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X-ray emission from young stars in the Tucanae association

B. Stelzer and R. Neuhäuser

Max-Planck-Institut für extraterrestrische Physik, Giessenbachstrasse 1, 85740 Garching, Germany

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Abstract. We report on X-ray emission from members of the recently discovered Tucanae association, a group of stars with youth signatures and similar space motion. The Tucanae association is the nearest known region of recent star formation ($\sim 45\,\mathrm{pc}$) far from molecular clouds (Zuckerman & Webb 2000). We have made use of the *ROSAT* Data Archive and searched for X-rays from Tucanae stars in both *ROSAT* All-Sky Survey (RASS) and pointed observations. While the RASS provides complete coverage of the sky, only three potential Tucanae members have been observed during PSPC pointings. All three stars have been detected. For the RASS the percentage of detections is 59%.

The comparison of the X-ray luminosity function of Tucanae to that of other star forming regions may provide clues to the uncertain age of the association. We find that the distribution of X-ray luminosities is very similar to the ones derived for the TW Hya association, the Taurus-Auriga T Tauri Stars, and the IC 2602 cluster, but significantly brighter than the luminosity distribution of the Pleiades. We conclude that the stars in Tucanae are most likely young, on the order of $10-30\,\mathrm{Myr}$.

Strong variability of most stars emerges from the X-ray lightcurves where several flares and irregular variations are observed.

Key words: X-rays: stars – stars: formation

1. Introduction

The discovery of the TW Hydrae association as a nearby group of co-moving T Tauri Stars (TTS) far from molecular clouds has motivated the search for additional associations of pre-main sequence stars (PMS) close to Earth. In the course of a study of the *Hipparcos* catalog around IRAS $60\mu\mathrm{m}$ sources Zuckerman & Webb (2000) recently announced the identification of a co-moving group of stars with general youth indicators.

Youth can be deduced from the presence of the $6708\,\mathrm{\AA}$ Li absorption line, Hα profile, rotation rate, IR excess indicative of circumstellar material, and X-ray emission. While any of these properties certainly are not sufficient to establish the youth of a star, the common presence of several of these characteristics is suggestive for PMS nature. However, no accurate age determination is possible by these means. In addition, for all but one probable Tucanae members, *Hipparcos* parallaxes are available (see Zuckerman & Webb 2000 and our Tables 2 and 3), so that the stars can be placed accurately into the H-R diagram. They all fall near and/or above the zero-age main sequence, hence are really young.

Based on proper motion, distance, and the above mentioned youth indicators Zuckerman & Webb (2000) have divided their sample of potential Tucanae members in two groups: probable members with common distance, space motion, and general signs of youth, and improbable members. This latter group consists of stars which either could be members without signs of youth, or stars which by chance have distances and proper motion similar to the association. Zuckerman & Webb (2000) have identified 11 of the probable members with X-ray sources from the *ROSAT* All-Sky Survey Bright Source Catalog (RASS BSC; Voges et al. 1999), but only one of the non-members.

In this paper we present a more detailed study of the X-ray emission of Tucanae candidates based on data obtained from the *ROSAT* Public Data Archives. In particular we use X-ray luminosity distribution functions (XLDFs) to obtain further clues to the age of this association. Comparative studies of young stellar clusters and star-forming regions based on observations by the *Einstein* IPC (see e.g. Feigelson & Kriss 1989, Damiani et al. 1995) have shown that the X-ray luminosity decays with stellar age. This is manifest in a decrease of the median of L_{x} and a corresponding shift of the XLDFs with respect to each other. A comparison of the XLDF for the Tucanae stars with that for well studied star forming regions should therefore allow to put constraints on the age of this association.

In Sect. 2 we describe the observations and analysis of the raw data. We also provide tables which summarize the X-ray properties of detected and undetected potential Tucanae members. The XLDFs of Tucanae candidates and comparison samples are discussed in Sect. 3. In Sect. 4 we present the X-ray lightcurves of all detected stars and discuss their variability. Our results are summarized in Sect. 5.

Send offprint requests to: B. Stelzer
Correspondence to: B. Stelzer (stelzer@xray.mpe.mpg.de)

Table 1. X-ray properties of stars in the Tucanae region as observed during pointed PSPC observations. Only three stars have been observed including HIP 103438, a star from the list of improbable members. The *ROSAT* request numbers of the respective observations are 201597p (HIP 92680), 200099p (HIP 100751), and 200404p (HIP 103438). Note, that HIP 103438 is a binary, and we have divided the observed count rate by two to obtain L_x. See text for a description of the entries in individual columns.

HIP	α_{2000} [hh:mm:ss]	δ_{2000} [dd:mm:ss]	Δ [$''$]	Exi ML	Expo [s]	Rate [cts/s]	L_x [10^{29} erg/s]	$HR1$	$HR2$
92680	18 53 05.2	-50 10 48	7.1	28078	22398	1.142 ± 0.007	28.8 ± 0.8	0.05 ± 0.01	0.00 ± 0.01
100751	20 25 38.4	-56 44 05	3.8	101	1098	0.034 ± 0.006	1.1 ± 0.2	-0.23 ± 0.16	-0.07 ± 0.26
103438	20 57 25.1	-59 04 17	26.8	39	3256	0.037 ± 0.005	0.3 ± 0.2	-0.66 ± 0.13	-0.36 ± 0.46

2. Observations

This study is based on the list of potential members of the Tucanae association provided by Zuckerman & Webb (2000). We analyze the *ROSAT* observations of all stars from their Table 1, i.e. both 'probable' members (Table 1a) and stars termed 'improbable' members (Table 1b).

The *ROSAT* satellite is equipped with two X-ray detectors in the focus of its telescope, the Position Sensitive Proportional Counter (PSPC) and the High Resolution Imager (HRI). See Trümper (1983), Pfeffermann et al. (1988) and David et al. (1999) for a description of the instrumentation for the *ROSAT* mission. The raw data of all observations can be retrieved from public archives. Our cross-correlation of Table 1 from Zuckerman & Webb (2000) with the archive showed that none of the stars was in the field of any HRI exposure. However, three stars have been observed in pointed observations of the PSPC. All stars in Tucanae have been observed during the *ROSAT* All Sky Survey (RASS).

In this section we describe our analysis of the PSPC data (in both pointed and survey mode) using the Extended Scientific Analysis System (EXSAS; Zimmermann et al. 1995). The results of source detection are presented and the properties of detected and undetected stars are summarized.

2.1. PSPC pointed observations

Three stars from the Tucanae membership lists are in the field of view of a pointed PSPC observation (HIP 92680, HIP 100751, and HIP 103438). The *ROSAT* observation request numbers (ROR) are 201597p, 200099p, and 200404p, respectively. After extracting the raw data from the archive we have performed source detection on these exposures using a combined local and map detection algorithm based on a maximum likelihood technique (Cruddace et al. 1988). For the cross-correlation of detected X-ray sources with the membership list introduced above we allow a maximum distance between X-ray and optical position of $40''$ (shown by Neuhäuser et al. 1995 to minimize the contamination by background sources). All stars are clearly identified with an X-ray source at an offset less than $30''$ from the optical position.

The number of counts in the background map at the source location is scaled to the photon extraction area and subtracted from the total number of counts. Count rates are computed using the information in the exposure maps, and transformed into luminosities applying the individual distances of the stars (derived from the *Hipparcos* parallax) and an energy-conversion-factor (ECF) determined from the hardness ratio.

Hardness ratios computed from the standard energy bands of the PSPC provide spectral information in case of low signal-to-noise. The PSPC hardness ratios are defined as follows

$$HR1 = \frac{H - S}{H + S} \quad (1)$$

$$HR2 = \frac{H2 - H1}{H2 + H1} \quad (2)$$

where H, S, $H2$, and $H1$ substitute the number of counts in the respective energy band: $S = 0.1 - 0.4\,\mathrm{keV}$, $H1 = 0.5 - 0.9\,\mathrm{keV}$, $H2 = 0.9 - 2.0\,\mathrm{keV}$, and $H = H1 + H2$.

