20. FUTURE PROSPECTS

An outline is given on various future uses of Tycho Catalogue results. Improved proper motions may be derived by means of positions given in the Tycho Catalogue and the Astrographic Catalogue. More accurate reduction of photographic plates and CCD images may be based on the Tycho Catalogue. The search for new variable stars may be based on Tycho epoch photometry. The prospects of a second Tycho processing are briefly discussed, concluding that better values may be obtained for the fainter half million stars of the present Tycho Catalogue, and positions and magnitudes for a total of up to 3 million stars.

20.1. Proper Motions Derived by Means of the Astrographic Catalogue

The median precision of the proper motion components in the Tycho Catalogue is about 30 mas/yr, while the typical proper motion of a star of magnitude 10 or 11 is of the order of 20 mas/yr. Thus, significant proper motions cannot be expected for the vast majority of the Tycho Catalogue stars from the Tycho data alone. The present section briefly outlines how this situation can be improved by the usage of ground-based data, most notably the Astrographic Catalogue.

Existing Proper Motions

About 10 per cent of the Tycho Catalogue stars are contained in the Hipparcos Catalogue. Thus, high-quality proper motions on the Hipparcos system with typical precisions between 1 and 2 mas/yr are available for these. The Catalogue of Positions and Proper Motions (PPM, Röser & Bastian 1991; Bastian *et al.* 1993) and its southern '90 000 Stars Supplement' (Röser *et al.* 1994) provide proper motions for about half of the Tycho Catalogue stars, with a typical precision of 4.5 mas/yr and 3.7 mas/yr on the northern and southern celestial hemispheres, respectively (see Volume 3, Chapter 19). However, these data suffer from rather large systematic errors. The regional distortions of the PPM system with respect to the Hipparcos system are of the order of 3 mas/yr on a 5 to 10° scale (again see Volume 3, Chapter 19, or Figure 18.7). Finally, the STARNET project (Röser 1996) has produced preliminary proper motions for practically all Tycho Catalogue stars. These are nominally on the PPM system and have an estimated precision of 5 to 7 mas/yr. The systematic errors are about 4 mas/yr, slightly larger than those of the Catalogue of Positions and Proper Motions.

The Astrographic Catalogue

The Astrographic Catalogue is a photographic sky survey initiated in 1887 and carried through mainly between 1895 and 1910. For a description of this huge world-wide collaboration see Eichhorn (1974). The project resulted in more than 8 million position measurements for about 4 million stars. The precision of the plate measurements is now known to be mostly between 0.25 and 0.35 arcsec. However, due to the lack of a dense reference system with stars on all plates with a matching precision, and due to the lack of computing power, up to very recently these plate measurements had not been transformed into celestial coordinates of similar quality.

Between 1985 and 1993, the printed volumes containing the Astrographic Catalogue measurements were transferred into machine-readable form at the Sternberg Astronomical Institute, Moscow. A first reduction of these data onto the FK5 system was carried out in the course of the 'Catalogue of Positions and Proper Motions' project. The precision of that Catalogue and STARNET proper motions rests to a large extent on the Astrographic Catalogue as a very early and precise first epoch. The Catalogue of Positions and Proper Motions combined the Astrographic Catalogue with all existing high-precision astrographic sky surveys (most notably AGK2, AGK3, Yale and Cape zone catalogues, CPC-2 and FOKAT), while STARNET combined the Astrographic Catalogue with the Guide Star Catalog as sole second epoch.

The Tycho Reference Catalogue

A combination of the Astrographic Catalogue with the Tycho Catalogue would give proper motions with a precision of about 2.5 mas/yr for practically all Tycho Catalogue stars. This is the basic idea of the Tycho Reference Catalogue project, a collaboration between scientists in Copenhagen, Lund, Moscow and Heidelberg. The major task to be performed in the framework of this project is a careful re-reduction of the Astrographic Catalogue (and the other astrographic sky surveys mentioned above) onto the Hipparcos system. The work is planned to be completed within about 2 years after the completion of the Tycho Catalogue.

The Tycho Reference Catalogue will surpass the Catalogue of Positions and Proper Motions (PPM) by a factor of 2.5 in the number of stars, and by a factor of 2 in the precision of the proper motions. The systematic errors should also be much smaller than in the PPM. With the very recent and very precise Tycho positions as second epoch, the median positional precision of the Tycho Reference Catalogue will stay below 60 mas for the next 15 years. With its mean density of 25 stars per square degree it will be the main reference catalogue for photographic astrometry for the near future.

