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X-ray Emission from Open Clusters

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Abstract. X-ray observations of open clusters are a key tool to study stellar coronae and their evolution. I will review the status of current knowledge and the open issues on coronal properties of open clusters. I will show how the high sensitivity of *Chandra* and *XMM-Newton*, with their spatial and spectral resolution, will help us in solving questions, like the evolution of the coronae down to the solar-age, the relevance of parameters other than rotation, the presence or the absence of magnetic cycles and the possible existence of coronae in very low mass stars and brown dwarfs. Early results of recent open clusters observations will be presented.

1. Introduction

Stellar clusters are the best sites to study the evolution of stellar phenomena and properties since they contain stars over a wide range of masses of known distance, age and metallicity. X-ray observations of open clusters allow us to study the evolution of stellar coronae and to understand the properties of the corona of the early Sun; by studying different clusters we can study the relevance of the initial conditions and the role of various physical parameters in determining the coronal properties.

Since young stars are intense X-ray emitters compared to the old more quiet field stars, through X-ray observations we can select young (cluster) low-mass stars, very difficult to be recognized with usual methods; as a consequence X-ray observations have an important role in deriving the low-mass tail of IMF. Furthermore we can use X-ray observations to pick up young main sequence field stars and to determine young population parameters such as their scale height and density. Large area X-ray surveys allow us to put constraints on the star formation rate in the solar neighborhood in the last billion of years, a range of age difficult to be studied with other methods.

The *Einstein* and *Rosat* observatories have given important contributions to the coronal astrophysics, establishing some well observed phenomena, and opening a number of questions on the physics of coronae and on their evolution. *Chandra* and *XMM-Newton*, with their sensitivity, broad band response and high spatial and spectral resolution will allow answering to these questions.

In the following I will summarize the new data obtained by *Chandra* and *XMM* on open clusters. In sect. 3 I will present the evidence for the evolution of X-ray luminosity level during the stellar life on the main sequence and the present observational limitations. Sect. 4 will illustrate the phenomenon of coronal stellar saturation, and sect. 5 will present the lack of long-term variability in X-ray emission of young stars. X-ray spectral properties of young stars will be presented in sect. 6 and the possible relevance of chemical abundance in determining X-ray properties will be discussed in sect. 7. Sect. 8 will discuss the status of our knowledge of X-ray emission from brown dwarfs and future perspective.

2. New Observations

Pleiades and NGC 2516 *Chandra* observations and NGC 2516 *XMM* observations have been already analyzed[1]. A large number of other open clusters covering a large spectrum of age, and metallicity will be observed by *XMM*.

The Pleiades are probably the cluster best studied in X-ray. The analysis of the first segment of the *Chandra* guaranteed time observation of the core of the Pleiades with ACIS-I for a total of 36 ksec (Krishnamurthi et al. 2000) has resulted in a total of 57 sources: 18 out of the 57 sources are identified with cluster members, a large fraction of the remaining sources are extragalactic, and only a few could be faint cluster members.

NGC 2516 is a very rich cluster with low metallicity (Cameron 1985; Jeffries et al. 1997; Jeffries et al. 1998) and the same age of the Pleiades. *Chandra* has observed this cluster in the calibration phase for a total of about 20 ksec with ACIS and 20 ksec with HRC, and in the GTO phase for a total of $\sim$ 50 ksec In the calibration fields (Harnden et al. 2000) 167 sources have been detected; about half of these sources are identified with photometrically selected cluster members. NGC 2516 has been observed also by *XMM/Newton* in the calibration phase with four pointing for a total of 74 ksec. The joint analysis of the two PN+MOS co-pointed observations for 34 ksec has detected 208 X-ray sources (Sciortino et al. 2001), with about 60% identified with photometric cluster members.

3. Evolution of X-ray Luminosity

Early studies on X-ray emission from open clusters showed that with the increasing age the median value of stellar $L_{\rm x}$ decays by 3 order of magnitude during the main sequence life (Stern et al. 1981; Caillault & Helfand 1985; Micela et al. 1985).

This mean decay is accompanied in each cluster by a spread of at least one order of magnitude. The spread observed in a given cluster is however much smaller than the spread observed in the field stars. The coronal activity decay is illustrated in Fig. 1 where the median values of $L_{\rm x}$ for solar-type stars vs. age, with their typical dispersion, are indicated. Circled symbols indicate X-ray selected samples that can be biased toward high values of $L_{\rm x}$. Diamonds in the plot are individual field stars with age determination based on lithium abundance.

