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LETTER

*Letter to the Editor*

# Kinematics versus X-ray luminosity segregation in the Hyades

**V.V. Makarov**

Copenhagen University Observatory, Juliane Maries Vej 30, 2100 Copenhagen Ø, Denmark (makarov@astro.ku.dk)
DASGAL, Observatoire de Paris-Meudon, bat 11, 5 place Janssen, 92195 Meudon Cedex, France

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**Abstract.** State of the art Tycho-2 proper motions of bona fide Hyades members are used in combination with the ROSAT X-ray survey of this open cluster in Stern et al. (1995) to study the internal velocity dispersion versus X-ray luminosity by the classical convergent point method. It is shown in this paper for the Hyades members with $B-V$ below 0.7 mag that stars brighter than $1.3\times10^{29}$ erg s$^{-1}$ (0.1–1.8 keV) have much more coherent motions than those with smaller X-ray luminosities and those not detected by ROSAT at all. In fact, the proper motions of the X-ray luminous members are in agreement with a null internal dispersion of velocities for this subpopulation, whereas the intermediate bright X-ray stars exhibit a dispersion at 320 m s$^{-1}$. The non-emitters, despite their being more massive and optically brighter, have a velocity dispersion of about 440 m s$^{-1}$. Probably related to this fact, the strong X-ray emitters are more concentrated within the tidal radius (10 pc) of the cluster centre than the non-emitters. Nearly half of strong X-ray emitters with coherent motions are visual or orbiting pairs with typical separations 5 to 50 AU. This find implies that a group of intermediate mass (1.0 to 1.5 solar masses) stars in the Hyades is significantly younger than the rest and their system is not yet dynamically relaxed.

**Key words:** Galaxy: open clusters and associations: individual: Hyades – stars: kinematics – X-rays: stars

The Tycho-2 Catalogue contains 2.5 million stars covering the entire sky (Høg et al. 2000). Precise proper motions are given for 96 percent of the stars from the observed positions in Tycho-2, Astrographic Catalogue and 143 other ground based catalogues, and their overall agreement with Hipparcos proper motions is asserted at a level below 0.5 mas yr$^{-1}$ (Urban et al. 2000). In the previous paper devoted to a general analysis of the Tycho-2 proper motions for 217 members of the Hyades open cluster by the classical convergent point method (Makarov et al. 2000) we have shown that Tycho-2 proper motions are indeed of the expected high quality, that they are superior to the Hipparcos proper motions in that they are less disturbed by orbital motion in unresolved binaries, and that they provide a model-independent estimate of the cluster's internal velocity dispersion at 220 to above 400 m s$^{-1}$ for subsets of different astrometric precision and binarity status. In this paper, I essentially repeat this analysis for the Hyades members, this time discriminating stars by their X-ray luminosity.

The basic parameters of the moving cluster method in use are:

– $\Delta$, the angle between the direction of the proper motion for each star and the direction from the star position to the common convergent point of the cluster;
– $\lambda$, the angular distance between the star position and the convergent point;
– $\mu$, the magnitude of proper motion in arcsec yr$^{-1}$;
– $v_\perp$, the transverse velocity component for each star, i.e. $v\sin\lambda\sin\Delta$;
– $\sigma_{\mu\perp}$, the formal standard error of the transverse proper motion component normal to the convergent point direction, which is computed from the coordinate proper motion components $\mu_\alpha\cos\delta = \mu_{\alpha*}$ and $\mu_\delta$ as $\sqrt{(\mu_{\alpha*}^2\sigma_{\mu\delta}^2+\mu_\delta^2\sigma_{\mu\alpha*}^2)}/\mu$, to a precision sufficient for the Hyades;
– $\boldsymbol{v}=(-6.28,+45.19,+5.31)$ km s$^{-1}$, the bulk velocity of the cluster adopted from Perryman et al. (1998);
– $\sigma_v$, the internal dispersion of velocities, assumed to be isotropic within the cluster.