As discussed by Fleming et al. (1995) for late-type stars the ECF can be computed from $HR1$ and is given by

$$ECF = (8.31 + 5.30 HR1)\, 10^{-12}\,\mathrm{erg\,cm^{-2}\,cts^{-1}}. \quad (3)$$

For early-type stars (HIP 100751 has spectral type B) this conversion may not be appropriate. In this case we have assumed thermal emission at $kT = 0.5\,\mathrm{keV}$ (see Berghöfer et al. 1996) and negligible absorption and computed the ECF following the Technical Appendix F to the *ROSAT* Call for Proposals. Alternatively, count rates have been converted to fluxes using standard EXSAS routines. The luminosities derived by the two methods were found to be in good agreement, showing that the Fleming relation holds for the Tucanae stars.

The pointed PSPC observations of stars from our membership list are summarized in Table 1. Next to the *Hipparcos* number, X-ray position, and offset between optical and X-ray position Δ (Column 4) we give the maximum likelihood of existence (Column 5), the exposure time (Column 6), and the broad band count rate (Column 7). To derive the X-ray luminosity (shown in Column 8) we have divided the count rate by the number of components in the system (HIP 103438 is a binary, the other two stars are singles; see also Tables 2 and 3 for the multiplicity of the Tucanae stars). This implies that all members contribute the same amount of X-ray emission and was shown by König et al. (2000) to be acceptable in almost all cases according to *ROSAT* HRI observations of resolved young binary stars in Taurus. Finally, Columns 9 and 10 contain the hardness ratios.

Table 2. RASS X-ray data for candidate members of the Tucanae association, i.e. stars from Table 1 in Zuckerman & Webb (2000). We give the designations from the *Hipparcos* catalogue. One star has no *Hipparcos* parallax and we list its PPM number. The X-ray position (Columns 2 and 3), distance to optical position Δ (Column 4), maximum likelihood of existence (Column 5), exposure time (Column 6), and broad band count rate (Column 7) are given. The distance (Column 8) is derived from the *Hipparcos* parallax. (For PPM366328 no parallax has been measured and the guess by Zuckerman & Webb 2000 has been used for the distance.) The spectral types listed in Column 10 are from Zuckerman & Webb (2000). $L_{\rm x}$ in Column 11 is computed under the assumption that all components in multiples emit the same amount of X-rays, i.e. we have divided the counts by the multiplicity (given in Column 9). Since for close multiples only one value of the combined V magnitude is available, the X-ray luminosity used to compute $\lg{(L_{\rm x}/L_{\rm bol})}$ (Column 12) is the observed value, i.e. the combined luminosity without taking account of the number of components in the system. Columns 13 and 14 contain the PSPC hardness ratios.

HIP	X-ray position [R.A.: h m s]	X-ray position [Dec.: d m s]	Δ [″]	Exi ML	Expo [s]	Rate [cts/s]	distance [pc]	Multi	Sp.Type	$L_{\rm x}$ [10^{29} erg/s]	lg $L_{\rm x}/L_{\rm bol}$	$HR1$	$HR2$
						Probable Tuc members							
1481	00 18 26.9	-63 28 39	7.4	111.3	195.1	0.289 ± 0.042	40.9	1	F8	4.2 ± 0.8	-4.02	-0.19 ± 0.14	-0.10 ± 0.23
1910	00 24 07.8	-62 10 58	2.4	19.9	97.6	0.155 ± 0.045	46.3	1	M0	2.8 ± 1.0	-2.30	-0.26 ± 0.27	-0.24 ± 0.48
2729	00 34 53.2	-61 55 09	9.7	156.8	142.5	0.523 ± 0.064	45.9	1	K4	9.7 ± 1.8	-2.76	-0.19 ± 0.12	-0.12 ± 0.20
92680	18 53 06.0	-50 10 42	7.1	390.6	143.3	0.986 ± 0.086	49.6	1	K0	23.8 ± 2.1	-3.25	-0.02 ± 0.09	0.12 ± 0.12
93815	19 06 20.0	-52 20 24	10.7	1052.1	134.9	2.055 ± 0.126	52.4	2	F7	31.8 ± 4.2	-3.98	0.21 ± 0.06	0.31 ± 0.08
99803	20 14 54.9	-56 58 29	3.8	26.6	176.7	0.127 ± 0.033	65.2	1	F6.5	6.1 ± 1.7	-4.37	0.21 ± 0.26	-0.63 ± 0.28
105388	21 20 50.7	-53 01 56	9.9	563.3	380.7	0.645 ± 0.043	45.8	1	G5	12.4 ± 1.4	-3.19	-0.13 ± 0.07	-0.12 ± 0.10
105404	21 21 00.1	-52 28 33	18.4	717.7	372.4	0.795 ± 0.048	46.0	2	K0	8.1 ± 0.6	-2.91	-0.04 ± 0.06	0.10 ± 0.09
107345	21 44 30.0	-60 58 29	9.5	70.4	329.3	0.152 ± 0.024	42.2	1	M1	2.4 ± 0.5	-2.03	-0.20 ± 0.16	-0.05 ± 0.25
107947	21 52 10.2	-62 03 08	3.2	396.7	389.2	0.448 ± 0.036	45.0	1	F6	8.8 ± 0.8	-3.91	-0.05 ± 0.08	0.14 ± 0.12
108195	21 55 12.8	-61 53 20	13.6	130.2	445.3	0.190 ± 0.023	46.5	2	F3	2.0 ± 0.2	-4.82	-0.06 ± 0.12	-0.10 ± 0.17
PPM 366328	23 15 00.6	-63 34 32	8.1	129.1	501.3	0.159 ± 0.020	50.0	1	K0	3.7 ± 0.5	-3.26	-0.09 ± 0.12	-0.20 ± 0.18
116748	23 39 40.1	-69 11 47	4.9	1187.5	475.	0.909 ± 0.045	46.2	2	G5+8	8.7 ± 1.0	-3.20	-0.15 ± 0.05	0.11 ± 0.08
						Improbable Tuc members							
103438	20 57 20.6	-59 04 16	22.1	21.8	291.2	0.067 ± 0.018	50.9	2	G2	0.5 ± 0.4	-4.65	-0.69 ± 0.22	-0.30 ± 0.68

2.2. RASS observations

During the first months of its operation *ROSAT* performed an All-Sky Survey. In the course of this program the whole sky was scanned by the 2° field of view of the PSPC. The FOV was shifted by $4'$ per scan, such that the total number of scans of a specific location in the sky is ~ 25. The exposure times depend on the ecliptic latitude β and scale with $1/\cos\beta$. For the Tucanae stars they range from $\sim 50 - 500$ s.

Owing to the short exposures ($\sim$ 30 s per scan) the sensitivity of the RASS is limited to $\sim 2\,10^{28}\,\mathrm{erg/s}$ at a distance of 45 pc. Its main advantage is therefore the spatial completeness. In contrast to the pointed observations, where only three Tucanae candidates have been observed, X-ray data for all potential Tucanae stars are available from the RASS.

We have retrieved the RASS raw data from the Public Archive. For the source detection we proceed in a similar way as described in Sect. 2.1 for pointed PSPC observations. The maximum offset allowed between optical and X-ray position is again $40''$. As a consequence of the scanning mode a given source has a different off-axis angle in each RASS scan. The compilation of count rates and luminosities follows the description outlined in Sect. 2.1. Since for non-detections no information about the spectral hardness is available, we use the mean of the ECF of detected Tucanae members for the conversion of upper limit counts to upper limit $L_{\rm x}$.

