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Letter to the Editor

HIPPARCOS results for ROSAT-discovered young stars

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Abstract. Out of $\sim$ 500 Lithium-rich ROSAT counterparts, which were presumed to be low-mass pre-main sequence stars, 21 stars have been observed by HIPPARCOS. We study their parallaxes, proper motions, and photometric data. For 7 out of 10 Taurus and Lupus stars in our sample, proper motions and parallaxes are not inconsistent with membership to these associations, while most of the stars in Chamaeleon and Scorpius appear to be young foreground stars. Combined with ground based photometry and spectroscopy, HIPPARCOS parallaxes allow us to place 15 stars on an H-R diagram. All these 15 stars lie above the Zero-Age-Main-Sequence and thus are indeed pre-main sequence stars with ages from 1 to 15 Myr. Only two of the stars are located on the Hayashi-tracks, whereas the other 13 are post-T Tauri stars located on radiative tracks. Although the sample is admittedly small, containing only 3% of the total sample of Lithium-rich ROSAT counterparts, it does not confirm recent predictions by other authors: We find no stars in the age range from 20 to 100 Myr. The foreground pre-main sequence stars may have been ejected towards us, or they belong to the Gould Belt system, a plane filled with young stars.

Key words: astrometry – stars: late-type – stars: pre-main sequence – stars: kinematics – H-R diagram

1. Introduction

Spectroscopic and photometric follow-up observations of sources from the ROSAT All-Sky Survey led to the discovery of many Lithium-rich stars. As Lithium is destroyed gradually in the deeper layers of the convection zone (Bodenheimer 1965), the detection of the LiI 6708Å line in low-resolution spectra was generally assumed to be a good indicator for the youth of a star. About 500 stars were classified as low-mass pre-main sequence (PMS) stars, and it was assumed that they were located at the same distance as previously identified classical T Tauri stars (cTTS) in the respective star forming regions (see Neuhäuser 1997 for a review). As most of these new stars lack infrared excess and strong $H\alpha$ emission, they were classified as weak-line T Tauri stars (wTTS), irregardless of whether they are on convective tracks, i.e. being coeval with cTTS, or on radiative tracks, i.e. being post-TTS. Unlike most cTTS, which are associated with dark clouds, the new wTTS show a much more wide-spread distribution.

Recently, Briceño et al. (1997) argued that a dispersed population of young (foreground) Zero-Age-Main-Sequence (ZAMS) stars with ages up to 100 Myr could account for the observed properties of the ROSAT sources as well. One can accept a ROSAT counterpart as PMS star only, if it shows Li stronger than ZAMS stars of the same spectral type (SpTy). The Li criterion does not work for G-type stars, as G-type ZAMS stars still show the primordial Li. Membership of a star to an association can be tested by studying its kinematics, i.e., its radial velocity RV and proper motion PM. Although RV consistent with membership to an association may be suggestive (Neuhäuser et al. 1997, henceforth N97), it is not conclusive for showing 3D kinematic membership (Frink et al. 1997, F97).

A better way to determine the evolutionary status is to measure the distance to a star, compute its luminosity, and place it on the H-R diagram. In order to solve the current dispute as to whether the Li-rich stellar counterparts to ROSAT sources are ZAMS or PMS stars, we study the HIPPARCOS data (ESA 1997) of 21 Li-rich ROSAT stars, discuss the kinematics, and present their evolutionary status.

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2. Li-rich ROSAT stars observed by HIPPARCOS

We have complied a list of all Li-rich ROSAT source counterparts which were claimed to be PMS stars – found in Chamaeleon (Alcalá et al. 1995, A95; Covino et al. 1997, C97), Lupus (Krautter et al. 1997, K97; Wichmann et al. 1997b, W97; Wichmann et al., in preparation, W98), Scorpius (Kunkel et al., in preparation, K98; c.f. also Brandner et al. 1996, B96), Taurus (Wichmann et al. 1996, W96; Magazzù et al. 1997, M97; N97), and Orion (Alcalá et al. 1996). 21 of the Lithium-rich ROSAT counterparts have been observed by HIPPARCOS (Table 1).

