The coronal evolution of pre-main-sequence stars

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Abstract

The bulk of X-ray emission from pre-main-sequence (PMS) stars is coronal in origin. We demonstrate herein that stars on Henyey tracks in the Hertzsprung-Russell diagram have lower log(L_X/L_☉), on average, than stars on Hayashi tracks. This effect is driven by the decay of L_X once stars develop radiative cores. L_X decays faster with age for intermediate mass PMS stars, the progenitors of main sequence A-type stars, compared to those of lower mass. As almost all main sequence A-type stars show no detectable X-ray emission, we may already be observing the loss of their coronae during their PMS evolution. Although there is no direct link between the size or mass of the radiative core and L_X, the longer stars have spent with partially convective interiors, the weaker their X-ray emission becomes. This conference paper is a synopsis of Gregory, Adams & Davies (2016).

1 Introduction

Copious coronal X-ray emission is a defining characteristic of pre-main-sequence (PMS) stars. With X-ray luminosities of log(L_X) ∼ 28−32 (with L_X in units of erg s^{-1}) and an average coronal temperature of ∼30 MK (Preibisch et al. 2005), they are far more X-ray luminous and hotter than the contemporary Sun (log(L_X) ≈ 26.4−27.7 at solar minimum and maximum, with a coronal temperature of ≈2 MK; Peres et al. 2000). PMS star X-ray luminosity increases with stellar mass and decreases with age (e.g. Preibisch et al. 2005; Preibisch & Feigelson 2005), albeit with large scatter in L_X at any given mass or age. However, the stellar rotation rate is less important for PMS stellar X-ray emission, at least for members of the youngest star forming regions. PMS stars typically all show saturated levels of X-ray emission unlike low-mass stars in main sequence clusters which follow the rotation-activity relation (e.g. Wright et al. 2011). Recently, Argiroffi et al. (2016) demonstrated that, within a sample of stars over a certain mass range in the intermediate age PMS cluster h Per, the slow rotators have begun to show evidence for unsaturated X-ray emission, and the fast rotators supersaturate.

In this work we investigate how the stellar internal structure influences the coronal X-ray emission. It is known that the large-scale magnetic topology of PMS stars is linked to the evolution of the stellar internal structure (Gregory et al. 2012, 2014; Folsom et al. 2016). More evolved PMS stars (those with large radiative cores) are found to have more complex, multipolar, and non-axisymmetric magnetic fields compared to less evolved stars (at least for those more massive than ∼0.5 M_☉, as little is known about the field topology of lower mass PMS stars; Gregory et al. 2012). An increase in the large-scale magnetic field complexity likely corresponds to a reduction in the available X-ray emitting volume, with stellar coronae becoming more compact. We therefore expect that there may be differences in the X-ray luminosities of fully and partially convective PMS stars. That is indeed what we find and discuss in this paper.

In §2 we briefly discuss the physics of radiative core development during the PMS contraction. In §3 we discuss our sample of PMS stars collated from the literature. We derive stellar masses, ages, and internal structure information from the models of Siess et al. (2000). We then continue by comparing the X-ray luminosities, and the temporal evolution of L_X, for fully and partially convective PMS stars, and for stars on Hayashi and Henyey tracks in the Hertzsprung-Russell (HR) diagram. Although in this paper we only consider the Siess et al. (2000) models, in Gregory et al. (2016) we considered three different PMS evolutionary models. All of the general results and conclusions discussed here remain the same, regardless of model choice. In §4 we argue that the lack of X-ray detections from main sequence A-type stars is a result of stars losing their coronae as the depth of their convective zone reduces during their PMS evolution. We conclude in §5.

2 The evolution of PMS stars across the HR diagram

When low-mass PMS stars first become optically visible they are located in the upper-right of the log(L_/L_☉) vs log(T_{eff}) HR diagram. From there, stars of different mass follow different paths across the HR diagram as they contract under gravity. Initially, they host fully convective interiors as they evolve along Hayashi tracks, where their surface luminosity, L_*, decreases with increasing age. The internal luminosity of the star increases monotonically from the centre of the star to the surface value whilst the interior is fully convective.

