Close-up of 2.5 million Tycho stars

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Abstract

The Tycho observations from the ESA Hipparcos satellite have been subject of a first reduction, producing the Tycho-1 Catalogue with astrometry and photometry of one million stars. A second reduction has recently been completed resulting in the Tycho-2 Catalogue of 2.5 million stars, i.e. all stars brighter than about $V = 12$ mag. A third Tycho reduction (Tycho-3) is now planned which will be a detailed study with resolution in angular space and in time for all 2.5 million stars of the Tycho-2 Catalogue. This will result in detection and measurement of duplicity and variability for tens of thousands of stars. A catalogue of relative astrometry and two-colour photometry for 10 000 close double stars (separation less than 3 arcsec) will be constructed.

1 Introduction

1.1 The Tycho-1 and Tycho-2 Catalogues

The observations from the Tycho experiment onboard the Hipparcos satellite have been exploited to produce the Tycho-1 Catalogue of 1 million stars with positions, proper motions and B_T, V_T magnitudes. The Tycho-1 Catalogue was published in connection with the main Hipparcos Catalogue of 120 000 stars (ESA 1997).

The Tycho-2 Catalogue (Høg et al. 1999, 2000a, 2000c) is the result of a second data reduction (Høg et al. 2000b), based on the Tycho observations and the results in the Hipparcos and the Tycho-1 Catalogues. An input catalogue of 4.3 million stars was constructed from the recent catalogues Hipparcos, Tycho-1, ACT, TRC, STARNET, GSC 1.2 and USNO A1.0. The reduction was carried out at the Copenhagen University Observatory from 1996-99 financed primarily by the Velux Foundation of 1981 and in collaboration with German colleagues U. Bastian, P. Schwekendiek and A. Wicenec. The Tycho-2 Catalogue contains positions, proper motions and B_T, V_T magnitudes for 2.5 million stars. The proper motions were derived by our U.S. colleagues S.E. Urban, T.E. Corbin and G.L. Wycoff from the Tycho-2 positions, the 100 year old positions in the Astrographic Catalogue (AC) and 143 other astrometric catalogues and are therefore much more accurate than those in the Tycho-1 Catalogue.

1.2 The third Tycho project

An important scientific treasure in the Tycho observations could not be fully exploited in the two first reductions. This is the information on double stars and variable stars. It was known from the beginning that this information could only partly be utilized in the Tycho-2 project, because of the limited available time for the work and the complicated data reduction that would be required. A utilization of the information is now proposed, based on the existing data base of Tycho observations, the now available Tycho-2 Catalogue and the experience gained during the production of that catalogue.

The vast majority of the 2.5 million stars in Tycho-2 are visually single stars without detectable trace of duplicity. But it is also true that the vast majority have not been subject to an examination in the detail that is possible with the Tycho observations. Tens of thousands of stars are detectable double stars and/or variable stars. Many of them are already known as such, but the Tycho data will often give more accurate results, especially on the magnitudes in two colours (B_T, V_T). Many will be new discoveries.

The proposed detailed study (close-up) of the 2.5 million stars will be the largest, most uniform and most detailed survey of the brightest stars in the sky. The bright stars have always been of special interest to astronomers from the surveys of Hipparchus and Tycho Brahe of 1000 stars, to the Bonner Durchmusterung by Argelander about the middle of the 19th century, and finally by the Hipparcos satellite. There are many reasons for the interest: The positions and proper motions provide a reference frame for observation of fainter stars, the sample contains many of the stars nearest to the sun, and the most detailed spectroscopic studies can be performed because of the high brightness.

2 Duplicity

2.1 Tycho observations

In the Tycho-1 Catalogue the limit of separation of double stars is about 2 arcsec. This limit has been improved to 0.8 arcsec in Tycho-2, and even much better is expected in the Tycho-3 project.

Duplicity can be detected and studied with Tycho observations by several methods. The following three methods have been exploited during the Tycho-2 Catalogue production and following research projects, and have resulted in data already published or submitted for publication:

- **Routine double star solution in the Tycho-2 production** (Høg et al. 2000a, 2000b, 2000c). It gave full solutions (astrometry and photometry) for 7 500 pairs with separations between 0.8 and about 2.5 arcsec, included in the Tycho-2 Catalogue. Resolved pairs with smaller separation were not included, although provisional checks showed that many of them are reliable resolutions, including a few hundred new binaries. As an important step for the routine solution, a list of 65 000 candidate double stars was created by means of a special detection procedure, based entirely on intermediate Tycho-2 data.

