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TUCANA ASSOCIATION

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ABSTRACT

Among star clusters, only the sparse Ursa Major nucleus is closer to Earth than the recently identified Tucana association. Based on new photometric *VRI* magnitudes, we construct a color-magnitude diagram composed of likely and possible Tucana members. The implied age of the Tucana association stars, $\lesssim 40$ Myr, is consistent with the age determined from a previous analysis by Stelzer & Neuhäuser of the X-ray luminosities of plausible association members. Based primarily on space motions and X-ray fluxes, we identify potential new members of the Tucana association not considered in earlier studies. Torres and coworkers recently identified a group of post–T Tauri stars, the Horologium association, which is located near the Tucana association in right ascension and declination. Because the Horologium stars have the same space motions, age, distance from Earth, volume density, and range of spectral types as Tucana stars, we suggest that, rather than being characterized as a separate group, it would be appropriate and economical to subsume the Horologium association stars into the Tucana stream.

Subject headings: open clusters and associations: individual (Tucana, Horologium association) — stars: kinematics — stars: pre–main-sequence

1. INTRODUCTION

Recent years have seen the discovery of young stellar associations within 100 pc of Earth. These include the TW Hydrae association (de La Reza et al. 1989; Gregorio-Hetem et al. 1992; Kastner et al. 1997; Webb et al. 1999; Sterzik et al. 1999; Zuckerman et al. 2001), the η Chamaeleontis cluster (Mamajek, Lawson, & Feigelson 1999), the MBM 12 association (Hearty et al. 2000), the Horologium association (Torres et al. 2000), and the Tucana association (Zuckerman & Webb 2000). Stars in these groups range between millions and tens of millions of years in age, and their study should tell us about the formation and evolution of sparse stellar associations. In addition, these stars are among the most favorable for imaging of dusty circumstellar disks and of cooling Jupiter-mass planets whose orbital semimajor axes lie in the range from tens to hundreds of AU.

Most of the above groups were identified initially because of strong X-ray emission from most (currently known) members. The Tucana association (hereafter Tucana), a notable exception to this rule, was identified instead from a study of the *IRAS* and *Hipparcos* catalogs (Zuckerman & Webb 2000, hereafter ZW). Nonetheless, most Tucana stars of spectral type later than mid-F are indeed quite strong X-ray emitters (ZW; Stelzer & Neuhäuser 2000; see Table 1).

Of all known clusters, only the sparse, much older Ursa Major nucleus is clearly closer to Earth than is Tucana. Data presented in the present paper expand the list of likely Tucana members and help clarify the nature and age of the cluster. We also consider the relationship between Tucana and the Horologium association and suggest that they are likely part of a common and widespread stream of young stars.

2. OBSERVATIONS

We used the 0.9 m telescope at Cerro Tololo Inter-American Observatory (CTIO) and a CCD imager to obtain *VRI* magnitudes for stars listed in Table 1. Standard CTIO Kron-Cousins filters were used at *R* and *I*. The data, obtained during 1999 August 18–20 UT, were reduced and calibrated in IRAF. Because of the wide range of brightnesses of the Tucana stars, in addition to the direct *V*, *R*, and *I* filters, we employed neutral density filters of 2.25, 5, and 7.5 mag. The pixel size was $0\farcs396$ pixel^{-1} and typical stellar FWHM was 4.5 pixels. Typical exposure times in a given filter ranged from a few seconds to a minute. Results from the *V*, *R*, and *I* filters are summarized in Table 1 and in Figures 1 and 2. The Table 1 column headed "Multi." gives the number of stars presently known for each HIP or PPM entry.

For each star, we obtained either three or five images in a given filter; if five, then three were obtained on August 18 and two on August 20. According to the standard CTIO meteorology report, the UT night of August 18 was photometric and August 19 nearly so. Some clouds were present on August 20. With only a few exceptions, the internal agreement of our data set for those stars observed on two nights and the agreement with $V-I$ colors from the *Hipparcos* Catalog (see Fig. 1) was quite good—typically better than 0.1 mag. For those few stars where our $V-I$ color differed noticeably from that of *Hipparcos*, surprisingly, ours was always redder (Fig. 1). We carefully checked our images for these stars but could discern no obvious problem with our data set. Consider, for example, HIP 2729, which in Figure 1 displays the largest discrepancy between our $V-I$ measurement ($=1.38$) and that of *Hipparcos* ($V-I = 1.10$). We observed this star on our first and third nights—the *V*, *R*, and *I* magnitudes all agreed within a few hundredths of a magnitude between the two nights. Thus, we see no reason to doubt our measurements.

