_{ac}	B_T	V_T
3	0.003	0.005	0.0004	0.0006		
5	0.005	0.009	0.0006	0.0010	0.003	0.003
7	0.008	0.019	0.0009	0.0019	0.008	0.007
9	0.015	0.037	0.0019	0.0039	0.026	0.022
11	0.033	0.072	0.0044	0.0079	0.12	0.12

and quoted standard errors should be taken fully into account. The published epoch photometry provides a combination of the measurements obtained during field transits – it took a stellar image around 20 s to cross the field of view, and results at higher time resolution have not been preserved.

The final reduction results as obtained by FAST and NDAC showed a correlation of residuals for constant stars ranging from 0.6 for the brightest stars to 0.8 for stars of $Hp = 7\ldots9$ down to 0.55 for the faintest stars ($Hp = 12$). These results were merged to form the Hipparcos Epoch Photometry Annex (HEPA) and Extension (HEPAE), described in Section 4. Table 1 provides a summary of the photometric accuracies obtained. The average total number of observations was 110, varying from 80 within 40° from the ecliptic, through 200 at distances of 45–50° from the ecliptic, to 115 close to the ecliptic pole.

2.3. The Tycho photometric reductions

The Tycho photometric data were obtained from the photon counts by the star mapper B_T and V_T photomultipliers. The star mapper signal consisted of four peaks at different interspacings, such that the signal provided a direct relation between position on the grid and position on the sky in one direction. By using both vertical and inclined slits, and observations from the two fields of view, the orientation of the satellite could be reconstructed, which was the main purpose of the star mapper data.

The Tycho experiment used the continuous data stream from the star mapper detectors with the aim of providing positional and photometric data for any star that could be detected. The photometric data was derived from scaling the observed signal to a 'single slit response function'. Different slit response functions were used for the various combinations of field of view, passband, slit group and upper or lower branch. The intensities were calibrated using calibration standards and a model describing the sensitivity of the detectors as a function of the position in the field of view and of star colour.

An important aspect of the Tycho photometry for fainter stars was the bias resulting from the detection of transits. By using only detected transits to derive mean magnitudes, the values that were obtained were inevitably too bright. This was corrected in a process called 'de-censoring', which took fully into account the non-detections, to derive non-biased end results. The Tycho photometry has been preserved at this level of slit group crossing, but accuracies are considerably less than the main mission photometry, such that only a relatively small selection of this epoch photometry is released on CD-ROM. The accuracies for the Tycho photometry are summarized in Table 1.

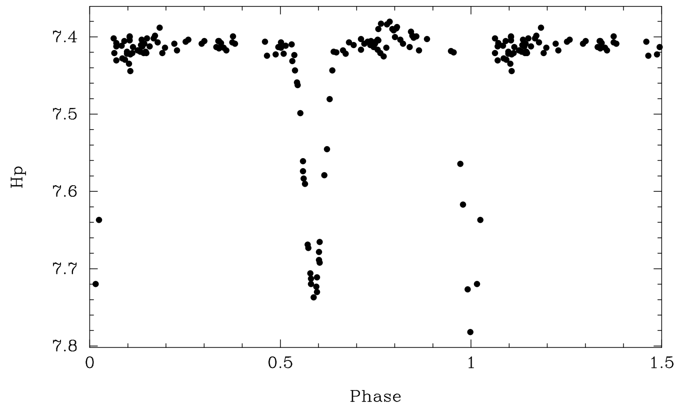

Fig. 3. Hipparcos Hp_{dc} photometry for a newly-discovered Algol type eclipsing binary (with eccentric orbit), HIP 270, which received the name V397 Cep.

3. Variability analysis

All Hp epoch photometry was investigated for variability (see van Leeuwen et al, 1997). First the level of variability was determined from various measures of the spread of the observations. Then, for some 12 000 stars with a significant spread, tests on periodicity of these variations were performed. In advance of these studies, a data base was established with references that could assist in this analysis. The analysis was carried out independently at the Observatoire de Genève and at the Royal Greenwich Observatory.

