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The Tycho-2 Catalogue of the 2.5 Million Brightest Stars ⋆

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Abstract. The Tycho-2 Catalogue presented here is an astrometric reference catalogue containing positions and proper motions as well as two-colour photometric data for the 2.5 million brightest stars in the sky. The Tycho-2 positions and magnitudes are based on precisely the same observations as the original Tycho Catalogue (hereafter Tycho-1) collected by the star mapper of the ESA Hipparcos satellite, but Tycho-2 is much bigger and slightly more precise, owing to a more advanced reduction technique. Components of double stars with separations down to 0.8 arcsec are included. Proper motions precise to about 2.5 mas/yr are given as derived from a comparison with the Astrographic Catalogue and 143 other ground-based astrometric catalogues, all reduced to the Hipparcos celestial coordinate system. Tycho-2 supersedes in most applications Tycho-1, as well as the ACT and TRC catalogues based on Tycho-1.

Key words: Astrometry – Stars: fundamental – Catalogs

1. The catalogue and its observational basis

The Tycho-2 Catalogue contains positions, proper motions and two-colour photometric data for the 2.5 million brightest stars in the sky. The sky is well covered to a magnitude about $V = 11.5$, and slightly deeper in some areas. The stellar density in Tycho-2 is shown in Fig. 1. Overviews of the catalogue content are given in Tables 1 and 2.

Positions and magnitudes were derived from the Tycho star mapper observations on the Hipparcos satellite. The observational period was from 1989.85 to 1993.21.

The proper motions are derived for 96 per cent of the stars from the observed positions in Tycho-2, the Astrographic Catalogue and 143 other ground-based catalogues.

Table 1. Principal characteristics of the Tycho-2 Catalogue. By means of proper motions the positions are transferred to the year 2000.0, the epoch of the catalogue. The median values of internal standard errors are given.

Mean satellite observation epoch	∼J1991.5
Epoch of the Tycho-2 Catalogue	J2000.0
Reference system	ICRS
coincidence with ICRS[1]	±0.6 mas
deviation from inertial[1]	±0.25 mas/yr
Number of entries	2 539 913
Astrometric standard errors[2]	
$V_T < 9$ mag	7 mas
all stars, positions	60 mas
all stars, proper motions	2.5 mas/yr
Photometric std. errors[3] on V_T	
$V_T < 9$ mag	0.013 mag
all stars	0.10 mag
Star density	
$b = 0°$	150 stars $\deg^{-2}$
$b = \pm 30°$	50 stars $\deg^{-2}$
$b = \pm 90°$	25 stars $\deg^{-2}$
Completeness to ∼ 90 per cent	$V \sim 11.5$
Completeness to ∼ 99 per cent	$V \sim 11.0$
Number of Tycho observations	$\sim 300 \times 10^6$

[1] about all 3 axes
[2] ratio of external to internal standard errors is ∼ 1.0 for positions and for proper motions.
Systematic errors are < 1 mas and < 0.5 mas/yr
[3] ratio of photometric external to internal standard errors at $V_T > 9$ is below 1.5

A total of 7 700 851 ground-based positions were used. Virtually all of the 4% of the stars without proper motions are at the faint end. They are concentrated in certain zones of the Astrographic Catalogue as shown in Høg et al. (2000b), cited herafter as H2000b. The mean position at the epoch J2000.0 is also given when the proper motion is available.

⋆ Based on observations made with the ESA Hipparcos astrometry satellite. The catalogue is distributed on CD-ROM and through the astronomical data centres, and further information is given on the website http://www.astro.ku.dk/∼erik/Tycho-2.

