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Effects of age and metallicity on coronal emission

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Abstract. I will review the state of art of our knowledge of coronal evolution during the stellar life, in particular through open cluster observations. I will also discuss the possible relationship between coronal emission level and chemical abundance, comparing X-ray luminosity functions of open clusters with similar age and different metallicity. The effect of metals on the X-ray activity level appears to be relevant for young dM stars, as shown by the comparison between the X-ray luminosity functions of dM stars in the Pleiades and in Blanco 1 open clusters.

1. Introduction

Stellar coronal emission is governed by stellar rotation (Pallavicini et al. 1981) and both evolve during stellar life. The relationship between rotation and coronal emission is complex since the two parameters interact. In fact rotational properties (surface rotational velocity, but also the differential rotation) determine the X-ray emission, and coronal emission is responsible for the angular momentum losses, regulating the evolution of the angular momentum.

Another parameter that can affect the X-ray emission level is the chemical abundance of the stars since it affects both coronal radiative losses and convection zone properties, that together with the rotation are responsible for the stellar magnetic activity. In the first part of this review I will present the status of our knowledge of evolution of coronal emission, while in the second part I will discuss the possible dependence of coronal activity level on chemical abundance. In both cases I will focus on open cluster observations, and on stars with age between 10^8 year and the age of the Sun.

2. Evolution of X-ray emission

X-ray observations of star forming regions and open clusters have shown very clearly that X-ray emission decreases with increasing age (see i.e. Rosner, Golub & Vaiana, 1985). In Figure 1 the medians of distributions of X-ray luminosity versus age for a number of star-forming regions and open clusters, together with a sample of nearby field stars, are shown. Vertical segments represent the $1-\sigma$ equivalent spread of the data, which amounts to about one order of magnitude in coeval stars. Figure 1 reports also the points relative to the Sun derived from Yohkoh observations during the minimum and maximum of solar cycle, and during a very bright flare (Peres et al. 2000). Variability in X-ray luminosity, as observed in the Sun, can give a significant contribution to the spread observed in stars of solar age, while there is no evidence for long-term variations in coronal emission of young stars (Stern 1998). Here I will consider only stellar clusters with known membership and not clusters for which the X-ray emission has been used as a membership criterion, in order to avoid biases towards X-ray bright stars. For more complete reviews on X-ray emission from open clusters see Jeffries (1999), Randich (2000), and Micela (2001).

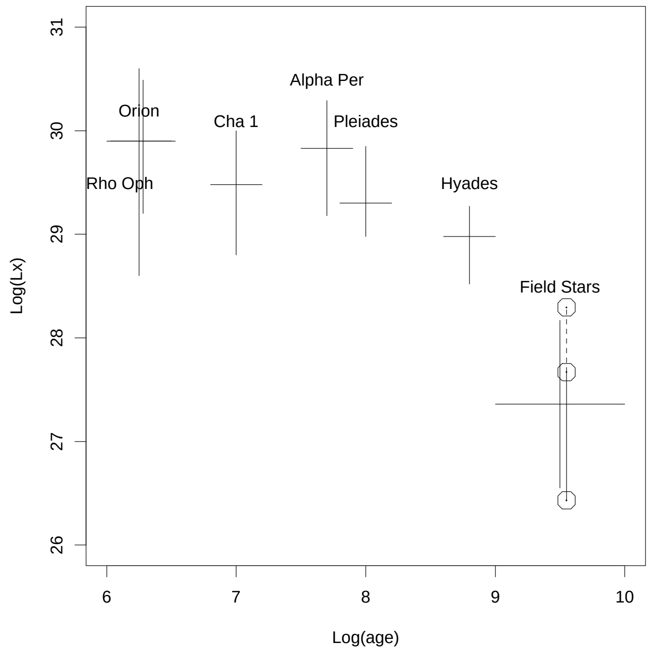

Figure 1. Medians of distributions of L_X versus age for a number of star forming regions, open clusters and nearby field stars (data from Casanova et al. 1995, Feigelson et al. 1993, Flaccomio et al. 2001, Micela et al. 1999a, Randich et al. 1996, Schmitt 1997, Stern et al. 1995). Vertical segments represent the $1-\sigma$ equivalent spread of the data. For comparison the data corresponding to the Sun during the minimum, the maximum and during a bright flare are reported (Peres et al. 2000).

