ROSAT and Hipparcos Observations of Isolated Pre–Main-Sequence Stars near HD 98800

Eric L. N. Jensen,[1] David H. Cohen,[2] & Ralph Neuhäuser[3]

ABSTRACT

We present new observations of the isolated young stars HD 98800 and CD $-33°7795$. Pointed *ROSAT* observations show that their X-ray properties, including X-ray luminosity and variability, are consistent with those of pre–main-sequence (PMS) stars. These observations do not reveal any additional PMS candidates in $40'$ fields centered on HD 98800 and CD $-33°7795$. Hipparcos observations of TW Hya (Wichmann et al. 1998) and HD 98800 (Soderblom et al. 1998) show that both stars are roughly 50 pc away and are PMS with ages of $\sim 10^7$ yr. We searched the Hipparcos catalog (complete down to $\sim$ 2–3 $L_\odot$ at this distance) for other PMS stars in the same area. In a 10-pc radius volume of space centered on the previously known PMS stars, we find one additional candidate PMS star (CD $-36°7429$) with a low space velocity, X-ray emission comparable to that of HD 98800, and Li absorption. There are eight other stars in this area that have dwarf spectral types and lie above the main sequence, but based on their weak X-ray emission, high space velocities, and lack of Li in low-resolution spectra (i.e. EW(Li) < 0.1 Å), these are probably mis-classified subgiants or giants. The current positions and proper motions of TW Hya, HD 98800, and CD $-36°7429$ are inconsistent with them having formed as a group.

Subject headings: stars: pre–main-sequence – X-rays – stars: kinematics – stars: individual (HD 98800; CD $-33°7795$; TW Hya; CD $-36°7429$)

[1]Arizona State University, Department of Physics & Astronomy, P.O. Box 871504, Tempe, AZ 85287-1504 USA. Email: Eric.L.N.Jensen@asu.edu

[2]University of Wisconsin – Madison, Department of Astronomy, 475 N. Charter Street, and Fusion Technology Institute, 1500 Engineering Drive, Madison, WI 53706 USA. Email: cohen@duff.astro.wisc.edu

[3]Max-Planck-Institut für extraterrestrische Physik, Giessenbachstraße 1, D-85740 Garching, Germany. Email: rne@rosat.mpe-garching.mpg.de

1. Introduction

Recent observations have revealed a small population of stars that bear many of the hallmarks of low-mass pre–main-sequence stars but lie far from any obvious region of recent star formation (as revealed by substantial dark clouds of molecular gas and dust). Gregorio-Hetem et al. (1992) identified 33 candidate T Tauri stars based on spectroscopy of stars in the *IRAS* Point Source Catalog and a few additional emission-line stars. One of the more interesting findings of their work was the identification of four stars (HD 98800, CD $-33°7795$, CD $-29°8887$, and Hen 3–600) within 10° of TW Hya, earlier identified as a possible isolated T Tauri star by Rucinski & Krautter (1983). The proximity of these five systems to each other suggested a possible loose cluster of young stars, possibly formed by a small molecular cloud that has since dissipated (e.g., Feigelson 1996).

In the absence of association with any known cloud complex, the distances to these stars were very uncertain, and thus their pre–main-sequence status was in question. To investigate whether two of these stars, HD 98800 and CD $-33°7795$, are in fact young and whether they are part of a larger group of young stars, we observed them with the *ROSAT* X-ray satellite. One distinguishing feature of low-mass pre–main-sequence stars is strong X-ray emission, presumed to arise from solar-like chromospheric activity (see, e.g., Neuhäuser 1997 for a recent review). Thus, X-ray observations can be used to search for young stars that may not have other hallmarks of youth such as infrared excesses or strong Hα emission. Observations of Taurus-Auriga with the *Einstein* satellite led to the discovery of the naked T Tauri stars, stars that have no circumstellar material but that are nonetheless coeval with classical T Tauri stars (Walter 1986).

Much observational attention has been focused on the stars in the vicinity of TW Hya recently, and several other investigations have proceeded in parallel with ours. Kastner et al. (1997) reported *ROSAT* observations of some of the same stars we report on here. They found that the strength of X-ray emission from these stars is consistent with them being young stars and argued that the five young stars in this area make up a physical association. Hoff et al. (1996, 1998) investigated TW Hya and CD $-29°8887$ and their surroundings with low spatial resolution using *ROSAT* PSPC pointed observations. Soderblom et al. (1998) and Wichmann et al. (1998) report Hipparcos distances to HD 98800 and TW Hya, respectively; both systems have ages of ~ 1–2×10^7 yr and distances of ~ 50 pc. The work we report here is complementary to this other recent work. We analyze the X-ray data of our target stars in more detail than Kastner et al. (1997) and explore the status of other X-ray sources in the surrounding fields. We also combine X-ray and Hipparcos data to search for other young stars in the vicinity in order to address the larger question of the origin of these isolated young stars.

In Sec. 2 we report the details of our observations. In Sec. 3 we show that the X-ray properties of the two target stars are consistent with their being pre–main-sequence (PMS) stars. We then investigate (Sec. 4) whether there is any evidence that the young stars near TW Hya formed as a group, using our X-ray observations as well as data from the Hipparcos satellite. Finally, in Sec. 5 we discuss the implications of our findings for our understanding of isolated young stars.

2. *ROSAT* HRI Observations

Observations of HD 98800 and CD $-33°7795$ were made with the High Resolution Imager (HRI) aboard *ROSAT*. The telescope consists of four nested Wolter type I mirrors with a peak effective area of almost 1000 cm^2 (Trümper 1983). The HRI, described in David et al. (1997), uses a two microchannel plate detector with a CsI photocathode. The mirror and detector combination is sensitive to X-rays with energies between 0.1 keV and 2.4 keV. Its very good spatial resolution is characterized by a response function having an on-axis FWHM of about $5''$. It has a field of view with an approximate diameter of $40'$.

With a low and well understood background, *ROSAT* has a sensitivity that is the best of any current or past large X-ray telescope. The minimum detectable flux in our observations is about 10^{-14} ergs s^{-1} cm^{-2}. The sensitivity declines slightly with off-axis angle, reaching 85 percent of the on-axis value at $20'$ for 1 keV photons. Because of the good sensitivity and spatial resolution the *ROSAT* HRI is well suited to identifying point sources in potentially crowded fields.

The pointed HRI observations were made consecutively over a period of 20 days. The HD 98800 observations took place from 1994 December 28 to 1995 January 7 with an effective exposure time of 23,051 s. The CD $-33°7795$ observations took place from 1995 January 9 to 17 with an effective exposure time of 30,604 s.

In both fields the central stars (HD 98800 and CD $-33°7795$, respectively) are the brightest X-ray sources, but in each case several other sources are also visible. To locate all statistically significant sources we used the source detection algorithms in the MIDAS/EXSAS software package (January 1995 version, Zimmermann et al. 1993). These algorithms use a three-step process in which sources first are located using a sliding window technique. Next a background map is made by excluding these sources and the sliding window search is repeated using the new background determination. Finally a maximum likelihood statistic $\mathcal{L}$ is calculated for each possible point source using the background map and knowledge of the point spread function. We used a maximum likelihood threshold value of 8, which corresponds to a probability that a spurious source is identified at a given position of 3.3×10^{-4}.

Before extracting the identified sources we examined the radial profiles. In general the source count rate became indistinguishable from the background level by $20''$. We chose a radius for each source extraction circle accordingly. We then extracted a background sample from a nearby, source-free region of the detector. The background count rate was scaled to the area of the source extraction circle and was subtracted from the source. The net count rate was then computed by summing over all 16 HRI energy channels.