3. DISCUSSION

3.1. *X-Ray Characteristics*

X-ray luminosity can be a useful gauge of stellar age, at least statistically (e.g., Gaidos 1998; Song et al. 2000). X-ray flux was not a factor in initial choice of potential members

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TABLE 1

POTENTIAL MEMBERS OF THE TUCANA ASSOCIATION FROM ZW

A. Probable and Possible Members of the Tucana Nucleus or Stream

HIP	HD	HR	Nuclear Member?	M_V	V	R_C	I_C	Multi.	Spectral Type	*ROSAT* (counts s^{-1})	On Main Sequence?
1481	1466	...	Y	4.39	7.45	7.14	6.86	1	F8	0.26	Yes
1910	...	...	Y	8.14	11.47	10.53	9.52	2[a]	M0	0.14	Above
1993	...	...	Y	8.60	11.47	10.57	9.66	1	K7	...	Above
2484	2884	126	Y	1.22	4.38	4.34	4.38	1 (?)	B9	...	ZAMS[b]
2487	2885	127	Y	0.94	4.55	4.38	4.30	2	A2 + A7[c]	...	[c]
2578	3003	136	Y	1.73	5.06	5.05	5.06	1 (?)	A0	...	ZAMS[b]
2729	3221	...	Y	6.32	9.63	8.92	8.25	1	K4	0.5	Above
92680	174429	...	...	4.77	8.25	7.82	7.40	1	K0	1.0	Above
93815	177171	7213	...	1.56	5.16	4.82	4.53	2	F7	2.08	Above
95261	181296	7329	...	1.79	[d]	[d]	[d]	2	A0	...	ZAMS[d]
95270	181327	...	...	3.51	7.03	6.75	6.50	1	F5	...	Yes
99803 SW	191869	...	...	3.86	7.93	7.68	7.39	1	F6.5	0.10	Yes
99803 NE	191869	...	...	3.99	8.07	7.74	7.50	1	...	[e]	Yes
100751	193924	7790	...	−1.86	1.91	1.92	2.05	2 (?)	B2 IV	0.034	?
104308	200798	...	...	2.58	6.69	6.53	6.41	1	A5	...	ZAMS[b]
105388	202917	...	...	5.33	8.68	8.27	7.88	1	G5	0.62	Yes
105404	202947	...	...	5.59	8.91	8.39	7.86	2	K0	0.67	Above
107345	...	...	...	8.49	11.62	10.72	9.79	1	M1	0.137	Above
107947	207575	...	...	3.95	7.22	6.93	6.66	1	F6	0.42	Yes
108195	207964	8352	...	2.57	5.90	5.65	5.44	2	F3	0.19	Above
PPM 366328	...	...	?	?	9.67	9.20	8.67	1	K0	0.15	?
116748 S	222259	...	Y	5.17	8.49	8.09	7.71	1	G5/G8 IV	0.81	Yes
116748 N	222259	...	Y	6.41	9.73	9.15	8.59	1	...	[e]	Yes
118121	224392	9062	Y	1.57	5.01	4.98	4.95	1 (?)	A1	0.06	ZAMS[b]

B. Improbable Members

HIP	HD	HR	Nuclear Member?	M_V	V	R_C	I_C	Multi.	Spectral Type	*ROSAT* (counts s^{-1})	On Main Sequence?
459	67		...	5.17	8.82	8.44	8.10	1	G5	...	Yes
1399	...	...	...	8.11	11.34	10.44	9.54	1	M0	...	Above
93096	175531	...	...	5.66	9.70	9.24	8.81	1	G8/K0	...	Yes
94051	177720	...	...	4.55	8.73	8.41	8.10	1	G0	...	Yes
94858	180134	7297	...	3.06	6.35	6.03	5.76	1	F7	...	Above
94997	...	...	...	8.06	11.95	11.29	10.78	1	[f]	...	Yes
95302	181516	...	...	4.64	9.03	8.63	8.26	1	G6 IV	...	Yes
97705	187101	...	...	3.87	8.03	7.71	7.39	1	F8/G0	...	Yes
101636	195818	...	...	4.49	8.59	8.27	7.95	1	G0	...	Yes
101844	...	...	...	8.83	11.35	10.46	9.60	1	K4	...	Yes
103438 E	199065	...	...	4.95	8.49	8.12	7.81	1	G2/G5	0.052	Yes
103438 W	199065	...	...	5.43	8.97	8.52	8.11	1	...	[e]	Yes
104256	200676	...	...	5.16	8.80	8.32	7.89	1	K1	...	Above
107806	207377	...	...	4.82	7.89	7.49	7.12	1	G6	...	Yes
109612	210507	...	...	6.18	9.63	9.10	8.65	1	K3	...	Yes
114236	218340	...	...	4.68	8.45	8.09	7.77	1	G3	...	Yes

[a] Faint companion discovered with adaptive optics imaging (P. Lowrance 2000, private communication).