[1] Recently *XMM* has performed two Pleiades observations that have not been yet analyzed

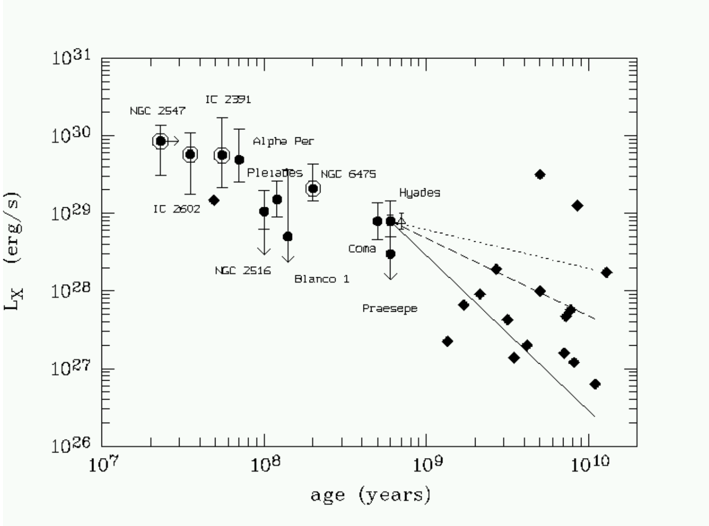

Figure 1. Median $L_{\rm x}$ vs. age for solar-type stars in clusters (circles) and in the field (diamonds). Circled symbols indicate X-ray selected samples (Figure from Randich 2000)

The dependence of X-ray luminosity on age is due to the relationship between $L_{\rm x}$ and rotation, that evolves with stellar age. The spread observed in the $L_{\rm x}$ distributions of cluster stars should reflect the spread present in rotational velocity distributions (apart the saturation phenomenon discussed below).

A large number of clusters have been observed with *Einstein* and *Rosat*, but no data are still available for clusters with age greater than 1 billion years, the Hyades age. As today we can determine the evolution of coronae after the Hyades age only from sparse data of field stars and, of course, the Sun. Unfortunately field stars are very difficult to date and do not permit to isolate effects of various parameters. The X-ray luminosity of the Sun suggests a rapid drop in $L_{\rm x}$, but the reality and the shape of this drop needs to be confirmed.

In Figure 2 we report distance vs. age for clusters within 1 kpc. Assuming a dependence of $L_{\rm x}$ on age derived from Hyades, Pleiades, and the Sun we can estimate, for a given flux, the distance at which we reach the median of the X-ray luminosity distribution for the G stars (on the left of Figure 2). In the Figure are indicated the curves at limiting fluxes of 10^{-13}, 10^{-14} and 10^{-15} ergs cm^{-2} s^{-1} that roughly correspond to limiting sensitivity of *Einstein*, *Rosat* and *Chandra* or *XMM*, respectively. With *Rosat* we have explored the coronal properties of G stars in clusters younger than Hyades, but not in older clusters. Only with *Chandra* and *XMM* observatories will be possible to reach the median of dG stars in NGC 752, the nearest old open cluster, that is a key cluster to solve this question. Regrettably up to now no *Chandra* or *XMM* observations on old clusters, deep enough to allow the study of emission of their normal dG stars, have been approved.

Panel on the right of figure 2 is the analogous plot for the M stars. In this case the situation is even worst, since young dM stars have X-ray luminosity

