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The evolutionary status of activity-selected solar-type stars and of T Tauri stars as derived from Hipparcos parallaxes: evidence for long-lived T Tauri disks?*

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Abstract. We have used the Hipparcos parallaxes to study the evolutionary status of a sample of stars with spectral types from late F to M0 (hereafter "solar-type stars"), selected on the basis of their activity, mainly from *Einstein*-based surveys. The parallaxes have been used to place the objects in the H-R diagram, determining their age by comparison with theoretical evolutionary tracks and observational main sequences. This age is compared with age estimates derived from the lithium abundance, the activity level and the presence of circumstellar disks. To complement our sample at the young end we have also studied the Hipparcos-determined distances of a sample of optically-selected pre-main sequence stars, mostly classical T Tauri stars (CTTS). Some CTTS appear to be much nearer to us than previously determined, and far away from their putative parent cloud. This implies a significantly larger age providing observational evidence for the existence of long-lived T Tauri disks which could produce slow rotators on the Zero-Age Main Sequence (ZAMS).

None of the above-mentioned age proxies appears to reliably and unambiguously select very young stars in the range of spectral types considered here, with some apparently very young objects effectively lying onto or very close to the main sequence. The attribution of ages to young solar-type stars on the basis of any of the standard proxies may thus significantly under- or over-estimate the evolutionary age of the object. Caution must therefore be exercised when attributing ages to individual stars, and claims about the large number of PMS stars found in X-ray based surveys may need to be at least in part reconsidered in this light.

Key words: stars: activity – stars: late-type – stars: evolution; stars: formation – x-rays: stars

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* Based on data from the ESA Hipparcos satellite.

1. Introduction

X-ray and EUV flux-limited surveys have identified a widespread population of young active solar-type stars (Favata et al. 1993; Tagliaferri et al. 1994; Jeffries 1995); while this is not surprising, given the age-activity relationship observed in open clusters, the precise age distribution of this population (and thus the meaning of "young" in the present context) is still an open (and somewhat controversial) issue. Taking for granted that active stars as a population are in general young in comparison with the Galactic disk, if a significant fraction of them has ages $\lesssim 10$ Myr, as it has in some case been claimed (see below), their presence far from obvious sites of star formation would have large implications on the understanding of the processes that govern the birth of solar-type stars, the dispersal of newly formed stars in the early stages of their life, and the evolution of stellar structure in young stars.

Ages for activity-selected stars have been mostly estimated through the use of proxies, which include the activity level, the photospheric abundance of lithium, and (for very young stars) the presence of circumstellar disks with appreciable mass accretion rates (i.e. the T Tauri phenomenology). These indicators, which have been calibrated on open clusters as well as on members of star-forming regions (SFRs), are however of limited reliability when used on individual stars, because (1) they are of an intrinsic statistical nature, with a large spread at any given age and (2) often show saturation effects. In addition, the influence of eventual binary companions on the evolution of both the activity level (Pye et al. 1994) and the lithium abundance (Ryan & Deliyannis 1995) is not yet fully understood. Finally, some of these proxies are dependent on stellar mass (in particular the lithium abundance), introducing additional uncertainties.

Several recent papers have dealt with the nature (and thus the age) of stars detected in the ROSAT All-Sky Survey (RASS) in the general direction and in a rather ample neighborhood of nearby SFRs. The approach taken in this line of work has mostly been to associate with the SFR (and thus place at the distance of the SFR) all stars which exhibit a measurable, or "large", lithium abundance (see for example Wichmann et al. 1997; Alcalá et al.

1997; Wichmann et al. 1996). Even when the large fraction of sources with a spurious "high" lithium abundance ($\gtrsim 50\%$, Covino et al. 1998) is removed[1], these samples still contain a large number of putative PMS sources.

The implications of the presence of a large number of dispersed stars still in their PMS phase, perhaps still on the Hayashi tracks, are rather far-reaching, yet their "lithium signature" (except at the lowest masses) makes them not distinguishable from significantly older stars of the same color. In the present paper we contribute to the debate on whether the RASS does contain large number of dispersed stars still in their PMS phase through an analysis of the reliability of the age proxies used thus far. Given that the RASS catalog is not publicly available we use sample of stars with similar selection criteria as the RASS. Our sample is mostly selected from *Einstein* surveys, which are representative of the general RASS-selected population, given that they have been selected purely on the basis of their soft X-ray emission, at a limiting flux similar to the RASS. Additionally, they have the significant advantage of being (see Sect. 2), unlike the RASS, completely identified. Most of the sample comes from regions of the sky far from SFRs and is thus not expected to contain PMS sources.

Given the lack of true PMSs in our X-ray selected sample we complement it at the young end by studying the Hipparcos-determined distances of an optically-selected sample of PMSs. Up to now, their age has been estimated assuming that individual stars were at the general distance of the SFR with which they are associated. A study of their actual distance allows to evaluate the reliability of this classical approach.

The present paper is organized as follows: Sect. 2 describes the samples of stars which have been studied, Sect. 3 discusses the methodology used to attribute ages to individual stars, while Sect. 4 describes the results, which are discussed in Sect. 5.

