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Evolution of Stellar Coronal Activity on the Main Sequence

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Abstract. Young stars have coronae much more active than present Sun, with emission in the soft X-ray bandpass up to $10^3 - 10^4$ times the solar level. Interestingly most of the decrease in X-ray luminosity occurs during the main sequence life. I will review the dependence of activity level on stellar age, and the state of art of our knowledge of the evolution of coronal temperature focusing on evolution on the main sequence between 10^8 years and the solar age.

1. Introduction

Since the first stellar X-ray observations, it was evident that X-ray emission is a common feature of late type stars, and that stars with the same optical characteristics can show very different level of X-ray activity (Vaiana et al. 1981). The main parameter responsible for the level of X-ray luminosity is the rotational velocity (Pallavicini et al. 1981), and, as a consequence, age, since rotation evolve with stellar age.

In this review I will summarize the status of our knowledge of evolution of stellar activity on the main sequence for stars of 1 $M_{\odot}$. I will focus on evolution of coronae of solar type stars, as observed in X-rays, with age greater than 100 Myr. In the next section I will discuss the evolution of X-ray activity level, then in section 3 I will present evidences for evolution of X-ray spectra. In section 4, using results of sections 2 and 3, I will derive the evolution of the flux of photons emitted by the corona, during the main sequence life and incident at 1 AU.

2. Evolution of X-ray Luminosity

The most common approach adopted to study the evolution of stellar parameters is through observations of stellar associations and open clusters. With this approach we can isolate the influence of various physical parameters and explore a wide range of masses.

A significant number of stellar associations and open clusters among the nearest ones have been studied in X-rays. Some of them have poorly known membership, and sometimes X-ray itself have been used to find new members. In these cases, although the method is very effective to explore the low mass population of clusters, the resulting X-ray properties can be biased toward X-

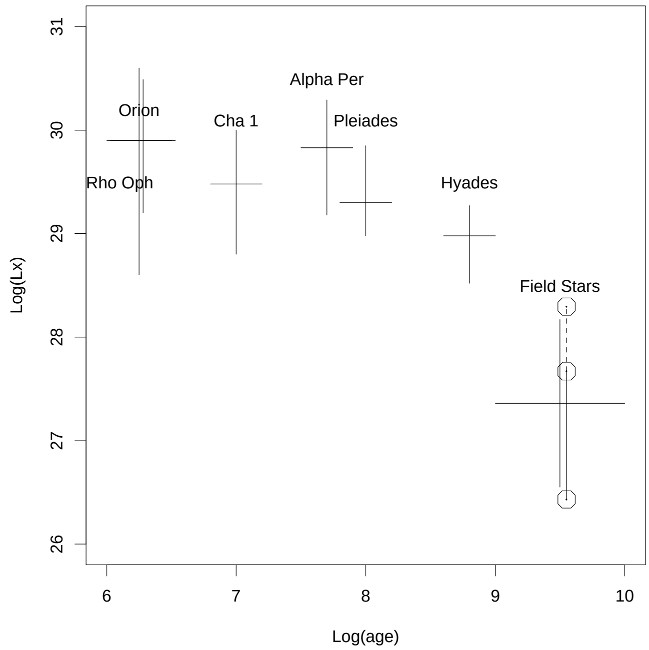

Figure 1. Medians of distributions of L_x versus age for a number of star forming regions and open clusters. Vertical segments represent the 1-sigma equivalent spread of data. (Data from Casanova et al. 1995, Feigelson et al. 1993, Flaccomio et al. 2001, Micela et al. 1999, Randich et al. 1996, Schmitt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

ray active stars and for this reason I will not include them in the following discussion. There are also a number of "peculiar" cases in the sense that some clusters behave in a way different from other clusters of similar age. The most known case is that of Praesepe (Randich & Schmitt 1995), that, notwithstanding being very similar to the Hyades, is underluminous in X-rays with respect to the Hyades. In the following I will not consider these cases, and I refer the reader to other reviews for further details (Jeffries 1999, Randich 2000, Micela 2001)

Observations of associations and open clusters show clearly a decreasing of X-ray luminosity level with the increasing of stellar age. In Fig. 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 data, which amounts to about 1 order of magnitude in coeval stars. The figure shows that stars appear to maintain more or less the same activity level up to the α Per age, then their luminosity starts to slowly decline up to Hyades age and much steeply after. Most of the decline occurs just in the decade between Hyades and solar age. Reported in figure are 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 that observed in the Sun can give a significant contribution to the spread observed in stars of solar age, while there is not evidence for long-term variations in coronal emission of young stars.