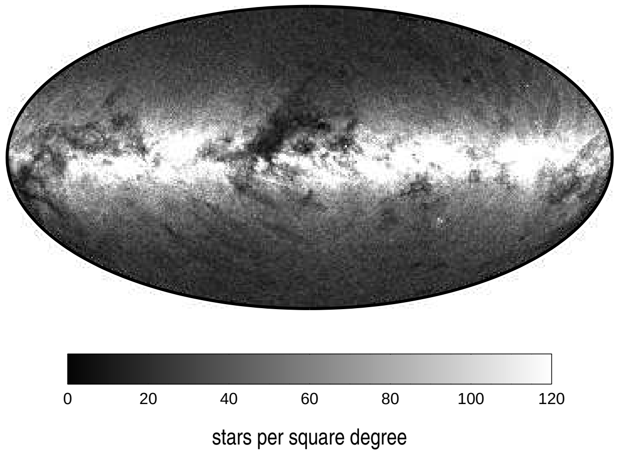

Fig. 1. The Tycho-2 Catalogue: number of observed stars per square degree, in galactic coordinates centred at $l = 0$. In some areas the density is above 400 stars deg^{-2}, with a maximum of 450. The average density is 150 stars deg^{-2} at $b = 0$ and decreases to 25 stars deg^{-2} at $| b |= 90°$. Traces of the Hipparcos scanning pattern appear as stripes with lower star density.

The Tycho-2 processing emphasized the optimal treatment of apparently single stars, which constituted the vast majority of targets observed. However, an effort was made to detect and measure double stars. This resulted in the measurement of 7 500 pairs with separations between 0.8 and 2.5 arcsec, while the lower limit of resolution in Tycho-1 was about 2 arcsec.

The Tycho-2 Catalogue supersedes in size and quality the Tycho-1 Catalogue itself with respect to photometry and astrometry of single and double stars. It also supersedes the astrometric reference catalogues ACT (Urban et al. 1998b) and TRC (Høg et al. 1998) both based on Tycho-1. The Tycho-2 is more complete than Tycho-1 at any given magnitude. Its construction and verification is described by Høg et al. (2000a), hereafter referred to as H2000a, and in H2000b.

1.1. Tycho observations

The observational capabilities and operational principles of the Hipparcos satellite have been presented in the literature, with the most complete and definitive treatment contained within the published Hipparcos and Tycho Catalogues (ESA 1997). Short descriptions are given by Perryman et al. (1997), Høg et al. (1997) and van Leeuwen et al. (1997).

The Tycho-1 Catalogue of one million stars was derived from photon counts obtained by scanning with the Hipparcos star mapper. The scanning was carried out simultaneously with the Hipparcos observations in the adjacent main field of view of the telescope. The Tycho-2 Catalogue of 2.5 times as many stars was obtained from the very same Tycho observations, but utilizing a more powerful data reduction technique. *A photon superposition for the whole mission* was applied as described in detail in H2000a, instead of detection of single transits. Also important was the use of calibration data from the first Tycho reduction, and the combination of several new catalogues, notably Hipparcos, Tycho-1, STARNET and GSC 1.2, into a new Tycho Input Catalogue (TIC2).

The key features of the Tycho observations were very similar to those of the Hipparcos main field observations and may be summarised as follows:

(a) the continuous scanning by the satellite, resulted in a catalogue of rather homogeneous limiting magnitude;

(b) the multiple epochs throughout the 3-year observation programme and simultaneous Hipparcos observations, resulted in a close connection to the Hipparcos astrometric reference frame represented by about 100 000 stars;

(c) the large number of observations per object, of order 130, and the various geometrical scan configurations provided accurate and homogeneous photometric information for each star, from which mean magnitudes in two passbands, B_T and V_T, were derived for both single stars and double stars. The two Tycho passbands are close to Johnson B and V and approximate transformations are given in ESA97, Vol. 1, Sect. 1.3. It is, however, recommended to use B_T and V_T directly since the transformation is dependent especially on luminosity class and reddening which are usually unknown.

Further studies of variability and duplicity, including narrower double stars, are possible based on the original Tycho observations.

1.2. Ground-based observations

The proper motions in Tycho-2 were computed by combining the Tycho-2 positions with those from ground-based transit circle and photographic programmes. Note that this is somewhat different than the procedure used for ACT (Urban et al. 1998b) and TRC (Høg et al. 1998a), where the proper motions were computed from essentially two positions: from Tycho-1 at epoch 1991.25 and from the Astrographic Catalogue (AC) at epoch about 1905. The Tycho-2 proper motions were derived using 143 transit circle and photographic catalogues in addition to the AC and Tycho-2 positions. Including these extra catalogues, generally observed at epochs between the AC and Tycho-2, allows for an improved determination of proper motions, greater investigation of individual stars' errors, and a higher confidence of identification especially in the case of high proper motion stars.