2. The samples

Our activity-selected sample (Table 1) is representative of the general source population of solar-type stars found in X-ray surveys, and has been assembled using as starting point the intersection between the X-ray selected stellar population from the *Einstein* Extended Medium Sensitivity Survey (EMSS, Gioia et al. 1990) and *Einstein* Slew Survey (ESS, Elvis et al. 1992) on one hand and the input catalog of Hipparcos (HIC, ESA 1992) on the other. Known binaries have been excluded from this group of stars. While the Hipparcos data are available only for a fraction of the original X-ray selected population, due to the selection criteria of the HIC, the resulting sample still allows useful insight in its characteristics (and by extension of the RASS, which has similar limiting X-ray fluxes). The biases present in the resulting sample are discussed in detail by Micela et al. (1997).

[1] These spuriously high lithium abundance were due to the inappropriate usage of low-resolution spectra in the assessment of the equivalent width of the lithium line (as for example inAlcalá et al. 1995 and Wichmann et al. 1996). See Favata et al. (1997b) and Briceño et al. (1997) for a detailed discussion

The stars in this sample can be classified in three sub-groups. In the first group we have placed the stars which have photospheric lithium abundance (from Favata et al. 1993 and Favata et al. 1995) higher than the typical abundance of field stars in the same mass range, and close to the primordial value. These stars also all have rather high activity levels ($L_{\rm X} \geq 10^{28.6}$ erg s^{-1}), and are thus expected to be the youngest in the sample. Stars with low photospheric lithium abundance (i.e. comparable to field stars) have been placed in the second group. They in general show lower activity levels than stars in the first group, and are expected to be older. The third group contains stars for which the lithium abundance is not known and which thus can be expected to contain a mixture of the populations represented by the two previous groups. We have also added some other well-known high-lithium, high-activity cool dwarfs for which the Hipparcos data were available, taken from the lists of stars discussed by Jeffries (1995) and Randich et al. (1993). These stars have primordial lithium abundance and have again all at different times been considered as probable PMSs. While not fully homogeneous in selection criteria with the rest of the sample, and not statistically representative, they clearly belong to the same parent population, and are of interest because of their extreme characteristics.

Some very well-known (and studied) objects are present, such as AB Dor (HD 36705), which has been at times considered a PMS object, HD 17925, a K0 nearby dwarf which, because of its large lithium abundance and space motions, has been considered as possibly associated with the Sco-Cen SFR, and Speedy Mic (HD 197890, Anders et al. 1993). The sample also includes little-studied objects for which no additional optical information is available.

The second sample (listed in Table 2) is a somewhat heterogeneous collection of stars which have all been classified in the literature as T Tauri stars, both of the classical (CTTS) and weak-lined (WTTS) variety. The sample has been generated by looking for entries in the Hipparcos catalog which match "well-known" (and typically optically selected) T Tauri objects, and has therefore no claim of completeness. It does however include the younger end of the age distribution of solar-type stars. By construction, the sample includes some very well studied PMS stars, as for example the CTTS BP Tau and the prototypical "isolated T Tauri" TW Hya. Only stars with $B-V \gtrsim 0.6$ have been considered in this sample.

3. Age determination

We have used the latest evolutionary tracks from D'Antona & Mazzitelli (1998) – DM98, computed for solar metallicity, which span the mass range 0.02–3.0 $M_\odot$, and follow the evolution of stars all the way from the birth-line into the early post-main sequence phase. They use the latest updates to the input physics, including opacities and convection theory. To ease the comparison with observational data we have transformed the tracks (which are expressed in the intrinsic physical quantities $T_{\rm eff}$ and $L_{\rm bol}$) to the $M_{\rm V}$ versus $B-V$ plane, using the recent calibration of $B-V$ versus $T_{\rm eff}$ and bolometric correction (BC) as a function of effective temperature of Flower (1996).

Table 1. The sample of activity-selected stars for which the evolutionary status has been determined using the Hipparcos parallaxes. The lithium abundance determinations are from Favata et al. (1993) and Favata et al. (1995), except where otherwise noted, while the X-ray luminosity has been recomputed on the basis of the Hipparcos parallax by Micela et al. (1997). Both $m_{\rm V}$ and $B-V$ are taken from the Hipparcos catalog. The parallax (π) and its associated error (σ_π) are in milliarcsec. The F2 statistics is a goodness-of-fit for the astrometric solution, discussed in detail in the text.

Name	HIP	$N(\rm Li)$	$B-V$	Spec.	$m_{\rm V}$	$\log L_{\rm X}$ ($\rm erg\,s^{-1}$)	π (mas)	σ_π (mas)	F2
X-ray selected high-lithium, high-activity stars									
HD 105	490	3.4	0.60	G0V	7.51	29.2	24.85	0.92	-1.29
HD 17925	13402	2.9	0.86	K1V	6.05	28.6	96.33	0.77	-0.43
GJ 182	23200	1.8	1.39	M1	10.05	29.8	37.50	2.56	0.55
HD 36705	25647	3.1	0.83	K1III	6.88	30.1	66.92	0.54	-0.01
HD 48189	31711	3.3	0.62	G1.5V	6.15	29.8	46.15	0.64	2.59
X-ray selected lower-lithium, lower-activity stars									
HD 10360	7751	< -1.0	0.88	K0V	5.76	27.5	122.75	1.41	-1.77
SAO 63275	63322	1.2	0.85	G6V	9.28	29.6	26.24	1.75	1.55
SAO 182743	71686	< 0.0	1.08	K5V	9.79	29.1	25.11	2.43	0.18
GJ 698	87768	< -0.2	1.18	K5	9.22	28.3	43.40	2.21	0.95
X-ray selected stars with unknown lithium abundance									
—	12787	–	1.42	K5	10.98	29.4	29.78	3.02	1.42
HD 80388	46298	–	0.59	G1V	8.33	29.1	19.20	0.88	1.47
—	48899	–	1.40	–	10.38	29.0	30.11	1.77	0.00
HD 155674	83988	–	1.15	K0	8.85	28.5	47.14	1.88	1.29
GJ 659 B	83996	–	1.26	K8	9.34	28.5	47.86	3.11	1.29
GJ 900	116384	–	1.33	M0	9.59	28.7	51.80	1.74	-0.59
Other activity-selected lithium-rich late-type stars									
HD 82558[3]	46816	3.1	0.93	K0V	7.82	–	54.52	0.99	1.14
HD 139084[2]	76629	3.6	0.82	K0V	8.14	–	25.15	1.09	0.82
HD 174429[2]	96280	3.9	0.78	G5	8.43	–	20.14	1.18	-0.43
HD 197890[1]	102626	3.1	0.94	K0V	9.44	30.2	22.52	1.64	0.93
– [3]	106231	3.1	1.05	K8	9.23	–	39.91	1.18	0.19