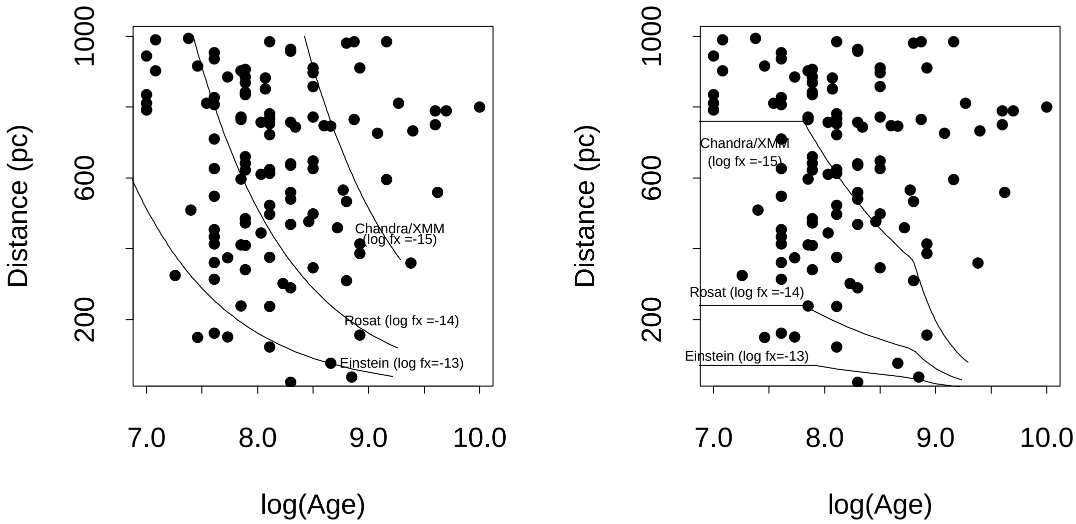

Figure 2. Distance vs. age for the clusters within 1 kpc. Lines mark the distance at which we reach th median of the X-ray distribution of dG stars. These three lines correspond approximately to the sensitivity of *Einstein*, *Rosat* and *Chandra* or *XMM* for dG stars (on the left) and for dM stars (on the right)

lower than young dG stars, and we have to wait for the next generation X-ray telescopes to completely describe the dM population of old clusters.

4. Saturation of Coronal of X-ray Emission

Cluster stars with rotational velocity below $\sim 10-$ 15 km/sec follow the $L_{\mathrm{x}} \propto v \cdot sin(i)^2$ relation originally found for nearby stars (Pallavicini et al. 1981). Fast rotators in the youngest clusters allowed us to show that for larger rotational velocity L_{x}, does not depend anymore on rotation, but reaches a maximum value that depends only on bolometric luminosity. This phenomenon is known as coronal saturation. Figure 3 shows the case of Hyades and Pleiades. Hyades (marked by plus) lie in the non-saturated part of the diagram, while Pleiades stars (squares), having rotational velocities spanning a larger range, reach the saturated regime. It is clear the presence of a break in the L_{x} − rotation relation at about 10 km/sec, with the stars rotating faster having L_{x} level depending only on spectral type. The saturation value correspond to about 10^{-3} L_{bol} and should be due to a saturation of the maximum quantity of the energy that the heating mechanism is able to deposit in corona.

5. Lack of Long-Term Variability

X-ray observations of active stars present large flares but no long-term variability associated with rotational modulation or with cycles (Stern 1998). The Sun

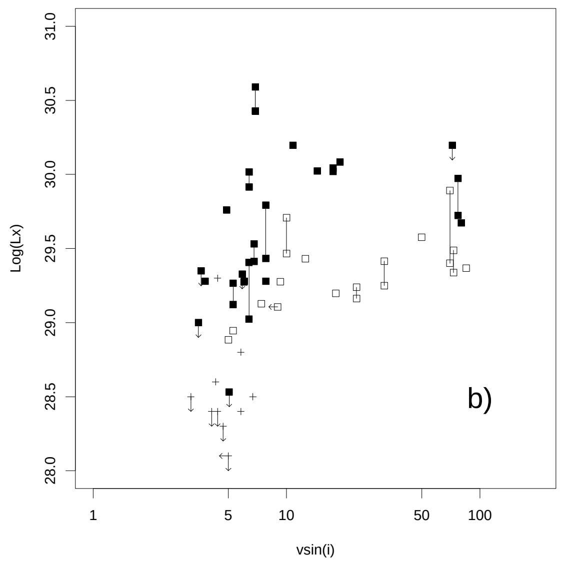

Figure 3. $L_{\rm x}$ vs. rotational velocity for K stars in Hyades (pluses) and Pleiades (squares). Filled and empty squares mark early and late K in the Pleiades, respectively. Different observations of the same star are connected by segments and give an order of magnitude estimate of the spread introduced by variability. (Figure from Micela et al. 1999a)

shows variations associated with rotation modulation with amplitude up to one order of magnitude, with even larger amplitude variations associated to cycles. If coronal emission in young stars can be interpreted as a scaled verson of the solar corona we would expect to observe large variations on time scales comparable with rotational period and with cycles.