From Fig. 1 is clear that most of the decline occurs in the decade between Hyades and solar age, just where data are poorer, and based on field stars, in general a mixture of stellar populations, age, and chemical composition.

In order to fill this gap I have recently analyzed a sample of well dated stars, from the sample studied by Ng & Bertelli (1998) derived from the sample of Edvardsson et al. (1993) who measured the chemical abundances of these stars. It does not represent the stellar population in the solar neighborhood from a statistical point of view, but can be used to explore some aspects of the coronal evolution. Knowing with good accuracy the chemical abundances, and the distances from Hipparcos observations, and using their evolutionary tracks,

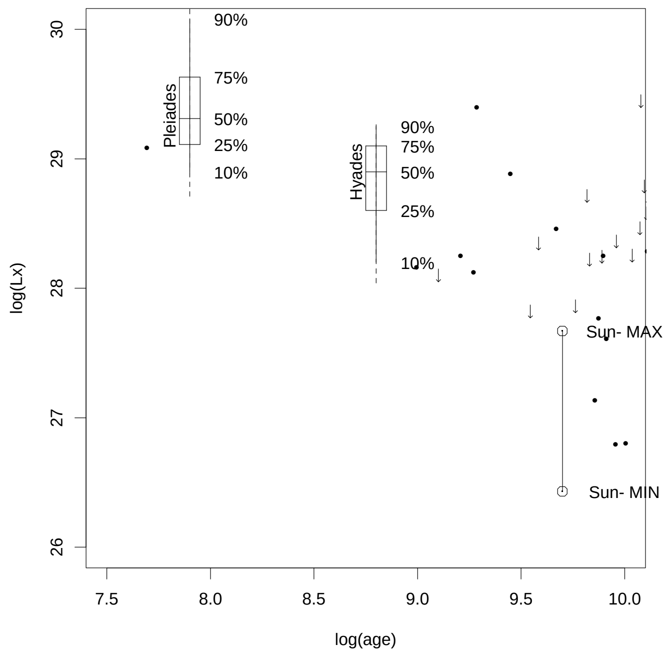

Figure 2. X-ray luminosity of stars of the sample of Ng & Bertelli (1998), compared with the Pleiades and Hyades distributions (boxes). The line at age 5×10^9 years connect the minimum and maximum of the Sun. Arrows mark the upper limits for the stars that have not been detected.

Ng & Bertelli have placed the stars on the H-R diagram, obtaining an age estimate for each star. For their stars in the $0.8-1.2$ $M_\odot$ range, I have collected the X-ray count rates derived from the RASS (*ROSAT All Sky Survey*), using RASS bright and faint sources catalogs, and computing the upper limits from the original RASS images for the undetected stars.

The results of such analysis are shown in Fig. 2. Boxes indicate the Pleiades and Hyades distributions, with some representative quantiles marked. Empty symbols indicate the solar X-ray luminosity during the minimum and maximum, while small points indicate the stars from the Ng and Bertelli (1998) subsample, and the arrows mark the upper limits for the stars that have not been detected in X-rays. The data show that the spread of L_X remains large up to advanced age, and that there are stars that mantain a high level of emission up to solar age. We cannot say how many and which stars and in which physical conditions maintain this high level of emission for long time but we can say that they exist. Such a large spread implies that X-ray emission cannot be used to date (otherwise that in a statistical sense) a star, and that a given star can follow different pattern in the L_X- age diagram.

2.1. Evolution of X-ray spectra

With the spectrographs onboard of CHANDRA and XMM high resolution X-ray spectra are only starting to be available now, and only for the brightest and nearest sources. Unfortunately star forming regions and open clusters are far away and we cannot collect good quality high resolution X-ray spectra of their stars but we can only deduce their properties from low resolution spectra.