An important quantity reflecting the degree of proper motion convergence for each star, is the relative directional deviation of the proper motion vector, $\Delta/\sigma_\Delta$, where $\sigma_\Delta$ is the total expected standard error of $\Delta$. As we have seen in the previous paper, the error is a quadratic sum of the relative astrometric error and the relative tangential velocity dispersion

$$\sigma_\Delta^2=\frac{\sigma_{\mu\perp}^2}{\mu^2}+\frac{\sigma_v^2}{v^2\sin^2\lambda}. \quad (1)$$

It is evident from this equation that the intrinsically very small velocity dispersion in the cluster can be best seen in the stars with the smallest astrometric errors. All the previous studies on the matter dealt therefore with subsets of stars of different observational precision (see also Gunn et al., 1988, for a similar analysis of radial velocities). This paper accounts kinematic properties of members of different X-ray luminosity.

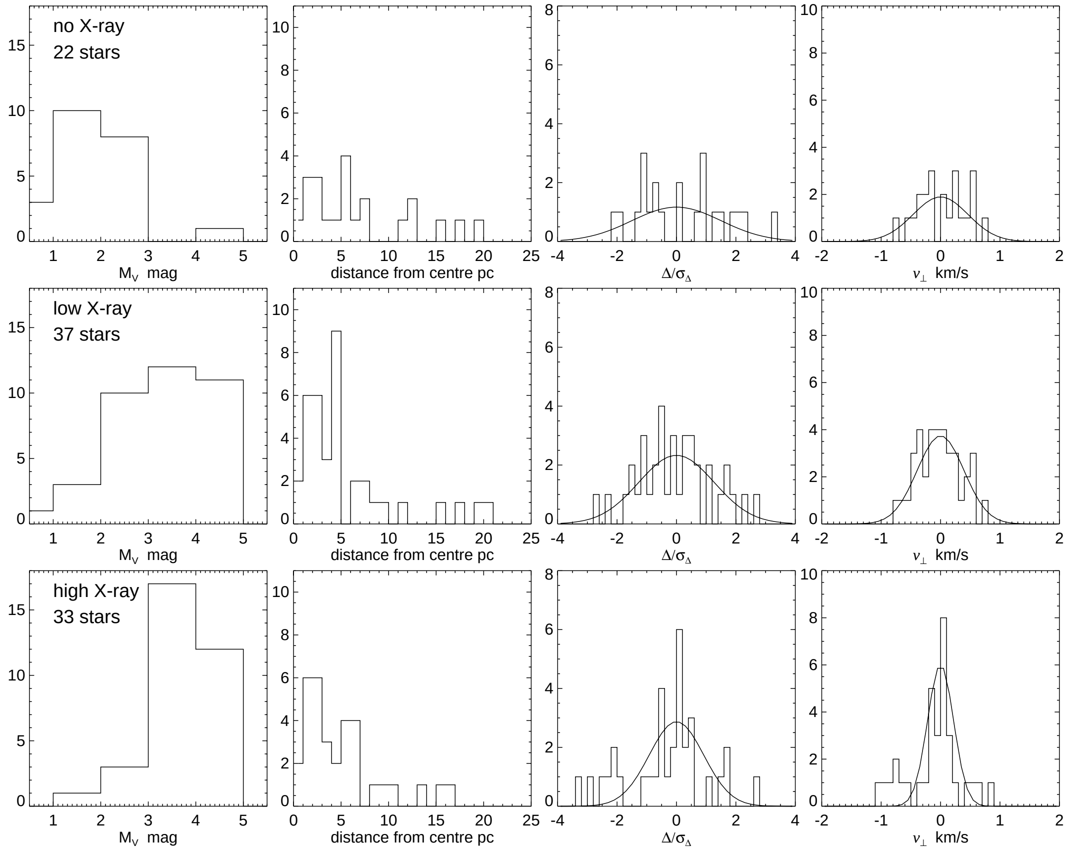


**Fig. 1.** Photometric and kinematic histograms for the Hyades stars with proper motions in the Tycho-2 catalogue and $B - V < 0.7$ mag. The following distributions are shown in columns, left to right: 1) absolute $V$ magnitudes as derived from visual magnitudes in the literature and 'kinematic' distances from the moving cluster method; 2) distances from the cluster centre; 3) relative deviations of the proper motion direction from the convergent point direction, $\Delta/\sigma_\Delta$; 4) observed transverse velocity component $v_\perp$ in $\mathrm{km\,s^{-1}}$. Full lines in the last two columns show least-squares Gaussian fits to the observed histograms, assuming for $\Delta/\sigma_\Delta$ a velocity dispersion $\sigma_v$ of 200 m $\mathrm{s^{-1}}$. The three rows of graphs correspond to the three non-overlapping subsets 1) stars not detected in X-rays in Stern et al. (1995); 2) stars detected with X-ray luminosities below $13 \times 10^{28}$ $\mathrm{erg\,s^{-1}}$; 3) stars with X-ray luminosities above $13 \times 10^{28}$ $\mathrm{erg\,s^{-1}}$. Three stars with $\Delta/\sigma_\Delta > 3.5$, one in the first subset and two in the second, were deleted from the analysis.