This is not the case: in the Pleiades, for example, both on six-months and on ten-years time scales, most of the stars show variability within a factor two-three as shown in Fig. 4 and the few stars that show larger variations present large flares and hence variability on shorter time scales. Similar results have been obtained for the Hyades (Stern et al. 1995).

The comparison between stellar and solar observations is in general very sensitive to the different instrumental setup; for example variability properties of solar emission are strongly dependent on the energy bandpass with the largest variations observed at high energy. The PSPC bandpass has a soft response with large area below the carbon edge at 0.28 keV. The broad band observations of the full Sun with *SOLRAD* and *GOES* are in general in harder passbands, hence the comparison between solar and stellar variability properties has to be considered with caution. However, we can confidently compare at least the Sun and the Pleiades, because, in this case, the hydrogen column ($\sim 3 \times 10^{20}$ cm^{-2}) cuts most of the photons below the carbon edge, making the effective PSPC bandpass similar to that used for the solar observations.

The apparent difference of behavior between the Sun and active stars suggests that dynamos operating in quiet (the Sun) and active stars could have

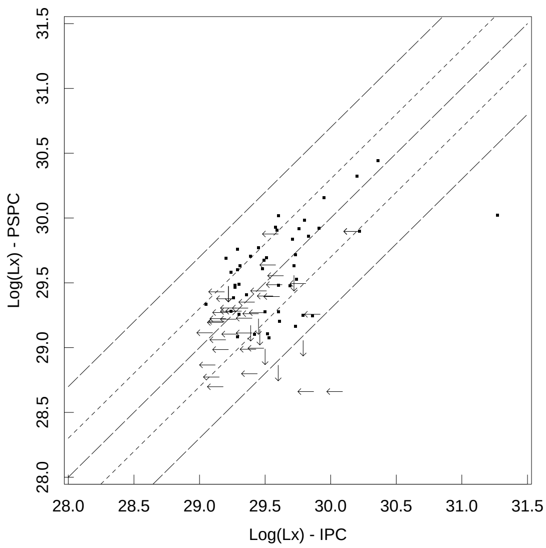

Figure 4. Rosat PSPC L_x vs. *Einstein* IPC L_x for the Pleiades. The short-dashed and long-dashed lines mark variations of a factor two and three, respectively. (Figure from Micela et al. 1996)

different properties with possibly the cyclic behavior of the quiet stars associated with the large scale dynamo and the "magnetic carpet" observed on the Sun (Title & Schrijver 1998) associated with the small scale dynamo (see Stern 1998 for a discussion) could dominate in active stars.

6. X-ray Spectral Properties of Young Stars

Coronae of young and active stars tend to be harder than those of old and quiet stars. Preibisch (1997), for example, has fitted with a continuous distribution of emission measure model a set of PSPC spectra of stars of various age, finding power indexes harder for the youngest stars, that have the highest maximum temperature and slope index α.

Furthermore stars of a given cluster, appear to have different X-ray spectra depending on stellar mass. In the Pleiades, Gagnè et al. (1995), using PSPC data have shown a dependence of fitted coronal temperature on stellar spectral type and rotation, with fast G rotators hotter than the other groups and F stars softer than all the others. Using the first set of ACIS data Krishnamurthi et al. (2000) have suggested that B-A and F stars have spectra softer than those of later type stars and intensity comparable with the very active stars. These authors conclude that this evidence seems to exclude that the origin of the emission of early type stars can be due to unseen companion and suggest that they are intrinsic sources. The ACIS observations of NGC 2516 seem to confirm this result for dF stars, but not for B and A stars. In fact these latter stars have spectra similar to those of late-type stars, as shown in Fig. 5 where X-ray and hardness ratio for cluster members are reported. Putting together

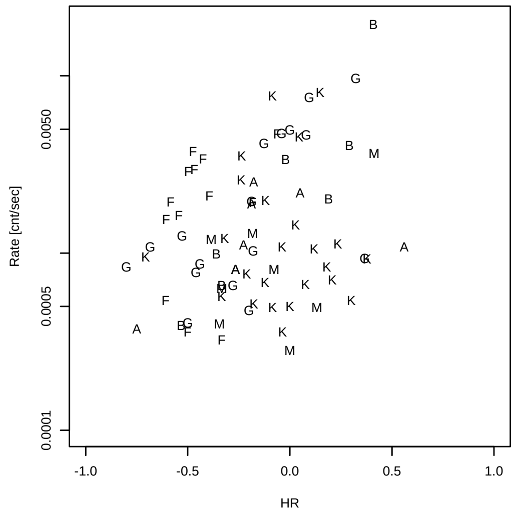

Figure 5. Count rate measured with ACIS on stars of NGC 2516 vs. the spectral hardness ratio. Different letters mark different spectral types. Note that F stars tend to be softer than stars of different spectral type and similar intensity.

