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THE TYCHO-2 SPECTRAL TYPE CATALOG

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ABSTRACT

The Tycho-2 Catalogue contains positions, proper motions, and B_T and V_T magnitudes for approximately 2.5 million stars. We have obtained spectral types for 351,864 of the Tycho-2 stars by cross-referencing Tycho-2 to several catalogs containing spectral types, using the VizieR astronomical database. The positional matching requirements were stringent (97.5% of the matches were within 1″), and the validity of the positional matches is further supported by the distribution of magnitude differences for matched pairs, which is symmetric about the median value $(dV)_{\rm med} = 0.043$ and has a small standard deviation, $\sigma_{dV} = 0.40$ mag.
Key words: catalogs — stars: fundamental parameters

1. INTRODUCTION

Recently, a need to cross-reference the Tycho-2 and Henry Draper catalogs was recognized by Fabricius et al. (2002). They determined Tycho-2 identifications for 353,473 (98.4%) of the stars in the Henry Draper (HD) catalogs and included the HD one-dimensional spectral types (a temperature class/subclass) in their catalog of matched objects. Our own research necessitated taking this idea one step further,[4] and to that end we present a catalog of spectral types and temperatures for 351,864 Tycho-2 stars. More than 240,000 Tycho-2 stars appear in both the Fabricius et al. catalog and in the catalog presented here, leaving approximately 110,000 stars in each catalog that do not appear in the other.

The spectral types in the catalog presented here were obtained by cross-referencing the Tycho-2 Catalogue to various other catalogs, which we shall refer to as "spectral type catalogs," that contain spectral types as either primary or secondary pieces of information. The Fabricius et al. (2002) results, which were released shortly before the completion of this project, are useful to us insofar as they provide an independent check of our matches, and we discuss this comparison later in the paper. However, the Fabricius et al. (2002) results are not sufficient for our purposes, because we preferentially select two-dimensional spectral types (a temperature class/subclass and a luminosity class), resorting to a one-dimensional spectral type only when a source has no other classification (as was the case for approximately half of our sources).

2. THE VIZIER SEARCH AND RESULTS

We created lists of star names from the following spectral type catalogs, in order of preference, to be cross-referenced (using VizieR) against the Tycho-2 main catalog and supplement 1: the Michigan Catalogue for the HD Stars, Volumes 1–5 (Houk & Cowley 1975; Houk 1978; Houk 1982; Houk & Smith-Moore 1988; Houk & Swift 1999); the Catalogue of Stellar Spectra Classified in the Morgan-Keenan System (Jaschek, Conde, & de Sierra 1964); the MK Classification Extension (Kennedy 1983); the Fifth Fundamental Catalogue (FK5) Part I (Fricke et al. 1988) and Part II (Fricke, Schwan, & Corbin 1991); and the Catalogue of Positions and Proper Motions (PPM), North (Röser & Bastian 1988) and South (Bastian & Röser 1993). The order of preference follows from the fact that the Michigan, Jaschek, and Kennedy catalogs contain two-dimensional spectral types, while the FK5 and PPM, which are astrometric catalogs, contain one-dimensional spectral types. The spectral types in the FK5 and the PPM South catalog are primarily HD classifications, while most of the spectral types in the PPM North catalog are taken from the AGK3 (Heckmann & Dieckvoss 1975), which in turn obtained spectral types from a wide variety of sources, only one of which was the HD catalog. We obtained the one-dimensional spectral classifications from the astrometric catalogs rather than from the one-dimensional spectral catalogs directly because the astrometric positions should provide tighter positional coincidences. If the spectral type catalog had multiple entries for a single star, the first was used.

One powerful feature of VizieR is that it resolves object names (such as HD or Durchmusterung [DM] numbers) with the SIMBAD astronomical database. Thus, when an object name is submitted to VizieR to cross-reference against a particular catalog, VizieR finds that object in SIMBAD and uses the most recent position available to match it to objects in the catalog of interest.