AB Dor is the closest young field star, that allows us to collect a good high resolution spectrum. This star has been observed both by MEG/HETG onboard of CHANDRA and by RGS of XMM/Newton. Figure 3 shows the emission measure distribution derived by Linsky et al. (2001) from the CHANDRA data, together with the values derived by Güdel et al. (2001) from a three temperature fit to the XMM data, and appropriately normalized. The two observations give consistent results, and a double peak, (as in the flaring Sun), typically observed in active stars, appears.

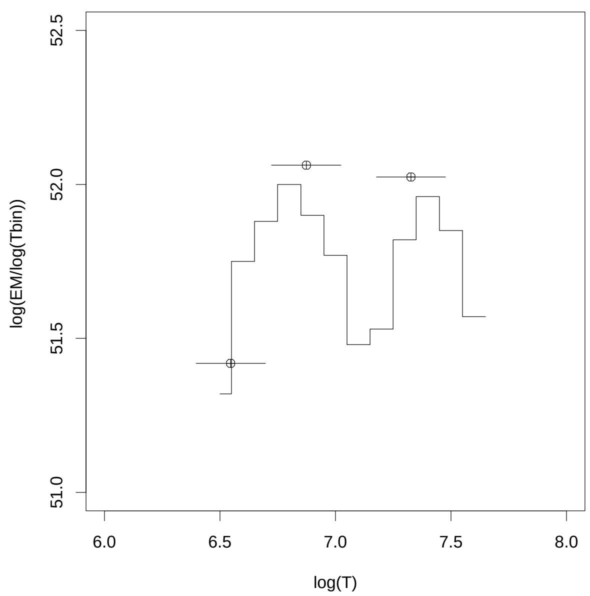

Figure 3. Emission measure distribution of the corona of AB Dor observed by MEG/HETG onboard of CHANDRA (Linsky et al. 2001). The three points mark the emission measures derived by three temperature fit to the RGS/XMM data (Güdel et al. 2001)

For the large majority of stars we can study only their low resolution spectra through the usual 1- or 2- temperature fitting procedure. To understand what is the meaning of the 1-T or 2-T fit is very instructive to analyze the solar case. In order to explore how the Sun would appear when observed as a star, Peres and collaborators (Peres et al. 2000) have developed a technique that makes use of Yohkoh data. They take advantage of the spatial resolution of the instrument and of its two filters to determine the effective temperature of each image pixel from which they derive the emission measure distribution of the Sun. Furthermore they can synthetize the emitted spectra and fold them through a "stellar" standard instrument, and analyze them as a typical stellar observation. In Fig. 4 the emission measure distribution of the Sun is reported, derived during the minimum and the maximum of the solar cycle (Peres et al. 2000). During the minimum the emission measure distribution peaks at $\sim 10^6$ K, while during the maximum the peak is broader and a significant quantity of hot material is present. Symbols in the figure mark the temperatures and the corresponding emission measures obtained when the emitted spectra, derived from the two emission measure distributions, are folded through the spectral response of the ROSAT/PSPC, (the instrument that to date has performed the largest number of stellar observations), and analyzed with a one- or two-temperature fitting procedure. In the case of the Sun observed during the minimum, the PSPC needs only one temperature, very close to the peak of the original distribution, to explain the spectrum, During the maximum two temperature components around the broad peak of the emission measure distributions are needed.