[b] Star lies on or near the ZAMS shown in Jura et al. 1998 and Lowrance et al. 2000.

[c] This binary star may lie on or near the ZAMS; see discussion in § 3.2.

[d] *VRI* data were not obtained because the 0.9 m telescope was pointed at a different star by mistake. A brown dwarf companion was discovered by Lowrance et al. 2000, who also give estimated *H*-band magnitudes for the primary and companion. HR 7329A lies on the ZAMS (see Fig. 3 in Lowrance et al. 2000).

[e] *ROSAT* flux associated with one or both members of the binary.

[f] The *Hipparcos* $V-I$ value was based on a ground-based measurement of the wrong star (GEN# +6.20145036, located ∼50″ south). Our measured $V-I$ and $B-V$ values from the literature correspond to an early K-type star.

of Tucana (ZW). However, "after the dust had settled," for stars of spectral class later than A type, correlation between X-ray luminosity and other indicators of youth such as space motions and lithium abundance was quite good (Tables 1 and 2 in ZW). At the time the ZW paper was written, the *ROSAT* All-Sky Survey Bright Source Catalogue was in the public domain. Subsequently, the *ROSAT* Faint Source Catalogue appeared (Voges et al. 2000), as well as an analysis (Stelzer & Neuhäuser 2000) of relevant data obtained with the *ROSAT* Position Sensitive Proportional Counter (PSPC). The Faint Source Catalogue and PSPC data reveal several X-ray luminous stars not in the *ROSAT* Bright Source Catalogue (compare Table 1A with Table 1A in ZW) that ZW deemed to be likely or