A catalog-specific search radius r was chosen, and the closest Tycho-2 match interior to r was retained for each star in the spectral type catalog. The search radius was 10″ for the Michigan, Jaschek, and Kennedy catalogs, and 1″ for the astrometric catalogs, FK5 and PPM. We deliberately chose a conservative search radius for the nonastrometric catalogs, because for our purposes it was more important to prevent false matches than to identify all real matches. Figure 1 shows the distribution of separation distance for all matched pairs in our catalog. While we certainly missed some real matches separated by more than 10″, the steep

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[4] We are in the process of updating the Infrared Astrometric Catalog, the original version of which is described in Egan & Price (1996).

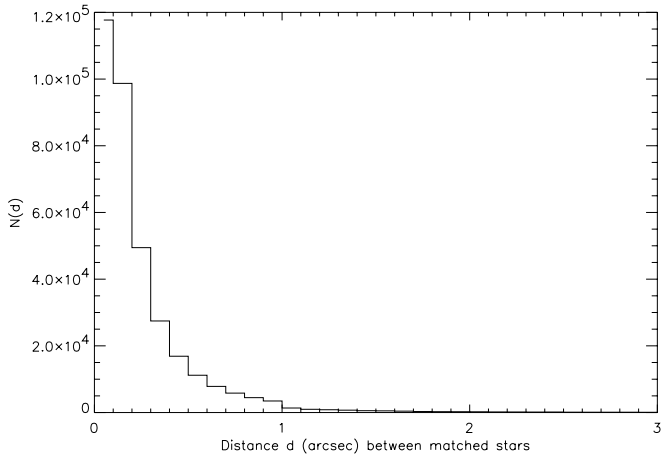

FIG. 1.—Distribution of the separation distance between a Tycho-2 star and its nearest match from a spectral type catalog.

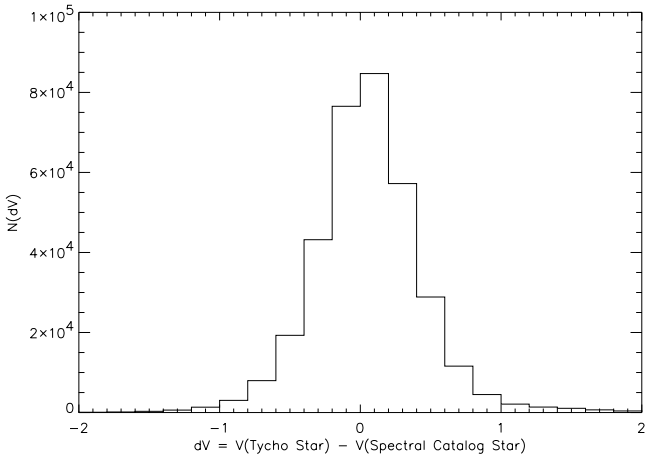

FIG. 2.—Distribution of difference in V magnitude between a Tycho-2 star and its nearest match from a spectral type catalog.

decline in number of matches with increasing separation distance indicates that we did not miss too many (note that the plot only extends to 3″, since the number of stars as a function of separation beyond 3″ is indistinguishable from zero on the scale of the plot).

If a positional match existed, then the spectral type was assigned to the Tycho-2 star, unless (1) the same Tycho-2 star was initially matched to more than one spectral type star, in which case the spectral type of the closest match was used, or (2) a spectral type had already been assigned to the Tycho-2 star from a higher priority spectral type catalog. Table 1 summarizes information about the 351,864 spectral type matches, of which 342,986 (97.5%) were within 1″, and only 471 (0.13%) were separated by more than 5″. The first column of Table 1 lists the spectral type catalogs; the second and third columns list the number of matches within 10″ and 1″, respectively; the fourth column lists a three-character code for the spectral type catalog; and the last column indicates which identifiers were submitted to VizieR for cross-referencing.