One of the first result of stellar X-ray observations is the dependence of level of emission on stellar rotation (Pallavicini et al. 1981), at least for rotational velocity smaller than the saturation level [1], that for 1 $M_\odot$ stars corresponds more or less to 30 km/sec (Pizzolato et al. 2001a). Excluding the case of binary systems with synchronized rotational velocities, the evolution of X-ray luminosity has to reflect the rotation evolution, with a plateau in the first phases when the rotation is above the saturation limit, and with a decay when the rotational velocity goes below this value. We have to consider also that at a given age, stars of the same spectral type can have very different rotation, in particular in the first phase of main sequence life (Bouvier 1997). The spread of rotational velocity decreases with increasing age implying that the braking of fast rotators is more rapid that the braking of slow rotators.

This difference is consistent with a different core-envelope coupling in rapid and slow rotators. Bouvier (1997), comparing observations with predictions from the models of MacGregor (1991) has suggested that solid-body rotation reproduces the rotational evolution of fast rotators, while the decoupled models reproduce evolution of slow rotators that have large internal velocity gradients. The differential rotation appears when the loss of angular momentum at the stellar surface is more efficient than the redistribution of angular momentum in the stellar interior. Since the magnetic activity depends on rotation and on differential rotation, the evolution of magnetic activity and hence of X-ray emission will be different for stars that are fast or slow rotators on the Zero Age Main Sequence. At the age of Sun essentially both fast and slow rotators converge at the same surface rotational velocity, implying that we cannot derive in detail the rotational and magnetic history of the Sun.

In the discussion above we note a critical gap in the observations: There is a certain amount of data on clusters with age less than one billion years, while our knowledge on the last 3-4 billion years is based only on field stars, that are poorly dated and inhomogenous in age, and chemical composition. The ideal approach to fill this gap is to observe in X-rays some clusters older than the Hyades. Unfortunately old clusters are on average farther away to the Sun than the youngest ones, and this, together with the lower X-ray activity of old stars, makes it very difficult to characterize the emission of solar normal type stars in such clusters. Probably only NGC 752 has the "right" distance and age to fill this gap with Chandra or XMM observations but, up to now, a such observation has not been performed or scheduled.

In order to explore late evolution on the main sequence with available data, the best we can do is to select a well known field star sample. With this aim

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[1] Stellar X-ray luminosity appears well correlated with rotational velocity for rotation smaller than a critical value. Above this value all the stars show the same L_x, apparently the maximum value that can be reached by a star, and we say that the star is saturated. The X-ray luminosity value at which this saturation occurs depend on the spectral type and is $\sim 10^{-3}$ of the bolometric luminosity.

I have analyzed the sample from the paper of Ng and Bertelli (1998) for which the authors have done the effort to date each star as accurately as possible. The sample does not represent the stellar population in the solar neighborhood from a statistical point of view, but in any case can be used to explore some aspects of the coronal evolution. The sample is derived from the sample of Edvardsson et al. (1993) who measured the chemical abundances of these stars. The sample was originally selected with the aim to have a similar number of objects in each age interval. Knowing with good accuracy the chemical abundance, and knowing the distance from Hipparcos observations, and using their evolutionary tracks, Ng & Bertelli have placed the stars on the HR 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 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 Ng and Bertelli (1998) subsample, and the arrows mark the upper limits for the stars that have not been detected in X-rays. I have not attempted to compute an X-ray luminosity function from these data, since they do not belong to a statistically significant sample, but they can give us useful information on evolution of coronae of solar type stars. In particular they show that the spread of L_x remains large up to advanced age, and that there are stars that maintain 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.

3. Evolution of X-ray Spectra

This section is focused on the spectral evolution of stellar coronae. Our knowledge in this field is much more limited, but something can be said. High resolution X-ray spectra are only starting to be available now, with the spectrographs onboard of Chandra and XMM, and only on the brightest and nearest sources. Unfortunately star forming regions and open clusters are in general not close enough to allow collecting good quality high resolution X-ray spectra and we can only deduce their properties from low resolution spectra.