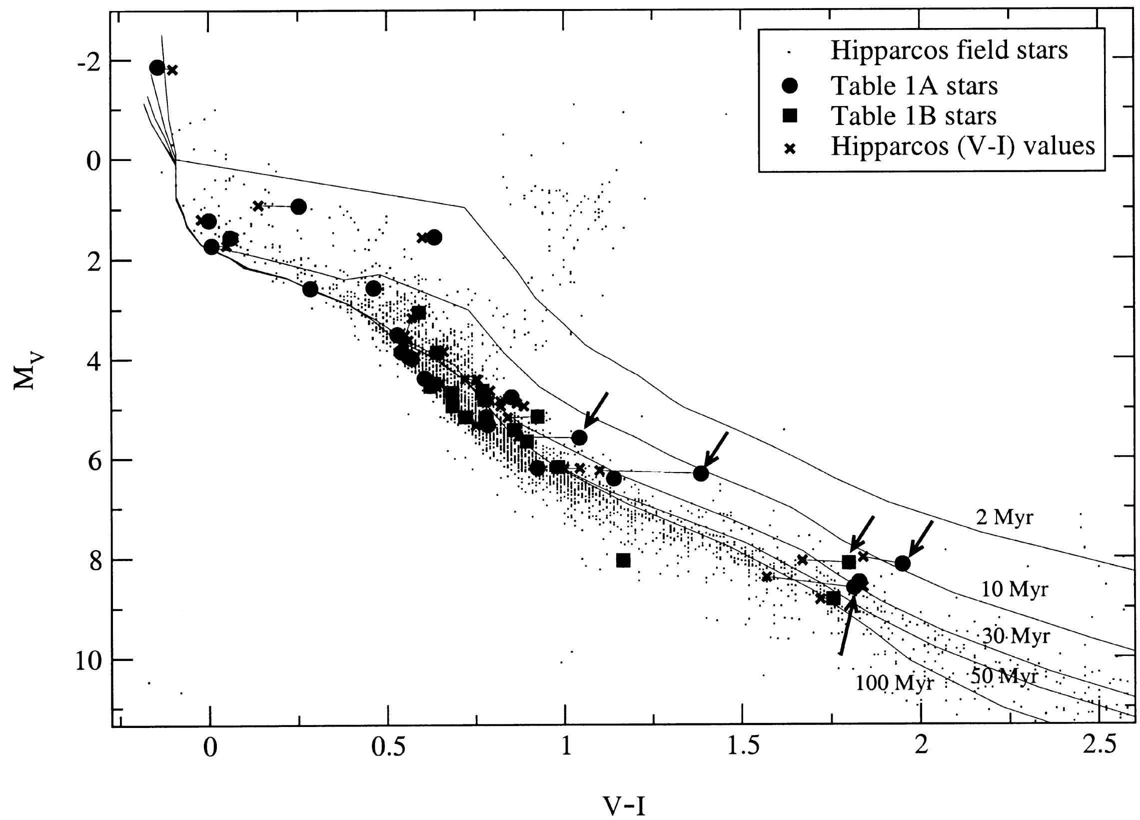

FIG. 1.—The $V-I$ color-magnitude diagram of stars in Table 1. Theoretical isochrones are from Siess, Dufour, & Forestini's (2000) $Z = 0.02$ model. Dots are *Hipparcos* field stars within 40 pc with 5% or better parallax measurement. Circles and squares indicate $V-I$ values obtained from our CTIO observation, and crosses denote $V-I$ values from the *Hipparcos* Catalog. Among the stars with significant discrepancies between *Hipparcos* and our $V-I$ values, five stars (marked with arrows: HIP 105404, 2729, 1399, 1993, and 1910, from blue to red, respectively) are variable stars with $H_p^{\max} - H_p^{\min} > 0.2$ mag (except for HIP 2729, with variability amplitude of 0.1 mag). HIP 94997 has an incorrect *Hipparcos* $V-I$ value (see Table 1, note f); thus, the *Hipparcos* value is not plotted.

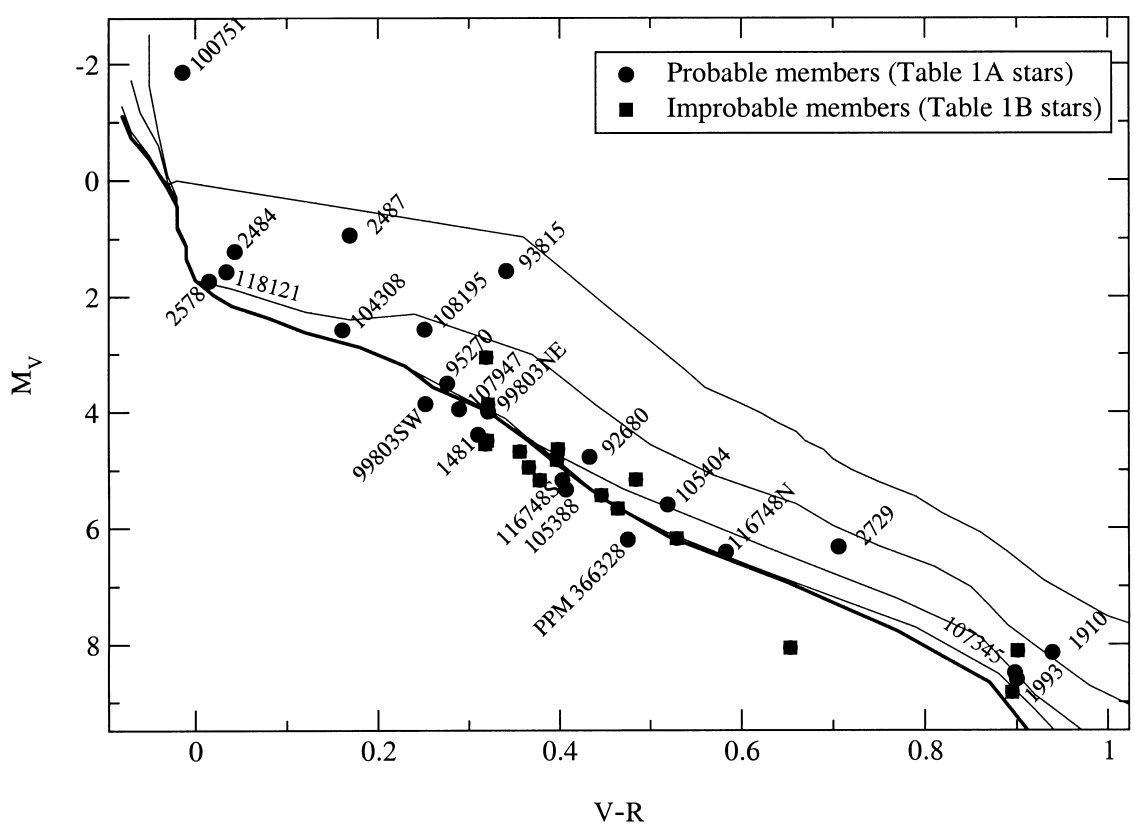

FIG. 2.—The $V-R$ color-magnitude diagram of Table 1 stars annotated with HIP numbers. Isochrones have the same meanings as in Fig. 1.