The GJ indication refers to Gliese & Jahreiss (1979). Spectral types, when available, are from the Simbad database.
[1] $N(\rm Li)$ from Anders et al. (1993). [2] $N(\rm Li)$ from Randich et al. (1993). [3] The $W(\rm Li)$ was taken from Jeffries (1995), and the $N(\rm Li)$ was computed for the present work.

The Hipparcos catalog (HIP, ESA 1997) includes, for each target star, the parallax together with a direct (i.e. satellite-based, from the Tycho experiment) determination of the V magnitude and $B-V$ color, supplying a homogeneous data set which allows a direct determination of the position of each star in the first sample on the evolutionary tracks. Note that while the catalog also include $V-I$ colors (in principle a better temperature indicator for late-type stars) they are not determined on-board, but rather collected from a large number of literature sources, making them less homogeneous, and thus we have preferred to use the $B-V$ colors.

Given the complexity and large uncertainties in the determination of their true photospheric $T_{\rm eff}$ and luminosity, we do not determine individual ages for the stars in the PMS sample.

3.1. Uncertainties in the age determination

To evaluate the uncertainties in the age determination, as well as to verify the behavior of the evolutionary tracks against a "reference main sequence", we have also compared the position of our sample objects in the H-R diagram with the position of the Hyades cluster members, using the data from Perryman et al. (1997) – P97. This represents the best observational ZAMS diagram available and it has been shown by P97 to be slightly more luminous (as expected due to the higher Hyades metallicity) than a solar-abundance ZAMS, by $\simeq 0.15$ mags. The Hyades known binaries are, in our plot, indicated with a different symbol. While many of the known binaries lie significantly above the main sequence, and the single stars define a rather tight observational main sequence, the lower main-sequence of the Hyades still shows a rather large scatter, $\gtrsim 0.75$ mags. Part of this is likely due to the presence of unrecognized binaries (although most Hyades members have been well studied), while some of the residual scatter can be attributed to the larger error present in the parallax of the fainter stars. Some of it possibly is "intrinsic": activity-related effects may play a role here, for example through spots which may alter the observed color of a star (see P97 for a detailed discussion). Dravins et al. (1997) show

Table 2. The sample of known PMS stars for which the Hipparcos parallaxes have been compared with the distance to the SFR. All columns but the last two have the same meaning as in Table 1. The last two columns are the 1 σ range for the distances implied by the Hipparcos parallax and the "canonical" distance for the putative parent SFR.

Name	HIP	$B-V$	Spec.	$m_{\rm V}$	π (mas)	σ_π (mas)	F2 pc	$d \pm 1\sigma$ pc	$d_{\rm SFR}$
V773 Tau	19762	1.079	K2	10.71	9.88	2.71	0.13	79.4–139.	140
V410 Tau	20097	1.330	K5	10.78	7.31	2.07	-0.28	107.–191.	140
BP Tau	20160	1.46	K5	11.96	18.98	4.65	0.36	42.3–69.8	140
RY Tau	20387	0.915	F8	10.20	7.49	2.18	0.36	103.–188.	140
HD 283572	20388	0.798	G2	9.02	7.81	1.30	0.46	110.–154.	140
T Tau	20390	1.116	G5	9.81	5.66	1.58	0.41	138.–245.	140
DF Tau	20777	1.470	M0	11.96	25.72	6.36	2.72	31.2–51.7	140
SU Aur	22925	0.833	G1	9.23	6.58	1.92	-0.04	118.–215.	140
Sz 6	53691	1.190	K2	11.22	6.97	1.87	-0.06	113.–196.	160
TW Hya	53911	1.35	K	10.92	17.72	2.21	0.42	50.2–64.5	–
HD 98800	55505	1.1	K4	8.89	21.43	2.86	1.50	41.2–53.9	–
Sz 68	77157	1.264	G	10.31	6.29	2.05	1.23	120.–236.	150
RU Lup	78094	0.7	G5	11.09	4.34	3.56	0.35	127.–1280	150
RY Lup	78317	0.93	G0	11.41	9.86	2.83	-1.89	79.–142.	150
AK Sco	82747	0.746	F5	9.21	6.89	1.44	0.91	120.–184.	160

that when the distances are evaluated not from the individual parallaxes but rather from a global solution which uses all the astrometric information and the assumption of kinematic coherence from the cluster, the scatter in the lower main sequence is much reduced (see their Fig. 2c). Such method is however only applicable to a homogeneous sample of stars such as an open cluster. Thus, from the point of view of the classification of a large sample of stars, the Hyades MS, with its observed scatter at the lower-mass end, represents the best available "observational" MS.