The simpler way to compare spectra of different stars is through hardness ratios, a sort of X-ray colors, or through a fitting procedure of the spectra with a model of thermal plasma. The coronal emitting material is an optically thin plasma and the radiation is emitted from plasma in a range of temperatures, but because of the limited resolution of the spectra, X-ray astronomers use to parameterize the X-ray spectra with one or two temperatures and the corresponding emission measures. This latter quantity is a measure of the amount of plasma present at the given temperature. It is possible to define this quantity since the emission of an optically thin plasma is dominated by collisional processes and the emission intensity is proportional to the product of the protons density and the electron density. In this case we can write:

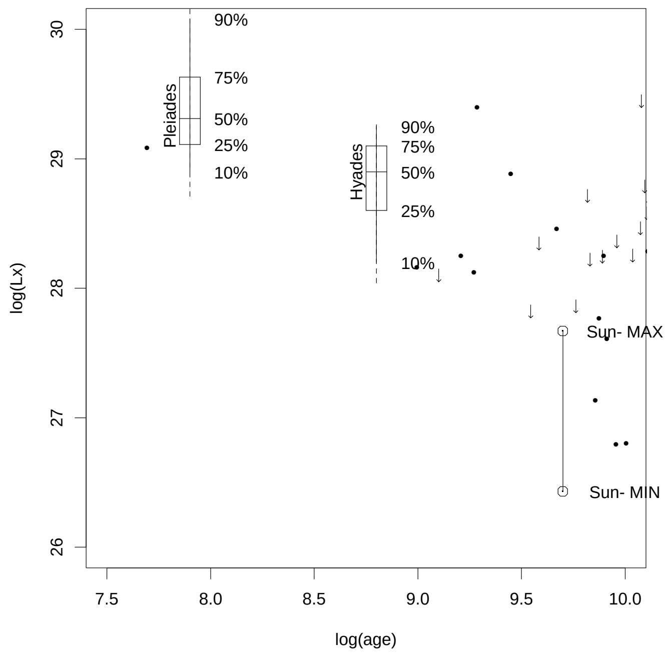

Figure 2. X-ray luminosity of stars of the sample of Ng & Bertelli (1998), compared with the Pleiades and Hyades distributions (boxes). Line at age 5×10^9 years connect the minimum and maximum X-ray emission level of the Sun. Arrows mark the upper limits for the stars that have not been detected.

$$L \propto n_p n_e \cdot V \cdot P(T) \sim n_e^2 \cdot V \cdot P(T)$$

where $P(T)$ is the plasma emissivity and contains the dependence on the temperature, while $n_e^2 \cdot V$ is called *Volume Emission Measure*.

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 make 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 this way they can study, for example, as the Sun would appear when observed as a star during different stages of the cycle, what is the effect of rotational modulational, what are the properties of individual coronal components as the active regions, flares, etc.

In Fig. 3 the emission measure distribution of the Sun is reported, derived during the minimum and the maximum of the solar cycle (Peres et al. 2000). We see that during the minimum the emission measure distribution peaks at

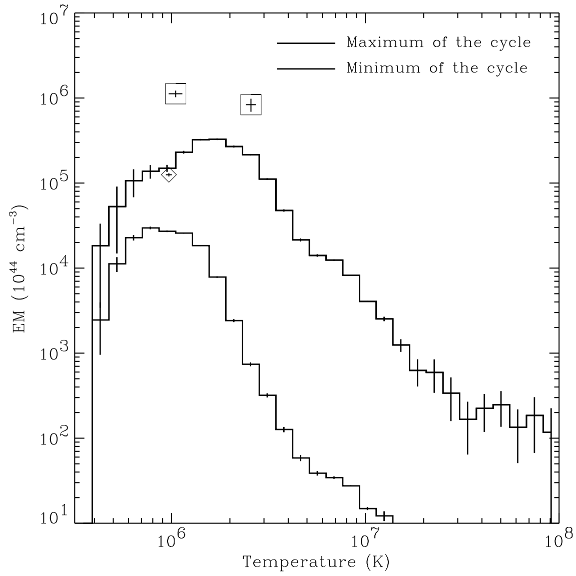

Figure 3. Emission measure distributions of the Sun, derived during the minimum and the maximum of the solar cycle (Peres et al. 2000). Symbols mark the temperatures and the emission measures obtained by the 1 or 2-T fit when the spectra, derived from the emission measure distributions, are folded through Rosat/PSPC.