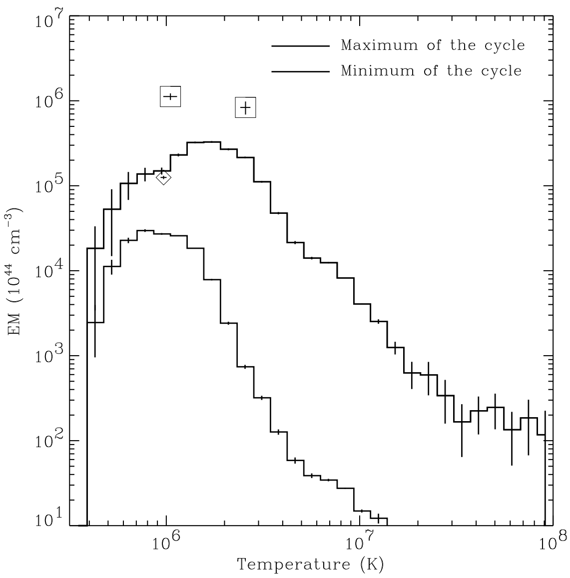

Figure 4. Emission measure distributions of the Sun, derived during the minimum and the maximum of the solar cycle (Peres et al. 2000). Symbols mark the temperatures and the emission measures obtained by the 1- or 2-T fit when the derived spectra, are folded through ROSAT/PSPC spectral response.

Figure 5 shows the emission measure distribution of the Sun during a bright flare. In this case a pronounced peak at temperature above 10 MK appears and the spectral fitting procedure indentifies the presence of hot plasma, finding one component above 10^7 K. Note the strong similarity (apart from an horizontal shift) of this emission measure distribution with that obtained on the young star AB Dor of Fig. 3.

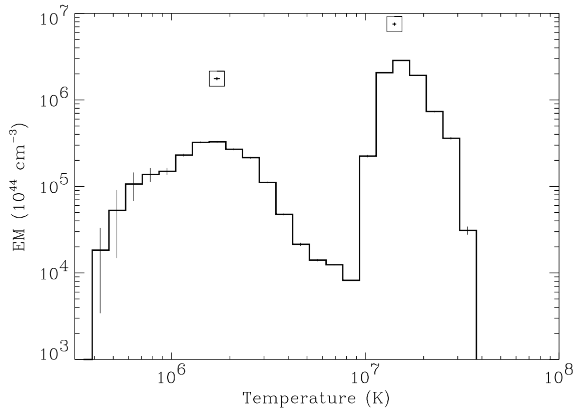

Figure 5. Emission measure distribution of the Sun, derived during a large flare (Peres et al. 2000). Squares mark the temperatures and the corresponding emission measures obtained when the emitted spectrum, derived from the emission measure distribution, is folded through ROSAT/PSPC

Generally young coronae are hotter than old ones, with a dependence of the X-ray spectra on spectral type and rotation (Gagné et al. 1995). Putting together 1- or 2-T fit results of the Pleiades (Gagné et al. 1995), Hyades (Stern et al. 1994), and nearby field stars with some age determination (Güdel et al. 1997) we can explore how X-ray spectra change with age.

The fitted two temperatures vs. age are shown in Fig. 6 where filled symbols represent the high temperature component, and the empty ones the low-temperature components. Large symbols are the temperatures derived from the composite spectra of the Pleiades fast and slow rotating dG stars (Gagnè et al. 1995). Both temperatures decrease with age, with a spread of about half an order of magnitude for stars of the same age. In figure 6 I report also the temperatures derived by Peres et al. (2000) for the Sun during the minimum, the maximum and the flare of Fig. 5. We note that the temperatures derived from the Sun during the flare are very similar to those derived in the very active and young Pleiades stars. The emission measures derived in the case of the flaring Sun are smaller than the corresponding values observed in the young stars, while the temperatures and the ratio between the two emission measures are very similar. This implies that the flaring Sun has a spectrum with a shape