The detection fraction is much larger among the likely members of Tucanae (13/22) than in the group of improbable members (1/15). The X-ray properties of all detected and undetected stars are given in Tables 2 and 3. The meaning of Columns 1 to 7 in Table 2 (detected sources) is the same as in Table 1. We provide the distance derived from the *Hipparcos* parallax in Column 8. The multiplicity of the stellar system is given in Column 9, and the spectral type in Column 10. The multiplicity is used to derive the X-ray luminosity (Column 11) as described in Sect. 2.1. The last three columns show the ratio of X-ray to bolometric luminosity, and the PSPC hardness ratios. $L_{\rm bol}$ was derived from the V magnitude and spectral type (as given by Zuckerman & Webb 2000) using the bolometric correction of Schmidt-Kaler (1982) and assuming negligible absorption. This is justified because of the small distance and lack of intervening gas in the line of sight. The low ($\simeq 0.0$) hardness ratios of the Tucanae stars also show that absorption is small if not negligible. Note, that no individual V magnitudes are available for the components in close multiple systems. Therefore, we have used the combined $L_{\rm x}$ as well as the combined $L_{\rm bol}$ (i.e. without scaling to the number of components) in order to compute $L_{\rm x}/L_{\rm bol}$.

For undetected sources (Table 3) we list the *Hipparcos* number, the optical position (Columns 2 and 3), exposure time (Column 4), upper limit to the broad band count rate (Column 5), the distance to the star (Column 6), multiplicity (Column 7), spectral type (Column 8), and upper limits to the X-ray luminosity (Column 9) and to the $L_{\rm x}/L_{\rm bol}$-ratio (Column 10). As for detected sources $L_{\rm x}$ has been computed by dividing the observed count rate by the multiplicity.

3. The age of the Tuc association (Comparison with other star-forming regions)

In this section the XLDF of the Tucanae candidates is studied. The X-ray emission declines with stellar age. Therefore, a comparison to XLDFs of other nearby regions of star formation should provide insight into the evolutionary stage of this association. In the following we describe the comparison samples.

3.1. TW Hydrae

Until the discovery of the Tucanae association, the TW Hydrae association was the only recognized nearby young stellar association far from molecular clouds. Strong X-ray emission is considered as (one of many) indicators for membership to the association since it was first studied in X-rays by Kastner et al. (1997). In subsequent studies which have added more stars to the group X-ray luminosities for the new members have been presented (see e.g. Jensen et al. 1998, Hoff et al. 1998, Webb et al. 1999, Sterzik et al. 1999, Hoff 2000). However, a systematic study of the X-ray properties of the whole sample has not been performed, and no XLDFs have been examined so far. In view of the similarity of the Tucanae and TW Hydrae regions, particularly the close and similar distance, it is intimating to compare their X-ray characteristics.

Fourteen TTS systems are known so far in the TW Hya region (see Rucinski & Krautter 1983, de La Reza et al. 1989, Gregorio-Hetem et al. 1992, Kastner et al. 1997, Jensen et al. 1998, Webb et al. 1999, Sterzik et al. 1999, Hoff 2000), all listed in Table 4. The multiplicities of these objects are given in Webb et al. (1999), Sterzik et al. (1999), and Hoff (2000). The possible spectroscopic binaries listed by Webb et al. (1999) have been confirmed as such (Torres et al., in prep.). The recently detected faint object next to TWA-7 (Neuhäuser et al. 2000a) has most recently been found to be a background K dwarf according to an H-band spectrum taken with ISAAC at the VLT (Neuhäuser et al. 2000b) so that we regard TWA-7 as single.

We have cross-correlated the list of TW Hydrae stars with the RASS BSC. All but one star (GSC 7739 2180) can be identified with an X-ray source at less than $40''$ from the optical position. In order to obtain the X-ray properties of GSC 7739 2180 which had no counterpart in the BSC we have checked the raw RASS data, and found that the star is located in a region of low exposure. We have detected an X-ray source with 10.7 cts at the optical position (RX J1121.1-3845). Thus, all TW Hydrae stars are X-ray emitters. Their X-ray characteristics are listed in Table 4. We give the designation of the star (Column 1), the X-ray position (Columns 2 and 3), the distance between optical and X-ray position Δ (Column 4), the exposure time (Column 5), the broad band count rate (Column 6), the multiplicity (Column 7), X-ray luminosity (Column 8) and hardness ratios (Columns 9 and 10). As for the Tucanae stars, the luminosity of multiples has been divided by the number of components. Our

Table 3. RASS X-ray data for undetected candidate members of the Tucanae association. Designations in Column 1 are the *Hipparcos* numbers. Upper limits have been measured at the optical position of the stars (see Columns 2 and 3). Column 4 contains the exposure time, and Column 5 the upper limit to the broad band count rate. The distance derived from the *Hipparcos* parallax is given in Column 6. The spectral types listed in Column 8 are from Zuckerman & Webb (2000). The multiplicity given in Column 7 was used to compute the X-ray luminosity (Column 9) for the individual components in multiples as described in the text. Note, that HIP 2484 and HIP 2487 build a triple but are listed separately because their optical position is different. For the compilation of the L_x/L_{bol} ratio given in Column 10 we have used the observed count rates, i.e. the combined luminosity of all components in case of multiples since only combined V magnitudes are available.

HIP	Position [R.A.: h m s]	[Dec.: d m s]	Expo [s]	Rate [10^{-3} cts/s]	Distance [pc]	Multi	Sp.Type	$\lg L_x$ [erg/s]	$\lg (L_x/L_{bol})$
Probable Tuc members									
1993	00 25 14.6	-61 30 48	50.5	< 46.0	37.4	1	K7	< 28.79	< -2.91
2484	00 31 32.6	-62 57 29	105.9	< 37.2	42.8	1	B9	< 28.81	< -5.98
2487	00 31 33.4	-62 57 56	105.9	< 39.4	52.7	2	A2+7	< 28.72	< -6.01
2578	00 32 43.8	-63 01 53	100.4	< 4.8	46.4	1	A0	< 28.00	< -6.66
95261	19 22 51.2	-54 25 25	61.7	< 42.8	47.6	1	A0	< 28.97	< -5.73
95270	19 22 58.9	-54 32 16	61.7	< 102.7	50.5	1	F5	< 29.40	< -4.63
100751	20 25 38.8	-56 44 06	265.5	< 13.6	56.8	1	B7	< 28.62	< -7.18
104308	21 07 51.2	-54 12 59	326.6	< 43.6	66.4	1	A5	< 29.26	< -5.12
118121	23 57 35.0	-64 17 53	283.0	< 81.0	48.7	1	A1	< 29.26	< -5.50
Improbable Tuc members									
459	00 05 28.3	-61 13 32	156.1	< 33.7	53.8	1	G5	< 28.97	< -4.37
1399	00 17 30.3	-59 57 04	136.7	< 43.1	44.3	1	M0	< 28.91	< -2.79
93096	18 57 56.6	-44 58 06	149.9	< 27.0	64.4	2	G8	< 29.03	< -3.99
94051	19 08 51.1	-54 02 17	172.1	< 11.8	68.4	1	G0	< 28.72	< -4.88
94858	19 18 09.8	-53 23 13	142.8	< 1.0	45.5	1	F7	< 27.28	< -6.90
94997	19 19 49.6	-53 43 13	101.1	< 41.4	59.9	1	M3	< 29.15	< -2.18
95302	19 23 20.5	-50 41 20	101.9	< 14.7	75.5	1	G6	< 28.90	< -4.62
97705	19 51 23.6	-58 30 34	140.6	< 1.2	67.8	1	F8	< 27.73	< -6.15
101636	20 36 02.3	-54 56 28	270.5	< 29.2	65.9	1	G0	< 29.08	< -4.52
101844	20 38 19.4	-55 36 19	258.7	< 36.2	32.0	1	K4	< 28.55	< -3.18
104256	21 07 17.5	-57 01 55	90.3	< 37.7	53.5	1	K1	< 29.01	< -4.26
107806	21 50 23.7	-58 18 17	346.6	< 33.8	40.8	1	G6	< 28.73	< -4.70
109612	22 12 16.8	-54 58 40	346.7	< 37.2	49.0	1	K3	< 28.93	< -3.87
114236	23 08 12.2	-63 37 41	445.3	< 0.2	56.7	1	G3	< 26.73	< -6.82

X-ray data agree well with previously published *ROSAT* data for TWA stars[1].