In the HD 98800 field we detected nine X-ray sources, and in the CD $-33°7795$ field we detected six sources. In Tables 1 and 2 we list the sources detected in the two fields, their positions, count rates, and fluxes. In each field the central star is more than an order of magnitude brighter in X-rays than any of the other sources; there are no X-ray sources in these fields of comparable brightness to the previously-known PMS stars HD 98800 and CD $-33°7795$.

The conversion of X-ray count rates to fluxes is model dependent because the effective area of the *ROSAT* HRI is a strongly varying function of photon energy. Late-type stars have optically thin thermal X-ray spectra that are typically fit by isothermal ($T \approx 10^7$ K) models (Schmitt & Snowden 1990). The reddening of both HD 98800 and CD $-33°7795$ is negligible, implying that interstellar attenuation of the X-rays is also negligible. We derived the fluxes of the central stars of the two fields assuming a Raymond and Smith isothermal model having a temperature of 10^7 K and attenuated by an interstellar column of $N_H = 5 \times 10^{19}$ cm^{-2}. This procedure effectively gave a count rate to flux conversion factor, which we then used for each of the other stars in the fields. This factor, of roughly 2.5×10^{-11} ergs s^{-1} cm^{-2} count^{-1}, is in good agreement with the values listed in the HRI handbook (David et al. 1997). We note that the count rate to flux conversion factor varies by no more than 30 percent over the range of spectral parameters $0.5 \lesssim T_X \lesssim 1.0$ keV and $10^{19} \lesssim N_H \lesssim 10^{20}$ cm^{-2}. This range of N_H values corresponds to visual extinctions of $A_V \approx 0.005$ to 0.05 magnitudes, consistent with the observed low extinction toward the central sources in our fields.

We use this same value to convert the fluxes in all of the sources. This assumption will be valid if the other sources are PMS stars or late-type main sequence stars at a distance similar to the central star in each field. If the sources are background sources then their intrinsic fluxes will tend to be higher than our estimates, due to the probable underestimate of the interstellar absorption. The fluxes are listed in Tables 1 and 2; the flux uncertainties quoted are derived from the uncertainties in the count rates added in quadrature with an assumed 15% uncertainty in the count rate to flux conversion.

Table 1. X-ray sources in the HD 98800 Field

Source	Count Rate (counts ks^{-1})	X-ray Flux (10^{-14} erg s^{-1} cm^{-2})
RX J112205.4−244641[a]	127 ± 2	326 ± 49
RX J112303.2−243629	1.52 ± 0.44	4.0 ± 1.3
RX J112157.4−244014	0.41 ± 0.18	1.1 ± 0.5
RX J112112.4−244032	1.23 ± 0.38	3.2 ± 1.1
RX J112229.2−244258	1.66 ± 0.33	4.3 ± 1.1
RX J112154.5−244413	0.94 ± 0.54	2.4 ± 1.4
RX J112204.4−245347	3.79 ± 0.43	9.7 ± 1.8
RX J112156.1−245503	1.52 ± 0.32	3.9 ± 1.0
RX J112216.6−245810	0.82 ± 0.26	2.1 ± 0.7

[a]HD 98800

Table 2. X-ray sources in the CD −33°7795 Field

Source	Count Rate (counts ks^{-1})	X-ray Flux (10^{-14} erg s^{-1} cm^{-2})
RX J113155.3−343630[a]	156 ± 2	400 ± 60
RX J113220.7−343343	0.60 ± 0.22	1.6 ± 0.6
RX J113126.2−343411	0.81 ± 0.18	2.1 ± 0.6
RX J113143.3−343704	0.46 ± 0.26	1.2 ± 0.7
RX J113213.6−344127	1.52 ± 0.28	3.9 ± 0.9
RX J113140.5−344246	0.50 ± 0.21	1.3 ± 0.6

[a]CD −33°7795

3. X-ray Properties of HD 98800 and CD $-33°7795$

3.1. X-ray Fluxes

The X-ray fluxes of HD 98800 and CD $-33°7795$ combined with their V magnitudes (Soderblom et al. 1998, Gregorio-Hetem et al. 1992) and bolometric corrections (Kenyon & Hartmann 1995) give L_X/L_{Bol} ratios of 2.8×10^{-4} and 1.2×10^{-3}, respectively.[4] The X-ray luminosity of HD 98800 given its distance of 46.7 pc (Soderblom et al. 1998) is 8.5×10^{29} erg s^{-1} cm^{-2}, or $\log L_X = 29.9$. Assuming the same distance for CD $-33°7795$ gives $\log L_X = 30.0$. The strength of X-ray emission from HD 98800 and CD $-33°7795$ is consistent with the interpretation that they are PMS stars; their X-ray luminosities are within the ranges found by Neuhäuser et al. (1995) for T Tauri stars in Taurus and are higher than all but the few most X-ray-luminous stars in the Pleiades or Hyades (Neuhäuser 1997). Even if the X-ray luminosity of HD 98800 is divided equally among the four stars in the quadruple system (Torres et al. 1995), the X-ray luminosity of each star is comparable to that from PMS stars. The L_X/L_{Bol} values are also in the range found for Taurus PMS stars (Neuhäuser et al. 1995).

3.2. Time Variability

The observations of HD 98800 and CD $-33°7795$ each span about ten days, and because of their relatively high count rates we can address the issue of time variability using these data. Because *ROSAT* is in low-Earth orbit the data are in sections of $t \approx 2500$ s, separated by slightly longer (and occasionally much longer) intervals. Individual orbits provide convenient time bins for tests of variability on timescales of hours. We also divided the data into 100 s bins to test for shorter-term variability.

In Figure 1 we show the light curves for each of the two stars with the 2500 s bins. In both stars there is a flare-type event with a rise time of approximately one day. For CD $-33°7795$ the amplitude of the event is at least 90 percent above the mean count rate. For HD 98800 it is at least 40 percent. In both cases the *ROSAT* count rates returned to the pre-flare levels within one day of reaching their peaks.

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[4] The value of L_X/L_{Bol} for HD 98800 is an upper limit for HD 98800 Aa (the brightest star in this quadruple system, Torres et al. 1995) that results from assigning all of the X-ray flux to Aa and using the V magnitude of this star from Soderblom et al. (1998). The true L_X/L_{Bol} ratios of the individual stars in the system are highly uncertain because it is unknown how the X-ray flux is divided among the four stars.

There is very little variability on shorter timescales as determined from the light curves with the 100 s bins. We fit the light curves from each separate orbit with a constant source model. In almost every case the data from each orbit are consistent with a constant source flux, although this constant source flux level is different for each orbit. For HD 98800 only 2 out of 12 orbits show short term variability with a significance greater than 95 percent. For CD $-33°7795$ only 1 out of 14 orbits shows short term variability above this significance level. The standard deviation of the source counts in the 100 s bins for each orbit is typically 20 percent of the mean count rate for that orbit, which is similar to the statistical uncertainties. We can therefore conclude that very little variability with amplitudes greater than 20 percent is seen on timescales of minutes, and none of this short timescale variability has an amplitude greater than 40 percent.