- **Photometric measurement of B_T, V_T for Hipparcos stars.** Photometric analysis at the positions of double star components according to the Hipparcos Catalogue gave results for 9473 pairs (Fabricius & Makarov 2000a). The separations were between 0.3 and 2.5 arcsec.

- **Resolving poor Hipparcos solutions** for double stars, using the Tycho-2 Catalogue and the raw observations data base for establishing the initial corrections. The published *Hipparcos Transit Data* have been used by Fabricius & Makarov (2000b) to revise solutions for 257 systems. Falin & Mignard (1999) and Söderhjelm (1999) have solved other such problem cases. Probably a few hundred more bad solutions remain in the Hipparcos Catalogue.

It should be noted that the intermediate data from the Tycho-2 routine double star solutions are neither fully exploited nor published as yet. For example, the detection of duplicity based on the *12-points method* (Høg et al. 2000b) indicated many thousands more suspected cases than were eventually resolved and included in the catalogue. A large list of candidate binary stars with estimated position angles should be generated, based on the 12-points data available in the solution log files, and offered for follow-up on-ground observations, e.g. by means of speckle interferometry. Moreover, some of the rejected double star solutions with separations from 0.66 to 0.80 arcsec have already been checked and confirmed, and their relative astrometry and photometry data are to be published within a Tycho Double Star Catalogue containing about 10 000 pairs measured by Tycho.

A few other methods, still requiring a software development, should be further exploited:

1. A search for wide binaries with separations up to 30 arcsec by analysis of proper motions and magnitudes. Wide binaries provide valuable clues to the conditions in star-forming regions and to the dynamics of the Galaxy (Gould et al. 1995). Provisional attempts showed that up to 12 000 statistically certain common proper motion (CPM) pairs can be found in the Tycho-2 Catalogue alone.

2. Detection of difference in positions of the B and V images. This indicates an unresolved double star with components of different colours. A few candidates are known, but probably thousands more exist.

3. Detection by subtraction of the counts corresponding to the 2.5 million stars in the Tycho-2 Catalogue. The remaining photon counts will reveal fainter components than could be detected and measured with the existing software for single and double stars, especially for separations between 1.5 and 2.5 arcsec.

4. Absolute astrometry of double stars with a new solution algorithm based on the Fast Fourier Transform, which hopefully will give better accuracy than the routine (downhill simplex + cleaning) algorithm and will work much faster, allowing more candidates to be investigated.

5. Photometric measurement of B_T, V_T for infrared sources. The large infrared survey, 2MASS, gives astrometry with an accuracy about 0.10 arcsec. D. Monet (1999, private comm.) has found a total of 1 027 000 common objects in Tycho-2 and 2MASS. In about 6 000 cases the positions in the two catalogues differ by more than 1.0 arcsec, a very significant value. A comparison with other catalogues by Urban (2000, private comm.) has shown that such a discrepancy is more frequently found for known double or multiple stars. This question should be investigated by means of the Tycho observations, e.g. by Tycho photometry with a method similar to the one used for Hipparcos double stars by Fabricius & Makarov (2000a), mentioned above.

While the first three methods have already been verified to work and even some provisional results have been obtained, Method 4 is to be developed from scratch. However, it might be potentially the most promissing, securing high quality information for tens of thousands of binary stars.

Figure 1 shows three wider separation pairs as examples of double stars that could be measured. They were serendipitously resolved in Tycho-2. Supposedly, many more exist, and can be discovered with Method 3. Case c shows a not unusual situation when the components have very different colour (compare the relative brightness in B_T and V_T) which also should be detected with Method 2.

The exploitation of the Tycho raw observations data base has already led to the discovery of two very blue subluminous components which we expect to be hot subdwarfs in relatively nearby