In addition to the well quantified uncertainties on the parallax and on the photometric quantities (well determined for each individual object in the Hipparcos catalog), the temperature calibration and bolometric correction will contribute to the total uncertainty in the age determination.

The metallicity dependence of the temperature calibration is expected to be a minor contributor to the total uncertainty, given that the T Tauri sample is expected to have photospheric abundances close to solar (Padgett 1996), as it also does the X-ray selected sample (as shown on a randomly selected subsample of the EMSS by Favata et al. 1997a).

The uncertainty in the temperature calibration is more difficult to assess because, among other things, of the possible influence of star-spots in the most active stars. Also, the color-temperature relationship still has a significant uncertainty at the cooler end, with differences of 0.1 mag common between different published calibrations. These can induce, close to the MS, significant systematic shifts in the derived ages of some tens of Myr. In addition, the typical observational uncertainty in the color determination is ± 0.02 mag, which, again for a near-ZAMS K0 star, is equivalent to an uncertainty of ± 10 Myr.

3.2. The absolute calibration of the main sequence

A possibly much more significant source of uncertainty in the estimation of stellar ages is related to the recent Hipparcos-based results on the distance to a number of open clusters (Mermilliod et al. 1997, van Leeuwen & Ruiz 1997). These are not in agreement with the distances estimated by main-sequence fitting of the different clusters, showing that the main sequence of disk-population stars is apparently multi-parametric, i.e. there exist different main sequences with different luminosities, with a shift which does not appear to be correlated to obvious parameters such as the cluster's metallicity (Mermilliod et al. 1997). While variations in the He abundance have been proposed as a possible cause for the observed difference in main-sequence luminosity, these would have to be quite large (van Leeuwen & Ruiz 1997) and difficult to reconcile with the limited range of He abundance observed in H II regions. In the absence of better explanations, this effect introduces a "hidden parameter" which induces a shift in the luminosity of a given star with respect to a fiducial main sequence of up to $\Delta M_V \simeq \pm 0.25$ mags.

Such a range in absolute magnitudes is therefore likely to be present also in field stars, adding an intrinsic uncertainty to the process of dating individual objects. Under the assumption that the shape of the tracks does not change and that the "hidden parameter" only causes a rigid shift in luminosity, the induced uncertainty has the effect of making it impossible to distinguish a ZAMS K0 star lying on the "bright" main-sequence from a star of the same color with an age of $\simeq 50$ Myr lying on the "faint" main-sequence. Thus, objects lying within $\simeq 0.5$ mags from a fiducial main-sequence can no longer be automatically classified as "young", as they could be simply lying on an older but more luminous main-sequence.

4. Results

The position in the H-R diagram of the stars in the activity-selected sample is plotted in Fig. 1. None of them occupy the region of the H-R diagram were T Tauri stars are expected, and (with the exception of HD 174429 and HD 139084, discussed later, which come from the group of very active stars but are not part of the X-ray selected sample) none are significantly above the main sequence. There is thus no compelling evidence pointing at the stars in the activity-selected sample being extremely young, and a fortiori as being in the T Tauri phase: the two K dwarfs with near-primordial lithium abundance in the X-ray selected sample, AB Dor and HD 17925, are main sequence objects (with identical evolutionary status on the basis of their position on the tracks), even though they both have in the past been considered as PMS objects and though their rotational velocity and activity level are very different (AB Dor being a much faster rotator than HD 17925). Given the shape of the evolutionary tracks for masses comprised between $\simeq 0.7$ and $\simeq 0.9\,M_\odot$ only a lower limit to the age of AB Dor can be derived (i.e. $\gtrsim 35$ Myr). Collier Cameron & Foing (1997) published a determination of the evolutionary status of AB Dor based on a recently determined VLBI radio parallax (at 66 ± 2 mas identical to the Hipparcos one) but using different photometric indices, and preferring a sligthly younger age (between 20 and 30 Myr). It is worth noting, however, that they derive an age for the M dwarf companion to AB Dor, Rst 137B, whose parallax has also been measured from the radio VLBI observations, of 30 to 100 Myr, so that the Hipparcos-derived age ($\gtrsim 35$ Myr) better fits the age of Rst 137B.