Each of the source catalogues was put on the Hipparcos system individually. It was decided not to use the extant AC 2000 (Urban et al. 1998a), but to re-reduce the AC plate measures using a new reference catalogue based

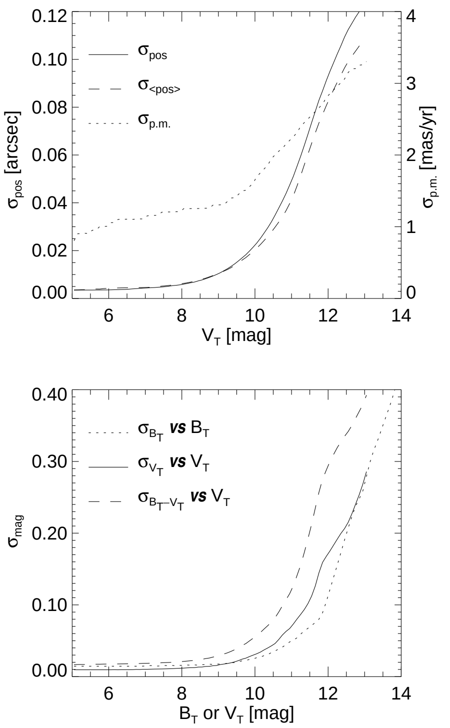

Fig. 2. The Tycho-2 Catalogue accuracy. (a): Standard errors of the observed position components, of the mean position at mean epoch, and of proper motion components; (b): standard errors of magnitudes and colour indices versus B_T or V_T (see also Table 2).

on the Hipparcos Catalogue and ground-based catalogues. Use of the photometry from Tycho-2 has minimized systematic errors due to stellar magnitude and colour. This is detailed in Urban et al. (in preparation). Weights for each of the positions were computed, and the proper motions were determined via weighted least-squares. Details of the computation of the proper motions are found in H2000a and H2000b, e.g. on the weighting of the source catalogues.

2. Main catalogue and two supplements

The Tycho-2 Catalogue contains positions and magnitudes for 2 539 913 stars. We normally give two positions for each star, viz. the *observed* position and the *mean* position. For all stars we give the *observed position*, based on satellite data only, at the Tycho observation epoch which is close to 1991.5. For 96 % of the stars, at least one ground-based observation was available and a proper motion was derived. The weighted least-squares solution giving the proper motion, also gave the *mean position* at the mean epoch. But in the catalogue we give the mean position, rigorously propagated to the epoch J2000.0 by means of the proper motion.

Stars brighter than about $B_T = 2.1$ or $V_T = 1.9$ could not be treated properly and are excluded from the catalogue. For the convenience of the user, stars from the Hipparcos and Tycho-1 Catalogues which – for various reasons – are not included in the Tycho-2 Catalogue, have been listed in supplementary catalogues giving astrometry and photometry from either the Hipparcos or the Tycho-1 Catalogue. The first supplement contains 17 588 good quality stars while the second supplement contains 1146 Tycho-1 stars which are either false or heavily disturbed by brighter stars. Any star from Tycho-1 marked with an astrometric quality flag of '9' and which was not detected in Tycho-2 processing was excluded from both supplements.

The catalogue provides cross references to the Tycho-1 Catalogue and to stars in the Hipparcos Catalogue and its annex of double and multiple stars with component solutions. In general a distance limit of 0.8 arcsec was used for the identification.

2.1. TYC numbers

For Tycho-2 we use the same system of star numbers as in Tycho-1, and the numbers are consistent. The system is basically the same as used in GSC, the Guide Star Catalog (Jenkner et al. 1990), but with a component number appended.

Each Tycho-2 entry, e.g. TYC 5311–1245–1, has a set of three identification numbers: TYC1, TYC2 and TYC3. TYC1 is the GSC region number, TYC2 is the running number within the region, and TYC3 is a Tycho specific component number. Double star components will either have two different running numbers or the same running number and different component numbers.