possible members of Tucana based on space motions and other indicators of youth. In contrast, for stars unlikely to be Tucana members, primarily because of discordant kinematics (Table 2B of ZW), no additional X-ray emitters beyond HIP 103438 (Table 1B of ZW) were revealed in either the faint source or PSPC surveys.

So, inspection of Table 1A of the present paper reveals that, excepting A- and late B-type stars for which X-ray emission would not be expected, almost all plausible Tucana members were detected by *ROSAT*. In contrast, likely nonmembers are not *ROSAT* sources (Table 1B). One may utilize this rather clean separation to identify likely new Tucana members even for stars that lack a measured radial velocity and for which (U, V, W) is, therefore, not now available. Such a procedure is discussed in § 3.3.

Note that HIP 118121, of spectral type A1, and HIP 100751, of spectral type B2 IV, appear in the Faint Source Catalogue and PSPC data, respectively. Both may be binaries containing a late-type, X-ray–emitting secondary, although Cohen, Cassinelli, & Macfarlane (1997) and Stelzer & Neuhäuser (2000) suggest that the B star may itself generate X-rays via shocks in a strong wind.

3.2. *Age*

By comparison of the X-ray luminosity distribution function of various young clusters, Stelzer & Neuhäuser (2000) deduce an age for Tucana stars in the range 10 to 30 Myr, or somewhat younger than that estimated by ZW on other grounds. The color-magnitude diagrams in Figures 1–3 can help to clarify the age of the Tucana stars.

Table 1A lists six K- and M-type probable Tucana members with *Hipparcos* measured distances. All lie above the main sequence and between the 10 and 40 Myr isochrones (Figs. 1–3). In contrast, of the six Table 1B K- and M-type stars (including HIP 93096) that are unlikely to be Tucana members, only HIP 1399 and HIP 104256 lie above the main sequence. The space motion of HIP 1399 is sufficiently close to that of Tucana (Table 2B in ZW) that HIP 1399 could be related to the Tucana association (see § 3.3). Thus, it appears that late-type stars in Table 1A have isochrone ages consistent with those estimated by Stelzer & Neuhäuser (2000) and are, in any event, younger than the typical late-type non–Tucana members in Table 1B.

At the other end of the Tucana mass range, excepting possibly HIP 2487, all six plausible members with spectral types between B9 and A5 lie on or near the zero-age main sequence (ZAMS) defined by young stars shown in Jura et al. (1998) and Lowrance et al. (2000). The ZAMS is where A-type field stars with ages of ten to tens of megayears reside. This age diagnostic can be derived because many of the A-type stars have late-type companions still on their pre–main-sequence tracks on the HR diagram.

The close binary HIP 2487 has been classified as A2 + A7, but both our *VRI* data and the $B-V$ color from the literature indicate that the primary is a late A-type star. In addition, the error of the *Hipparcos* parallax is an order of magnitude larger than the parallax error for HIP 2484. Based on the parallaxes of the nine members of the Tucana nucleus (Table 1A in ZW), we judge that HIP 2487 is probably significantly closer to Earth than the nominal *Hipparcos* distance. If so, then the M_V listed in our Table 1A is too bright. Similarly, the secondary might contribute significantly at V (Dommanget & Nys 2000). All in all, it is perhaps premature to plot HIP 2487 on a color-magnitude diagram.