Table 1. Lithium-rich ROSAT stars in HIP

Designation	Area	SpTy	Ref.	Li	Ref.
BD+11°533	Tau	G2	M97	0.10	M97 (a)
HD 284149	Tau	G1	W96	0.20	W96
BD+17°724B	Tau	G5	W96	0.41	W96
HD 283798	Tau	G7	W96	0.29	W96
HD 81485	Cha	G3	A95	0.05	C97 (b)
HD 84075	Cha	G1	A95	0.16	C97 (b)
HD 92727	Cha	G1	A95	0.03	C97 (b)
HD 99827	Cha	F5	A95	0.08	C97 (c)
RXJ1158.5−7754a	Cha	K4	A95	0.48	C97 (c)
RXJ1159.7−7601	Cha	K4	A95	0.50	C97 (c)
RXJ1224.8−7503	Cha	K2	A95	0.25	A95
HD 109138	Cha	K1	A95	0.13	C97 (c)
HD 137727	US-B	K0	B96	0.13	K98
HD 138009	US-B	G6	B96	0.34	K98
HD 140637	US-B	K3	B96	0.43	K98
RXJ1504.8−3950	Lup	F8	W97	0.33	W97
HD 134974	Lup	G7	K97	0.17	W98
HD 141277	Lup	K0	K97	0.60	K97
CoD−36°10569	Lup	K3	K97	0.48	W98
HD 143677	Lup	K1	K97	0.58	W98
HD 143978	Lup	G2	K97	0.17	W98

Remarks: 'US-B' stands for Upper Scorpius B (cf. B96). All stars are classified as 'wTTS' (by ref. given for SpTy). 'Li' is equivalent width W_λ(Li) of the LiI 6708Å line in Å. W_λ(Li) for K97 and W96 stars are from R. Wichmann (private communication); spectra are shown in K97 and W96. SpTy for A95 stars are from C97. (a) Classified 'PMS?' (M97), RV inconsistent with membership (N97). (b) RV inconsistent with membership (C97). (c) RV consistent with membership (C97).

3. HIPPARCOS astrometry results

To check whether our stars could be members of the respective associations regarding distances and kinematics, we need to know PM, RV, and distances of bona-fide TTS. HIPPARCOS data of well-known PMS stars are given by Wichmann et al. (1997c). Averaging the parallaxes of the stars in each region, they obtain the following distances: Taurus (5 PMS stars used) at (142 ± 14) pc, Lupus (5) at (190 ± 27) pc, and Cha I (3) at (160 ± 17) pc. De Bruijne et al. (1997) give (145 ± 2) pc as mean distance to early-type stars in the Upper Sco association. These values agree with previous distance estimates. Since all these associations extend by tens of pc in the plane of the sky, we have to expect a similar extent in distance.

TTS in **Taurus** show a mean PM of $(\mu_\alpha \cdot \cos\delta, \mu_\delta)$ = (6.4, −22.0) mas/yr (Jones & Herbig 1979), or (4.0, −18.7) mas/yr, if one includes the W96 and M97 stars, with $\sim$ 6.5 mas/yr scatter (F97). While the S/N of the HIPPARCOS data of BD+17°724B is too low for any conclusion, the data for the other three Taurus stars are not inconsistent with membership and agree well with data given in F97. Members of **Upper Scorpius** show a mean PM of $(\mu_\alpha \cdot \cos\delta, \mu_\delta)$ = (−25, −10) mas/yr (de Bruijne et al. 1997). Space motions and distances indicate that HD 137727, HD 138009, and HD 140637 are with not kinematic members of Upper Sco. Nevertheless, they are young post-TTS with ages between 5 and 11 Myr. Eight cTTS in **Lupus** are listed in the STARNET/PPM and show a mean PM of $(\mu_\alpha \cdot \cos\delta, \mu_\delta)$ = (−12, −26) mas/yr with a scatter of $\sim$ 7 mas/yr (Frink et al., in preparation). Of our six Lupus stars, four have distances consistent with the association, and three of those four also have PM consistent with membership, while RXJ1504.8-3950 and CoD−36°10569 are not members of the Lupus T association. All seven stars in **Chamaeleon**, for which we could derive HIPPARCOS distances, appear to lie in the foreground of the molecular clouds. Five stars are young post-TTS with ages between 10 and 16 Myr, and RXJ1158.5-7754a is a wTTS with an age of 3 Myr. HD 89499 (HIP 49616, RXJ10077-8504), classified as a possible PMS star by A95 and C97, was also observed by HIPPARCOS. Its large PM indicate that it is a halo star, albeit with an unusual high Li-strength (Balachandran et al. 1993). Its parallax is 8.93 ± 0.73 mas, i.e. 112^{+10}_{-8} pc.