From Table 1 in (Stern et al. 1995), representing the ROSAT All Sky Survey data for the Hyades, I found 195 stars with proper motions in the Tycho-2 catalogue. Only 126 of them have detected X-ray luminosities. I further select 95 stars out of the 195 with $B-V < 0.7$ mag (photometry from the literature), that is roughly main sequence stars heavier than the Sun. Stars of smaller masses than the Sun seem to have remarkably larger velocity dispersions, which is likely due to a larger influence of orbital motion in unresolved (astrometric) binaries (Gunn et al. 1988 and Makarov et al. 2000). Stars with $B - V > 0.7$ mag are not considered in this paper since the subtle effect of the internal velocity dispersion can not be evaluated for the fainter stars, where it is drowned in the dominating astrometric errors. The group of 95 is divided into approximately equal subsets of stars with no detection in X-rays, detected stars with $L_X(D) < 13 \times 10^{28}$ $\mathrm{erg\,s^{-1}}$ and stars with $L_X(D) > 13 \times 10^{28}$ $\mathrm{erg\,s^{-1}}$. The luminosities $L_X(D)$ were re-computed from the observed $L_X$(45 pc) using our more accurate kinematic distances $D$. The resulting distributions from the convergent point analysis are presented in Fig. 1.

It is completely surprising to see that both distributions of relative angular deviations from the convergent point $\Delta/\sigma_\Delta$, and absolute transverse velocity $v_\perp$ become much narrower with increasing X-ray luminosity (going from top row to bottom row of the figure). The standard deviations for the three groups, estimated from least-squares Gaussian fits, are 1) (22 stars) 1.50 and 0.46 $\mathrm{km\,s^{-1}}$, 2) (37) 1.27 and 0.40 $\mathrm{km\,s^{-1}}$, 3) (34) 0.92 and 0.22 $\mathrm{km\,s^{-1}}$. The expected error $\sigma_\Delta$ is computed by Eq. 1 assuming a fixed value for $\sigma_v$ of only 200 $\mathrm{m\,s^{-1}}$. For each of the three samples, one can find a matching $\sigma_v$ producing a distribution of $\Delta/\sigma_\Delta$ of unity standard deviation. The internal velocity dispersions thus estimated are for the first group (nondetections in X-ray) 440 $\mathrm{m\,s^{-1}}$, for the second (moderate X-ray emitters) 320 $\mathrm{m\,s^{-1}}$, and for the third (strong X-ray emitters) null.