As contraction proceeds, the temperature increases in the
core and the opacity drops, eventually inhibiting convection in the central regions if the star is massive enough (stars of mass $\lesssim 0.35 \, M_\odot$ remain fully convective for their entire evolution). The now radiative core grows outwards at the expense of the convective zone depth. Mass shells interior to the core-envelope boundary lose heat, while those exterior to the boundary gain heat. The base of the convective zone is heated and the interior luminosity of the star rises from the centre to a maximum before dropping towards the surface. This internal luminosity maximum radiatively diffuses towards the stellar surface, and eventually the surface luminosity, $L_*$, begins to increase with increasing age as stars evolve onto Henyey tracks. Note that stars of mass $\lesssim 0.65 \, M_\odot$ reach the ZAMS while still on Hayashi tracks. By the time stars evolve onto Henyey tracks, the bulk of the stellar mass is contained within the radiative core ($\sim 60-70\%$; Siess et al. 2000), which occupies a smaller proportion of the star by radius. Thus, stars are more centrally condensed by the time their surface luminosity has begun to increase.

In this work we compare the coronal X-ray emission of fully and partially convective PMS stars, and of Hayashi track and Henyey track PMS stars. Stars on Hayashi tracks can be either fully or partially convective, while those on Henyey tracks have mostly radiative interiors. The delay between radiative core development and a star evolving onto its Henyey track is significant. As one example, using the models of Siess et al. (2000), a solar mass star becomes partially convective after $\sim 2.5 \, \text{Myr}$ and evolves onto its Henyey track at $\sim 15 \, \text{Myr}$. Therefore, a solar mass star spends longer with a partially convective interior than it does with a fully convective interior while on its Hayashi track. A solar mass star spends $\sim 40\%$ of its entire PMS lifetime of $\sim 30 \, \text{Myr}$ with a radiative core on its Hayashi track.

In the following subsection we compare the coronal X-ray emission properties of fully and partially convective PMS stars, and of those on Hayashi tracks to those on Henyey tracks in the HR diagram.

### 3 The decay of PMS star X-ray emission

To compare the X-ray properties of fully and partially convective PMS stars we considered five of the best studied star forming regions: the Orion Nebula Cluster (ONC), NGC 6530, NGC 2264, IC 348, and NGC 2362. We obtained X-ray luminosities ($L_X$), spectral types, observed photometry, binary star status, and cluster distance estimates from the literature. We redetermined the photometry using intrinsic colours appropriate for the spectral type, from the PMS calibrated scale of Pecaut & Mamajek (2013). We then calculated bolometric luminosities by applying a spectral type-dependent bolometric correction and with an assumed distance modulus appropriate for each cluster. We also assigned effective temperatures from the same scale of Pecaut & Mamajek (2013). Extensive details can be found in Gregory et al. (2016). Figure 1 is a HR diagram showing the stars in our sample, with mass tracks and isochrones from the models of Siess et al. (2000), from which we obtained stellar masses, ages, and internal structure information.

Known or suspected spectroscopic / close binaries were removed from our sample in cases of confusion in the optical or X-ray data. With the exception of IC 348, we used the X-ray luminosities from the MYSXIX (Massive Young Star-Forming Complex Study In Infrared and X-ray) project (Feigelson et al., 2013), in particular those listed in the MPCM (MYSXIX Probable Complex Members) catalog of Broos et al. (2013). For IC 348, we took X-ray fluxes from Stelzer et al. (2012). Our final sample consisted of 984 stars, of which 34 are $L_X$ upper limits (all from IC 348).

Several previous studies have reported that PMS stars on radiative tracks in the HR diagram have lower average values of $\log(L_X/L_\odot)$ compared to those on convective tracks (e.g. Feigelson et al. 2005; Piaccommo et al. 2003; Rebull et al. 2006; Currie et al. 2009; Mayne 2010). For stars of mass $1-2 \, M_\odot$, Rebull et al. (2006) report a factor of about 10 reduction in $\log(L_X/L_\odot)$ for partially convective stars compared to fully convective stars. About 28% of the stars considered by Rebull et al. (2006) are $L_X$ upper limits. The re-analysis of archival data during the MYStIX project, using the modern methods of Getman et al. (2010) which allows $L_X$ values to be derived for faint sources that have too few counts for traditional X-ray spectral fitting methods, has eliminated almost all $L_X$ upper limits. This, combined with enhanced spectroscopic surveys of the star-forming regions (e.g. Hillenbrand et al. 2013), and new empirical colours / temperature scales calibrated for PMS stars (Pecaut & Mamajek 2013; Herczeg & Hillenbrand 2014), warrants our re-examination of differences in the X-rays properties of fully and partially convective PMS stars.