Table 2. Binary stars in the sample

Designation	ρ [arc sec]	θ	ΔH_p [mag]
HD 81485	9.025 ± 0.005	194°	1.15 ± 0.03
HD 92727	4.981 ± 0.010	347°	1.60 ± 0.05
HD 137727	2.214 ± 0.003	183°	0.31 ± 0.02
HD 138009	1.531 ± 0.006	26°	0.18 ± 0.04
HD 143677	0.290 ± 0.007	152°	0.34 ± 0.08

In Table 2, we list binary companions found by HIPPARCOS: Angular separation ρ, position angle θ, and magnitude difference ΔH_p in the HIPPARCOS system. The HIPPARCOS binary parameters for HD 92727, HD 137727, and HD 138009 agree well with the B96 results from sub-arc second seeing observations with SUSI at the ESO-NTT. From the same data set, we also confirm the parameters measured by HIPPARCOS for the pair HD 81485, although this wide pair was not included in B96. The companion to HD 140637 could not be confirmed, neither by HIPPARCOS nor by near-infrared speckle (R. Köhler, private communication). Re-examination of the SUSI/NTT data shows that the apparent binary companion was an artefact due to telescope movement during the exposure. HIPPARCOS also observed the A-type star HD 135619 (HIP 74797) in Scorpius, which is located just 18″ off the Li-rich ROSAT star CoD−34°10292B (K98), a close binary (B96); the parallax of HD 135619 yields $\approx$ 124 pc, consistent with Scorpius. HIPPARCOS lists CoD−34°10292B as companion to HD 135619.

4. The H-R diagram based on parallaxes

Combining SpTy, V, and I (A95, Wichmann 1994, K98) with HIPPARCOS parallaxes yield the absolute bolometric luminosities of our stars, assuming intrinsic colours, bolometric corrections, and a SpTy–$T_{\rm eff}$ relation of late-type dwarfs (Hartigan et al. 1994). We estimate ages and masses by comparison with theoretical isochrones and tracks from D'Antona & Mazzitelli (1994). In Table 3 we present luminosities, ages, and masses.

According to the H-R diagram, shown in Fig. 1, all of our stars are PMS stars: HD 143677 and RXJ1158.5−7754a are as

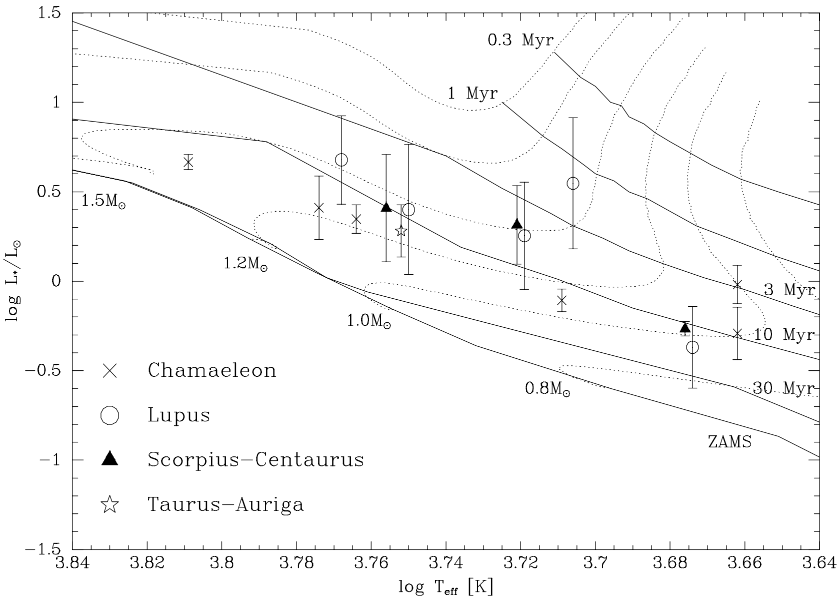

Fig. 1. H-R diagram for our stars with theoretical tracks and isochrones from D'Antona & Mazzitelli (1994) with Alexander opacities and CM convection. Error bars are calculated from errors in the HIPPARCOS parallaxes.