the results derived from Pleiades and NGC 2516 we can conclude that dF stars appear to have X-ray spectra different than those of other spectral type stars, while we cannot exclude that the origin of the emission of B and A stars is due to unseen companion.

7. Is the X-ray Luminosity of a Cluster Determined Only by Age?

Rosat observations have posed the question if the X-ray properties of a cluster are determined by its age, or other parameters, related to initial conditions and/or its evolution, are important.

Observations have shown that clusters of same age can have significantly different level of X-ray emission. The more conspicuous case is that of the Hyades and Praesepe that have same age and very similar properties. Randich & Schmitt (1995) have shown that the median level of the emission of Praesepe G stars is smaller by a factor two than the median level of G stars of the Hyades, while the high luminosity tails of the X-ray luminosity functions are similar. Many attempts have been done to explain the observed difference but this puzzle has not yet solved.

A quantity that in principle can affect coronal emission is the chemical abundance, and some efforts to quantify its importance are ongoing.

The effect of metallicity on coronal emission can be very complex since metals can have influence on coronae in different ways. First of all metallicity affects the opacity and hence the depth of convection zone, a fundamental ingredient of the dynamo. We expect that for a given stellar mass, the depth of the convection zone, and hence the dynamo efficiency, increases with metallicity and that the onset of convection and activity occurs at higher masses in high metallicity stars. Furthermore metal abundance has a direct influence on the radiative coronal losses that for typical coronal temperatures are dominated by ions of heavy metals. The size of this effect depends on the coronal temperature and decrease with the increasing of the temperature. As a consequence of the different radiative losses the differential emission measure distribution of the plasma changes, since it is determined by the balance between heating, conduction and radiative losses. If coronal emission depends on metallicity, also rotational evolution and hence coronal evolution will be different for stars of different metallicity. Understanding the overall effect it is not straightforward and some efforts in this directions is just started.

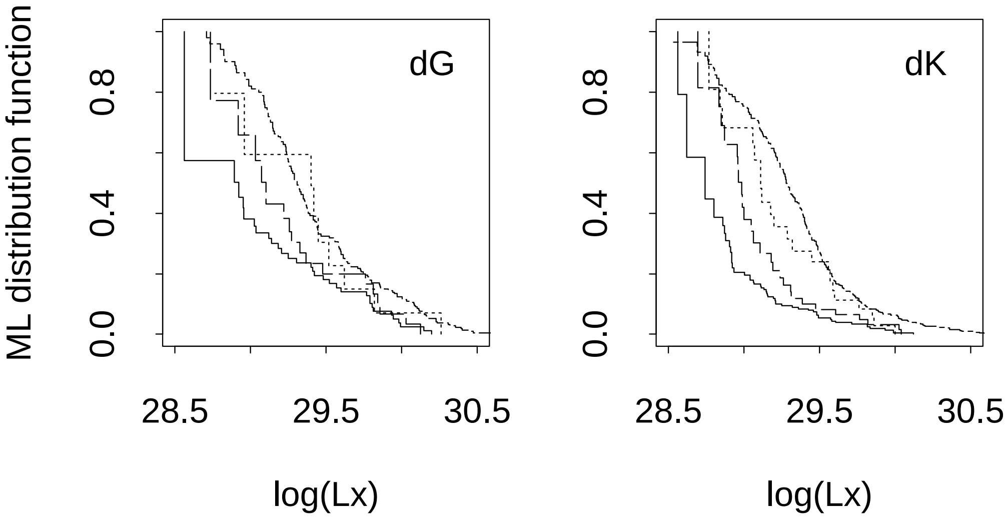

Figure 6. Maximum Likelihood luminosity functions of dG (left) and dK stars (right) for Pleiades (short-dashed line), Blanco 1 (pointed lines, Pillitteri et al. in preparation) and NGC 2516 (solid line for *XMM* data, Sciortino et al. 2001 and long-dashed line for *Chandra* data, Harnden et al. 2000).