3.2. Taurus-Auriga

Taurus-Auriga is one of the nearest ($d = 140$ pc; Elias 1978, Wichmann et al. 1998) and best studied regions of star formation. The region is particularly rich in late-type PMS stars. In an analysis of RASS data Neuhäuser et al. (1995) found that the subclass of weak-line TTS (i.e. TTS with weak Hα emission lines) in Taurus-Auriga are X-ray brighter than classical TTS (which are defined by equivalent widths of H$\alpha > 10$ Å). Because the Tucanae members appear to be somewhat evolved, they are probably all weak Hα emitters (naked weak-line post-TTS on radiative tracks near the ZAMS). Therefore, for our comparison we select only the weak-line TTS from Taurus-Auriga. We also note, that the classical TTS in Taurus-Auriga appear to be less X-ray bright than the wTTS although being younger (Neuhäuser et al. 1995, Stelzer et al. in prep). This may be due to magnetic star-disk coupling during the cTTS phase which prevents spin-up, and restricts the dynamo efficiency. The X-ray luminosity, therefore, shows a peak at the stage of the wTTS, and the decrease in X-ray luminosity with age sets in only after the disk is dissipated.

[1] For HR 4796, a pair comprised of an A type and an M type star with separation of just 7.6″, an elongated X-ray source has been detected in the HRI pointed observation. We can therefore distribute the photons detected here in the RASS equally among the two components, as in the other binaries. Note that Huélamo et al. (2000) give a different HRI X-ray luminosity for HR 4796 than Jura et al. (1998), because Jura et al. (1998) converted the HRI X-ray photons using the PSPC energy conversion factor, while Huélamo et al. (2000) used the correct HRI conversion.

Table 4. RASS X-ray data of stars in the TW Hydrae association. X-ray data are derived from the RASS Bright Source Catalog with the exception of RX J1121.1-3845 (GSC 7739 2180), which is in a region of low exposure and therefore has no entry in the BSC. For this star we have extracted and analyzed the RASS raw data. The distances of the stars are computed from the *Hipparcos* parallax when available, otherwise we adopt a value of 55 pc, the mean of the *Hipparcos* distances measured for four TW Hya members. Multiples are listed only once. The meaning of the columns is the same as in Table 2.

Designation	BSC X-ray position [R.A.: h m s]	[Dec.: d m s]	Δ [″]	Expo [s]	Rate [cts/s]	Multi	L_x [10^{29} erg/s]	$HR1$	$HR2$
TWA-6	10 18 28.8	-31 50 02	1.4	336	0.29 ± 0.03	2	3.6 ± 0.9	-0.29 ± 0.10	0.30 ± 0.17
TWA-7	10 42 30.3	-33 40 17	2.5	370	0.32 ± 0.03	1	9.2 ± 1.0	-0.08 ± 0.09	0.05 ± 0.14
TW Hya[a]	11 01 51.9	-34 42 17	5.2	337	0.57 ± 0.04	1	24.8 ± 7.0	0.58 ± 0.06	-0.12 ± 0.08
CoD-29 8887	11 09 13.9	-30 01 39	7.8	325	0.34 ± 0.03	2	4.4 ± 0.9	-0.22 ± 0.09	-0.02 ± 0.15
RX J1109.7-3907	11 09 40.1	-39 06 48	9.8	367	0.12 ± 0.02	1	3.8 ± 0.7	0.15 ± 0.16	0.08 ± 0.21
Hen 3-600	11 10 28.0	-37 32 07	11.1	336	0.28 ± 0.03	3	2.8 ± 0.3	-0.01 ± 0.11	-0.06 ± 0.16
RX J1121.1-3845[b]	11 21 05.2	-38 45 27	0.0	100	0.11 ± 0.04	1	3.3 ± 1.2	0.05 ± 0.39	0.02 ± 0.52
RX J1121.3-3447	11 21 16.8	-34 46 43	3.9	473	0.43 ± 0.03	2	6.1 ± 0.6	-0.08 ± 0.07	0.03 ± 0.11
HD 98800[a]	11 22 05.2	-24 46 40	8.3	330	0.66 ± 0.05	4	3.7 ± 0.3	0.06 ± 0.06	-0.02 ± 0.10
CoD-33 7795	11 31 55.5	-34 36 27	5.6	122	0.66 ± 0.08	3	5.3 ± 1.4	-0.31 ± 0.10	0.29 ± 0.18
TWA-8	11 32 41.5	-26 51 55	2.7	307	0.32 ± 0.04	2	4.9 ± 0.5	0.03 ± 0.10	-0.06 ± 0.15
CoD-36 7429[a]	11 48 24.2	-37 28 49	11.4	122	0.34 ± 0.06	2	3.7 ± 0.9	-0.23 ± 0.16	-0.18 ± 0.26
TWA-10	12 35 04.3	-41 36 39	9.5	341	0.12 ± 0.02	1	3.8 ± 0.7	0.08 ± 0.16	-0.29 ± 0.20
HR 4796 A[a,c]	12 36 01.0	-39 52 10	15.8	284	0.11 ± 0.02	2	2.4 ± 0.6	-0.24 ± 0.17	0.53 ± 0.19
HR 4796 B[a,c]	12 36 00.6	-39 52 16	14.9			2	2.1 ± 0.6		

[a] Distance from the *Hipparcos* parallax,
[b] Position from the RASS raw data.
[c] Components A and B have different L_x because of the difference in the ECF between early and late spectral types (HR 4796 A is an A0 star, and HR 4796 B an M2 star; see also Sect. 2.1).

We have re-computed the XLDF for the RASS data of Taurus-Auriga weak-line TTS including also stars which have been discovered since the study of Neuhäuser et al. (1995). These newly discovered stars are listed in König et al. (2000). Most of them were not detected during the RASS. We do not include all those TTS, which were originally discovered by *ROSAT*, in order to avoid a bias towards X-ray bright TTS.

3.3. IC 2602

IC 2602 is a 30 Myr (Mermilliod 1981) old open cluster whose stars are about to reach the main-sequence. With a distance of $\sim 150\,\mathrm{pc}$ (see Whiteoak 1961) the cluster is relatively nearby. The X-ray emission from IC 2602 was studied by Randich et al. (1995) who have analyzed pointed PSPC observations and selected probable cluster members on the basis of the photometry of the optical counterparts. For the comparison of the XLDFs we have made use of Table 4 in Randich et al. (1995) (see Sect. 3.5).

3.4. Pleiades

Due to their relatively small distance (116 pc; Mermilliod et al. 1997) the $100\,\mathrm{Myr}$ old Pleiades cluster has often been used in comparative evolutionary studies. Detailed investigations of the X-ray emission from the Pleiades have been presented e.g. by Stauffer et al. (1994), Micela et al. (1996), and Micela et al. (1999) based on observations performed by the *Einstein* and *ROSAT* satellites. A study of the full set of archived *ROSAT* observations will be presented in a later publication (Stelzer et al., in prep). Here, we anticipate the XLDF composed of all Pleiades stars which have been in the field of view of any pointed PSPC observation. Upper limits for non-detections are included. A detailed description of the data analysis will be given in the subsequent paper.