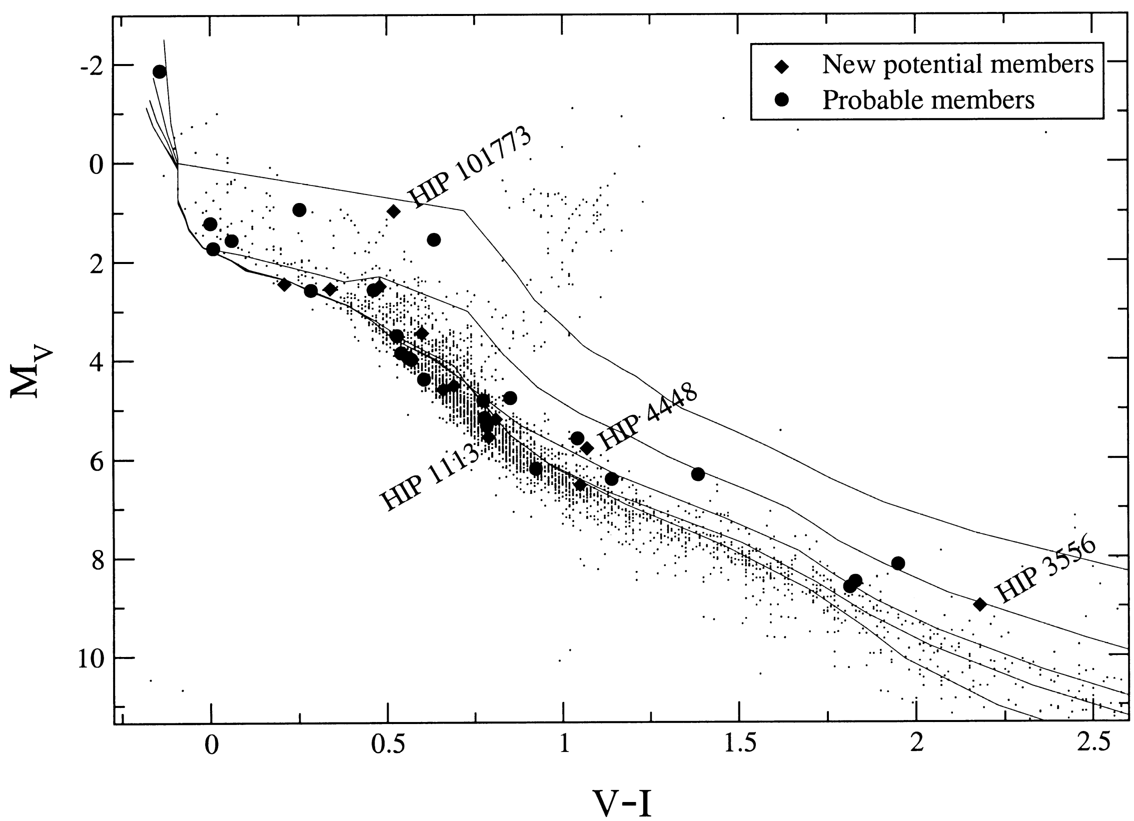

FIG. 3.—Probable (Table 1A) and new potential (Table 2) members of Tucana association. Isochrones and background stars have the same meanings as in Fig. 1. For Table 2 stars, $V-I$ values are from *Hipparcos*.

Finally, we note that HIP 93815, classified as a luminosity class V star, nonetheless lies well above the main sequence, even accounting for its binary nature.

3.3. *Plausible Newly Identified Members of the Tucana Association*

Stars in the Tucana nucleus all have (U, V, W) space motions (km s^{-1}) that do not differ much from $(-11, -21, 0)$ (ZW). Stars in Table 1A that are not nuclear members have a wider range of (U, V, W) (see Table 2A in ZW). It is certainly plausible that some Table 1A stars not in the nucleus are not Tucana members but are members of the Local association proposed by Eggen (see, e.g., Jeffries 1995 and references therein). Table 2 includes stars that may be members of the Tucana association, but because of their fairly wide range in (U, V, W), some of the stars may instead be Local association members, for example, HIP 92024 and HIP 101612.

Recalling the discussion in § 3.1, Table 1 demonstrates that if a star of spectral type later than mid-F with the distance and proper motion of a Tucana star was detected by *ROSAT*, then it is very likely a Tucana member. Conversely, a star of spectral class later than mid-F and not detected by *ROSAT* is unlikely to be a Tucana member. We obtained echelle spectra of HIP 1113, HIP 3556, and 4448 on the 2.3 m telescope at Siding Spring Observatory in Australia (I. Song, M. Bessell, & B. Zuckerman 2001, in preparation). These spectra indicate that HIP 1113 and 3556 have the same space motions (U, V, W) as the Tucana nucleus stars. However, although a young star, the space motion of the binary HIP 4448 appears to be different, and it may not be an association member (see I. Song, et al. 2001, in preparation for additional details).