Table 3. HIPPARCOS astrometry results and physical parameters of stars

Designation	HIP no.	Proper motion [mas/yr] $\mu_\alpha \cdot \cos\delta$	μ_δ	Parallax π [mas]	Dist. [pc]	logT$_{\rm eff}$ [K]	log L/L$_\odot$	Age [Myr]	Mass [$M_\odot$]
BD+11°533	18117	6.4 ± 1.8	-16.6 ± 1.5	6.6 ± 1.6	153^{+50}_{-30}	3.768			
HD 284149	19176	6.0 ± 1.6	-15.4 ± 1.2	6.4 ± 1.8	156^{+62}_{-35}	3.774			
BD+17°724B	20782	-6 ± 26	-33 ± 21	8 ± 17	(1),(2)	3.760			
HD 283798	21852	-0.7 ± 1.4	-20.6 ± 1.0	8.7 ± 1.4	115^{+21}_{-16}	3.751	$0.28^{+0.15}_{-0.13}$	12	1.3
HD 81485B	45734	-107.4 ± 1.3	70.4 ± 1.1	13.8 ± 1.2	73^{+7}_{-6}	3.764	$0.35^{+0.08}_{-0.09}$	14	1.2
HD 84075	47135	-72.9 ± 0.7	49.8 ± 0.6	15.9 ± 0.7	63^{+3}_{-3}	3.774			
HD 92727	52172	3.3 ± 1.6	16.8 ± 1.4	7.8 ± 1.5	128^{+29}_{-20}	3.774	$0.40^{+0.18}_{-0.15}$	16	1.2
HD 99827(3)	55746	-48.0 ± 0.6	12.1 ± 0.6	12.1 ± 0.6	83^{+4}_{-4}	3.809	$0.67^{+0.04}_{-0.04}$	15	1.4
RXJ1158.5−7754a(4)	58400	-41.4 ± 1.4	-0.8 ± 1.1	11.6 ± 1.3	86^{+11}_{-9}	3.662	$-0.02^{+0.11}_{-0.10}$	3	1.0
RXJ1159.7−7601	58490	-39.9 ± 1.7	-4.7 ± 1.5	10.8 ± 1.7	92^{+17}_{-13}	3.662	$-0.29^{+0.15}_{-0.13}$	10	1.0
RXJ1224.8−7503	60553	-240 ± 20	-3 ± 14	41 ± 18	(1)	3.690			
HD 109138(3)	61284	-93.3 ± 1.1	13.5 ± 1.1	15.2 ± 1.1	66^{+5}_{-4}	3.706	$-0.11^{+0.06}_{-0.05}$	14	1.1
HD 137727	75769	23.9 ± 2.8	40.1 ± 3.1	11.5 ± 2.6	87^{+25}_{-16}	3.720	$0.32^{+0.22}_{-0.18}$	5	1.5
HD 138009	75924	-28.3 ± 2.8	-31.7 ± 2.8	10.9 ± 3.2	92^{+38}_{-21}	3.756	$0.41^{+0.30}_{-0.23}$	10	1.4
HD 140637	77199	-68.2 ± 1.1	-99.7 ± 0.9	24.4 ± 1.4	41^{+2}_{-2}	3.675	$-0.27^{+0.04}_{-0.04}$	11	1.0
RXJ1504.8−3950	73777	-30.4 ± 1.8	-32.8 ± 1.5	10.6 ± 1.7	94^{+18}_{-13}	3.792			
HD 134974	74565	-19.8 ± 2.2	-31.4 ± 1.6	5.1 ± 1.8	195^{+101}_{-50}	3.751	$0.40^{+0.36}_{-0.26}$	9	1.5
HD 141277	77524	-24.5 ± 2.0	-25.2 ± 1.8	6.6 ± 1.9	151^{+62}_{-34}	3.720	$0.25^{+0.30}_{-0.22}$	5	1.5
CoD−36°10569	78345	-16.2 ± 2.8	-48.9 ± 2.6	13.8 ± 3.2	73^{+22}_{-14}	3.675	$-0.37^{+0.23}_{-0.19}$	15	0.95
HD 143677	78684	-14.1 ± 2.4	-25.5 ± 1.9	7.0 ± 2.4	143^{+75}_{-37}	3.706	$0.55^{+0.37}_{-0.26}$	1.5	1.7
HD 143978	78774	-26.5 ± 1.4	-46.6 ± 1.3	6.2 ± 1.5	161^{+53}_{-32}	3.768	$0.68^{+0.25}_{-0.19}$	8	1.5

Remarks: (1) S/N lower than 2.5, i.e., the error in the parallax is too large to give a meaningful distance. (2) Star B is a few arc seconds off the A-type star BD+17°724, which has π = (8.0 ± 1.5)mas, i.e. 124^{+29}_{-20} pc. (3) No V or V-I measurements could be found in the literature. Thus we rescaled the luminosity estimates given by Alcalá et al. (1997). (4) The companion to this star has SpTy M3 with W_λ(Li)= 0.60 Å (C97) located ≈ 15″ south of companion *a* (A95), i.e., most certainly not bound.

young as 1.5 Myr to 3 Myr and contract along the Hayashi-tracks. The other stars have ages between 5 Myr to 15 Myr, and are thus post-TTS on radiative tracks. We find it remarkable that these stars form such a coherent sample with very similar physical properties (i.e., age and mass) even though they are spread out over a large region of the sky. The HIPPARCOS observations confirm earlier PMS classifications based mainly on Li and kinematics. Micela et al. (1997) argued that one of their two high-Li EMSS stars above the MS according to HIPPARCOS parallaxes is a post-MS giant. Eleven of our 15 PMS stars, however, do have Li stronger than in giants. Of the remaining four other stars, at least two have high rotational velocities ($v \cdot \sin i \approx 40\ km/s$, C97). One of them has SpTy later than