3.5. X-ray luminosity functions

To compute the XLDFs for the different stellar associations we have used the ASURV statistics package (see Feigelson & Nelson 1985) which ensures a proper treatment of censored data points, i.e upper limits for undetected sources. For unresolved multiples we have assumed that all components emit X-rays at the same level. The observed L_x has, therefore, been divided by the number of components, and all components are considered in the XLDF.

In Fig. 1 we display the RASS XLDF of the group of probable members of the Tucanae association. The subsample of late-type stars is also shown. For these stars the XLDF is somewhat steeper indicating that the early-type stars are the weaker X-ray emitters. Five of the early-type stars in the Tucanae sample

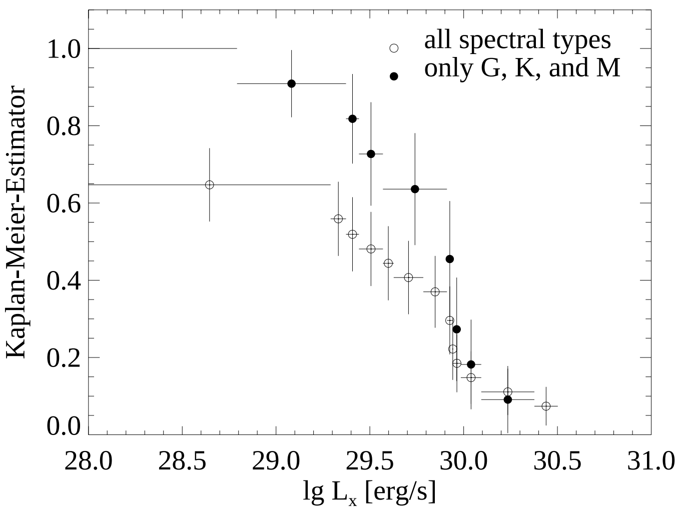

Fig. 1. RASS XLDF for stars from Zuckerman & Webb (2000): (a) probable members with any spectral type, (b) probable members with late spectral type. See text for a description of the samples.

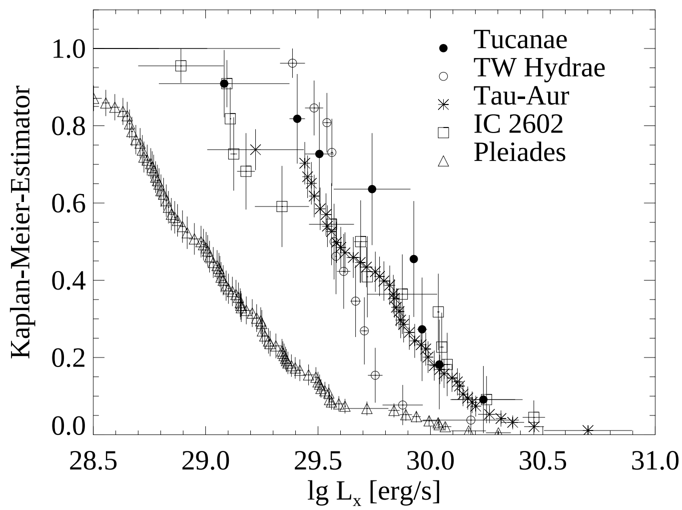

Fig. 2. Comparison between XLDFs of late-type stars (spectral types G, K, and M) for different star forming regions as observed by *ROSAT*: *filled circles* - Tucanae, *open circles* - TW Hydrae, *crosses* - Taurus-Auriga, *squares* - IC 2602, and *triangles* - Pleiades. See text for a description of the samples.

have spectral type A. For A type stars no mechanism producing X-rays is known, consistent with our finding that all A stars in Tucanae are undetected in the RASS. O and B stars can generate X-rays in shocks associated with their strong winds. None of the B stars from our sample is detected in the RASS, but one B star is detected in a PSPC pointing. For late-type stars with convective envelopes of substantial depth (starting from $\sim$ F5; Walter 1983) the X-ray emission is thought to be related to magnetic dynamo activity. All stars in Taurus-Auriga are TTS, i.e. late-type PMS stars. Therefore, to obtain homogeneous samples for the comparison of XLDFs with other star-forming regions only the G, K, and M stars among the Tucanae members should be retained. Due to the non-detection of stars earlier than spectral type F in the Tucanae sample, reducing the sample to G, K, and M stars mainly effects the number of upper limits involved in the XLDF.

We have reduced the other samples in the same way to G, K, and M members. In TW Hydrae most stars have very late spectral types. Only one star, HR 4796A (spectral type A0), had to be excluded. All TTS in Taurus have spectral types G and later. The sample of IC 2602 is composed of all stars from Table 4 in Randich et al. (1995) which are labeled 'photometric members' (flags 'Y' or 'Y?') and have $B - V > 0.6$. In this table the authors give $\lg L_{\rm x}$ for all *ROSAT* PSPC X-ray sources in the cluster with optical counterparts. To treat the multiples among these stars consistently with the other stellar groups we have made use of the Open Cluster Data Base compiled by C. Prosser and colleagues (available at ftp://cfa-ftp.harvard.edu/pub/stauffer/clusters). The multiplicities given in the Open Cluster Data Base are used to derive $L_{\rm x}$ of the individual components as described in Sect. 2.1. The membership list in the Pleiades is based on the entries of the Open Cluster Data Base. For the XLDF computed for comparison with Tucanae we restrict this sample to G, K, and M type stars which have been observed in any pointed PSPC observation (see Stelzer et al., in prep. for more details).

The Kaplan-Meier Estimator for the late-type stars of all stellar groups introduced in the previous subsections is shown in Fig. 2. All distributions except that of the Pleiades are remarkably similar. Particularly, the XLDF of the 30 Myr old IC 2602 cluster and the PMS regions occupy the same region in the diagram. The distribution for TW Hydrae shows the steepest slope, i.e. smallest spread of luminosities. The narrow luminosity distribution of the TW Hydrae sample might be explained by two effects: (i) Since only for four systems the parallax has been measured, we have adopted a mean distance of 55 pc for the remaining stars. Therefore the real spread in distance is probably underestimated. And (ii) the spectral type distribution is very homogeneous in TW Hydra. Most stars have spectral types late K or M, while for the other samples the spread in spectral types is larger (a substantial number of G and early K stars enter the distributions). We note, that the distribution of the Pleiades and IC 2602 have been derived from pointed data, while the XLDF of Tucanae, TW Hydrae and Taurus-Auriga are obtained from RASS observations. However, in the displayed luminosity range the lower sensitivity limit of the RASS should not play a role, and all distributions should be complete.

The general coincidence of the shape and location of the XLDF of Tucanae, TW Hydrae, Taurus-Auriga, and IC 2602 suggests that the stars in the Tucanae association are young (10 to 30 Myr). Certainly, their age is well below that of the Pleiades (10^8 yrs) whose XLDF is clearly shifted to lower luminosities. This is also manifest in Table 5 where we give the mean and median of the X-ray luminosity for all examined samples. The values presented in Table 5 have been derived with ASURV, i.e. upper limits have been taken account of. The weakly X-ray emitting stars of early spectral type in Tucanae reduce $\langle \lg L_{\rm x} \rangle$

Table 5. Mean and median of the X-ray luminosity $L_{\rm x}$ for the stellar samples compared in Fig. 2 computed with ASURV. Results for all stars (regardless of spectral type), and for the samples restricted to G, K, and M stars are given. The number of stars in each sample and number of upper limits among them are listed in columns 'Size' and '(u.l.)'.