In about 4 500 cases, new consistent running numbers within GSC regions were constructed for Tycho-2.

2.2. The proximity indicator

When selecting stars from a catalogue like Tycho-2, it is often useful to know if there are other stars present in the neighbourhood. For this purpose we give a proximity indicator for each star, which is simply the distance to the nearest neighbour in the main catalogue or in the main supplement. Stars in the second supplement, i.e. false Tycho-1 stars, were ignored.

3. Astrometric accuracy

The internal standard errors of the observed Tycho-2 positions in RA and Dec are given for each star in the catalogue. The errors are plotted as function of V_T magnitude in Fig. 2a and they appear in Table 2. The errors are discussed in detail in H2000a.

For the mean positions, standard errors are derived based on the weights of the source catalogues and their respective errors. When more than two positions are avail-

Table 2. Number of stars and the precision of Tycho-2 within the given intervals of V_T magnitude.

Interval of V_T	<7.0	7–8.0	8–9.0	9–10.0	10–11.0	11–12.0	>12.0	All	<9.0
Median V_T , mag	6.39	7.63	8.62	9.61	10.61	11.54	12.28	11.41	8.34
N (positions)	14 145	27 770	78 296	207 569	536 565	1 127 627	547 935	2 539 913	120 211
$N_{\mathrm{Suppl-1}}$	109	49	202	1 218	6 768	7 482	1 733	17 588	360
N (proper motions)	13 773	27 684	78 146	207 125	533 549	1 069 268	500 918	2 430 468	119 603
Mean epoch of positions	1991.37	1991.23	1990.75	1989.25	1986.89	1982.67	1978.21	1984.34	1990.99
Median standard errors in astrometry (mas or mas/yr):									
Position (Tycho)	3.8	5.0	7.9	15.9	35.4	71.3	103.5	64.0	6.6
Position (mean epoch)	4.0	5.0	8.0	15.0	30.0	63.0	92.0	55.0	7.0
Proper motion	1.0	1.2	1.3	1.5	2.0	2.5	3.0	2.4	1.2
Median standard errors in photometry (mag):									
B_T	0.015	0.016	0.020	0.033	0.068	0.173	0.248	0.143	0.018
V_T	0.010	0.011	0.014	0.023	0.050	0.114	0.198	0.100	0.013

Explanation: 'N' is the number of stars in the main Tycho-2 Catalogue. '$N_{\mathrm{Suppl-1}}$ ' is the number of stars in the first supplement to Tycho-2. 'Mean epoch' is the weighted mean epoch for the source catalogues from which the proper motion is derived; the median value for the N stars is given. 'Position (Tycho)' refers to the position observed by the satellite. 'Position (mean epoch)' refers to the mean position at the mean epoch.

able, a standard error based on the scatter was also computed (see H2000a). We include the ratio of these two error determinations in the catalogue as a measure of the goodness of fit.

External errors in astrometry have been studied by comparisons with the Hipparcos Catalogue. The ratio of external to internal standard errors of positions is about 1.0. The same ratio is found for proper motions. The Hipparcos and Tycho-2 proper motions are equally accurate for stars fainter than $V_T = 9$. For brighter stars a comparison is pending.

The systematic errors of positions and proper motions have been studied by considering the average differences between Hipparcos and Tycho-2 values for the common stars in areas of typically $6° \times 6°$. Assuming the systematic errors of Hipparcos astrometry to be negligible in this context, the systematic errors of Tycho-2, on angular scales of 6 deg or more, are less than 1 mas for positions and less than about 0.5 mas/yr for proper motions.

4. Photometric accuracy

Internal standard errors of the Tycho-2 photometry are shown in Fig. 2b. It is concluded in H2000a, from a comparison with ground-based photometry, that the ratio of the external and internal standard errors is close to 1.0 for stars brighter than magnitude 7.5 and then gradually rises to at most 1.5 at magnitude 10 and fainter.

The Tycho-2 magnitudes are systematically correct down to magnitudes 13 and 12 in B_T and V_T, respectively. Fainter magnitudes are not trustworthy, and magnitudes in the catalogue fainter than respectively 15 and 14 should be understood to mean that the star was not detected in that colour.

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