The Tycho Reference Catalogue will be a very important supplement to the Hipparcos Catalogue for the study of galactic kinematics. If we define a 'significant' proper motion as one being at least 3 times as large as its mean error then in these terms, Hipparcos provides about 100 000 significant proper motions, the PPM about 200 000 (i.e. about 100 000 in addition to Hipparcos, but with the systematic errors mentioned above), and the Tycho Reference Catalogue will provide of the order of 700 000, i.e. 600 000 in addition to Hipparcos.

More details about the Tycho Reference Catalogue can be found in Röser & Høg (1993).

20.2. Reductions of Photographic Plates and CCDs using the Tycho Catalogue

The Tycho Catalogue will bring significant improvements to the present situation regarding reduction of wide field plates, both because of the larger star density than existing catalogues, and because of the better astrometric and photometric accuracy.

Astrometric and photometric quality have been discussed in the previous chapters. Concerning the star density, there is a factor of three to four with respect to current astrometric catalogues such as the SAO catalogue, frequently used in the past, or the more recent Catalogue of Positions and Proper Motions (PPM). The Tycho star density is eight to ten times larger than the Hipparcos star density.

A more detailed discussion of the use of Tycho data for Schmidt plate astrometric reductions has been presented by Robichon *et al.* (1995), as summarized in Volume 3, Section 19.5. This discussion was based on the use of preliminary Hipparcos and Tycho data as astrometric reference stars. The results obtained showed that the ultimate accuracy from a single Schmidt plate can be better than 0.10 arcsec for stars brighter than the Tycho limit of 11 mag. Actually, the modelling of Schmidt plate field distortions appears more reliable when the reduction is carried out using the numerous, though less accurate, data from Tycho, than when the Hipparcos data alone are used.

Obviously, the proper motions to be derived from the joint use of the Tycho Catalogue and the Astrographic Catalogue, as described in the previous section, will be of critical importance as soon as the photographic plates are taken at epochs significantly different from the Tycho mid-epoch.

The need for accurate proper motions for complementing Tycho data when exposures are obtained at dates only a few years from the Tycho mid-epoch will be even more acute for CCD data. It has been claimed that a precision of about 20 mas can be achieved (according to Zacharias *et al.* 1995 and Zacharias 1996, private communication) for CCD observations obtained with a wide-field astrograph, namely for the average of double exposures and for stars between 6 and 13.5 mag. The high star density of the Tycho Catalogue will be of great help for providing astrometric reference stars for large CCD frames.

For small-field applications, a still denser reference catalogue will be needed, which can be derived from a re-reduction of STARNET onto the Hipparcos system, or from the 3 million stars extended Tycho Catalogue described in Section 20.4.

20.3. Search for New Variables in the Epoch Photometry

A search for variable stars by means of the Tycho epoch photometry was performed among about 480 000 stars brighter than $V_T = 10.5$ mag, as described in Section 19.3. This process was not based on all the transits valid for photometry, but only on those where photometric measurements were actually obtained. Therefore, if a variable star was too faint for detection of the Tycho transits during a part of the mission, it could be

detected as a variable star only if the variability appeared in the actual measurements. A search for variable stars taking also the non-detections into account, and the application of this method to all the Tycho stars is planned.

The importance of using the non-detections, was already seen in Tycho photometry, when the magnitudes of faint stars were 'de-censored' (see Chapter 9). The principle of de-censoring was to calculate the probability law of the magnitude that would have been measured if a measurement had been obtained. The de-censoring was used to convert the missing measurements into a distribution function that was added to the histogram of the magnitude measurements of any star. The V_T scatter of the faint stars was derived with this method.

The search for variable stars will be another application of de-censoring. The principle could be as follows: The probability law of the signal recorded for any transit would be computed, without considering whether the transit was detected or not. A theoretical histogram of the magnitude observations would then be derived, and it would be compared to the histogram actually obtained from de-censoring. The two histograms should be similar when the magnitude of the star is actually constant, but they should differ when it is variable.

20.4. The Second Tycho Processing

All processing of Tycho observations described so far in this volume was based on detections at each group crossing above a certain signal-to-noise ratio (1.5 or 1.8).

Further improvement of the limiting magnitude by about 0.4 mag could be obtained by superposition of the photon counts for each star from two consecutive observations in the preceding and following fields of view. This was beyond the available capabilities with respect to software development and computing facilities when discussed in 1991.