3. VERIFICATION OF POSITIONAL MATCHES

The VizieR matches are defined by purely positional criteria, so it is important not only to impose strict positional matching requirements, but also to verify the positional matches with additional information. We were able to compare magnitudes for the 345,545 matches (98% of all matches) that had both Tycho-2 B_T and V_T magnitudes, and a magnitude from the spectral type catalog. We estimated a Johnson visual magnitude for each Tycho-2 star as $V = V_T - 0.090(B_T - V_T)$ (Høg et al. 2000) and compared it with an actual visual magnitude (if available) for the corresponding star from a spectral type catalog, or with an estimated visual magnitude if the magnitude of the spectral type star was photographic, blue, or unspecified. The visual magnitude was estimated from a photographic magnitude with the relation $m_{pg} - V = (B-V) - 0.11$ (Zombeck 1990), while in the four cases where the spectral type magnitude was blue, the visual magnitude was estimated directly as $V = B - (B-V)$. The $B-V$ color of a star depends on its spectral type and luminosity class, and the values used in both conversions were from FitzGerald (1970). Unspecified magnitudes were compared directly to the estimated Johnson visual magnitude of the Tycho-2 star.

In Figure 2, we show the distribution of $dV = V$(Tycho star) − V(spectral catalog star), where V(Tycho star) is the estimated Johnson visual magnitude of the Tycho-2 star, and V(spectral catalog star) is the actual or esti-

TABLE 1
RESULTS OF CROSS-REFERENCING TYCHO-2 TO SPECTRAL TYPE CATALOGS

Spectral Type Catalog	Matches with $r < 10''$	Matches with $r < 1''$	Catalog Code	Main Identifiers Used
Michigan Vol. 1	35092	33704	mc1	HD
Michigan Vol. 2	30002	28705	mc2	HD
Michigan Vol. 3	29661	28384	mc3	HD
Michigan Vol. 4	32427	31035	mc4	HD
Michigan Vol. 5	30543	28973	mc5	HD
Jaschek et al. 1964	10075	9169	j64	HD or DM
Kennedy 1983	10685	9659	k83	HD or DM
FK5 I	77	77	fI	FK5
FK5 II	899	899	fII	FK5
PPM North	144460	144441	ppN	PPM
PPM South	27941	27940	ppS	PPM
Total	351862	342986		

mated visual magnitude of the nearest match from a spectral type catalog. The distribution of the magnitude difference dV is symmetric about the median value, $(dV)_{\rm med} = 0.043$ mag, with an average value of $\langle dV \rangle = 0.055$ mag. The standard deviation of this distribution is $\sigma_{dV} = 0.40$ mag, and 97.5% of matches with magnitude information have a magnitude difference $|dV| < 1$ mag, while 99.8% of the matches have a magnitude difference $|dV| < 2$ mag. The dispersion and small bias in the distribution may be due to the need to transform the magnitudes of several magnitude systems and to the fact that no interstellar extinction or reddening corrections were made. For comparison, the cross-reference between the Tycho-2 and the HD catalogs by Fabricius et al. (2002) required the magnitude difference between matched objects to be less than 5 mag.

The large number of stars in the Tycho-2 catalog necessitates an automated approach, but we investigated more closely all objects (nearly 1800, or 0.5% of the catalog) with a positional separation of more than $5''$, with a magnitude difference of more than 2 mag, or with a TYC3 > 1 identifier.[5] We checked objects in the first two categories to ensure the reliability of matches at the tails of the separation and magnitude distributions. Objects in the third category were investigated more closely because a TYC3 > 1 identifier indicates that the star is a member of a multiple star system and usually has a TYC3 $= 1$ counterpart with the same values of TYC1 and TYC2 at a virtually identical position. Thus, for such stars, the likelihood of confusion is greater than normal when basing the match primarily on position.

We used SIMBAD to investigate these 1800 objects further. SIMBAD has determined cross-identifications for some of the Tycho-2 stars, and in this way we confirmed several hundred matches. For another several hundred Tycho-2 stars that were not present in the SIMBAD database, we submitted the alternate name of the star to SIMBAD and obtained a *Hipparcos* cross-identification for it, then confirmed the matches with a VizieR search of the Tycho-2 catalog, which includes *Hipparcos* cross-references.