The M dwarf GJ 182 lies slightly ($\simeq 0.5$ mag) above the nominal DM98 model main sequence, on the 0.7 $M_\odot$ track and above the lower envelope of the Hyades main sequence (supposedly defining the "true" ZAMS), with an implied evolutionary age of 40–50 Myr. Its lithium abundance is significanly higher than predicted, at this model age, from standard stellar evolution theory, which predicts that a $\simeq 0.7\,M_\odot$ star should have depleted surface lithium by 2 orders of magnitude already at 10 Myr (D'Antona & Mazzitelli 1994). Even by keeping into account the various sources of uncertainty in the determination of the age of GJ 182 (including the possibility that the star belonged to a "faint" main sequence), the minimum likely age for GJ 182 is still $\simeq 20$ Myr (with a corresponding higher mass, $\simeq 0.8\,M_\odot$), still too old, according to standard stellar evolution, for its lithium abundance. However, standard models do not consider several effects which might considerably slow down interior mixing and therefore lithium depletion. Among them, the magnetic field (B) has thus far not been considered in the models. Its inhibiting effect on lithium depletion has recently been discussed by Ventura et al. (1998), who show how the presence of even a relatively moderate magnetic field can change the adiabatic gradient in the convection zone and thus significantly alter its structure, reducing mixing and therefore lithium depletion. GJ 182 is a rather active stars, implying a high surface magnetic field. While the scaling of magnetic fields from the surface to the stellar interior is not well determined, it is not unlikely that the higher magnetic field may extend deep inside the star. Also, GJ 182 has a higher than average (for its spectral type) rotational velocity (Favata et al. 1995); stars which have not spun down (for example because of their being members of a tidally-locked binary) show significantly higher lithium abundance than normally spun-down coeval stars (Ryan & Deliyannis 1995). Finally, the standard models are computed for a solar abundance mix; lithium depletion is a rather sensitive function of metallicity, and a lower-than-solar metallicity will result in significantly slower lithium depletion. Thus, alternate mechanisms can contribute to explain the longer permanence of lithium in the photosphere of GJ 182. At the same time, its combination of age and lithium abundance points to the danger of using lithium as a deterministic age indicator, even for early M stars. The position of GJ 182 in the H-R diagram is similar to the one of HIP 48899, an otherwise unknown star with high proper motion for which nothing is know in the literature.

One EMSS object (HIP 46299/HD 80389) was reported by Micela et al. (1997) as lying significantly above the main sequence. However, further study has shown that the apparent PMS status of this object actually is the result of an error in the HIC, which in turn can be traced to some error in the SIMBAD stellar database. In fact, HD 80389 is reported in SIMBAD as an M2 star of $V \simeq 10$, and this has been used as source for the HIC entry, and propagated in the final Hipparcos catalog. HD 80389 is catalogued as companion to HD 80388, a $V = 8.1$ G dwarf. Inspection of a sky image shows that HD 80389 is of comparable brightness to HD 80388, and a low-resolution optical spectrum recently acquired (L. Terranegra, private communication) to study its supposed PMS status shows HD 80389 to be a G dwarf. In addition, the Hipparcos photometry shows it to be much brighter and bluer than reported by SIMBAD, at $V = 8.67$ and with a Tycho-determined color index typical of a G-type star. The much redder $B - V$ and $V - I$ colors reported in the Hipparcos catalog (again carried from the HIC) are in strong disagreement with the Tycho-determined colors. Thus, HD 80389 appears to also be a main-sequence object and not, as previously claimed, a PMS object. Given the lack of sufficient optical information, it has been elimitated from our sample.

The other lithium-rich K-dwarfs (the fourth group in Table 1), with the two exceptions discussed below, are also lying on the main sequence. When discovered Speedy Mic (HD 197890) was considered a PMS, given its primordial lithium abundance and very high activity level and rotational velocity. Yet, similarly to AB Dor its position is clearly on the MS. The only objects which appear to be above the MS are HD 174429 (PZ Tel) and HD 139084 (V343 Nor). While PZ Tel does not show radial velocity variations and is thus considered a single star (Innis et al. 1988), the multiplicity status of V343 Nor is unclear, with contrasting indications in the literature. Both stars have near-solar abundance (Randich et al. 1993 report [Fe/H] of -0.25 and 0.0 for PZ Tel and V343 Nor, respectively). The nominal position of both stars in the H-R diagram implies an age of $\simeq 20$ Myr, on the radiative tracks. Interestingly, at the time of their discovery AB Dor and PZ Tel were attributed very similar ages and evolutionary status (Innis et al. 1986), on the basis of the observed