While X-ray flares are seen in late-type stars of all ages (Schmitt 1994), the presence of flares in both of our targets within a relatively short time suggests that these stars are part of an active population. Gagné et al. (1995) estimated that late-type Pleiades cluster members (ages $\sim 7 \times 10^7$ yr) undergo large flares roughly 1% of the time. Thus, if our target stars have a similar flaring frequency, the probability that we would observe a ~ 1 day flare in a single 10-day observation of a given star was $\sim 10\%$. The probability that we would observe flares in *both* stars was about 1%. Thus, the observations suggest a somewhat higher flaring frequency than that of the Pleiades, consistent with younger ages for these stars. Neuhäuser & Preibisch (1995) estimate an X-ray flare rate of roughly one flare every 40 days for T Tauri stars in Taurus-Auriga. If the flare rate for CD $-33°7795$ and HD 98800 is similar to that of T Tauri stars, this gives a $\sim 25\%$ probability that we would see a flare in a 10-day observation of one star, and a $\sim 6\%$ probability of seeing flares in both. This indicates that HD 98800 and CD $-33°7795$ are at least as active as T Tauri stars, though the X-ray flare rate determined by Neuhäuser & Preibisch (1995) is very uncertain. We conclude that the level of X-ray activity in HD 98800 and CD $-33°7795$ is consistent with their being young stars.

3.3. Spectral Properties

Although the *ROSAT* HRI data sets do not afford us the opportunity to perform quantitative X-ray spectral fitting, we were able to perform some spectral modeling using the shorter PSPC observations of HD 98800 and CD $-33°7795$ taken from the *ROSAT* All-Sky Survey (RASS). With the RASS, the whole sky has been observed with the PSPC (Positional Sensitive Proportional Counter), which offers moderate spectral resolution. The RASS fluxes of the previously known five PMS stars in this field have been presented by

Kastner et al. (1997). However, they do not list hardness ratios, which are basic spectral information derived from the relative fluxes in the different energy bands of the PSPC (Neuhäuser et al. 1995)[5]. Therefore, we include the basic spectral analysis below for all five stars.

In Table 3, we list the five previously known PMS stars with their maximum likelihood $\mathcal{L}$ of existence as X-ray sources in the RASS, as well as the RASS exposure times, hardness ratios (HR 1 and HR 2), and X-ray fluxes, derived using an energy conversion factor of 1 count = $(5.30 \times \mathrm{HR1} + 8.31) \times 10^{-12}$ erg s^{-1} cm^{-2} (Schmitt et al. 1995). The hardness ratios were derived using the procedure given in Neuhäuser et al. (1995).

We caution that the fluxes in Table 3 and in Kastner et al. (1997) for HD 98800, CD $-29°8887$, and Hen 3–600 are fluxes of unresolved multiple systems. There is no *a priori* way to know how to divide the X-ray flux among the components. Even a conclusion drawn from the hardness ratios may be in error, as the individual companions may have different ratios.

The hardness ratios of the five stars in Table 3 can be compared to typical values for TTS in Taurus. Neuhäuser et al. (1995) found significantly different hardness ratios for classical T Tauri stars (cTTS) compared to weak-line T Tauri stars (wTTS), which they interpreted to be due to more absorption of soft X-rays in cTTS due to their circumstellar material.

Adopting the usual dividing line of EW(Hα) = 10 Å as boundary between cTTS and wTTS (e.g., Bertout 1989), TW Hya, Hen 3–600, and CD $-33°7795$ are cTTS while HD 98800 and CD $-29°8887$ are wTTS. However, as noted by Kastner et al. (1997), some authors consider the presence of an infrared excess an additional criterion for classification as a cTTS, and in the present case this criterion may be more relevant as an influence on the X-ray emission. Using only the presence or absence of an infrared excess as the selection criterion switches the classification of HD 98800 from wTTS to cTTS and CD $-33°7795$ from cTTS to wTTS.

For cTTS in Taurus, Neuhäuser et al. (1995) found mean hardness ratios of $\langle \mathrm{HR1} \rangle = 0.994 \pm 0.027$ and $\langle \mathrm{HR2} \rangle = 0.42 \pm 0.27$, where the errors given are the standard deviations. Hence, all five stars, regardless of cTTS or wTTS status, show lower values, i.e. softer X-ray emission. Indeed, several of the stars have negative values of HR1, softer

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[5]If Z_{s}, Z_{m}, and Z_{h} denote count rates in the soft (0.1 to 0.4 keV), medium (0.5 to 0.9 keV), and hard (0.9 to 2.1 keV) PSPC bands respectively, then HR 1 $= \frac{Z_{\mathrm{h}}+Z_{\mathrm{m}}-Z_{\mathrm{s}}}{Z_{\mathrm{h}}+Z_{\mathrm{m}}+Z_{\mathrm{s}}}$ and HR 2 $= \frac{Z_{\mathrm{h}}-Z_{\mathrm{m}}}{Z_{\mathrm{h}}+Z_{\mathrm{m}}}$; both ratios can range from -1 to $+1$.

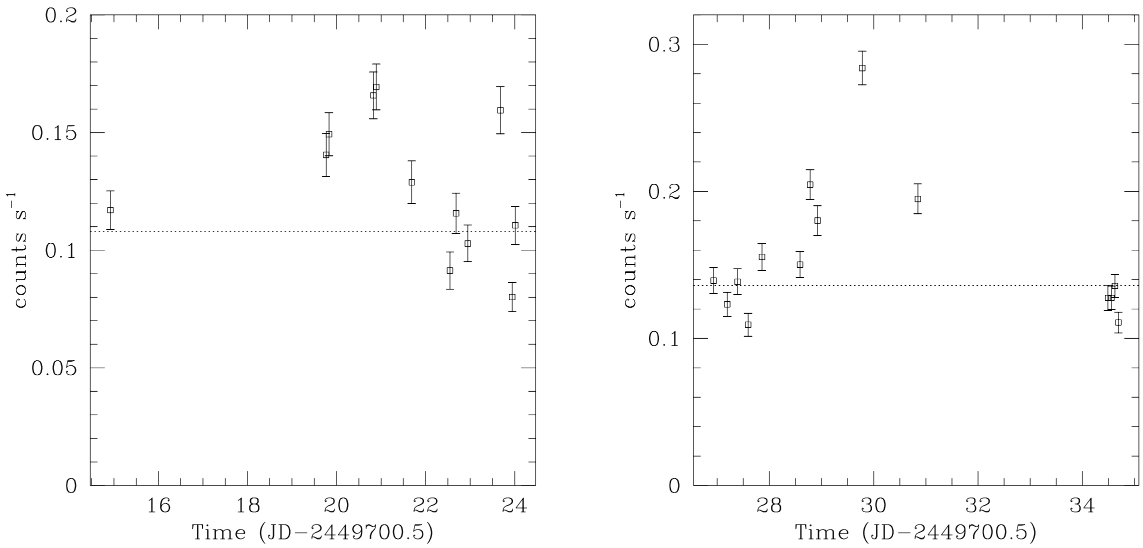

Fig. 1.— X-ray light curves of HD 98800 (left) and CD $-33°7795$ (right). Each point represents one orbit, or approximately 2500 s of effective observing time. The dashed lines indicate the mean count rates for each target excluding the flare events.

Table 3. X-ray spectral properties of previously-known young stars near TW Hya

Name	$\mathcal{L}$	Exposure Time (s)	HR 1	HR 2	Flux/10^{-12} erg s^{-1} cm^{-2}
TW Hya	7	337	0.58 ± 0.06	-0.12 ± 0.08	6.49 ± 0.54
CD $-29°8887$	8	325	-0.22 ± 0.09	-0.02 ± 0.15	4.72 ± 0.48
Hen 3–600	10	336	-0.01 ± 0.11	-0.06 ± 0.16	2.31 ± 0.35
HD 98800	7	330	0.06 ± 0.23	-0.78 ± 0.43	5.69 ± 1.33
CD $-33°7795$	8	122	-0.31 ± 0.10	0.29 ± 0.18	4.40 ± 0.76

Note. — For comparison, hardness ratios for TTS in Taurus are HR 1 = 0.3–1.0 (median = 0.89) and HR 2 = 0.0–1.0 (median = 0.25) for wTTS, HR 1 = 1.0 (for all but one cTTS) and HR 2 = 0.1–0.7 (median = 0.34) for cTTS. (Neuhäuser et al. 1995).

than any of the TTS observed in Taurus by Neuhäuser et al. (1995). This may be partly due to lower interstellar extinction, since the stars are much closer than Taurus. It also indicates the lack of molecular gas in the immediate vicinity of these stars, either because gas from their formation has dispersed or because they were formed elsewhere. TW Hya, however, is thought to be viewed pole-on (Kastner et al. 1997). If so, even its substantial circumstellar disk would not contribute strongly to X-ray absorption, yielding low hardness ratios. For the other stars, the low hardness ratios even in those stars with infrared excesses may suggest that either they are also viewed pole-on, or that their circumstellar material is less attenuating than in Taurus TTS, possibly indicating disks with lower masses and/or larger grains than those typically found around cTTS.