$\sim 10^6$ K, while during the maximum the peak is broader and a significant quantity of material at hot temperatures is present. We have to stress that these are the emission measures of the corona and that a large quantity of cooler material ($10^4 - 10^5$ K) is present in the transition region, emitting mainly in the ultraviolet bandpass. Since Yohkoh is sensitive to X-ray emission, this material is not present in the derived distributions. Symbols in figure mark the temperatures and the corresponding emission measures obtained when the emitted spectrum, derived from the two emission measure distributions, are folded through the spectral response of the Rosat/PSPC, the instrument that has performed the largest number of stellar observations to date, and analyzed with a one- or two-temperature fitting procedure. We see that in the case of the Sun observed during the minimum, to explain the spectrum the PSPC needs only one temperature, very close to the peak of the original distribution, while during the maximum two temperatures around the broad peak are needed.

In the same way it is possible to derive the emission measure distribution when the Sun undergoes a large flare. In this case a very pronounced peak appears at temperature above 10 MK and the spectral fitting procedure identifies the presence of hot plasma, finding one component above 10^7 K as shown in Fig. 4.

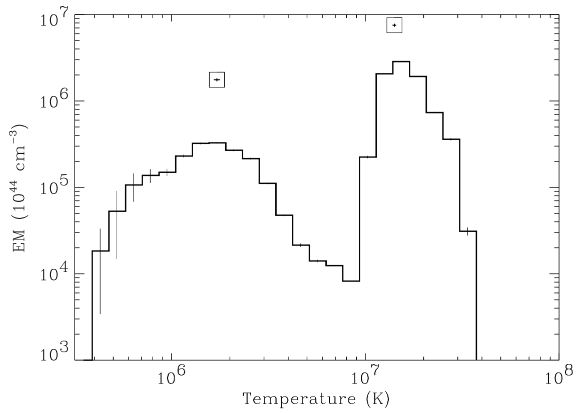

Figure 4. Emission measure distribution of the Sun, derived during a large flare (Peres et al. 2000). The squares mark the temperatures and the corresponding emission measures obtained when the emitted spectrum, derived from the emission measure distribution, is folded through the spectral response of the Rosat/PSPC

This procedure of thermal fitting has been largely applied to stellar X-ray spectra, and in the following we will summarize the results in terms of stellar evolution.

In Fig. 5 the temperatures derived from the 2-T fits of stars of the Hyades and Pleiades are reported: on average Hyades stars have temperatures lower than Pleiades stars. Results of the fits of the composite spectra of Pleiades stars grouped by spectral type and rotational velocity are also shown (data from Gagné et al. 1995). A dependence of properties of X-ray spectra on spectral type and rotation is evident with the fast G rotators being hotter than the other groups and the F stars cooler than all the others. Both the high and low temperature components of young stars are hotter than those of older stars and fast rotators appear hotter than slow rotators of similar age.

In the context of their project of “the Sun in time”, Güdel et al. (1997) have tried to explore the evolution of X-ray spectra during the main sequence life, through the analysis of a small sample of nearby solar-mass field stars that can be dated on the basis of membership to moving groups, or of an average rotation-age relationship, or of star model isochrones. They have used both ASCA and Rosat data. Putting these data together with those of Pleiades and Hyades, we can have a better idea of X-ray spectra change with age. For consistency with results on Hyades and Pleiades, here we will consider only the Rosat data

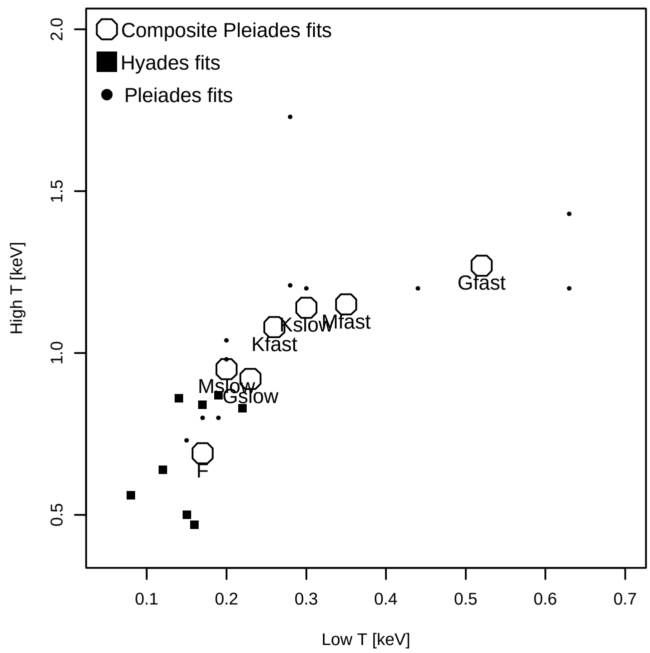

Figure 5. Temperatures derived from the 2-T fit for Hyades (data from Stern et al. 1994) and Pleiades (data from Gagnè et al. 1995). Large symbols represent the fits obtained for stars in the Pleiades grouped by spectral type and rotational velocity.