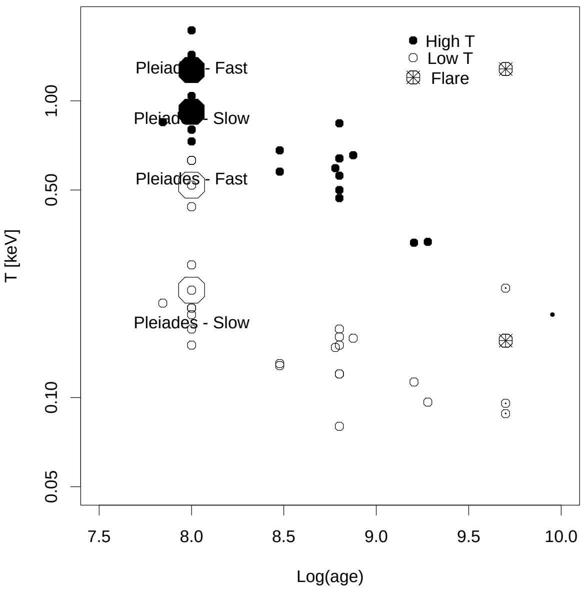

Figure 6. Temperatures derived from spectral fit of ROSAT/PSPC data versus age for dG stars. Filled symbols represent the high temperature component, and the empty ones are the low-temperatures. Larger symbols are the temperatures derived from the composite spectra of fast and slow rotating dG Pleiades stars. Points at log(age)=9.7 mark the temperatures derived for the Sun during different phases of solar activity.

similar to those of active stars, but that its overall luminosity is much smaller. This is consistent with the hypothesis that the emission observed in the most active stars can be due to a continuous flaring activity.

Knowing the temperature and the emission measure evolution we can also derive how the number of emitted photons in a given range of energy evolves. This is particularly important for the study of the evolution of planetary environments, which are strongly affected by the ionizing radiation. The results (Micela 2002) indicate that the decay of the photons flux is steeper in the hardest band, where photons are also more penetrating. In particular the flux in the 1-10 keV band incident at the Earth decreases by about two orders of magnitude since the Sun was the same age as the Pleiades. This estimate does not take into account the large flares often observed in young stars. To evaluate their effects, systematic studies of flaring rate, duty cycles, power involved, etc. at different age are needed.

3. Influence of metallicity on coronal properties

Metal abundance can affect coronal properties through different mechanisms, first of all through effects on the convection zone: variations of chemical abundance produce changes of opacity and as a consequence of the convection zone properties, one of the fundamental ingredient of the dynamo process. There is also a direct effect on X-ray radiative losses, dominated by radiation of highly ionized atoms, that depend on temperature. Furthermore the effect on the radiative losses influences the emission measure distribution that is governed by the balance between heating, conduction and radiative losses. In principle such differences can cause different coronal and rotational evolution and in this section I will discuss evidences for presence or absence of such effects.

In order to explore the effects of chemical abundance on coronal properties we can compare X-ray properties of clusters with same age but different metallicity. In particular I will compare the Pleiades data with those of Blanco 1 that has a similar age but chemical abundance twice the solar one. This cluster has been observed with the HRI of ROSAT (Micela et al. 1999b) and will be observed with XMM/Newton. For Blanco 1 an astrometric membership derived from the GSC−II project has been recently obtained and X-ray luminosity functions accordingly derived (Pillitteri et al. in preparation). Then we can compare these two clusters with NGC 2516 that has a similar age but chemical abundace about half of solar one and for which both CHANDRA and XMM observations have been already published (Harnden et al. 2001, Sciortino et al. 2001). For this cluster only photometric membership is available and a project for a more reliable membership based on radial velocity is ongoing by Jeffries and collaborators.

In Fig. 7 the X-ray luminosity functions of dG and dK stars for the three clusters are reported. NGC 2516 appears to be underluminous with respect to the other clusters. This comparison seems to suggest that metal poor solar-like stars have an X-ray emission level below the level of solar metal rich stars.

Fig. 8 shows the X-ray luminosity functions of dM stars in the three clusters (Pillitteri et al. in preparation). In this case the stars of Blanco 1 appear to be overluminous with respect to the dM stars of the other clusters. The difference is in the body of the distribution, while the X-ray high luminosity tail does not differ. It is worth to note that the effect of chemical abundance on X-ray emission in dM stars appear to be dominant with respect to the effect of age as it is evident by the comparison (Pillitteri et al. in preparation) with the X-ray luminosity function of dM stars of the younger cluster α Per (Randich et al. 1996). This function is undistinguishable from that of the Pleiades while it is underluminous with respect that of Blanco 1.