Thus, the X-ray luminosity and variability of HD 98800 and CD $-33°7795$ are consistent with those of PMS stars. Their X-ray spectral properties are somewhat different, perhaps reflecting the difference between their current environment and that in Taurus-Auriga.

4. Search for Additional Young Stars

It has been suggested that HD 98800 and CD $-33°7795$, along with the other three stars in Table 3, are part of an isolated group of young stars that formed together (Gregorio-Hetem et al. 1992, Feigelson 1996, Kastner et al. 1997). To test this idea, we searched for additional young stars in the area using both our X-ray observations and observations from Hipparcos.

4.1. Optical Counterparts to X-ray Sources

Our X-ray detections of HD 98800 and CD $-33°7795$ were within $3''$ of their optical positions, a typical value for the boresight offset of the HRI (David et al. 1997). To search for optical counterparts to the other X-ray sources, we used images of the HRI fields from the Digitized Sky Survey (DSS; Morrison 1995). Most previously-known X-ray sources observed by HRI were detected with $10''$ of their catalog positions (David et al. 1997). Therefore, we set $10''$ as an upper limit for the permitted offset between the X-ray position and any candidate optical counterparts. The DSS images were examined visually to identify optical sources within a $10''$-radius circle centered on each X-ray position. For each X-ray source, only one optical counterpart was found within this radius. The coordinates of the optical sources are given in Tables 4 and 5. All optical counterparts appeared stellar (not extended) in the DSS images except for that of RX J113220.7−343343 which is slightly elongated.

To measure magnitudes for the optical counterparts, we used the IRAF *apphot* package. The sky background level was measured at eight places in each image and found to be constant to better than 1% across the image; the average of these eight sky values was then subtracted from each image. An additional 500 counts were subtracted from each image since the DSS photometric calibration is defined in terms of the total signal that is more than 500 counts above the background. We then set all negative pixels in each image to zero and measured the integrated signal for each source. This signal was converted to a SERC-J magnitude using the photometric calibration from the DSS.[6] The magnitudes are given in Tables 4 and 5. All but one of the optical counterparts (besides the central stars) were fainter than the $J = 18$ limit of the DSS photometric calibration. As a check, the J magnitudes of HD 98800 and CD −33°7795 were measured; these magnitudes agree with their *Guide Star Catalog* magnitudes (which come from the same plates) within the errors.

The extreme faintness of the other optical counterparts strongly suggests that few if any of them are pre–main-sequence stars associated with HD 98800 and CD −33°7795. We compared their measured magnitudes to those predicted by the evolutionary tracks of D'Antona & Mazzitelli (1994). We used a SERC-J to Johnson B conversion of $B = J + 0.28(B - V)$ (Lasker et al. 1990) and used values of $(B - V)$ and bolometric corrections from Kenyon & Hartmann (1995) to convert the theoretical tracks to observed magnitudes. At a distance of 50 pc, a star with $J > 18$ would lie below the main sequence if it has a spectral type earlier than M2.5. In order to be coeval with HD 98800 (10^7 yr) and lie at the same distance, a star with $J > 18$ would have to have a spectral type later than M5. While this could be true for individual stars in our sample, it is extremely unlikely that any cluster of young stars around HD 98800 or CD −33°7795 would contain *only* very-late-type stars aside from the central stars. The low X-ray fluxes of the other sources (1–2 orders of magnitude fainter than HD 98800 or CD −33°7795) further indicates that it is unlikely that any of the other stars in these fields are PMS stars.

Hoff et al. (1996, 1998) used a similar technique to search for additional young stars in the vicinity of TW Hya and CD −29°8887, with the same result. Their deep *ROSAT* PSPC observations and follow-up optical spectroscopy revealed no additional young stars in the 2°-diameter PSPC fields around each star.

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[6]The photometric calibration is available at http://www-gsss.stsci.edu/dss/photometry/index.html. The southern sky images in the DSS are digitized from SERC-J photographic plates (IIIa-J emulsion + GG395 filter). The photographic J bandpass (not to be confused with the $\lambda = 1.25$ μm Johnson J band) is a blue bandpass similar to the Johnson B (see, e.g., Kron 1980, Lasker et al. 1990).

Table 4. Optical counterparts in the HD 98800 Field

X-ray source	R.A. (optical) (J2000)	Dec. (optical) (J2000)	Offset (arcsec)	B_J (mag)
RX J112205.4−244641[a]	$11^h22^m05\overset{s}{.}6$	$-24°46'39\overset{''}{.}5$	2.6	10.1 ± 0.4
RX J112303.2−243629	$11^h23^m03\overset{s}{.}1$	$-24°36'27\overset{''}{.}1$	2.9	> 18
RX J112157.4−244014	$11^h21^m57\overset{s}{.}1$	$-24°40'15\overset{''}{.}5$	4.8	> 18
RX J112112.4−244032	$11^h21^m12\overset{s}{.}6$	$-24°40'34\overset{''}{.}8$	2.9	> 18
RX J112229.2−244258	$11^h22^m29\overset{s}{.}1$	$-24°42'59\overset{''}{.}9$	2.8	> 18
RX J112154.5−244413	$11^h21^m54\overset{s}{.}5$	$-24°44'12\overset{''}{.}8$	0.7	> 18
RX J112204.4−245347	$11^h22^m04\overset{s}{.}4$	$-24°53'45\overset{''}{.}1$	1.9	> 18
RX J112156.1−245503	$11^h21^m56\overset{s}{.}3$	$-24°55'01\overset{''}{.}5$	2.1	> 18
RX J112216.6−245810	$11^h22^m16\overset{s}{.}9$	$-24°58'08\overset{''}{.}7$	4.1	> 18

[a]HD 98800

Table 5. Optical counterparts in the CD −33°7795 Field

X-ray source	R.A. (optical) (J2000)	Dec. (optical) (J2000)	Offset (arcsec)	B_J (mag)
RX J113155.3−343630[a]	$11^h31^m55\overset{s}{.}5$	$-34°36'28\overset{''}{.}1$	2.9	13.3 ± 0.6
RX J113220.7−343343	$11^h32^m21\overset{s}{.}1$	$-34°33'49\overset{''}{.}7$	7.7	17.1 ± 0.8
RX J113126.2−343411	$11^h31^m26\overset{s}{.}4$	$-34°34'10\overset{''}{.}1$	3.0	> 18
RX J113143.3−343704	$11^h31^m43\overset{s}{.}2$	$-34°37'04\overset{''}{.}0$	2.0	> 18
RX J113213.6−344127	$11^h32^m13\overset{s}{.}8$	$-34°41'25\overset{''}{.}6$	2.2	> 18
RX J113140.5−344246	$11^h31^m40\overset{s}{.}8$	$-34°42'43\overset{''}{.}6$	4.5	> 18

[a]CD −33°7795

While our deep HRI observations did not reveal any additional pre–main-sequence stars, this does not rule out the presence of additional stars in a cluster, since the area covered was fairly small. At 50 pc, each $40'$ HRI field covers an area projected on the sky with a radius of roughly 0.3 pc. The median projected separation of young stars in the Taurus-Auriga star-forming region (excluding close binary companions) is ~ 0.3 pc (Gomez et al. 1993). Thus, it is perhaps not surprising that we did not detect additional young stars in our HRI fields. The PSPC observations of Hoff et al. (1996, 1998) cover roughly three times the area of our HRI observations, suggesting that any group in the TW Hya area may be less dense than Taurus-Auriga. Clearly we need to probe a larger area in order to test for the presence of a cluster of young stars. In the following section, we discuss our search for additional members of a putative group over a larger area using Hipparcos data.