Sp.Type	Sample	Size	(u.l.)	$\lg L_{\rm x}$ [erg/s] Mean	Median
All	Tucanae	27	(10)	29.19 ± 0.18	29.41
All	TW Hydrae	27	(0)	29.63 ± 0.04	29.57
G,K,M	Tucanae	11	(1)	29.76 ± 0.13	29.83
G,K,M	TW Hydrae	26	(0)	29.64 ± 0.04	29.57
G,K,M	Tau-Aur	95	(35)	29.61 ± 0.05	29.57
G,K,M	IC 2602	22	(0)	29.61 ± 0.11	29.66
G,K,M	Pleiades	192	(66)	29.00 ± 0.04	28.97

significantly. All values for $\langle \lg L_{\rm x} \rangle$ of late-type stars except the Pleiades are compatible with each other within their uncertainties.

The mean ratio of the logarithm of the X-ray to bolometric luminosity for the RASS detected Tucanae members (Table 1a of Zuckerman & Webb 2000) is -3.47 ± 0.19, which is typical for late-type stars generally characterized by $\lg{(L_{\rm x}/L_{\rm bol})} \simeq -3$. Four Tucanae stars display an $L_{\rm x}/L_{\rm bol}$ value slightly higher than this saturation limit. But note, that two of these show strong variability (see lightcurves in Fig. 4) which may have led to an overestimation of the quiescent X-ray emission. For the probable members $L_{\rm x}/L_{\rm bol}$ correlates well with the equivalent width of Li I, a commonly accepted age indicator. The correlation is shown in Fig. 3 (filled circles). The stars labeled as 'improbable' members by Zuckerman & Webb (2000) do not follow the $L_{\rm x}/L_{\rm bol} - W_{\rm Li}$ relation (open circles). In most stars from this group neither the Li I line is detected nor are they known to be X-ray emitters consistent with them not being part of the association.

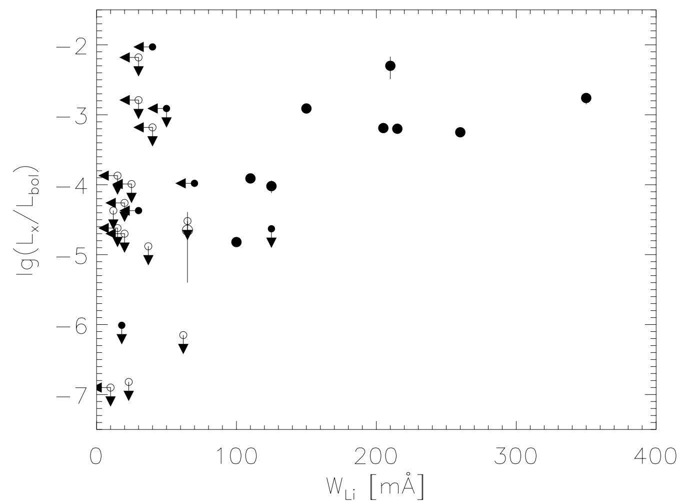

Fig. 3. Correlation between the X-ray to bolometric luminosity ratio and the equivalent width of Lithium for stars of the Tucanae association: Filled symbols are probable members (according to Zuckerman & Webb 2000). Improbable members are represented by open symbols. Arrows indicate upper limits.

4. Variability

In order to investigate whether the X-ray emission of the Tucanae stars is variable we have generated lightcurves for all detected sources from the arrival time information of the photons counted within the source extraction radius. The background counts were extracted from the background map as described in Sect. 2.1. An alternative method of background acquisition consists of constructing a separate background lightcurve at a source free position, and subtracting it from the source lightcurve. This procedure is sensitive to local variations in the background. We have applied both methods to the Tucanae stars and found no significant differences. The count rates have been corrected for vignetting, i.e. effects due to detector off-axis position and support structure.

For the RASS lightcurves the photons have been binned into 5600 s intervals (corresponding to the duration of one satellite orbit around the Earth). Note, however, that the actual exposure times in individual bins range between $\sim$ 10 - 30 s. For pointed observations we use a binsize of 400 s. This interval corresponds to the wobbling motion of the telescope. The wobble is performed to ensure that no source remains hidden behind the entry window's support structure, and may produce apparent variability in a lightcurve if the binning is smaller than that period.

Most of the lightcurves show strong variability. To examine the variations in a quantitative way we have computed the relative luminosity change between the bin with maximum ($C_{\rm max}$) and minimum count rate ($C_{\rm min}$) for each star, i.e.

$$\Delta C_{\rm x} = \frac{C_{\rm max} - C_{\rm min}}{\frac{1}{2}\,(C_{\rm max} + C_{\rm min})} \quad (4)$$

and its $1\,\sigma$ uncertainty from the errors of the respective count rates. In Fig. 4 we display all RASS lightcurves for which the change in count rate $\Delta C_{\rm x}$ in the course of the observation amounts to at least $3\,\sigma$. For clarity we provide the number of counts and the exposure time in each bin on top of each lightcurve. The variability is significant at the $3\,\sigma$ level for 10 of the detected Tucanae members (77%). The values $\Delta C_{\rm x}$ and its significance are given in Table 6 together with the minimum and maximum luminosity observed in the lightcurve. For variable stars the amplitude of the lightcurve is displayed in Fig. 5, where we have plotted maximum versus minimum count rate. Constant sources would lie on the dotted line. The dashed line corresponds to a factor of 10 change.

Among the pointed PSPC observations, only the lightcurve of HIP 92680 shows significant variability. However, the other two observations (ROR 200099p and 200404p) are rather short, and therefore long-term variations on HIP 100751 and HIP 103438 (an improbable member) might have been missed. The lightcurve of HIP 92680 is displayed in Fig. 6. Remarkably, this star was among the few sources not found to be variable (at the $3\,\sigma$ level) during the RASS (see Table 6).