3.4. *Relationship between the Tucana and Horologium Associations*

Torres et al. (2000) proposed that a group of stars centered near 2^h15^m right ascension and $-60°$ declination makes up a diffuse, nearby association (~ 60 pc from Earth) that they call the Horologium association. Figure 4 illustrates that Horologium is located close to the Tucana association in the plane of the sky. The two associations have, to within the errors, the same (U, V, W) and age (~ 30 Myr). As proposed by Torres et al. (2000), Horologium lies somewhat farther from Earth than does Tucana. However, we note that this distance difference can be eliminated and a tighter clustering of the stars in Horologium obtained if the membership proposed by Torres et al. (2000) is revised as follows.

Five of the probable or possible members proposed by Torres et al. (2000; ERX 14, 16, 45, 49, and 53) do not have measured trigonometric parallaxes and are likely to be significantly farther from Earth than the other proposed Horologium members, and farther away than any Tucana star in our Table 1A. We suggest eliminating these five and substituting instead the early-type stars HD 10144, 10269, 10472, 14228, and 20888, listed in Table 7 of Torres et al. (2000) as possible members but without X-ray emission (actually, HD 10472 is a likely faint *ROSAT* source). Our calculations of space motions indicate that the (U, V, W) of HD 14228 and HD 20888 are similar to (U, V, W) for Horologium stars. With our proposed substitutions, the distance from Earth of Horologium becomes ~ 50 pc, i.e., very similar to that of Tucana. Also, the diameter of Horologium then drops to $\lesssim 25$ pc, or about half that suggested by Torres et al. (2000). With the addition of these five early-type stars, the range of spectral types in Horologium, from late B to early M, becomes essentially identical to that in the Tucana nucleus and stream.

HD 10647 is a very interesting F9 star located near the center of Horologium in the plane of the sky (Fig. 4, *cross*) but apparently not considered at all by Torres et al. (2000; probably because it is much closer to Earth than any star in their Horologium group). As noted by ZW, this star has the correct space motion to be a member of the Tucana stream (and thus also of Horologium), and it is a dusty far-infrared–excess source (Decin et al. 2000). Finally, we also suggest HIP 12394 (=HD 16978) as a Horologium member. This B9 III star, plotted as a square in Figure 4,

TABLE 2

New Potential Members of the Tucana Association

HIP	HD	α (J2000)	δ (J2000)	m_V	$B-V$	Spectral Type	*ROSAT* (counts s^{-1})	π (mas)	Proper Motion[a] α	Proper Motion[a] δ
1113[b]	987	00 13 52.8	−74 41 17	8.8	0.72	G6	0.52	22.86	87	−47
3556[b]	...	00 45 28.1	−51 37 33	11.9	1.48	M3	0.042	25.97	98	−58
4448[b]	5578	00 56 55.4	−51 52 32	9.0	1.02	K3/K4	0.79	22.95	93	+5
92024[b]	172555	18 45 26.9	−64 52 15	4.8	0.19	A7	0.1	34.21	30	−149
94235	178085	19 10 57.8	−60 16 19	8.3	0.58	G0	0.16	17.49	8	−105
97508	186602	19 49 07.2	−61 48 53	7.3	0.49	F7/F8	0.07	17.21	39	−94
101612[b]......	195627	20 35 34.8	−60 34 53	4.7	0.27	F1 III	...	36.27	73	−182
101684[c]......	195772	20 36 38.3	−63 07 15	6.3	0.35	F2	...	17.05	11	−81
101773[d]......	195961	20 37 35.2	−61 31 47	4.9	0.42	F5m	...	16.73	58	−72
105441.......	202746	21 21 24.3	−66 54 56	9.0	1.01	K2p	0.52	32.52	96	−102
107649[e]......	207129	21 48 15.6	−47 18 10	5.6	0.60	G2	0.067	63.95	166	−297
108422.......	208223	21 57 51.4	−68 12 49	8.9	0.75	G8	0.70	18.20	40	−82

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

[a] Proper motions, in milliarcseconds per year, are an average of the *Hipparcos* and PPM values, if both exist.

[b] See § 3.3 for a discussion.

[c] Spectroscopic binary, $V_{\rm radial} = 9$ km s^{-1} (Grenier et al. 1999), and $(U\,V W) = (-3.3, -24.0, -4.4)$.

[d] $V_{\rm radial} = 8$ km s^{-1}, and $(U, V, W) = (-11.0, -19.9, -15.5)$.

[e] Listed in text of ZW as a Tucana stream member.