4.2. Hipparcos Sources

The biggest obstacle to identifying isolated young stars is typically the uncertain distances to any candidates. Without an associated molecular cloud or cluster, the distance to a star is very uncertain (unless it is close enough to have a measured parallax) and it cannot be placed on an HR diagram to determine its age from theoretical evolutionary tracks. Instead, more indirect arguments must be used. The identification of a distributed population of young stars via X-ray emission and Li absorption has recently been called into question by Briceño et al. (1997), who point out the similarities in X-ray and optical properties of stars with ages from 10^6 to 10^8 yr. The Hipparcos catalog (ESA 1997; see also Perryman et al. 1997) alleviates this problem somewhat, since it contains distances to over 10^5 stars in the solar neighborhood, allowing accurate age determinations of many more stars than was previously possible.

We used the Hipparcos catalog to test the question of whether there is an additional population of $\sim 10^7$ yr old stars in the vicinity of the five previously known young stars in the TW Hya area identified by Gregorio-Hetem et al. (1992). We placed all of the stars observed by Hipparcos in this region on an HR diagram, and identified candidate pre–main-sequence stars by choosing stars above the main sequence. Because stars selected in this way can be either pre–main-sequence or post–main-sequence or unresolved multiple ZAMS or MS stars, we also studied the kinematics and X-ray properties of the candidate young stars.

For a specific comparison, we took the properties of the Taurus-Auriga molecular cloud complex as typical of low-density star forming regions and used these properties to define a search region in the Hydra area. The known pre–main-sequence stars in Taurus-Auriga are distributed over an area roughly $14^\circ \times 14^\circ$ on the sky. Within this area, there are several distinct subgroups with radii of ~ 0.5–1 pc and internal velocity dispersions of ≤ 1–2 km s^{-1} (Jones & Herbig 1979, Gomez et al. 1993). The group sizes are similar to the Jeans length for the associated dark clouds and to the measured size of the clumps in the molecular gas, suggesting group formation from gravitational instabilities (Gomez et al. 1993).

One of these small groups of stars placed at the distance (~ 50 pc) and age ($\sim 10^7$ yr) of HD 98800 would look quite different from its present day appearance in Taurus. A velocity of 1 km s^{-1} corresponds to a distance traveled of 10.2 pc in 10^7 yr. Thus, if it is not gravitationally bound, a group of this age at a distance of 50 pc should have an angular radius of order 10°. The intrinsic proper motions of any group members should also be relatively small; a lateral motion of 1 km s^{-1} at 50 pc gives 4.2 mas yr^{-1}. Indeed, the space motions of TW Hya and HD 98800 in the plane of the sky are only a few km s^{-1} (see Table 6 and Sec. 4.2.1).

We used $11^{\rm h}15^{\rm m}$ $-32^\circ 20'$ (J2000), the mean RA and Dec. of the five previously-known young stars in this area, as the center of our search area; four of the five lie within $\sim 5^\circ$ of this point, with HD 98800 at $\sim 8^\circ$. We searched an area 10° in radius and selected all stars from the Hipparcos catalog with parallaxes in the range 15.5–24.3 mas. This is the range of the parallaxes of TW Hya and HD 98800 plus or minus their 1σ uncertainties, corresponding to distances of 41.2–64.5 pc. Thus, our search encompasses a volume of space roughly 10 pc in radius, centered on the five previously known young stars in this area. Additional selection criteria (which in practice excluded only a few stars) were the presence of a $B-V$ measurement in the Hipparcos catalog and a parallax uncertainty of less than 8.1 mas.

This search yielded 60 stars. We rejected those with luminosity classes I, II, or III (3 stars) and plotted the rest on an HR diagram. Bolometric corrections and the conversion from spectral type to effective temperature were taken from Kenyon & Hartmann (1995). For a few stars, no spectral type was available, and $B-V$ color was used instead. We did not correct for extinction; since the effective temperature for most of the stars was determined from their spectral types rather than $B-V$ colors, the primary effect of any extinction will be to make stars appear fainter than they really are. Since an unresolved binary companion can raise the apparent luminosity of a star by up to a factor of two, we selected as candidate young stars only those stars that lie more than a factor of two above the zero-age main sequence (ZAMS).[7] This yielded 11 stars, including HD 98800 and

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[7]In practice our criteria exclude most 10^7-yr-old stars earlier than about F2, since a line a factor of two above the ZAMS intersects the 10^7 yr isochrone at $T_{\rm eff} \approx 6800$ K.

TW Hya, the only two of the five previously known young stars that are in the Hipparcos catalog. The candidate young stars are listed in Table 6 and plotted in Figure 2; we discuss them in detail below.

Four of the 11 stars are known multiples. For each of these, we determined the magnitude of the primary and used that to plot the system on the HR diagram. For CD $-36°7429$ and HD 96202 we used the primary magnitude from the Catalog of Components of Double and Multiple Stars (CCDM; Dommanget & Nys 1994). For HD 95221, we used the flux ratio and combined system magnitude from the Hipparcos catalog to determine the individual component magnitudes. For HD 98800, we used the primary (component Aa) magnitude of $V = 9.40$ from Soderblom et al. (1998). Correcting the magnitude of HD 96202 places it less than a factor of two above the ZAMS; we retain it in our sample for consistency in later comparisons with other samples selected in the same way (see below), since it passed the original selection criteria.

All but one of the stars have MK spectral types; for CD $-36°7429$, the CCDM gives a spectral type of Mp. Since the $B - V$ value (1.66 ± 0.4) has such a large uncertainty, we adopted a spectral type of M0 to place it on the HR diagram. If the spectral type is later than this, the inferred age will be even younger.

As Figure 2 shows, there are several stars whose positions on the HR diagram (if they are PMS stars) imply ages of 1–2 $\times 10^7$ yr, consistent with the ages previously found from Hipparcos data for TW Hya (Wichmann et al. 1998) and HD 98800 (Soderblom et al. 1998). To further explore these stars' properties, we examined the *ROSAT* All-Sky Survey to determine their X-ray fluxes.

Of the stars listed in Table 6, two are clearly detected in the RASS, namely CD $-28°8704$ and CD $-36°7429$, while HD 99076 is marginally detected (at $\sim 2\sigma$ significance). The X-ray source found near CD $-28°8704$ might, however, be unrelated. The X-ray source is $1'$ off the optical position while most X-ray sources found near the Taurus TTS are within $40''$ (Neuhäuser et al. 1995), and there are two other stars in the DSS image of the field that lie with $40''$ of the X-ray position.