The existing cross-references in SIMBAD also revealed several incorrect identifications in our catalog (composed almost exclusively of stars with a TYC3 $= 2$ identifier for which the correct match was the TYC3 $= 1$ counterpart). In these cases, we removed our original match from the catalog and replaced it with the SIMBAD match, after checking by hand the 22 stars for which the SIMBAD match did not satisfy our original separation requirements. Twenty of the stars were astrometric stars for which the SIMBAD match was separated by less than $2''$, and this was considered acceptable. The remaining two SIMBAD matches (which were both to the *second* closest Tycho-2 star) were separated by more than $10''$, but since the magnitude differences greatly improved (the original designations had $|dV| > 2$ mag, while the new matches yielded $|dV| = 0.17$ and 0.37 mag), these matches were also accepted.

For the remaining unverified matches with $r > 5''$, if SIMBAD revealed that no astrometric position was available for the object, the larger distance was deemed acceptable. For the remaining TYC3 > 1 objects, the original match was kept if the TYC3 $= 1$ counterpart was not within the specified distance limit of the spectral type match. If the TYC3 $= 1$ counterpart was within the distance limit, then both components were reevaluated, and the one with the better magnitude match was retained.

In the end, 104 objects remained with problematic matches, because no further information was available to us. These include 10 objects with $r > 5''$, yet for which an astrometric position was found to exist in SIMBAD, and 94 objects with $|dV| > 2$ mag, whose matches we were unable to confirm or reject using SIMBAD. We have optimistically included these objects in the catalog, but as a cautionary note, we also list them in Appendix A to our catalogs.

4. THE TYCHO-2 SPECTRAL TYPE CATALOGS

We have compiled the spectral type information for the matches into the Tycho-2 Spectral Type Catalog. The catalog lists the Tycho-2 identifier, J2000.0 right ascension and declination in decimal degrees, V_T and B_T magnitudes (all from the original Tycho-2 catalog), followed by information about the closest matching object. Specifically, the next columns contain a three-character code for the spectral type catalog that was the source of the closest match to the Tycho-2 object, an alternate name for the star, the distance in arcseconds to the closest match, the spectral type as it appeared in the original spectral type catalog, the magnitude from the spectral type catalog, and a flag that indicates what sort of magnitude it is. The columns, format, and content of this catalog are summarized in columns (1)–(3) of Table 2. The spectral type catalog codes are found in column (4) of Table 1. Objects in the catalog appear in order of increasing TYC1 identifier, objects with the same TYC1 identifier are listed in order of increasing TYC2 identifier, and objects with the same TYC1 and TYC2 identifiers are listed in order of increasing TYC3.

We also compiled a special version of the catalog, the Tycho-2 Spectral Type Short Catalog, which includes a more user-friendly (i.e., *shorter*) presentation of the spectral type. The original format of the spectral types was often somewhat cumbersome, e.g., K2/3 III, A9/F2 V, B2.5 V, or G8 IV/V, sometimes with extraneous parentheses about the subclass or luminosity class or followed by comments or notes. This is fine on an individual basis, but a different formatting procedure is necessary to use the spectral type information *en masse*, for instance to obtain other stellar properties (such as temperature or color) from a table. Hence, the short version of the catalog breaks the original spectral type (which was up to a 20 character string) into a temperature class, a subclass, and a luminosity class, and puts that information into identical format for every star. The default in ambiguous cases was to take the first value in each category. Thus, in the short version, K2/3 III becomes K2 III; A9/F2 V becomes A9 V; B2.5 V becomes B2 V; G8 IV/V becomes G8 IV, and so forth. For 17 of the stars, the spectral type was not in a form easily translated to the short format (e.g., the spectral type was listed as "Delta del",

[5] Tycho-2 stars are identified by three integers, TYC1, TYC2, and TYC3. TYC1 is the Guide Star Catalog region number (Jenkner et al. 1990), TYC2 is a running number within the region, and TYC3 is a component identifier that is usually 1, but can take on values 2, 3, or 4 in the case of a multiple star system.