The result seems even more striking in view of the fact that the stars in the first group are mostly brighter than $M_V = 3$ mag (see the first column of graphs in Fig. 1), i.e. they have masses above 1.5 solar masses, while the group 3 is chiefly composed of stars with masses between 1.0 and 1.5. One would expect, on dynamical principles, the heavier stars to have less dispersed velocities. Not only are the heaviest stars in the Hyades poor X-ray emitters, they also have less coherent motions. The moderate X-ray emitters in the second group have more coherent motions. Most remarkably, the strong emitters exhibit absolutely parallel space motions, within the given astrometric precision.

The distributions of stars on the distance from the cluster centre (second column in Fig. 1) seem also different for the three groups, although perhaps less convincingly[1]. The more massive non-emitters seem to have a long tail reaching beyond 15 pc, whereas the strong emitters are not found beyond 16.3 pc. Only 4 stars among the strong emitters are beyond the tidal radius of the cluster, which is about 10 pc. It is found that $3/4$ of all stars in each subset are contained within 11.0 pc for group 1, 6.7 pc for group 2 and 6.4 pc for group 3.

The distribution of transverse velocities for the group of strong emitters (lower rightmost plot in Fig. 1) appears to be markedly non-Gaussian. It is composed of a very sharp core and enhanced wings. In the wings, 8 stars out of the 33 are found with $|v_\perp| > 600\ \mathrm{m\,s^{-1}}$. Five stars out of the 8 deviants are known to be spectroscopic and/or visual binaries (HIP 20440, 20553, 20719, 21474, 22607). Quite likely, their proper motions are disturbed by long-period orbital motions. Two of the 3 remaining apparently single stars are outside the tidal radius of 10 pc (HIP 19789 and 22566) and one (HIP 19796) is at a distance of 5.5 pc from the cluster centre. This implies a twofold reason for the deviants in the wings of the kinematic distribution. The majority have probably proper motions dispersed by long-period orbital motions. A smaller part may have experienced encounters with other stars and are on their way out of the cluster.

Fig. 2 shows a scatter plot of the ratio of X-ray to bolometric luminosities against the relative misalignment $\Delta/\sigma_\Delta$ for the same members bluer than 0.7 in $B - V$. As estimated from the 16th and 84th percentiles, the internal dispersion seems to suddenly decrease for stars with the highest $L_X/L_{\rm Bol}$ in the present sample. But the correlation is not as clear as when differentiating stars by $L_X$. The reason probably lies in the fact that sorting stars by $L_X/L_{\rm Bol}$ gives preference to faintest stars in the sample, even if they are not very luminous in X-rays, and leaves some of the optically bright X-ray emitters out. Including redder stars would bring into this picture many faint stars of moderate or low X-ray luminosity, because the average $L_X/L_{\rm Bol}$ monotonously increases with absolute magnitude, cf. Fig. 15 in (Stern et al. 1995). It is found that a sample of stars with $B-V < 0.6$ mag and $\log(L_X/L_{\rm Bol}) > -4.8$ still reveals a null velocity dispersion, but it includes only 22 stars. It is concluded that the group of stars with absolutely coherent motions inside the cluster mostly contains stars with $L_X$ excessive for their magnitude bins rather than those with highest overall $L_X/L_{\rm Bol}$, which have lower masses.

Enhanced X-ray luminosity of stars is commonly associated with their young age. The fundamental fact that the mean X-ray luminosity of main-sequence stars decreases with age was already inferred from the *Einstein* surveys of nearby Galactic clusters and field disk stars (e.g., Micela et al. 1988). The mean $\log L_X$ for G type stars ($B - V$ in 0.6 to 0.8 mag) drops from 29.7 in the $\alpha$ Persei cluster (age $\sim 50$ Myr) to 29.4 in the Pleiades (80 Myr), according to Randish et al. (1996), and furthermore to 28.9 at 600 Myr for the Hyades (Stern et al. 1995). Field solar-like stars have the mean $\log L_X$ as low as 27.7 (Micela et al. 1988). Bluewards of the G stars, the outer convective envelope of stars becomes increasingly thinner and disappears altogether somewhere at the mid-F type, which explains the observed drop in dynamo-related coronal activity (e.g., Stauffer et al. 1994). A slow decrease of X-ray luminosity for stars later than G can be expected from the decreasing surface area. Although the wealth of available X-ray observations for open clusters seem to generally fit this model, a few important facts remain unexplained, notably the large spread of X-ray luminosities for stars of the same spectral type within each cluster, and how the evolution of $L_X$ depends on stellar mass (Micela et al. 1999).