We list the X-ray properties of the three X-ray detected stars in Table 7, including the offset between the X-ray and optical positions, the likelihood of existence $\mathcal{L}$ in the RASS, the individual exposure times, and the broad band (0.1 to 2.4 keV) count rates (background subtracted and corrected for vignetting). As in the case for the other young stars in this area with RASS fluxes, some spectral information can be obtained using the hardness ratios. These hardness ratios are given in the following two columns. Count rates from RASS observations were converted to fluxes using the hardness ratios as above in Sec.

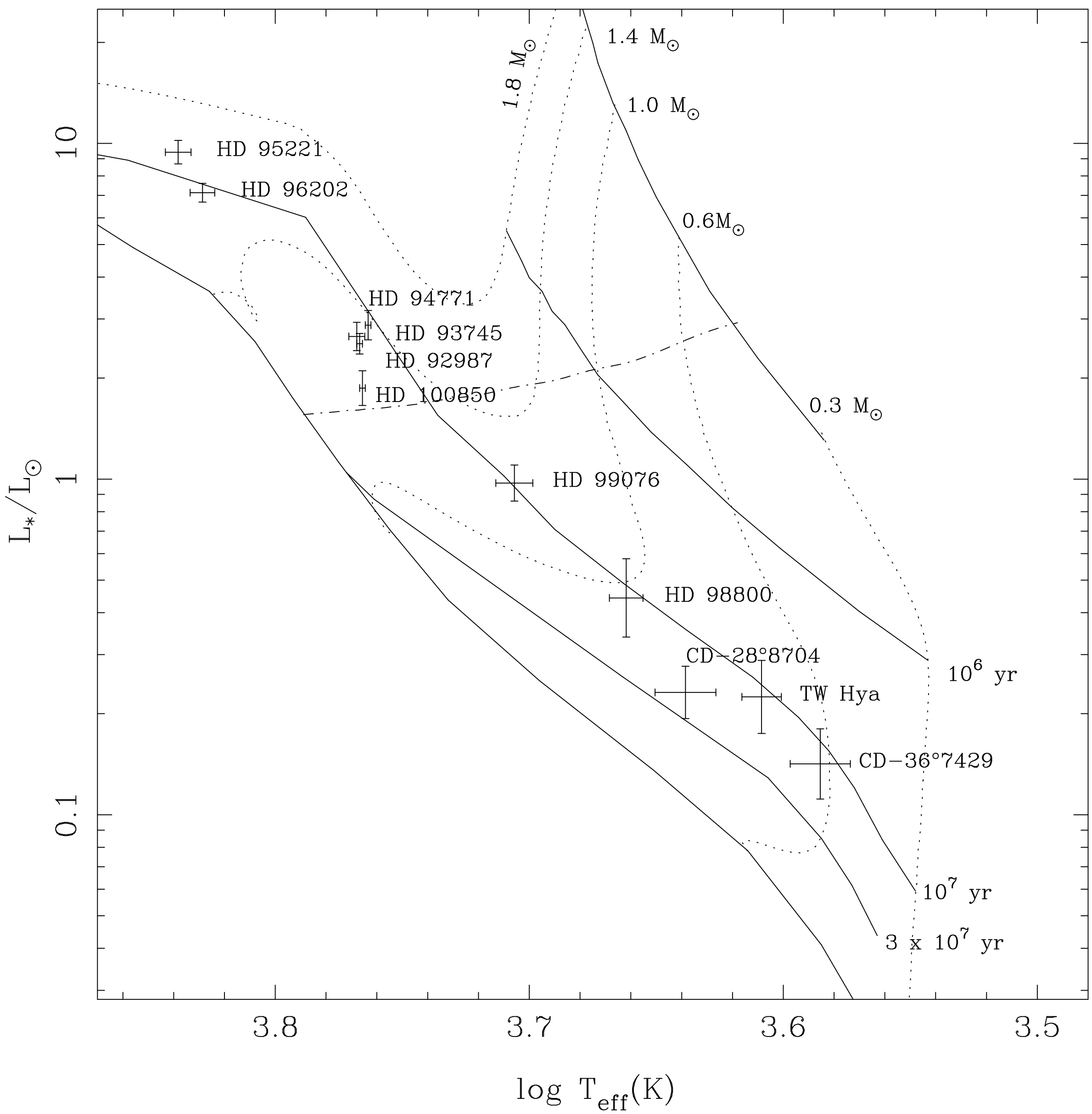

Fig. 2.— HR diagram of candidate young stars. The evolutionary tracks and isochrones are from D'Antona & Mazzitelli (1994) with Alexander opacities and CM convection. The dashed line shows $V = 7.8$ at a distance of 50 pc, with a bolometric correction added; the Hipparcos catalog is incomplete below this level.

Table 6. Candidate young stars near TW Hya from Hipparcos

Star	Spectral type	Distance (pc)	Multiplicity	V_{LSR}[a] (km s^{-1})
HD 95221	F2 V	48.6 ± 2.0	binary	15.8
HD 96202	F3 IV/V	43.5 ± 1.4	binary	25.4
HD 93745[b]	G2 V	55.5 ± 2.7	single	64.4
HD 92987[b]	G2/G3 V	44.0 ± 1.5	single	16.2
HD 100850[b]	G3 V	59.9 ± 3.6	single	39.4
HD 94771	G3/G5 V	54.7 ± 2.8	single	9.4
HD 99076[c]	K1 V	49.9 ± 3.1	single	33.5
HD 98800	K4 V	46.7 ± 6.2	quadruple	4.5
CD −28°8704	K5 V	50.6 ± 4.5	single	10.5
TW Hya	K7 V	56.4 ± 7.0	single	3.9
CD −36°7429	Mp[d]	50.3 ± 6.0	binary	2.2

[a]Transverse velocity relative to the local standard of rest based on Hipparcos proper motion and distance.

[b]Classified as "inactive" by Henry et al. (1996) based on Ca II H and K emission.

[c]Classified as "active" by Henry et al. (1996) based on Ca II H and K emission.

[d]Spectral type of M0 used to plot on HR diagram.

3.3. The final column gives the X-ray luminosity.

CD $-36°7429$ has hardness ratios and $L_{\rm X}$ in the range of values given for the young stars in Table 3. As discussed in the following section, its transverse velocity is also the closest to that of HD 98800 and TW Hya, suggesting a possible physical relationship. CD $-28°8704$ and HD 96771 are fainter in X-rays than the previously-known young stars near TW Hya. However, the X-ray emission levels of these stars are not unheard of for T Tauri stars; Feigelson et al. (1993) found a mean X-ray luminosity of $\log L_X = 29.2$ for T Tauri stars in Chamaeleon. The fact that CD $-28°8704$ and HD 96771 are detected only at the 2–3 σ level indicates that their X-ray fluxes are near the sensitivity limit imposed by the short exposure times of the RASS, which could account for the non-detection of some of the other stars. However, the fact that none of the G stars in Table 6 were detected in X-rays suggests that they may be older, since PMS G stars tend to have higher X-ray luminosities than PMS stars of later spectral types (Feigelson et al. 1993, Gagné et al. 1995, Neuhäuser et al. 1995).

The stars as a group do not show evidence of enhanced chromospheric activity in optical observations. Five of them were observed in the Ca II H and K lines by Henry et al. (1996). Of these, three were classified as "inactive"; only HD 99076 was classified as "active". HD 98800 was observed but was not classified in either of these groups due to the difficulty of determining the underlying photospheric level near the H and K lines for cooler stars; it has Ca II H and K emission that is stronger than most field stars of its color (Soderblom et al. 1996).