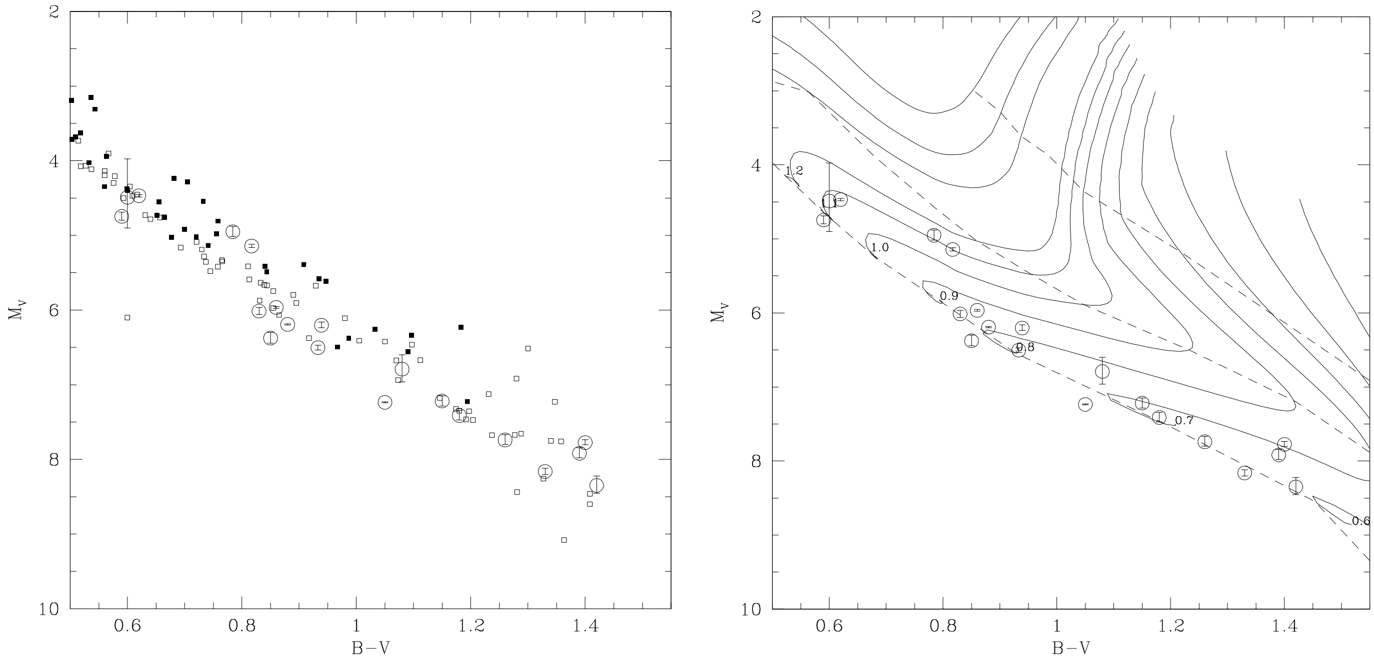

Fig. 1. The evolutionary H-R diagram for the stars in our X-ray selected sample, plotted as open circles, with the uncertainty on the absolute magnitude deriving from the distance uncertainty overplotted as error bar. In the left panel they are shown together with the Hyades observed main-sequence of P97 (open squares are single stars, filled squares are double stars), while in the right panel they are plotted with the evolutionary tracks of DM98, transformed to $m_{\rm V}$ and $B-V$ as described in the text. The dashed lines are the 10^6, 10^7 and 10^8 yr isochrones. The 10^9 yr isochrone (not plotted) is essentially undistinguishable from the 10^8 yr one. The mass for each track is indicated by the small number at the end of each track near the 10^8 yr isochrone.

proxies, yet the precise parallax shows their evolutionary status to be rather different.

4.1. The T Tauri sample

Most of the T Tauri stars in our sample have distances fully compatible with the assumed distance of their parent cloud, with no bias in the canonical determinations of their age. There are however two rather surprising exceptions, i.e. BP Tau and DF Tau, whose Hipparcos parallaxes indicate that they lie much closer to the Sun than the Taurus-Auriga SFR. The leading edge of the Taurus molecular cloud is (as determined by Kenyon et al. 1994, using the reddening of high-mass stars in the region) at $d \simeq 140 \pm 10$ pc (i.e. at a parallax of $\simeq 7.2$ mas, in good agreement with the Hipparcos parallax of most of the Taurus CTTSs), with no evidence for any portion of the cloud lying significantly closer to the Sun. The Hipparcos-derived $1\,\sigma$ ranges for the distances of BP Tau (42–70 pc), and DF Tau (31–52 pc) are therefore in contrast with their being located within the Taurus SFR.

Both BP Tau and DF Tau have been studied in detail by Kenyon & Hartmann (1995) – hereafter HK95, who determined their age (from their position on evolutionary tracks and assuming their distance to be $\simeq 140$ pc) at $\simeq 0.6$ and $\simeq 0.006$ Myr, respectively[2], typical for members of the Taurus cloud. If their total luminosity is however evaluated on the basis of the Hipparcos parallax, they both become much fainter and thus older. Qualitatively, the luminosity of a T Tauri on the convective track decays with time roughly as $L \propto t^{-2/3}$ (VandenBerg & Laskarides). Given that the inferred absolute luminosity goes as $L \propto d^2$, age goes as $t \propto d^{-3}$. Their revised distances thus lead to ages a factor of, respectively, $\simeq 20$ and $\simeq 60$ times larger, i.e. some tens of Myr and some Myr. To quantify this, the position of BP Tau and DF Tau on the DM98 evolutionary tracks, using the KH95 stellar parameters scaled to the 140 pc and to the Hipparcos parallax, is shown in Fig. 2: the age of BP Tau increases from $\lesssim 1$ Myr to $\simeq 35$ Myr, while DF Tau moves from the somewhat anomalous position it was occupying in the H-R diagram (likely due to the erroneous temperature discussed above) to an evolutionary age of $\simeq 2$ Myr.

It is worth noting that, while no detailed spectroscopic determinations of the atmospheric parameters are available for TW Hya, so that it cannot be accurately placed on the H-R diagram as done for BP Tau and DF Tau, its broad-band colors imply a characteristic age of 10–30 Myr, thus making it an object similar to BP Tau in evolutionary status.

The Hipparcos parallax and the consequent evolutionary status of BP Tau and of DF Tau[3] imply, at face value that they are far ($\simeq 100$ pc) from the the Taurus SFR itself with which they have until now been associated. Also, they lead to a significantly higher age estimate, of $\simeq 35$ Myr. If born in the Taurus SFR,

[2] Although Hartmann – priv. communication – reports that the color of DF Tau used by KH95 is too red, and the star thus has a comparable age to BP Tau

[3] Given the likely similar evolutionary age related the actual colors of BP Tau they will in the following be discussed together.