To explore the effect of metallicity on coronal emission we have compared the X-ray properties of three clusters of similar age and different metallicity: Pleiades, Blanco 1 and NGC 2516: The Pleiades are well known in X-ray (see for example Stauffer et al. 1994, Micela et al. 1996), have a reliable membership, age of about 10^8 years and solar abundance (Boesgaard & Friel 1990). Blanco 1 has the same age and is metal rich with abundance about twice the solar one (Edvardsson et al. 1995). *Rosat* HRI data (Micela et al. 1999b), together with new astrometric membership obtained by the GSC-II (Hawkins et al. in preparation) are available. NGC 2516 has also a similar age of the previous two clusters and metal abundance about half the solar one (Cameron 1985; Jeffries et al. 1997; Jeffries et al. 1998). *Chandra* (Harnden et al. 2000) and *XMM* (Sciortino et al. 2001) -derived luminosity functions, with a photometric membership (Jeffries et al. in preparation) will be used in the following comparison. In Figure 6 we show the luminosity functions for G and K stars in the three clusters. In the case of NGC 2516 we report the X-ray luminosity functions derived both with *Chandra* (Harnden et al. 2000) and with *XMM* (Sciortino et al. 2001) since *XMM* surveyed a larger region of the sky with respect to *Chandra*, resulting in different luminosity functions. Sciortino et al. (2001) have verified that this discrepancy is not due to problems in cross-calibrating the two instruments, but that could be due to a real effect or to an increased star contamination in the larger field of view of *XMM*.

The comparison of the X-ray luminosity functions of G and K stars of these three clusters suggests that stars of the metal poor cluster NGC 2516 (regardless if *XMM* or *Chandra* data are considered) have lower luminosity than the analogous stars in the more metal rich clusters. This result has to be taken with caution since field star contamination in NGC 2516 sample could produce such a spurious result. The comparison between Blanco 1 and Pleiades is unconclusive, and the plot seems to suggest that the dK stars of Blanco 1 are slightly less luminous than dK stars in the Pleiades, but this difference is not statistically significant and we should wait for the future planned *XMM* observation of Blanco 1 to better explore the high-metallicity range.

The comparison between the X-ray luminosity functions of dM stars of these three clusters (Fig. 7) indicates that stars of NGC 2516 and the Pleiades have similar luminosity while suggest that metal rich cluster dM stars could have higher luminosity compared with the Pleiades and NGC 2516.

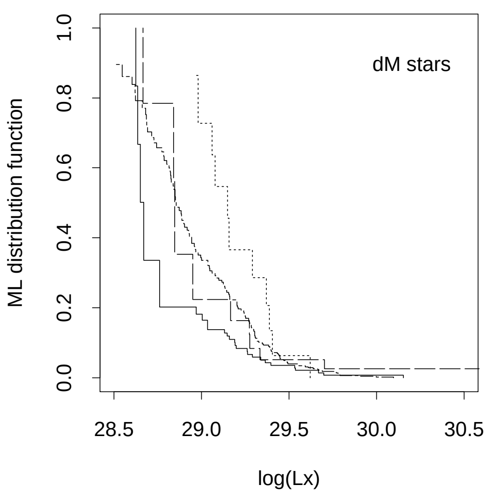

Figure 7. Maximum Likelihood luminosity functions of dM stars (right) for Pleiades (short-dashed line), Blanco 1 (pointed lines, Pillitteri et al. in preparation) and NGC 2516 (solid line for *XMM* data, Sciortino et al. 2001 and long-dashed line for *Chandra* data, Harnden et al. 2000) .

The influence of metallicity on X-ray emission appears to be complex, with different behavior depending on metallicity range and spectral type, and detailed studies of individual effects are needed (see for example Pizzolato et al. this issue). We note that in the previous comparisons we have compared stars in the same color range, but not in the same mass range, due to the dependence of color-mass relation on metallicity.

8. Brown dwarfs

A further point is the possible X-ray emission of very low mass stars. These stars are fully convective and cannot have a standard α-ω dynamo, but can have strong chaotic magnetic field generated by a thermally driven turbulent convection (see for example Cattaneo 1999). *Rosat* detected very few PMS brown dwarfs before (BD, Neuhauser et al. 1999) and recently *Chandra* detected flaring emission from the field BD LP 944-20 (Rutledge et al. 2000).