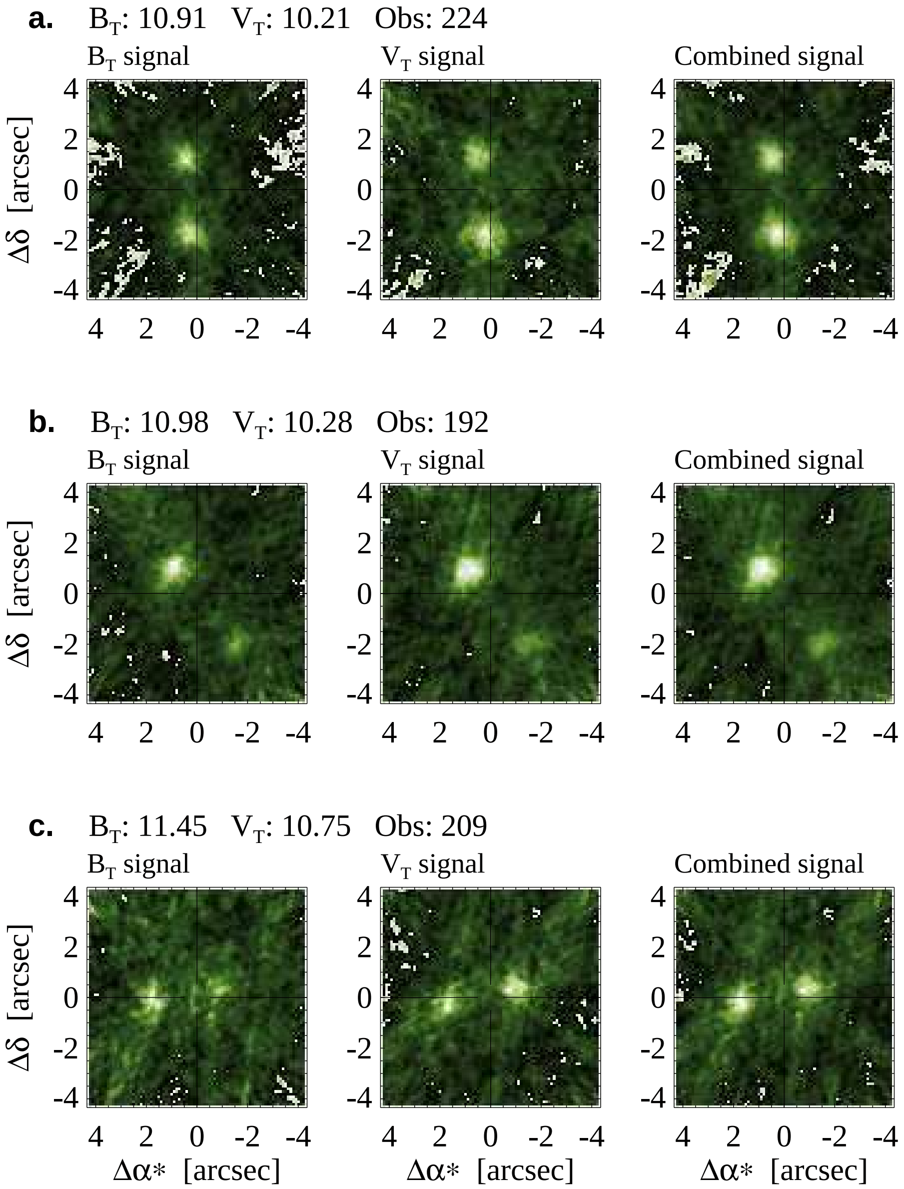

Figure 1: Three cases of double stars where two rather faint components are serendipitously measured in the Tycho-2 Catalogue. The B_T and V_T magnitude of the brightest component and the number of stacked observations are given. The recognition of duplicity was possible only because of the unusual circumstance that the input catalogue happened to contain two entries close to each other and because one of them was a Tycho-1 star. In thousands of other cases the Tycho-2 routine processing was not able to detect the fainter component. The proposed close-up processing will be able to detect and measure all such faint components.

visual binaries (Makarov & Fabricius 1999). This is an important discovery since there was only one such star known before. It will, if confirmed, allow the first direct determination of the mass of this kind of star from the visual binary orbit. In the wide CPM pairs (Method 1), dozens of possible hot subdwarfs can be found, suitable for ground-based spectroscopic observations.

Today about 80 000 double star systems are known, but for most of them the astrometric information is of low quality. The CCDM catalogue contains 34 031 definitely identified double or multiple star systems, given with coordinates and ID numbers. The Hipparcos Catalogue, Annex C, contains 12 195 solutions. The WDS (Washington) contains 78 100 double star systems, but it is not an astrometric catalogue. The RA is given to 0.1 min only.

It is expected that 10 to 20 thousand of the 80 000 systems will be measured in the new project, and that the absolute astrometric positions obtained by the Tycho observations will complement the Hipparcos Catalogue and establish a new level of orderly identification of double star systems. We expect to reach an angular resolution of 0.4 arcsec for components of similar magnitudes. The two-colour photometry from Tycho will be by far the most complete and uniform information of its kind.

2.2 Ground-based observations

Detection of double stars from Tycho data should be accompanied by ground based observations. They are required to verify the statistical reliability of the detections and to enhance the scientific outcome.

We intend to verify duplicity in collaboration with other observers, and this has already started with observers at the Observatoire de Cote d'Azur in France (F. Mignard et al.) and at the U.S. Naval Observatory in Washington and Flagstaff (S. Urban, B. Mason, D. Monet et al.).