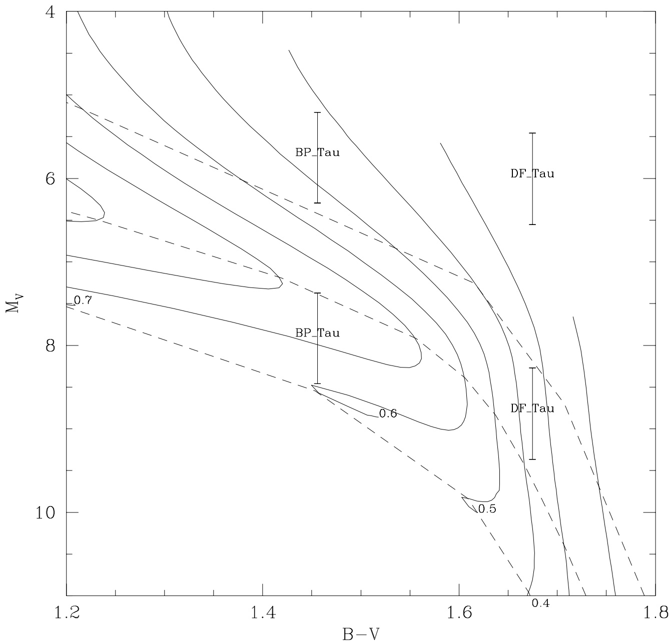

Fig. 2. The position of BP Tau and DF Tau on the evolutionary tracks of DM98, using the stellar parameters of Kenyon & Hartmann (1995) scaled for a distance of 140 pc and for the new Hipparcos parallaxes. Also indicated are the 10^6, 10^7 and 10^8 yr isochrones. The tracks are spaced by $0.1\,M_\odot$, and the mass is indicated by the small number at the end of each track near the 10^8 yr isochrone.

they would have needed a peculiar velocity of $\simeq 3\,\mathrm{km\,s^{-1}}$ to travel from their place of birth to the present position, a velocity higher than the customarily assumed velocity dispersion in a SFR ($\simeq 1\,\mathrm{km\,s^{-1}}$) but not exceptional. In fact, after 35 Myr the actual parent cloud could be located some tens of pc away even in the assumption of a modest peculiar velocity, or could even have dissipated. The Hipparcos-distance also has implications for the disk accretion rates, which have been estimated (Hartigan et al. 1995) at $\dot{M} = 1.6 \times 10^{-7}$ and $1.3 \times 10^{-6}\,M_\odot\,\mathrm{yr}^{-1}$ for BP Tau and DF Tau respectively. If these estimates are rescaled (using the same formalism of Hartigan et al. 1995) to the Hipparcos distances, they become $\dot{M} = 5.5 \times 10^{-9}$ and $1.4 \times 10^{-8}\,M_\odot\,\mathrm{yr}^{-1}$, i.e. sufficiently low as to be compatible with an age of some tens of Myr even under the assumption of their being sustained rates through the object's lifetime.

Thus, the Hipparcos-determined distances would make BP Tau and DF Tau similar to TW Hya, an object long recognized as a isolated T Tauri far away from obvious sites of star formation (Rucinski & Krautter 1983). The Hipparcos parallax of TW Hya implies a rough age estimate (based on the broad-band photometric characteristics) of some 20 Myr, significantly older than most CTTS in Taurus, thus showing that BP Tau and DF Tau are not necessarily unique.

4.2. *Could the Hipparcos parallaxes be in error?*

The parallaxes of BP Tau and DF Tau are in stark contrast with their putative membership of the Taurus SFR and have potentially far-reaching implications. Other elements do however point toward a distance for BP Tau and DF Tau compatible with their being in Taurus. Their Hipparcos-determined proper motions are consistent with the values for other Taurus members, and their radial velocity (Hartmann & Stauffer 1989) is very close to the velocity of the molecular gas they are projected on (Herbig 1989). In addition, their optical spectra show Na I interstellar absorption corresponding to this same velocity, implying that they must be behind at least part of the absorbing material.

Could the parallaxes themselves then be somehow in error? Hipparcos is a unique experiment, whose measurements cannot be independently repeated from the ground; thus, the assessment of the quality of its data comes from internal checks. The fraction of individual measurements rejected and a goodness-of-fit statistic (the F2 entry) are two indicators which can be used to assess the quality of the astrometric solution for a given star. Most of the objects in the PMS sample have no rejected data points, with the exception of HD 98800 (1%), BD Tau (2%), RU Lup (6%), BP Tau (2%) and DF Tau (5%). Such small rejected measurement fractions are considered fully normal.

The two indicators available in the Hipparcos catalog for assessing individual astrometric solutions are the fraction of individual measurements rejected and a goodness-of-fit statistic (the F2 entry). The F2 statistic is observed to be distributed, for single stars, normally, with a mean of $\simeq 0.21$ and a standard deviation of 1.08, while for multiple stars there is an excess of large values, so that "even values above 3 can however represent rather 'good' solutions" (ESA 1997). In our T Tauri sample most objects have $|\mathrm{F2}| < 1.5$, with two exceptions: RY Lup (-1.89) and DF Tau (2.72). DF Tau (whose binary status is well known also from ground-based observations) is however classified, in Hipparcos, as a "variability-induced mover", meaning that the photocenter moves due to variability of the components in an unresolved binary system; speckle interferometry shows (Thiébaut et al. 1995) that the separation of the components was $\simeq 80$ milliarcsec around the time of the Hipparcos observations, with the position angle changing by tens of degrees during the Hipparcos lifetime, given that the system was close to periastron. The binary period is however sufficiently large (82 ± 12 yr) that it cannot bias the derived parallax (as it could if, for example, the period was close to the period of the apparent parallactic motion, i.e. 1 yr). Still, the additional photocenter displacement induced by the moving binary component is likely to cause additional scatter in the final solution and explain the high F2 value. Two other objects in our sample, have the same status of variability-induced mover (i.e. V773 Tau and RY Tau), with no evident effects on the solution quality.