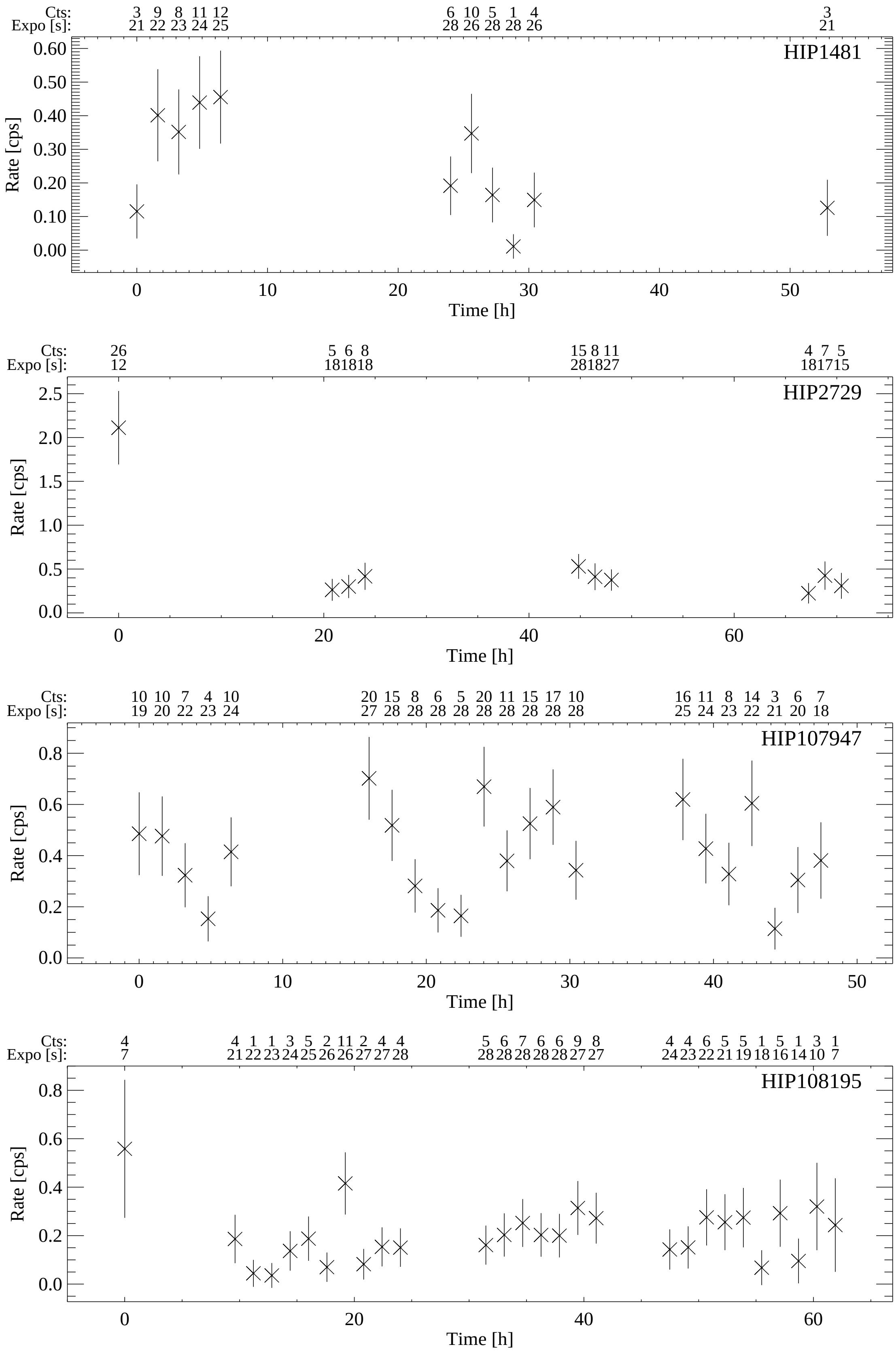

Fig. 4. RASS lightcurves of variable stars, i.e. stars for which the relative change in count rate $\Delta C_{\rm x}$ within the observation is significant at $\geq 3\,\sigma$. Shown are $1\,\sigma$ uncertainties. Arrows indicate the background for scans without source counts. The labels on top of each panel give the number of counts and exposure time (in s) for each scan.

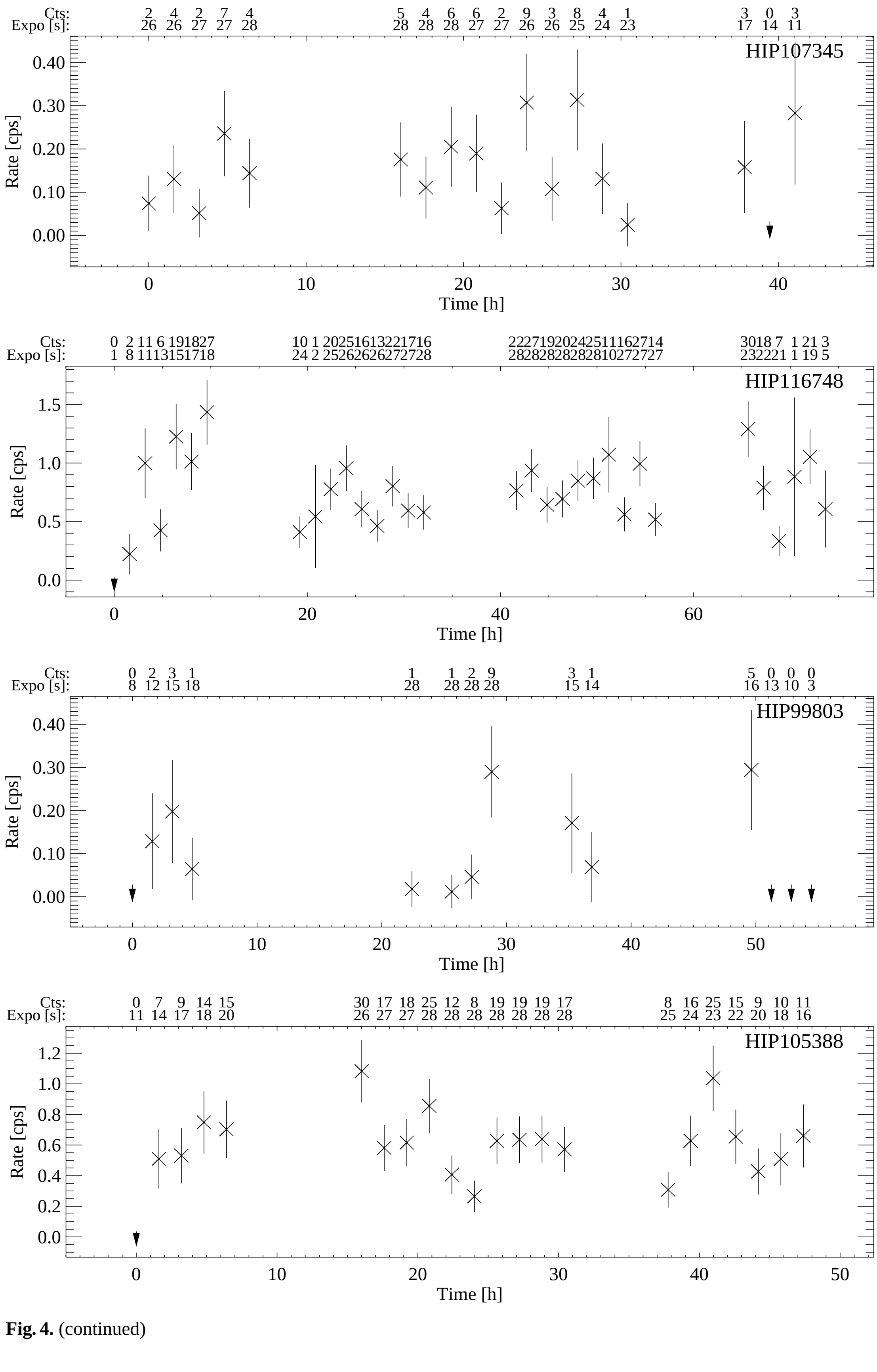

Fig. 4. (continued)