TABLE 2
TYCHO-2 SPECTRAL TYPE CATALOGS

Main Catalog			Short Catalog		
Column (1)	Format (2)	Description (3)	Column (4)	Format (5)	Description (6)
1:3	a3	TYC Label	1:3	a3	TYC Label
5:8	i4.4	TYC1	5:8	i4.4	TYC1
10:14	i5.5	TYC2	10:14	i5.5	TYC2
16	i1	TYC3	16	i1	TYC3
18:29	f12.8	R.A. degrees (J2000.0)	18:29	f12.8	R.A. degrees (J2000.0)
31:42	f12.8	Decl. degrees (J2000.0)	31:42	f12.8	Decl. degrees (J2000.0)
44:49	f6.3	V_T mag	44:49	f6.3	V_T mag
51:56	f6.3	B_T mag	51:56	f6.3	B_T mag
58:60	a3	Cat. Code	58:60	a3	Cat. Code
62:76	a15	Star Name	62:76	a15	Star Name
78:83	f6.3	Distance (arcsec)	78:83	f6.3	Distance (arcsec)
85:104	a20	Sp. Type	85	a1	Temp. Class
106:111	f6.2	Magnitude	87	a1	Subclass
113	a1	Flag	89:91	a3	Lum. Class
			93:100	f8.2	Temp. (K)
			102:107	f8.2	Magnitude
			109	a1	Flag

"emission", or even left blank), so for these stars we used the spectral type that appeared in SIMBAD instead. These 17 stars are denoted with the letters "sim" in the catalog code column. We used the simplified spectral types to assign temperatures (Lang 1992) to all of the stars in the catalog. The columns, format, and content of the short catalog are listed in columns (4)–(6) of Table 2. The catalogs will be made available to the astronomical community through CDS, under catalog number III/231.

5. COMPARISON TO FABRICIUS ET AL. (2002)

We compared our catalog to the Fabricius et al. (2002) catalog of HD identifications for Tycho-2 stars. There were 241,935 Tycho-2 objects in common between the two catalogs, 170,635 of which had HD identifications as the alternate star name in our catalog, and thus could be compared directly with the matches made by Fabricius et al. (2002). We found excellent agreement between our catalog and the Fabricius et al. (2002) catalog among the 170,635 objects, with 170,522 (99.93%) of the Tycho-2 stars having the same HD designation in the two catalogs. We investigated further the 113 Tycho-2 stars for which different HD identifiers were assigned. Three of the 113 stars appeared in the Fabricius et al. (2002) catalog twice, and in all three cases it was the second designation that caused the discrepancy. For another 10 stars, the two distinct HD designations turned out to reference the same star, and we suspect that this might be the case for up to 36 additional stars.[6] Four of the stars were members of double star systems, and the TYC3 = 1 and TYC3 = 2 components were switched in the two catalogs versus their HD matches. For the remaining cases with different identifiers, it is difficult to determine with certainty which (if either) is correct, since the disagreement arises precisely because the cases are ambiguous in some way. The small number of discrepancies is a testament to the robustness of the matching criteria used in both catalogs. There were 111,408 unique Tycho-2 stars that appeared in the Fabricius et al. (2002) catalog that were not present in ours, most likely due to our more stringent position and magnitude criteria. We include those stars, along with their one-dimensional HD spectral types, in Appendix B to our catalogs.

We wish to thank the anonymous referee for many useful comments. This research has made extensive use of the SIMBAD database and the VizieR service, operated at CDS, Strasbourg, France.

[6] HD identifiers 1-272150 correspond to the Henry Draper Catalog and Extension (Cannon et al. 1918–1924; Cannon 1925–1936), while HD identifiers 272151-359083 correspond to the Henry Draper Extension Charts (Cannon et al. 1949). There is overlap between the two catalogs, in which case a single star may end up with two HD designations. SIMBAD lists two HD designations for 10 stars on the list of 113, and this is suspected to be the case for as many as 36 additional stars where our HD number is from the HD Catalog and Extension, and the Fabricius et al. (2002) HD number corresponding to the same Tycho-2 star is from the HD Extension Charts, or vice versa.

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