5. Discussion

None of the objects in the X-ray selected sample shows evidence of extremely young model ages (i.e. $< 10^7$ years), having position in the H-R diagram compatible with their lying onto or close the main-sequence (as defined by the Hyades cluster). GJ 182 lies $\simeq 0.5$ mags above the nominal main sequence, at a model age of $\simeq 30$ Myr, significantly older than implied by its lithium abundance according to the "standard" models of stellar evolution. Its high lithium abundance could be due to the presence of additional factors slowing down the depletion of lithium (see Sect. 4) and not accounted for in the standard models (as for example the presence of an internal magnetic field). The highly active stars HD 174429 (PZ Tel) and HD 139084 are also found above the nominal main sequence, at an inferred age of $\simeq 20$ Myr.

These data show that solar-type stars with very similar mass and evolutionary state can look very different. HD 17925 and HD 36705 (AB Dor) are on the same evolutionary track (assuming that they lie onto the same main sequences) and with age estimates overlapping at the 1σ level, yet they differ widely in terms of X-ray emission level, rotational velocity and lithium abundance. On the other hand, primordial lithium abundance, very high activity levels and very high rotation rates are present in both HD 36705 (AB Dor) and HD 174429 (PZ Tel), yet their evolutionary ages are quite different, with PZ Tel still approaching the main sequence on the radiative track and an age of $\simeq 20$ Myr, while AB Dor appears to be already on the main sequence and it lies on the nominal 100 My isochrone, although only a lower limit of $\simeq 35$ Myr can be put on its age.

The Hipparcos parallaxes point toward the existance of nearby objects with all the optical characteristics normally associated with CTTS and therefore with an accretion disk (emission line spectrum, veiling, UV and IR excesses) but with ages of the order of 30 Myr. If taken at face value, these ages imply much longer-lived disks than previously inferred from CTTS ages, with correspondingly smaller accretion rates. Long-lived disks can be related to the existance of the slowest rotators in young clusters: current theories of angular momentum evolution in young solar-type stars predict that they will experience their maximum rotational velocity on the ZAMS, with the pre-ZAMS spin-up being due to the contraction and the MS spin-down due to the braking effect of the magnetic fields through the stellar winds (Bouvier et al. 1997). The magnetic coupling between the central star and the disk in a CTTS is expected to have a braking effect, and indeed CTTSs are observed to rotate generally slower than coeval WTTSs, in which the braking effect of the disk is missing. The presence on the ZAMS (for example in the α Per and Pleiades clusters) of slow rotators mixed with fast rotators can be explained by assuming that the slow rotators had much longer lived disks than the fast rotators. Indeed, the stars that on the ZAMS have rotational velocities of just few km s^{-1} are likely to have been braked until the end of their Hayashi-track phase by the presence of a disk, and BP Tau (together with TW Hya) could be an example of such a long-lived disk. Long-lived disks are necessary in current models to explain the observed ZAMS rotational velocity distribution, but thus far no experimental evidence for them has been available (Bouvier et al. 1997).

As discussed above, the evidence for the distance of BP Tau and DF Tau is contradictory, with independent observational data indicating a distance much smaller than the canonical distance to the Taurus cloud. However, independent verification of the Hipparcos parallaxes will have to wait for the next generation of space astrometry missions, and the possible contradiction cannot currently be resolved.

If these stars are indeed "old" T Tauri, an important question is how large is their population, and what's their relative fraction with respect to the canonical "young" T Tauri stars? Our sample is too small and is not unbiased, and cannot therefore answer this question in a quantitative and statistically significant way. However, the observed 2 out of 6 Taurus objects raise the possibility that the fraction of isolated and old T Tauri stars may not be negligible.

Both the activity-selected sample and the T Tauri one show that the observational proxies from which young age and PMS status for stars of unknown distance are usually deduced cannot, alone, be used to attribute a precise a reliable age to a given individual star. Large lithium abundance and high activity levels are observed in activity-selected G, K and even M0 stars with positions in the H-R diagram not implying extreme youth. The Hipparcos parallaxes also imply that active disks are present in CTTSs located far away from obvious sites of star formation and with ages of up to tens of millions of years in age.

Therefore, the usage of standard proxies and assumed distances (for example by association with an otherwise unrelated but nearby SFR) may lead to strongly under- or over-estimate the evolutionary age of a given star. Even when accurate distances are known, accurate estimate of ages is made uncertain by the lack of a priori knowledge of the relative fiducial main sequence position. The extrapolation of accurate ages from the proxies discussed here, and the consequent inferences about, for example, the star formation history in a given volume of space or in a given X-ray selected population, appears to be at best a very uncertain process. In this light, the recent claims about large numbers of pre-main sequence stars near (but significantly outside) known SFRs, newly discovered on the basis of their X-ray emission and defined as TTS on the basis of their lithium abundance, may have to be considered with caution, with alternative explanations being possible.

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