In the Hyades, one of the two peaks of $L_X$ is reached at $B - V$ around 0.5, cf. Fig. 8 in Stern et al. (1995), where the late F and early G stars exhibit a full amplitude scatter of nearly 1 in $\log L_X$. The scatter is even a little larger than the difference in the mean $\log L_X$ between the Hyades and $\alpha$ Per clusters. Formally, our sample of 33 strong emitters, having $\log L_X$ above 29.1 comes somewhere in between the level of $L_X$ typical for the Hyades and the Pleiades. It may therefore be suggested that

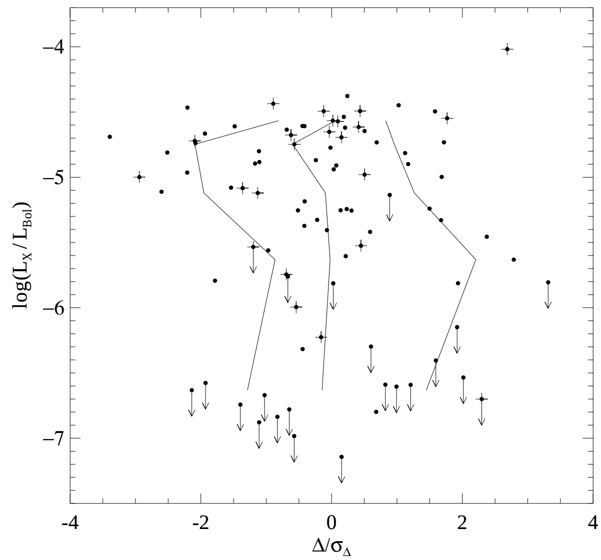


**Fig. 2.** The ratio of X-ray to bolometric luminosity versus the relative deviation of the observed tangential motion from the common convergent point direction for the Hyades stars with proper motions in the Tycho-2 catalogue and $B - V < 0.7$ mag. Upper limits are given for non-detections in X-rays, as indicated by downwards arrows. Solid lines show the 16th, 50th (median) and 84th percentiles of $\Delta/\sigma_\Delta$ distributions in bins of 18 stars each. Known visual and long-period orbiting stars are marked with crosses. The relative deviation $\Delta/\sigma_\Delta$ is computed assuming a $\sigma_v = 200$ km s$^{-1}$.

[1] A position vector of the cluster centre $b_{\rm C} = (-43.37, +0.40, -17.46)$ pc, in galactic coordinates, was adopted from Perryman et al. (1998)

the observed spread of X-ray luminosities can in part be due to a real segregation by age. Stauffer et al. (1994) suggest that the statistical dependence of X-ray luminosity on age is not a direct one, but it is rather conditioned by a physical relation of $L_X/L_{\rm Bol}$ to rotational velocity. In the Pleiades, they found a significant correlation between the two for stars with $B-V > 0.6$ mag. During the initial main-sequence evolution stage, more massive stars spin down much quicker than less massive stars. In the Hyades, a good correlation between $L_X/L_{\rm Bol}$ and rotational velocity is found for stars redder than $B-V = 0.45$ mag, although the projected rotational velocities for stars with colours in the interval 0.45 to 0.60 are nearly all below 10 km $s^{-1}$ (Soderblom et al. 1993), in contrast to the median 20 km $s^{-1}$ in the Pleiades. These facts do not fit together very well, and the true relation between age, X-ray activity and rotational velocity remains largely a mistery.