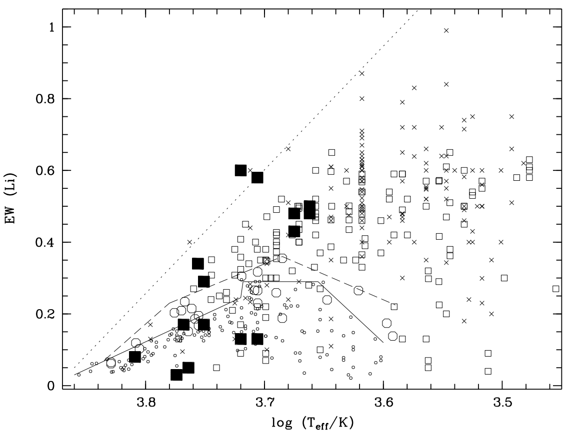

Fig. 2. Lithium equivalent width versus effective temperature: The stars in our sample with age estimates (filled squares) are compared to TTS in the Taurus clouds (crosses), IC 2602 (large circles), Pleiades (small circles), and Li-rich ROSAT counterparts (open squares), c.f. N97 for references; almost all Li data are from high-resolution spectra. The Li content of our PMS stars ranges from the primordial value to almost complete depletion. The lines indicate the upper envelope to Pleiades (full), IC 2602 (broken), and T Tauri stars (dotted).

G0, and thus rotates significantly faster than a typical post-MS giant (Gray 1989).

Briceño et al. (1997) argued that the majority of the ROSAT sources – claimed to be PMS stars – is a dispersed population of young stars with ages up to 10^8 yr. Their model assumes continuous star formation over 10^8 yr, but does not include recent star formation in clouds; they admit that many Li-rich ROSAT counterparts found on or near clouds actually are PMS stars. They predict that there should be roughly three times more 3 to 10×10^7 to yr old stars than $\leq 3 \cdot 10^7$ yr old stars off the clouds, which we cannot confirm. All the 15 stars, which we can place into the H-R diagram, are younger than $1.6 \cdot 10^7$ yr.

Comparing the W_λ(Li) distribution of these 15 stars with the other Li-rich ROSAT sources (Fig. 2) shows that our HIPPARCOS sample – with the exception of maybe two stars – is not biased towards high-Li stars. As only a few of our stars show more Li than Pleiades of the same SpTy, but all are PMS stars, the Li criterion – originally used to classify these stars as PMS stars – is conservative. Hence, there can be both PMS and ZAMS stars among stars with Li as low as ZAMS stars like the Pleiades of the same SpTy, while all stars with more Li than ZAMS stars of the same SpTy are younger and therefore PMS stars. A few of our ≈ 10 Myr old PMS stars show Li even lower than the Pleiades (Fig. 2), which may indicate that Li depletion is not well understood. However, we cannot completely rule out the possibility that these stars are unresolved binaries, and thus are erroneously placed too high in the H-R diagram (cf., e.g., Brandner & Zinnecker 1997).

Most of the Scorpius and Chamaeleon stars are located foreground to the associations, as conjectured by Briceño et al. (1997). Yet, all of the stars are PMS stars with ages below 16 Myr. Unlike cTTS, which are closely associated with dark clouds, most of the stars in our sample do not lie in the neighbourhood of a molecular cloud, but are isolated. Of the stars with estimated ages, all but two are several degrees off the nearest clouds; HD 141277 and HD 283798 are projected onto the Lup III and L1537 clouds, respectively. To investigate whether these isolated PMS stars may have been ejected towards us, we need to know their RV. For the Scorpius stars, RV are unknown. Four of the Chamaeleon stars have RV (C97) consistent with membership, while the RV of HD 81485B, HD 84075, and HD 92727 indicate that they may well have been ejected towards us, i.e. being run-away TTS (Sterzik & Durisen 1995). However, given the large errors in the proper motions, it is difficult to trace back the place of origin of these ~ 10 Myr old post-TTS. Guillout et al. (1997) studied the photometric distances of stars observed by both ROSAT and TYCHO. By comparing the distance distribution of stars on the Belt with those off the Belt, they found evidence for the Gould Belt system being a filled plane. Thus, the foreground stars may belong to the Gould Belt, if this system is an expanding plane – forming new stars only at its outer edge.

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