The lack of strong X-ray emission from most of these stars suggests that some of them may be 10^9-yr-old subgiants that are just leaving the main sequence rather than 10^7-yr-old PMS stars. However, early F stars have very weak X-ray emission even in the PMS phase, so this alone does not reveal whether these stars are young or old. To further investigate the origin of these stars we examined their kinematics and compared this field with other fields at the same Galactic latitude. The kinematics not only help discriminate between old

Table 7. X-ray properties of candidate young stars near TW Hya

Name	Offset	$\mathcal{L}$	Exposure Time (s)	counts ks^{-1}	HR 1	HR 2	Flux/10^{-12} erg s^{-1} cm^{-2}	$\log L_X$ (cgs)
CD $-28°8704$	$63''$	13	322	39 ± 14	-0.03 ± 0.35	0.03 ± 0.49	0.32 ± 0.11	29.0
HD 99076	$30''$	5	95	43 ± 28	0.77 ± 0.66	≥ -0.21	0.53 ± 0.42	29.2
CD $-36°7429$	$19''$	115	133	345 ± 54	-0.19 ± 0.16	-0.23 ± 0.25	2.52 ± 0.61	29.9

and young stars; they also allow us to test the suggestion that the young stars near HD 98800 formed together as a group, perhaps from a rapidly-moving cloudlet (Feigelson 1996, Kastner et al. 1997).

4.2.1. Kinematics of the young stars

If the young stars near TW Hya were formed in a group from the same molecular cloud, they should have similar space motions. To test this, we subtracted the motion of the Sun relative to the Local Standard of Rest (LSR) from the observed proper motion of each star.[8] The resulting motions are shown in Figure 3; the proper motions of the stars have been projected backward in time to show the positions of the stars on the sky relative to each other 10^7 yr ago. It is clear that over this amount of time, roughly their estimated ages, the stars were not near each other. Thus it seems unlikely that they formed together.

All of the stars besides HD 98800, TW Hya, and CD $-36°7429$ have transverse space velocities greater than 10 km s^{-1}. Even ignoring the radial component of their motions, their relative velocities (Table 6 and Figure 3) are much greater than the few km s^{-1} velocity dispersion seen for young stars in Taurus (e.g., Jones & Herbig 1979). These high velocities are more characteristic of giants than of young stars. In contrast, CD $-36°7429$ has a space velocity similar to that of HD 98800 and TW Hya, and it is the brightest X-ray source of the group. Its X-ray brightness and low space velocity suggest that it may well be a pre–main-sequence star.

We conclude that most of the stars in Table 6 are probably not young (being perhaps mis-classified subgiants or giants, or unresolved triple systems), while CD $-36°7429$ is quite likely a 10^7-yr-old PMS star. As this paper was nearing completion, we obtained spectra of these stars as part of another observing program. These observations confirm the conclusions above: of the candidate young stars in Table 6, only CD $-36°7429$ has detectable Li absorption; the others all have EW(Li) < 0.1 Å. We will report in detail on these spectroscopic follow-up observations in a later paper, where we shall also present the radial velocities.

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[8]We used an LSR velocity of $(U, V, W) = (9, 12, 7)$ km s^{-1} (Delhaye 1965), where U, V, and W are positive in the directions of the Galactic center, Galactic rotation, and North Galactic Pole, respectively.

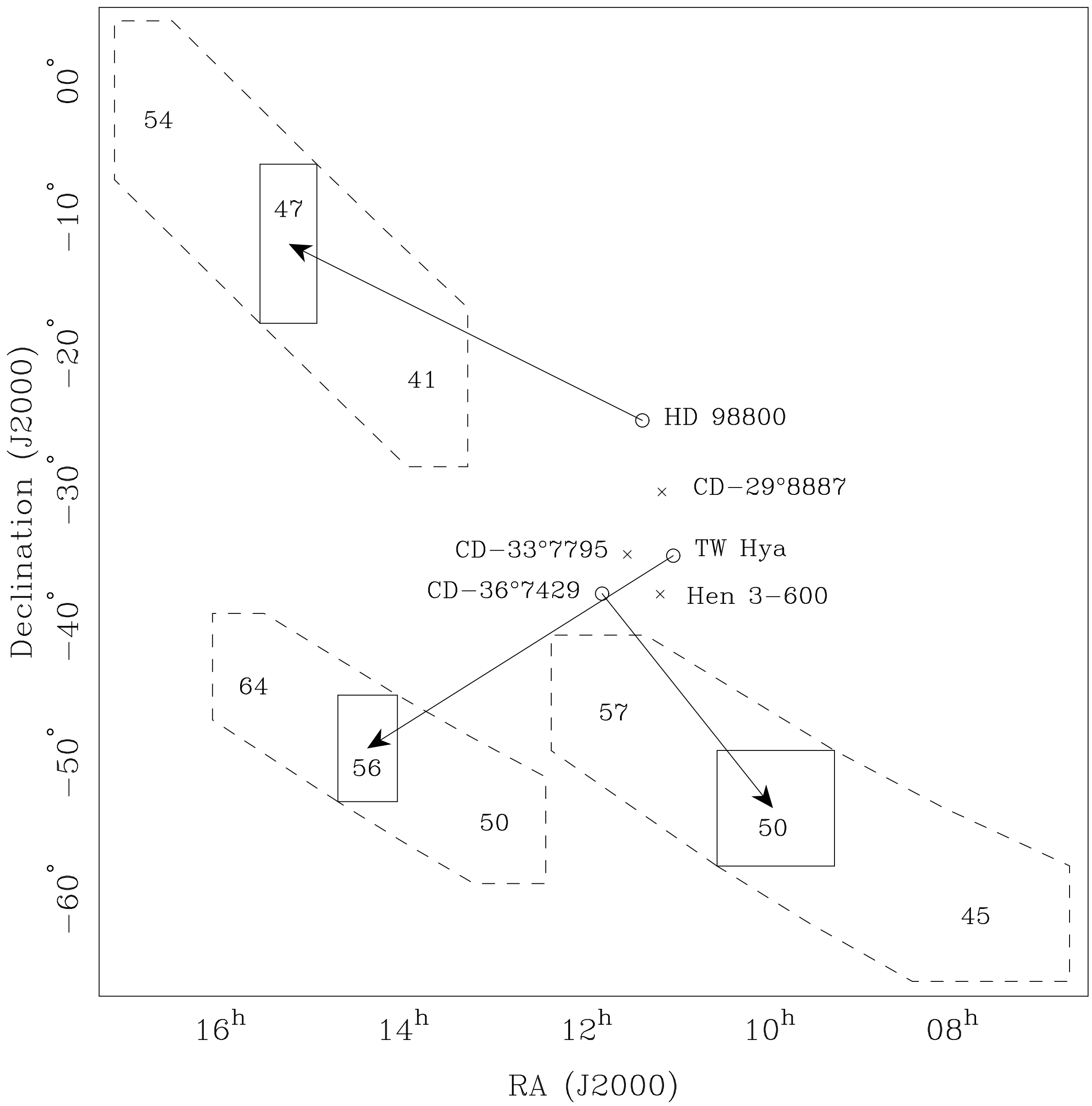

Fig. 3.— Proper motions of confirmed young stars, projected back in time from the stars' current positions. The tips of the arrows show the stars' positions on the sky 10^7 yr ago; the boxes show the uncertainty on the proper motion. If the stars formed together, the arrows should point toward their common place of origin. This appears not to be the case. Note that the length of the arrows represents motion over the estimated 10^7 yr ages of TW Hya and HD 98800. Young stars without known proper motions are shown with crosses. The dashed lines show the effect of 1σ distance uncertainties on the subtracted solar motion. The numbers represent the current distances in pc used to calculate the motions.