that refer to 7 stars. The resulting two temperatures are shown in Fig. 6 where filled symbols represent the high temperature component, and the empty ones the low-temperature ones. Large symbols are the temperatures derived from the composite spectra of the Pleiades of fast and slow rotators dG stars (Gagnè et al. 1995). Both temperatures decrease with age, with a spread of about half an order of magnitude for stars of 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 a bright flare. 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.

Fig. 7 shows the evolution of the volume emission measures with age. Both the cool and hot emission measures decrease with age, with the slope of the hard component slightly steeper than the soft component one. A large spread in stars of same age is present. 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 means that a solar flare has a spectrum with a shape similar to those of active stars, but the overall luminosity is much smaller. This is consistent with the hypothesis that the emission observed in the most active stars is due to a continuous flaring emission.

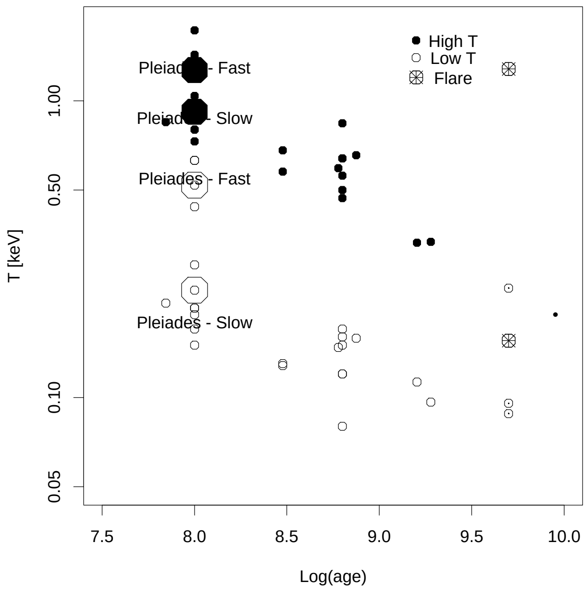

Figure 6. Temperatures derived from spectral fit of Rosat/PSPC data versus age for dG stars. Filled symbols represent the high temperature component, and the empty ones are the low-temperatures. Large symbols are the temperature derived from the composite spectra of fast and slow rotators dG Pleiades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

4. Evolution of coronal photon flux at 1 AU

One of the important parameters that can significantly affect a planetary environment is the number of ionizing photons incident on the atmosphere. In this section I will discuss how the number of such photons generated by the corona evolve. This number can be computed knowing how the X-ray luminosity and the spectrum evolve. The following computation has been done in the very rough approximation of the one or two temperature model description considered above. The derived numbers are therefore only indicative and have to be taken with caution.

Knowing the temperature and the emission measure of the emitted spectrum we can compute the number of emitted photons in a given range of energy. In Fig. 8 I report the evolution of the number of photons per second emitted by stellar coronae and incident at 1 Astronomical Unit. Different symbols indicate the number of photons between 0.1 and 1 keV and those with energy above 1 keV. The plot indicates that the decay of the flux of photons is steeper in the hardest band, where photons are also more penetrating. In particular the flux