Assuming that these objects experience a saturation phenomenon similar to that observed on the low mass stars with log $L_{\rm x}/L_{\rm bol}$=-3.3 we can estimate the maximum level of $L_{\rm x}$ as function of age. Since the bolometric luminosity decreases during the contraction (low mass objects last for very long time), the maximum $L_{\rm x}$ of a brown dwarfs decreases with age. Fig. 8 shows how the maximum $L_{\rm x}$ evolve during the contraction for a set of masses ranging from 0.9 to 0.017 $M_\odot$. The edge between solid and dashed lines corresponds to the boundary between stars and brown dwarf evolutionary tracks (evolutionary tracks, as computed by D'Antona & Mazzitelli 1997).

Using the relation between $L_{\rm x}$ and age derived as described above, we can compute the distance at which we can detect such sources at a given limiting flux, as we have done in the previous sections for dG and dM stars. The maximum distance for three different thresholds is reported in Fig. 9. At fluxes reachable with typical *Chandra* or *XMM* exposures we will be able to detect BD in the youngest clusters, if these objects emit close to the saturation limit.

In this context the Pleiades can play a key role since they have been deeply studied to search brown dwarfs (see for example Hambly, Hawkins & Jameson 1993 or Bouvier et al. 1998), and their distance and age will allow us to "easily" detect in X-ray brown dwarfs close to saturation limit (even more easy it should be the detection of X-ray emission from "PMS" brown dwarfs). The Pleiades ACIS field of view does not contains known brown dwarfs and none of the BD photometric candidates of Krishnamurthi et al. (2000) show X-ray emission. This observation does not allow us to discriminate if the ACIS field of view does not contain any BD, and we need a different pointing to explore the BD emission in the Pleiades, or BDs in the Pleiades emit below 4 10^{27} erg/sec (the saturation limit at Pleiades age). The *XMM* pointings on the Pleiades already observed, but not yet analyzed, contain some of the cluster known brown dwarfs and will allow us to explore this issue.

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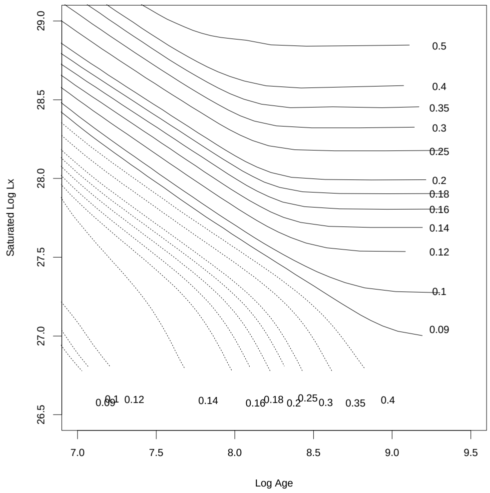

Figure 8. $L_{\rm x}$ vs. age for low mass stars assuming ia saturation level at log($L_{\rm x}/L_{\rm bol}$=-3.3 vs. age. Solid lines mark evolutionary track from D'Antona and Mazzitelli (1997) for low mass stars, while dashed lines mark brown dwarfs. Mass corresponding to each track is indicated

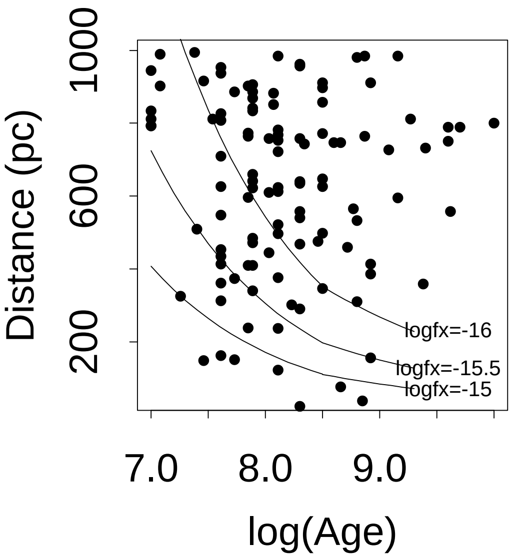

Figure 9. Solid lines mark, for a given threshold, the distance accessible with the limiting fluxes attainable with *Chandra* and *XMM* to detect brown dwarfs, assuming they emit close to the saturation limit.

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