3.1. Chemical abundance and subphotospheric convection: what effect on X-ray emission?

It is widely accepted that the ratio (the so-called rossby Number) between the rotational period and a color-dependent scaling function, approximately equal to the convective turnover time $\tau_{\rm conv}$, determine the link between the stellar internal structure and the stellar activity (Noyes et al. 1984). The τ_{conv} is a property of the convection zone, and therefore it is affected by the chemical abundance.

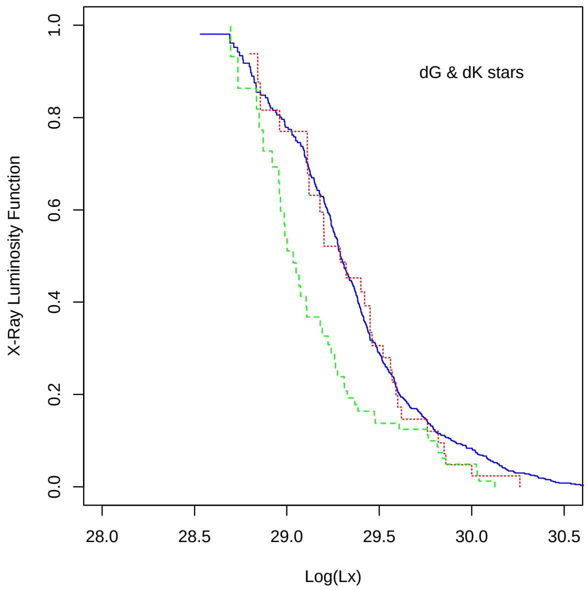

Figure 7. X-ray luminosity functions for dG and dK stars in Blanco 1 (dotted line, Pillitteri et al. 2002), Pleiades (solid line, Micela et al. 1999a), and NGC 2516 (dashed line, Harnden et al. 2001)

Pizzolato et al. (2001) have explored the expected effects of chemical abundance on the Rossby number and have evaluated what are the final effects that can be observed.

In particular Pizzolato et al. have computed the convective turnover time using the model of Ventura et al. (1998) with the classical Mixing Lenght Theory (MLT) anf the Full Turbulence Spectrum (FST) for three different metallicity values: $z = 0.01, 0.017, 0.03$. the main results do not depend on the models and indicate that the abundance is important in determining the convective time for G stars while is irrelevant for redder stars. For stars of 0.6 $M_{\odot}$ the τ_{conv} doubles when z increase from 0.01 to 0.03. When we compare stars with same color this behavior inverts, as stars with the same color, but different metallicity, have different mass, since a star tends to become redder when opacity increases, in such a way that F and G stars with high metallicity have mass higher that stars with low metallicity. Fig. 9 shows the difference in the Rossby number induced by a difference in abundance, assuming the same rotational period for stars with same color. The expected effect is up a factor 2.5 for late dF stars and decrease to zero for early dK stars.

In order to test their predictions Pizzolato et al. (2001) have also taken into account the influence of chemical abundance on the coronal radiative losses. At typical coronal temperature most of the emission is due to emission lines from highly-ionized atoms, and is thus very sensitive to abundance variations. At T$\sim 10^6$ K the plasma emissivity increases more or less linearly with abundance, while at T$\sim 10^7$ K increases with an exponent between 0.6 and 0.8. The authors