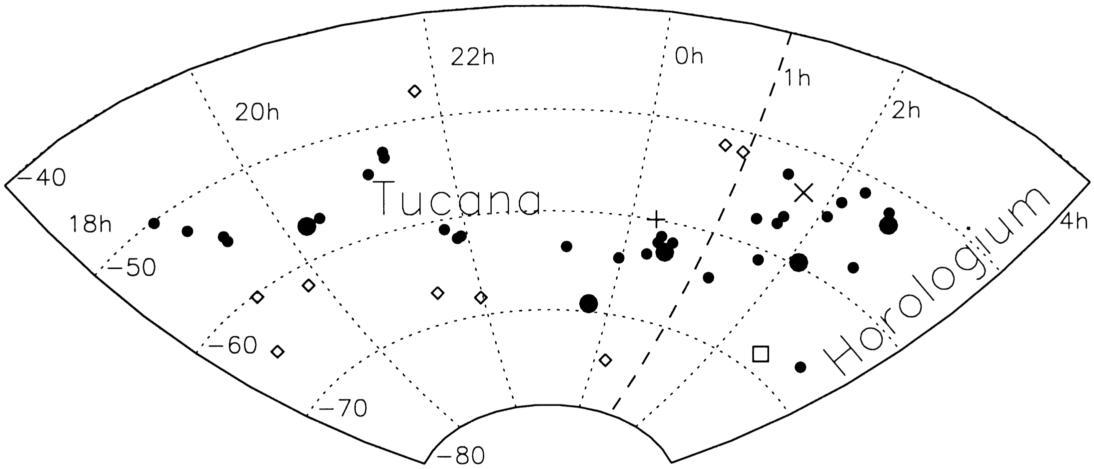

FIG. 4.—Stars in the Tucana and Horologium associations. Small circles to the left of 1^h R.A. are from Table 1A. Small circles to the right of 1^h R.A. are members of Horologium but are modified as described in § 3.4 from the initial set of stars proposed by Torres et al. (2000). Diamonds are several stars from Table 2 that we regard as likely members of the Tucana stream. The plus sign is HIP 1399 (Table 1B), the cross is HD 10647, and the square is HIP 12394 (=HD16978). Large circles indicate binaries or triples. The spatial distribution of the points across the figure, as well as other characteristics discussed in § 3.4, suggests that all stars should be regarded as part of a common stream.

has the same space motion and distance as typical Horologium stars.

In Figure 4 we plot all probable or possible members of the Tucana association (nucleus and stream) from Table 1A and similar stars from our revised Horologium membership list as described above. We also plot some stars taken from Table 2 that we regard as likely members of Tucana.

A plausible interpretation of the picture shown in Figure 4 is that the Tucana nucleus sits near the center of a stream of approximately comoving stars that extends to earlier and later right ascensions. The nucleus is distinguished from the stream by its greater density of stars per cubic parsec. This greater density is only partially evident in Figure 4 because the nuclear members have less spatial dispersion along the line of sight from Earth than do the Horologium stars. In light of Figure 4 and other similarities mentioned above, we suggest that the Horologium association be subsumed into the Tucana stream and not be considered a separate kinematic entity.

Given the great extent of the Tucana/Horologium kinematic group, one naturally wonders what relationship it has to the Local association. A final answer must await a more complete census of nearby young stars. In the interim, we note that the tight grouping of stars in the Tucana nucleus, so close to Earth, is quite unusual and sets it apart from other Local association stars. Based on our work to date, we anticipate that few, if any, additional comparable groups will be found in the *Hipparcos* Catalog. If our estimates and those of Stelzer & Neuhäuser (2000) and Torres et al. (2000) for the age of Tucana/Horologium stars are correct, then these stars may be significantly younger than most Local association stars, whose average ages could be 50 Myr or more.

4. CONCLUSIONS

Color-magnitude diagrams and new X-ray data solidify the previous identification of the Tucana association, a comoving group of young stars within 50 pc of Earth (Zuckerman & Webb 2000). Our inspection of the *Hipparcos* and other catalogs reveals additional stars beyond those considered by Zuckerman & Webb (2000) that are likely members of Tucana. Although we have focused our search on *Hipparcos*, additional Tucana members may be present in the Tycho or other faint star catalogs.

We list reasons why the recently proposed Horologium association (Torres et al. 2000) could logically be subsumed into the Tucana stream, and if so, then Horologium should not be given a separate designation. We anticipate that many young stars close to Earth remain to be identified. Some of these might be sufficiently densely packed to warrant consideration as an association or cluster; e.g., the HD 199143 (van den Ancker et al. 2000) and the HD 141569 (Weinberger et al. 2000) groups. If so, with the relationship between Tucana and Horologium stars already in question, interested members of the community might consider how best to deal with such matters should they arise in the future.

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