3 Variability

3.1 Tycho observations

Variability can be detected by statistical tests on the approximately 130 Tycho observations obtained for each star. Such detection has only been done in few cases at this time, but enough to ensure that a thorough study would be worthwhile. Large computations are required with software which has to be developed.

A similar work for the half million brightest stars can be done with the Annexes A and B which were by-products of the Tycho-1 processing. A project of this kind is being undertaken at CDS, Strasbourg. It is noted however, that due to the very different and more straightforward way of astrometric/photometric processing in Tycho-2, the results for the stars in common may differ. The use of the Tycho-2 database will in many cases provide important advantages. For example, there is no problem of ambiguous "non-detections" in Tycho-2, and this simplifies and enhances a search for variable stars. It is also useful that we have access to the original observations for difficult cases, such as contamination by parasitic signals or abnormal sky background. Re-analysis and direct examination is then possible. Figures 2 and 3 show examples of light curves of variable stars as they appear in the Tycho data.

Most of the known bright variable stars are contained in the Combined General Catalogue of Variable Stars (CGCVS) with about 32 000 entries (Kholopov et al. 1998).

We will do our best to detect all kinds of variable stars, which are generally separated into the two classes of physical and eclipsing variables. Detection of variable stars from Tycho data

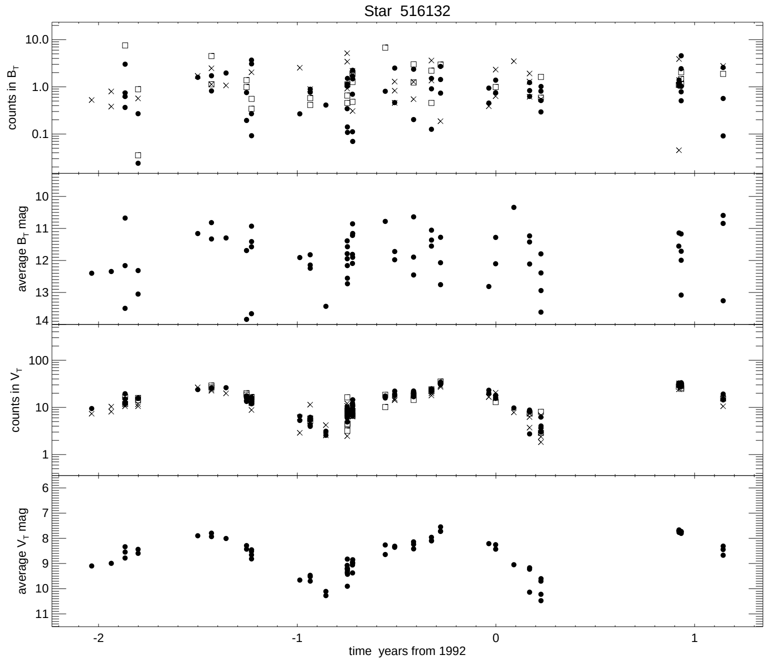

Figure 2: Observations of the known variable RV Cen, Var type: Mira, Period 447 d. If the variability had not been known it could have been detected by the increased scatter of the observations, compared to a constant star.

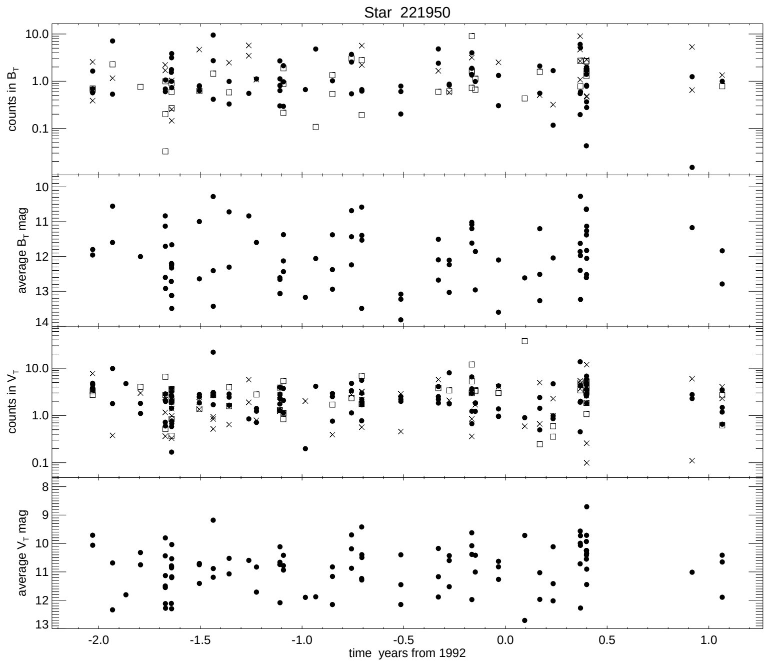

Figure 3: Observations of the known variable KN Cen, Var type: Classical Cepheid, Period 34.05 d. If the variability had not been known it could have been detected, as in Fig. 2. The period and epoch could in this case not be safely determined from Tycho observations alone.

should be accompanied by ground based observations. They are required to verify the statistical reliability of the detections and to enhance the immediate scientific yield.