4.2.2. Comparison with other fields

Is there an excess of young stars near HD 98800? We searched other fields at similar Galactic latitudes to find out. The center of our original search field corresponds to Galactic coordinates $(l, b) = (280.^{\circ}3, +26.^{\circ}3)$. We selected 28 other fields centered at $|b| = 26.^{\circ}3$, starting at $l = 16^{\circ}$ and separated by increments of $l = 24^{\circ}$ (which gives an angular separation of $21.^{\circ}4$). Thus the edges of these 10°-radius fields are separated by roughly $1.^{\circ}4$ and cover most of the sky at $|b| = 26.^{\circ}3$. The only fields excluded were (280°, $26.^{\circ}3$), which overlaps our original field, and (184°,$-26.^{\circ}3$), which includes the Hyades.

We applied the same selection criteria used for the original field (parallax of 15.5–24.3 mas, parallax uncertainty $<$ 8.1 mas, and presence of a $B - V$ measurement) to each of these fields. As before, we rejected stars with luminosity classes I, II and III, plotted the remaining stars on the HR diagram, and counted the number of stars in each field that were more than a factor of two above the ZAMS.

First, we simply compared the number of stars meeting our selection criteria without knowledge of whether these stars are pre– or post–main-sequence. The average for 28 fields is 11.4 stars, with a standard deviation of 3.9, not significantly different than the 11 stars found in our main search field. Limiting the comparison to only stars later than G0 (to match the range of spectral types for T Tauri stars) and eliminating any stars with spectral class IV gives 7.2 $\pm$ 3.5 stars per field in the comparison fields, compared with 9 in our main search field, again not a significant difference; similar results are found for stars K0 and later. Even adding CD $-33^{\circ}7795$, CD $-29^{\circ}8887$, and Hen 3–600 to our main search field sample and comparing against the Hipparcos-only sample in other fields gives only a 1σ excess of stars K0 and later. Comparing the percentages of stars meeting these criteria rather than the absolute numbers does not change the results.

Thus, the presence of 11 Hipparcos-selected stars above the main sequence in the field near HD 98800 represents not an unusual excess but rather the norm in a 10°-radius field for that Galactic latitude and distance. However, if most of the stars selected in this way are post–main-sequence stars rather than pre–main-sequence stars, as suggested by the X-ray emission and kinematics of the candidates in our main search field, then this comparison does not tell us whether the young-star population near TW Hya is unique.

As noted above, HD 98800, TW Hya, and the X-ray bright CD $-36^{\circ}7429$ have lower transverse space velocities relative to the LSR than do most of the other stars in their field. Thus, we also compared the number of stars with low transverse space velocities in our main field to that in other fields. We counted the number of stars in each field that meet our initial selection criteria and also have $V_{LSR} \leq 5$ km s^{-1}. In our main search field, there are three. Of the other 28 fields, 22 have no candidates with velocities this low, five have one candidate, and one has two candidates. This gives an average of 0.35 per field (including our main field). Given this average rate, the Poisson probability of three or more low velocity stars in a field is 0.005. Thus, the main search field does have a low-velocity population that is significantly above the mean. We note that we had no *a priori* knowledge of the stars' space velocities in choosing this field. However, we caution that we did not choose the velocity cutoff *a priori* though it is physically plausible based on velocity dispersions of known young stars. If low transverse velocity is a reliable discriminant between old and young stars, as the close relationship between space velocity, X-ray flux, and Li shown above suggests, the area around TW Hya does indeed seem to have significantly more young stars than other fields at the same distance and Galactic latitude.

5. Discussion

Feigelson (1996) suggested that the five young stars in the vicinity of HD 98800 and TW Hya might have formed from a rapidly-moving cloudlet that has since dissipated. In this model, the young stars might have high space velocities but should have a relatively low velocity dispersion among them. This hypothesis is ruled out for HD 98800 and TW Hya by the very different direction of their space motions.

Two of the young stars, TW Hya and CD $-36°7429$, apparently were relatively close to each other (at least in projection) a few million years ago. Without knowing their radial velocities it is difficult to tell how close they were. However, extrapolating their present motions to their birth epoch of roughly 10^7 years ago places them far apart.

It is still possible that one or more of the other three stars (CD $-33°7795$, CD $-29°8887$, and Hen 3–600) shares a common origin with HD 98800, CD $-36°7429$, or TW Hya. In addition, it is likely that more young, late-type stars exist in this area. The completeness limit of the Hipparcos catalog depends on Galactic latitude and spectral type; it is $V = 7.8$ for stars later than G5 and $V = 8.4$ for stars earlier than or equal to G5 at $b = 26\overset{\circ}{.}3$ (Turon et al. 1992). Even taking the faint end of this completeness limit (the dashed line in Figure 2), the Hipparcos catalog is seriously incomplete for K and M stars at a distance of 50 pc. However, until the proper motions of these fainter stars can be measured, there is no evidence that a group of pre–main-sequence stars formed together in this area.

This fact, combined with the statistical analysis in the previous section, leads to a puzzling result. There seems to be an excess of young stars in this area, and yet their space velocities suggest that at least some of them did not form together. Studies of the kinematics of the other young stars in this area may help resolve this apparent paradox.

Finally, we note that the apparent excess of young stars in this area from the work of de la Reza et al. (1989) and Gregorio-Hetem et al. (1992) was discovered partly by chance. Neither CD $-29°8887$ nor CD $-33°7795$ meet the original selection criteria (an *IRAS* detection) of these studies. After CD $-29°8887$ was observed spectroscopically, the *IRAS* source nearby that led to its original selection was found to be associated with a galaxy projected nearby. CD $-33°7795$ was identified later because of its spectroscopic similarity to CD $-29°8887$. While these two stars are most probably pre–main-sequence based on their X-ray properties, there may be many more such sources in areas that have not been surveyed spectroscopically in as much detail.

6. Summary and Conclusions

We have presented pointed *ROSAT* observations of the isolated young stars HD 98800 and CD $-33°7795$. Their X-ray fluxes and X-ray variability are consistent with them being pre–main-sequence stars. No other pre–main-sequence stars were found among X-ray sources within $40'$ of these stars.

Hipparcos observations of the area reveal the presence of nine additional stars that lie above the main sequence in a volume roughly 10 pc in diameter centered on the five previously known young stars. The X-ray properties and kinematics of these stars indicate that one of them (CD $-36°7429$) is quite likely a PMS star with an age of 10^7 yr, while the others are more likely post–main-sequence stars. Observations of Li abundances in these stars confirm this conclusion.

Comparison with other fields at the same Galactic latitude shows that other fields selected in the same way show similar numbers of stars above the main sequence. However, the field around TW Hya has significantly more stars with low space velocities (less than 5 km s^{-1} relative to the LSR) than the other fields. Thus, there is some indication of an excess of young stars in this area. Nonetheless, the proper motions of HD 98800, TW Hya, and CD $-36°7429$, if extrapolated back in time, do not indicate a common place of origin.

Note added in proof:

Our analysis of whether HD 98800, CD $-36°7429$, and TW Hya could have formed as a group neglected an important source of uncertainty. The uncertainty in distance to these stars, while it does not affect the observed proper motions, does introduce uncertainty into the solar motion that must be subtracted in order to determine the stars' intrinsic proper motions with respect to the LSR. The 1σ effect of this uncertainty is shown by the dashed lines in Figure 3. Including this uncertainty indicates that TW Hya and CD $-36°7429$ could plausibly have formed together; only a 1.5σ error on their distances is required. Regarding HD 98800, bringing its current distance 2σ closer, to 36.8 pc, would allow its projected point of origin to overlap with those of the other two stars. However, this distance makes HD 98800 a main-sequence star, in conflict with its observed properties and, more importantly, of a very different age than the other two stars. We conclude that HD 98800 is unlikely to share a common origin with TW Hya or CD $-36°7429$.

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