Binaries, especially wider visual pairs, may provide an important insight into the dynamical history of the cluster. Hard binaries with large binding energies are the basic source of kinematic heating and evaporation of the cluster, since upon encounters with other stars they release part of their binding energy and become yet harder (Heggie 1975). Soft binaries with large orbital periods, on the countrary, are ionised (disrupted) by encounters, which causes the depletion of, e.g., G dwarfs in pairs of long periods ($\log P > 3$, Kroupa 1995a). All the known visual binaries resolved by speckle interferometry from Patience et al. 1998 and Mason et al. 1993, as well as new long-period binaries in the Hipparcos catalogue (ESA 1997) with the 'component' solutions (flag C in the field H59), 'acceleration' (G) and 'orbital' (O) solutions, in common with the given sample, are marked with crosses in Fig. 2. It is not surprising that these soft binaries tend to have increased $L_X/L_{\rm Bol}$, because a subsolar mass companion can contribute a lot to the total $L_X$ of the system, and very little to the total $L_{\rm Bol}$. It is however quite striking that half of the strong X-ray emitters ($L_X/L_{\rm Bol} > -4.8$) with highly coherent motions ($|\Delta/\sigma_\Delta| < 1$ at $\sigma_v = 0$) are visual binaries. How could soft binaries survive in such a considerable proportion, retaining undisturbed motion, if they have indeed had a 600 Myr of dynamical evolution behind them? There are 15 visual long-period binaries with $L_X > 1.3 \times 10^{29}$ erg $s^{-1}$ (out of 32) in our sample, with typical separations 0.1 to 1.0 arcsec, or 5 to 50 AU. This appears to be a proportion more typical for T Tauri stars than for nearby field dwarfs. The 15 stars are HIP 18658, 20215, 20440, 20553, 20661, 20686, 20935, 21008, 21053, 21543, 22221, 22496, 22550, 22607 and TYC 1265-00224-1. When a null velocity dispersion $\sigma_v$ is assumed in Eq. 1, only 5 stars among the 15 have $|\Delta/\sigma_\Delta| > 1$, namely HIP 20440, 20553, 22496, 22607 and TYC 1265-00224-1. There is a clear tendency that the 5 outliers have larger separations and orbital periods. For example, HIP 22607 has a computed $\Delta/\sigma_\Delta = -3.70$, separation 0.46 arcsec (second largest in the sample) and period $34\,786$ d. A binary like HIP 20661 has a separation of 0.086 arcsec and a period of 2192 d (Griffin et al. 1988), so that its orbital motion is nicely smoothed out over the time-base of Tycho-2 proper motion measurements ($\Delta/\sigma_\Delta = +0.20$). The largest angular separation in this sample, 1.33 arcsec, is determined for HIP 20440, and it is a kinematic outlier ($\Delta/\sigma_\Delta = +2.08$). It appears that some of the kinematic outliers have proper motions perturbed by orbital motions with periods comparable to 100 years. A shorter period orbital motion does not perturb the Tycho-2 proper motions.

The expected velocity dispersion inside the Hyades in dynamical equilibrium is 230 m $s^{-1}$, which is believed to be an accurate estimate (Gunn et al. 1988). The present result does not leave any doubt that a considerable part of the cluster (about 30 stars) is not in the state of dynamical equilibrium, most likely because they are too young. The more massive stars, important for age determination, are older, surprisingly.

For the young open clusters IC 2391 and $\alpha$ Per Eggen (1991) suspected a wide distribution of ages or even a double star formation burst. If such multiple star formation events are not exceptions but a rule, stars of different masses can be born at different times within an open cluster. The relaxation time of an open cluster is known to be strongly dependent on the original core radius, from dynamical simulations (Kroupa 1995b). If more massive stars are born first in a compact volume of space, their system has already been relaxed and they have spread into a much larger volume by the time less massive stars are born. For these newborn stars the core radius may be so large that their relaxation time may be of order 100 Myr or longer. In view of the detected kinematic segregation, the star formation history of the Hyades can be more protracted and more rich in events than was believed before.

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