One of the brightest known Cepheid stars (HD 32456, $B_{max} = 8.2$ mag) was in fact detected during the first analysis of Tycho observations by Makarov et al. (1994). It was among suspected variables on a list of 35 stars from the Tycho Consortium. That it was of the interesting Cepheid type was however only realized when the stars on the list were observed visually by German amateur astronomers. That gave only little credit to the Tycho Consortium, but it showed how necessary it is to be directly involved in follow-up observations.

3.2 Eclipsing binaries

Detached, double-lined eclipsing binaries are the main source of accurate (1-2 %) data on stellar masses and radii. They are thereby extremely important for detailed empirical tests of models for stellar structure and evolution. Moreover they define the empirical mass-luminosity relations.

From studies of detached eclipsing binaries, accurate dimensions for about 100 stars are available (Andersen 1991, 1997). More that 50 % of these results have been achieved by the long-term Copenhagen binary project. Nearly all the binary components are main-sequence stars covering a wide range from about 23 to 0.21 $M_\odot$. Data from two groups in particular are, however, still scarce:

- massive, moderately evolved systems, i.e. spectral type B5 or earlier and masses > 6 $M_\odot$, needed for a better understanding of convective energy transport in the stellar cores and thereby establishment of accurate stellar ages, and
- late F, G and K systems with components masses around and below 1 $M_\odot$, where the few well-studied cases can not be reproduced by current stellar models (Popper 1997, Clausen et al. 1999a).

Hipparcos observed and listed 917 eclipsing binaries of which 343 were new. This was an important contribution to the approx. 4000 known systems (CGCVS and the 'Finding List' by Wood et al. 1980) but a much larger number of new binaries, including members of the above mentioned groups, is expected to be present among the 2.5 million Tycho stars. From the short list of 35 suspected variables, prepared by the Tycho Consortium, two have already been confirmed to be eclipsing binaries (Bastian & Born 1997, 1998 and Campos-Cucarella et al. 1997).

About 40 of the Hipparcos candidates were included in a large, systematic search for and study of late F, G and K type systems (Clausen et al 1999b), and $3 - 4$ have turned out to be ideal for determination of accurate masses and radii; accurate light curves and spectroscopic observations have now been obtained by the Copenhagen group. There is, however, still a severe lack of late G and K type systems, and a systematic search among Tycho candidates should be done.

3.3 Ground-based observations of eclipsing binaries

Experiments show that eclipsing binary candidates can be extracted from the B_T and V_T photometry of the Tycho-2 Catalogue, but ground based photometry, preferably done in the Strömgren *uvby* system, is needed for a safe classification of the candidates. The first, natural step is to select a few hundred of the brightest Tycho candidates with $B_T - V_T$ colours indicating that they are either OB stars or GK stars, i.e. belong to the two groups mentioned in Sect. 3.2. From $10 - 20$ observations per candidate, a catalogue with safe classification and information on possible activity (starspots on GK stars) can be established. For about 70 % of the sky such observations can be carried out at the Strömgren Automatic Telescope (SAT) at ESO, La Silla, operated by Copenhagen University Observatory.

The photometric observations and the establishment of the catalogue will be done in collaboration with Danish and Spanish colleagues J.V. Clausen, B.E. Helt and E.H. Olsen (for GK candidate stars) and A. Giménez and I. Ribas (for OB candidate stars). The results will immediately be used by these collaborators for detailed light-curve and spectroscopic observation and subsequent analyses of the most promising eclipsing binaries.

4 Nearby stars

In principle, parallaxes for nearby stars could be directly derived from Tycho observations, similarly to what has been done in the first Tycho processing. But they would be statistically significant only for stars brighter than about $V_T = 9$. It is believed that all such stars closer than 25 pc to the sun are known, but we have the opportunity to check that.

Another possibility is to select all main-sequence stars, using the Michigan spectral survey and look for nearby dwarfs, which must be rather bright. A similar work has been done (e.g., Upgren et al. 1992), but we have the advantage of the much more precise photometry in Tycho-2.

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