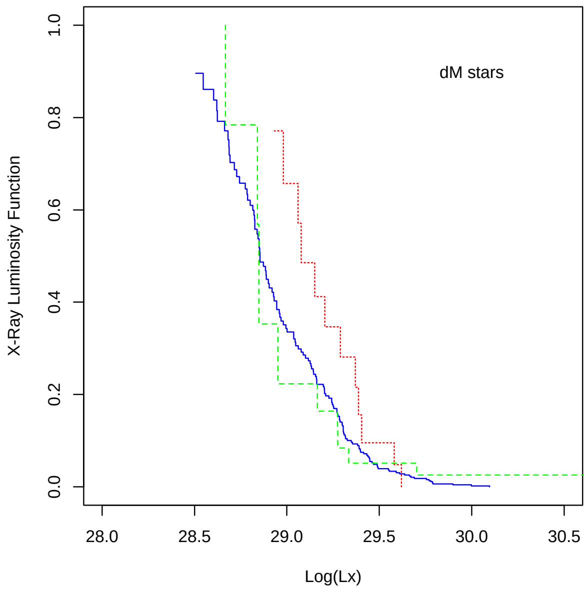

Figure 8. X-ray luminosity functions for dM stars in Blanco 1 (dotted line, Pillitteri et al. 2002), Pleiades (solid line, Micela et al. 1999a), and NGC 2516 (dashed line, Harnden et al. 2001)

have compared their expectations with the medians of L_X observed in NGC 2516, Pleiades and Blanco 1, assuming the same rotational distributions for the three clusters. Furthermore they have assumed a coronal temperature T= $10^6 - 10^7$ K, and a relationship between the X-ray luminosity and the Rossby number:

$$L_x \propto R_O^{-\alpha} \propto \tau_{conv}^{\alpha}$$

with $\alpha = 1 - 2$. Fig. 10 shows the expectaction for dG stars (normalized to the Pleiades) togheter with the median values observed in the three clusters. The shaded area in the top panel, indicates the uncertainty introduced by the uncertainty in the exponent between the relationship between the L_X and the Rossby number. Since the τ_{conv} varies very rapidly with the color in this range of mass, the panel on the right shows how the predictions change with color. In practice for the earliest spectral type the dominant effect is on the convective turnover time and the X-ray luminosity is expected to decline with the increasing metallicity. For intermediate colors the effects on the τ_{conv} and on the radiative losses compensate, and for later spectral types, the latter dominate and an increasing of L_X with metallicity is expected. On average in this color range the predictions well agree with the median values observed in the clusters.

Fig. 11 shows the analogous predictions for dK stars where only the effect on the radiative losses is important. The point relative to Blanco 1 is well below the expectations, while the NGC 2516 data point is in agreement with the predictions. The reasons for the discrepancy observed in Blanco can be of various nature. First of all the sample could be contaminated by field stars

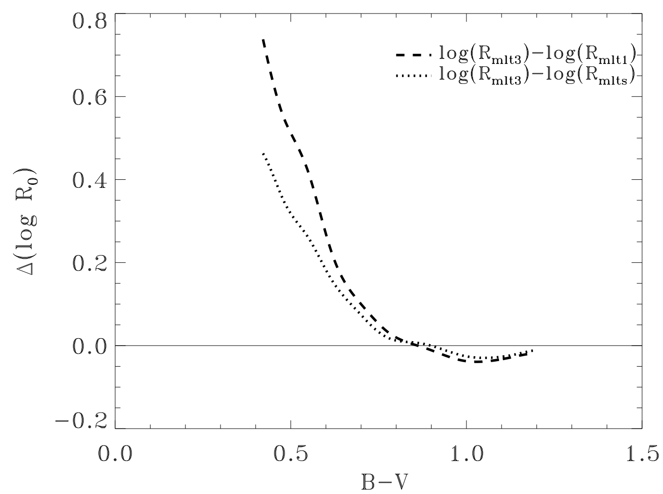

Figure 9. Variations of the Rossby number induced by different metal abundances

that tend to lower the luminosity function of the cluster, but recent improved membership determination tends to exclude this reason (Pillitteri et al. 2002). Of course the rotation distribution can be very different but unfortunately rotational measurements for Blanco 1 are limited and further investigations are needed.

4. Summary

In the first part of this review I have summarized how X-ray emission evolves during the main sequence life. During this time the emission level decreases by three order of magnitude, but stars of same age shows a significant spread in X-ray luminosity that amounts to one order of magnitude. The analysis of a well dated sample of field stars indicate that stars with age similar to the Sun can have very high luminosity level, reinforcing the conclusion that stars of a given age can have very different luminosities.