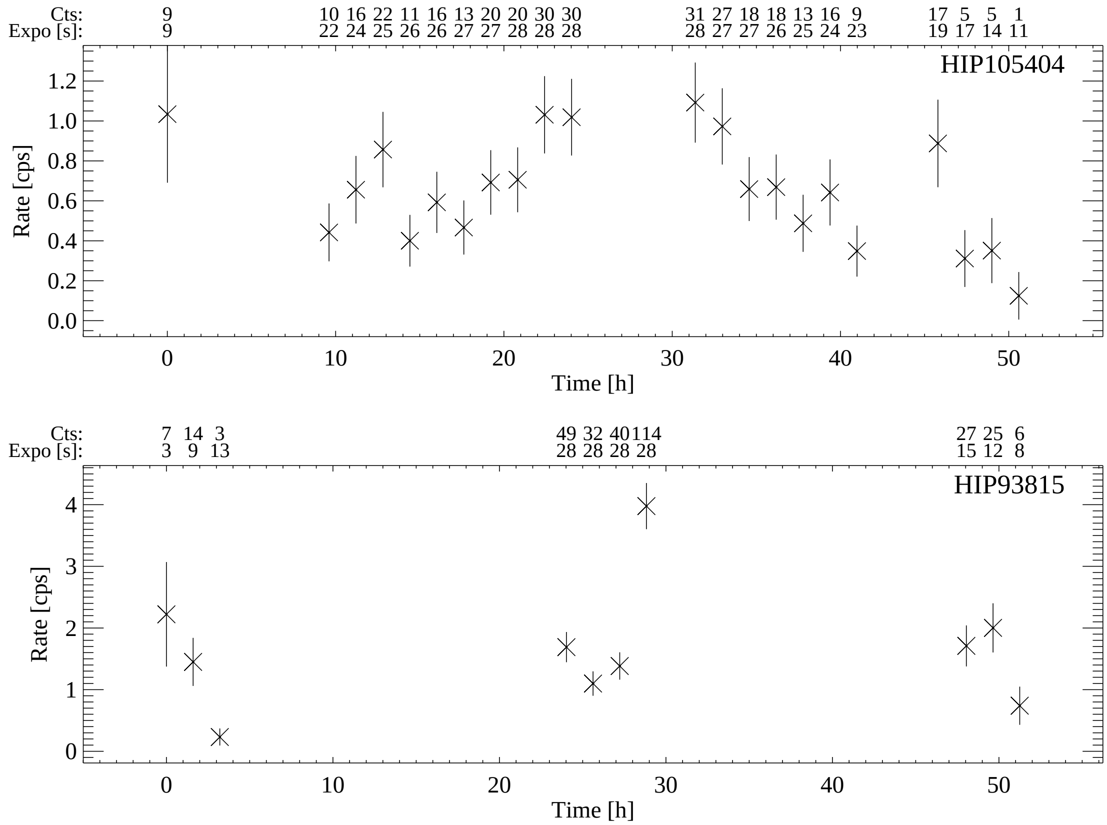

Fig. 4. (continued)

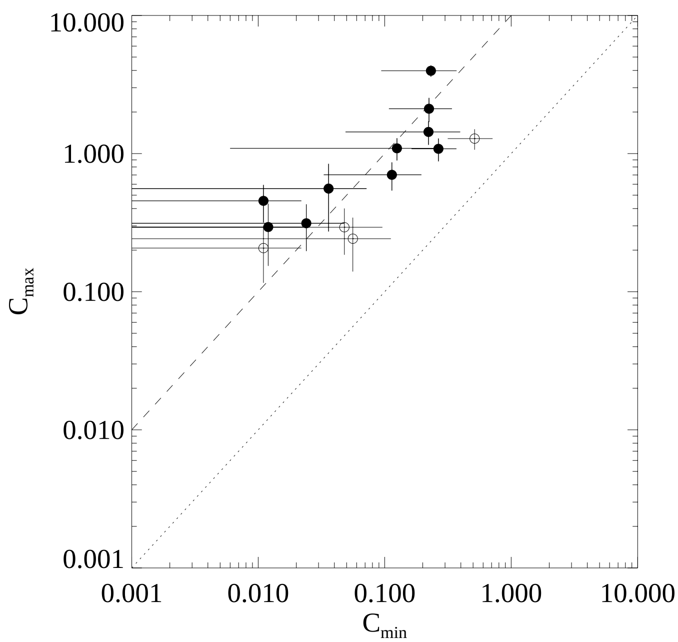

Fig. 5. Count rate variations for individual stars during the RASS observation. Displayed are the minimum (x-axis) and maximum (y-axis) count rates observed in the RASS lightcurves. Variations which are significant at the $3\,\sigma$ level are marked by filled symbols. The dotted line corresponds to a constant source, and the dashed line represents a change by a factor of 10.

5. Conclusions

We have searched the *ROSAT* All-Sky Survey for X-ray emission from potential members of the recently identified Tucanae association. 59% of the stars labeled 'probable' members by Zuckerman & Webb (2000) are detected, but only 7% of the 'improbable' members. The RASS XLDF of the probable members is very similar to the XLDF for the Taurus-Auriga star forming region, and the young open cluster IC 2602. The XLDF of the TW Hydrae association has the same $\langle \lg L_{\rm x} \rangle$, but shows a somewhat smaller spread of luminosities. This is presumably due to the narrow range of spectral types among the TW Hydrae stars and/or the assumed uniform distance of 55 pc for all stars without measured parallax. The similarity of the XLDF for the above mentioned regions indicates that the X-ray emission does not change significantly with age from the early PMS stage (Taurus-Auriga) until the phase when the main-sequence (MS) is reached (IC 2602). However, the XLDF of the 100 Myr old Pleiades cluster is characterized by significantly weaker X-ray emitters than all other samples and suggests that once on the MS the stellar X-ray luminosity decreases. From this comparison we infer an age between $10-30$ Myr for the Tucanae association.

Most of the RASS detected Tucanae members have highly variable lightcurves. The only star observed in a long PSPC pointed exposure shows strong variations there, but was not significantly variable during the RASS. This strengthens the hypothesis that probably all Tucanae stars are variable given long enough observing time. The strong X-ray variability ob-

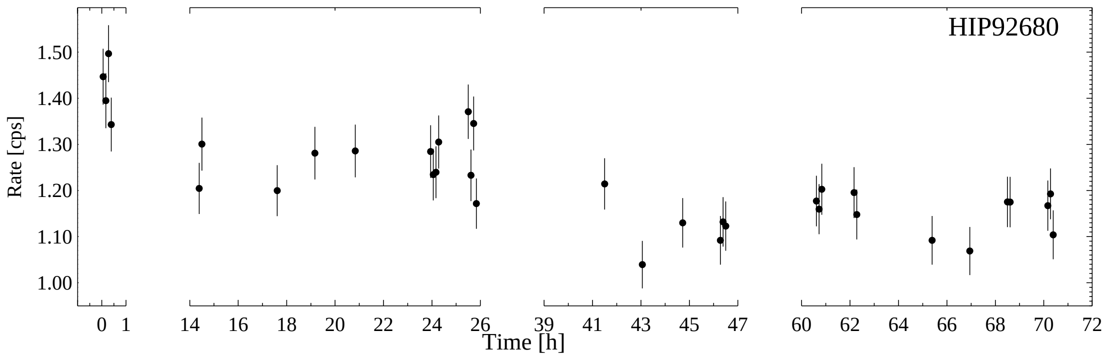

Fig. 6. PSPC pointing lightcurve of HIP 92680. Binsize 400 s, 1 σ uncertainties.

Table 6. Variability in the RASS lightcurves of the Tucanae stars measured through the relative change in count rate $\Delta C_{\rm x}$ during the observation (see text). Column 3 provides a measure of the significance of the variation. All changes larger than $3\,\sigma$ have been considered significant, and the corresponding lightcurves are displayed in Fig. 4. Columns 4 and 5 are the minimum and maximum luminosity inferred from the lightcurve using distance and ECF as described in the text.

HIP	$\Delta C_{\rm x}$	$\frac{\Delta C_{\rm x}}{\sigma_{\Delta C_{\rm x}}}$	$L_{\rm min}$ $[10^{29}\ {\rm erg/s}]$	$L_{\rm max}$ $[10^{29}\ {\rm erg/s}]$
1481	1.91	6.22	0.2	6.7
1910	1.25	1.83	1.0	4.3
2729	1.62	8.38	4.1	39.0
PPM366328	1.43	2.68	1.1	6.9
107947	1.44	3.99	2.2	13.7
108195	1.76	5.10	0.7	11.5
107345	1.71	3.08	0.4	4.9
116748	1.46	3.93	4.3	27.6
99803	1.85	3.76	0.6	14.2
105388	1.21	4.46	5.1	20.8
105404	1.59	4.45	2.6	22.4
93815	1.78	14.19	7.2	123.0
92680	0.86	2.48	12.4	31.0
103438	1.80	2.63	0.2	3.0

served can be considered another indicator for the youth of these systems.

The youth and close distance of the Tucanae stars makes them good candidates for direct imaging of substellar companions, both brown dwarfs and even giant planets, because substellar objects are hot and bright when young (Burrows et al. 1997) and well separated when nearby. I.e. they are detectable with the current technology (e.g. Neuhäuser et al. 2000a). The Tucanae members are as well suited for this purpose as the TW Hya members and the MBM 12 T Tauri stars (Hearty et al. 2000a, Hearty et al. 2000b).

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