A photon superposition for the whole mission would give a still higher gain and is planned for the near future. This idea was proposed in principle by Høg *et al.* (1982), but had to be abandoned in favour of the more modest approach described in this volume. A second Tycho processing of all raw counts should be based on the available satellite attitude, the Tycho Catalogue of one million stars, and an input catalogue of about 6 million stars from a new reduction of the Guide Star Catalog and the Astrographic Catalogue so that a position accuracy about 0.25 arcsec at the observation epoch is provided. This will facilitate the processing which is planned as a cooperative effort between scientists in Copenhagen and Heidelberg. This processing is expected to give better astrometric and photometric values for the fainter half of the present one million stars. The major reason is that an astrometric estimation based on very few photons does not achieve the Cramér-Rao limit (see Yoshizawa *et al.* 1985). An estimation based on all photons from many transits will come much closer to that limit. Furthermore, many transits of the faint stars were below the limit of signal-to-noise ratio for the detection and were thus completely lost. Good results are expected for altogether up to 3 million stars, brighter than about $V = 12$ mag. Expected external standard errors at $V = 11.0$ and 12.0 mag are respectively $\sigma_{\alpha,\delta} \simeq 50$ and 100 mas and $\sigma_V \simeq 0.10$ and 0.20 mag.

An illustration of the number of lost Tycho transits is provided by Figure 20.1. The number of stars observed by Tycho versus V_T magnitude is also shown (dotted). This,

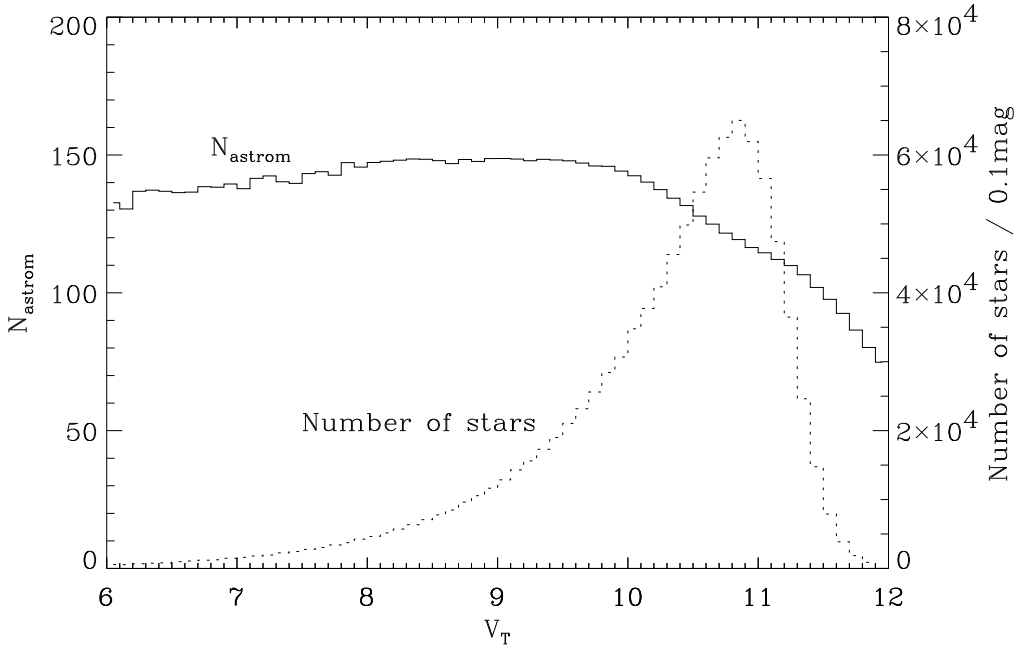

Figure 20.1. *The number N of stars with a V_T magnitude actually observed by Tycho; the number of accepted astrometric transits, $N_{\rm astrom}$.*

therefore, does not include the stars in the similar Figure 17.1 having another magnitude than V_T. It was concluded in Section 17.1 and is also shown by the present figure that about 10 per cent of the stars on the sky with V_T = 11.5 mag were detected by Tycho.

The curve for $N_{\rm astrom}$ shows that the number has a maximum of 150 transits at $V_T \simeq$ 10 mag, decreasing to typically 100 transits at V_T = 11.5 mag due to a censoring of transits. The slight decrease towards brighter magnitudes is explained as due to the model for σ_u in Equation 7.8 giving too small values at bright magnitudes, leading to too tight rejection limits. It appears that about 90 per cent of the stars were lost at V_T = 11.5 mag, and that about 30 per cent of the transits of the remaining stars were censored. For all stars on the sky with V_T = 11.5 mag, including those not contained in the Tycho Catalogue, a larger fraction of about 50 per cent of the transits were censored. Further details on the number of transits are given in Section 16.4.

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