At the same time the X-ray spectrum softens with the dominant coronal temperatures cooling and the hotter temperature decreasing more steeply. As a consequence the flux of ionizing photons decreases with the X-ray photons evolving much rapidly than the EUV photons. In particular the flux of coronal photons in 1−10 keV band decreased by two orders of magnitude since the Sun was the same age of the Pleiades with possible consequences on primitive planetary atmospheres.

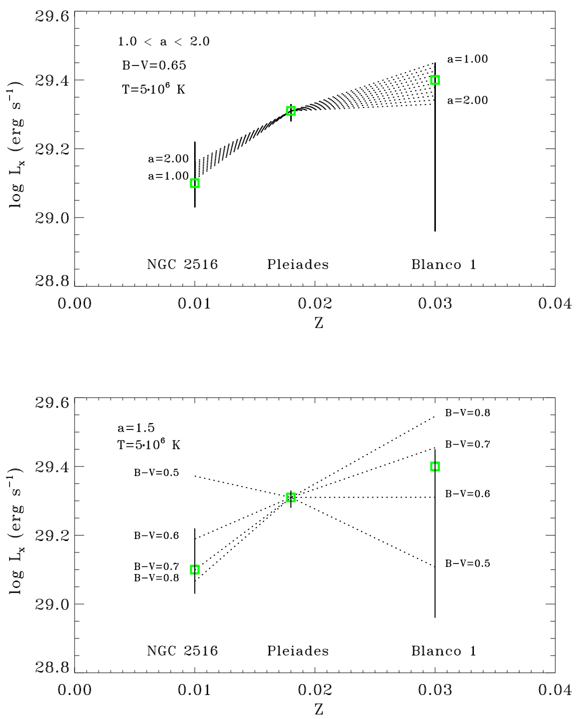

Figure 10. Comparison between the median X-ray luminosity of dG type stars (points with their formal errors) for NGC 2516 (Harnden et al. 2001), Pleiades (Micela et al. 1999a), and Blanco 1 (Pillitteri et al. 2002). The dashed area in the top panel indicates the predictions by Pizzolato et al. (2001), with the spread introduced by different index in the power law relating L_X and Rossby number. The lower panel indicates the expectations for various B−V values.

Both the observations and the predictions based on stellar models seem to indicate that chemical abundance can influence the observed emission both through effects on radiative losses and through the effect on the convection zone depth. In dG stars the two effects tend to cancel, while in the latest spectral types only the effect on the radiative losses is important. Observations of dG stars in open clusters with similar age but different metallicity are consistent with this picture, while the observations of dK stars in the metal-rich cluster Blanco 1 do not fit. Further observations, mainly of rotational velocity, are needed to understand the origin of a such discrepancy. Chemical abundances seem to have an important role in emission of dM stars.

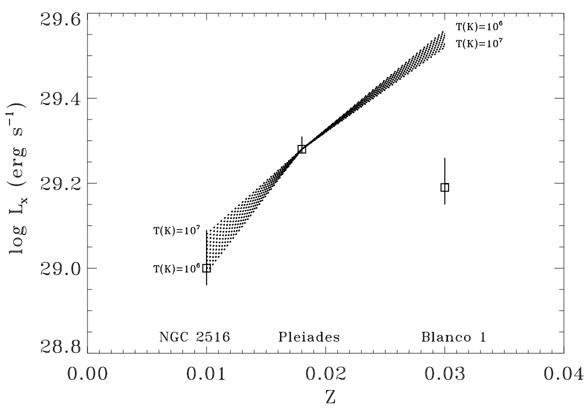

Figure 11. Comparison between the median X-ray luminosity of dK type stars for the three clusters as in the previous plot. The dashed area indicates the expected trend due to different metal abundance, assuming coronal temperature spanning the $10^6 - 10^7$ K range

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