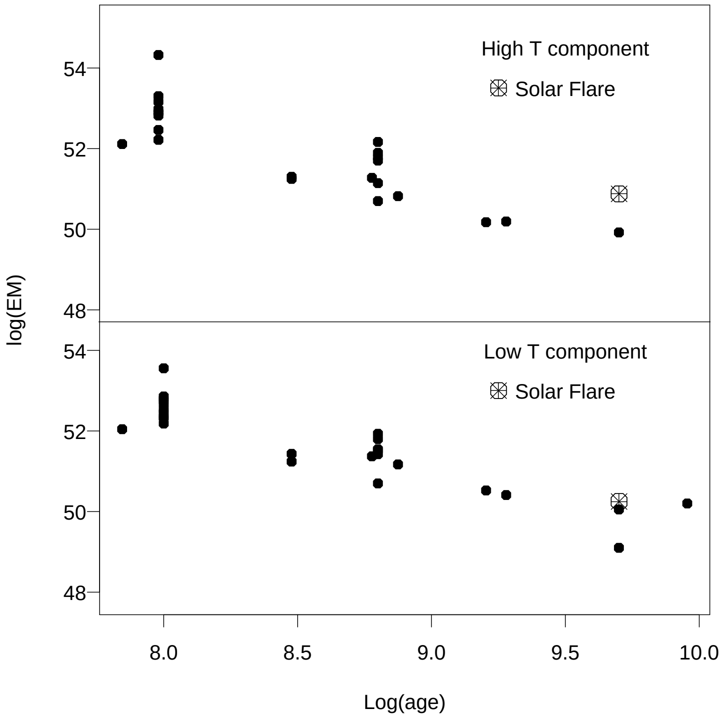

Figure 7. Volume emission measure of high temperature (upper panel) and low temperature (lower panel) coronal components versus age. The points at log(age)=9.7 mark the data relative to the Sun.

of X-ray photons at the Earth is decreased by about two orders of magnitude since the Sun was the same age as the Pleiades.

I stress that the contribution of the corona only is reported. A large number of EUV/UV photons generated by the transition region is not taken into account here. However the relation between X-ray and EUV or UV radiation indicate that X-ray photons span a much more large range than EUV/UV ones, implying that the evolution of the number of less energetic photons is much flatter than the hardest ones, although they dominate the flux of photons.

I want also to stress that I have considered only the evolution of the "quiescent" coronal emission, while flares have likely a large impact on planetary environment. We know that in the pre main sequence, and in the first phases of the main sequence, stars exhibit very powerful flares. These sudden releases of large quantities of very energetic photons in the pre-main sequence phase will very likely play a role on planetary formations (Glassgold et al. 2000), while in the first phases of the main sequence they will affect the planetary environment, depending on the duty cycles and power released during these flares. Unfortunately a systematic knowledge of the evolution of coronal variability (flaring rate, duty cycle, power involved, etc.) in stars is yet lacking.

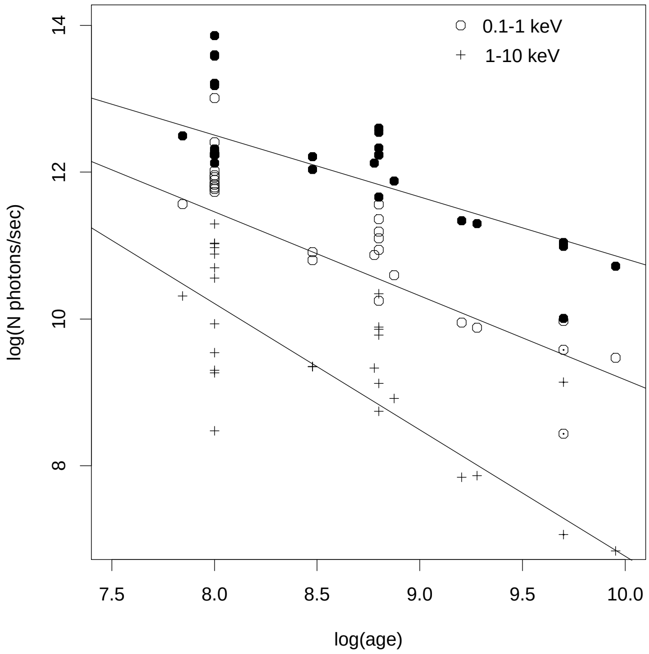

Figure 8. Number of photons per second emitted by stellar coronae and incident at 1 Astronomical Unit versus stellar age. Empty symbols mark photons in the $0.1-1$ keV bandpass, while pluses are photons with energy above 1 keV.

5. Conclusions

In this review I summarized our knowledge on evolution of coronal emission during the main sequence between 10^8 year and the solar age. During this time the emission level decreases by three orders 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 that stars of a given age can have very different luminosities.

During the main sequence life the effective temperatures dominant in corona decrease, with the hotter temperature decreasing more steeply than the cool temperature. The level of the emission and the spectral properties of X-ray emission of young stars are consistent with the hypothesis that their emission is due to a continuous flaring emission.

The knowledge of the evolution of X-ray luminosity and spectrum, allows us to evaluate how evolve the flux of ionizing photons, generated by the corona, and incident at 1 AU. In particular I obtain that the X-ray photons evolve much rapidly than the EUV photons, and that the flux of coronal photons in $1-10$ keV band is decreased by two orders of magnitude since the Sun was the same age of the Pleiades.

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