A total of 11 597 stars were found to be at least possibly variable. Of these, 2712 were found to be periodic (with 970 newly discovered) and 5542 stars were found to be definitely variable, but no period was detected (of these 4145 are newly discovered). The remaining 3343 stars include possible micro variables and were not further investigated. Very noticeable was the relatively large number of newly-discovered eclipsing binaries, where 343 of the 917 such systems detected were new discoveries. Over 3000 newly-discovered variables were considered well enough determined to receive an official variable star name, a task that was carried out at short notice and in very little time by the Sternberg Institute in Moscow. Figure 3 shows an example of a newly-discovered eclipsing binary.

Periods given in the catalogue are mostly based on Hipparcos measurements only. However, for some eclipsing binaries with long periods the Hipparcos data alone did not contain sufficient information for a period determination. In these situations ground-based data was also incorporated. Reference epochs are given as epoch of the first primary minimum (eclipsing binaries, RV Tauri stars) or the first maximum (all other types) following BJD 2448500.0.

Given the very limited time-span that was available for these investigations, they cannot be considered exhaustive, and corrections can be expected for periods and types of especially newly-classified variables.

4. Summary of the data products

4.1. The epoch photometry files

There are three epoch photometry files, two for main mission (Hipparcos Catalogue) photometry, (HEPA and HEPAE) and one for Tycho Catalogue photometry (TEPA). The first two provide all corresponding photometry available, while the third provides only a small selection. The HEPA and HEPAE files are constructed such that when accessing a given record number in one file, the same record number in the other file will provide the supplementary information for exactly the same observation. They therefore use the same index file. The HEPA file contains the most important data: the $Hp_{\rm dc}$ magnitudes, their standard errors, the epochs of observation (in TT) and a summary flag explaining any sort of recognized problems that may exist for that observation. The HEPAE file adds to this the $Hp_{\rm ac}$ magnitudes and their standard errors, the coordinates of the other field of view for this particular star during the observation (for identifying accidental disturbing images), a coincidence index referring to a file of identified accidental disturbances (giving separation and magnitude of the object(s) found), and finally the background levels as detected by the two data reduction processes (important for very faint stars, where problems with background estimation could have seriously influenced the final results). Header records provide additional information on mean magnitudes, the colour index used in the data reductions, the numbers of transits available, and of transits accepted for the determination of mean values and summary information on variability.

The Tycho Epoch Photometry Annex (TEPA) contains B_T and V_T epoch photometry for mainly the brighter stars. The epoch photometry records provide the B_T and V_T magnitudes and their standard errors with a reference epoch. In addition, there is information on the orientation of the slits on the sky for each data point, as well as a number of flags identifying the slit group and any rejected measurements. The header records provide information on mean magnitudes, numbers of records available and used, and a number of flags identifying different problems that have been recognized for a star.

4.2. Variability results

The results of the variability analysis are presented in the form of two tables, one for periodic variables and one for unsolved (mainly non-periodic) variables. These tables provide information on periods, reference phases (if relevant), magnitude ranges and significance levels of the estimated amplitude. All periodic variables had their light curves fitted, and from these fits accuracies of the periods were derived (see van Leeuwen et al, 1997). Pointers to notes and literature references, given in separate tables, are also provided. In addition, there is an atlas providing three sets of light curves: A) folded light curves, showing also the fitted curves when available; B) not-folded light curves, using calibrated AAVSO light curves as background; and C) selected not-folded light curves, mainly for stars with long time-scale semi-regular or irregular variations. Summary variability information is provided in the main catalogue in the form of statistical indicators for variability and as references to the summary tables for periodic and unsolved variables.

4.3. Photometric data in the main catalogue

The main catalogue contains both mission photometry (median Hp and scatter values) as well as ground-based photometry ($B-V$ and $V-I$ colour indices). In addition, there are variability indicators based on analysis of the Hp epoch photometry. When available, the Tycho B_T and V_T are also provided. Associated errors, and the $(V-I)$ indices used in the reductions, are also given.

5. Conclusions

As an extensive, homogeneous, and uniformly calibrated all-sky photometric survey, the Hipparcos and Tycho epoch photometry and their derived products will serve for many years to come as a photometric reference frame, to be used in the calibration of ground-based systems, and in the study of variable stars.

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