In Figure 2 we compare the distributions of the logarithmic fractional X-ray luminosities, $\log(L_X/L_\odot)$, for fully and partially convective PMS stars, and for stars on Hayashi and Henyey tracks in the HR diagram. There is a large
Figure 2: Notched and variable width (scaled to the square root of the sample size in each case) box plots with outliers for the distribution of $\log(L_X/L_\ast)$ for (left-to-right) fully convective (conv), partially convective (rad), Hayashi track (Hay), and Henyey track (Hen) PMS stars. The cross is the mean value in each case. A difference in medians is significant when the notches of the box plots being compared do not overlap (e.g. McGill et al. 1978). Partially convective PMS stars have, on average, lower $\log(L_X/L_\ast)$ compared to fully convective stars. The deficit is greater when comparing Hayashi to Henyey track PMS stars. The difference is caused by the decay of $L_X$ when stars develop substantial radiative cores, see text and Figure 3. Figure modified from Gregory et al. (2016).

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Figure 3: The correlation between $L_X$ and $L_\ast$ for fully convective (top left, $L_X \propto L_\ast^a$ with $a = 0.93 \pm 0.04$) and for partially convective PMS stars (top right, $a = 0.33 \pm 0.09$). Points are coloured as in Figure 1. Downward pointing arrows are stars with a $L_X$ upper limit. The almost linear relationship between $L_X$ and $L_\ast$ is maintained for Hayashi track stars (bottom left, $a = 0.92 \pm 0.04$), however, $\sim$90% of the such stars are fully convective. If we instead consider only Hayashi track stars with radiative cores (bottom middle) the gradient of the correlation is only $a = 0.61 \pm 0.08$. In all cases the probability of there not being a correlation, from generalised Kendall’s $\tau$ tests, is $<5e^{-5}$, with the exception of Henyey track PMS stars (bottom right) for which there is no correlation. Figures modified from Gregory et al. (2016).
Figure 4: The decay of $L_X$ with age for stars of the indicated mass. Points are coloured as in Figure 1. Downward pointing arrows are stars with a $L_X$ upper limit. $L_X$ decays faster with age, $t$, for higher mass stars with $L_X \propto t^a$ where $a = -0.28 \pm 0.08, -0.53 \pm 0.10, -0.86 \pm 0.19, \text{ and } -1.19 \pm 0.35$ for 0.5-1, 1-1.5, 1.5-2, and 2-3 $M_\odot$ respectively. $P(0) = 0.0059$ for the 2-3 $M_\odot$ mass range and $<5e-5$ for the others. Figure from [Gregory et al. 2016](https://doi.org/10.5281/zenodo.6964026).
4 Do intermediate mass stars lose their coronae on the PMS?

The young early K-type to late-G type PMS stars in our sample will evolve into main sequence A-type stars (Siess et al., 2000) which lack outer convective zones. The decay of their X-ray emission with substantial radiative core growth, discussed in the previous section, is consistent with the lack of X-ray detections of main sequence A-type stars.

Figure 5 shows the X-ray detection rate of early type stars, with the approximate spectral type boundaries indicated. Most A-type stars go undetected in X-rays. Of those that are, almost all are known binaries with later spectral type companions. Figure modified from Schmitt (2009), following Schröder & Schmitt (2007).

5 Conclusions

We have compared the X-ray emission properties of fully and partially convective PMS stars and of PMS stars on Hayashi and Henyey tracks in the HR diagram. We have found that the growth of the radiative core plays an important role in determining the behaviour of X-ray emission from PMS stars. Our results can be summarised as follows:

- Partially convective PMS stars have a lower average \( \log(\frac{L_X}{L_\star}) \) compared to fully convective PMS stars. The deficit is larger for Henyey track PMS stars compared to those on Hayashi tracks in the HR diagram.
- The lower average \( \log(\frac{L_X}{L_\star}) \) for partially convective PMS stars is driven by a decay in \( L_X \) with radiative core growth. \( L_X \) reduces with age and does so faster for higher mass PMS stars.
- The longer PMS stars have spent with radiative cores the less X-ray luminous they become.
- The (roughly) linear correlation between \( L_X \) and \( L_\star \) is only valid for fully convective PMS stars. The exponent of the correlation (i.e. the value \( a \) where \( L_X \propto L_\star^a \)) is less when considering partially convective PMS stars.
- There is no correlation between \( L_X \) and \( L_\star \) for Henyey track PMS stars (which have mostly radiative interiors) due to many having \( L_X \) values well below what is typical of Hayashi track PMS stars of similar \( L_\star \).
- Stars which are the progenitors of (X-ray undetected) main sequence A-type stars are already losing their coronal X-ray emission during their PMS evolution.
More details, a greater discussion of the sample of stars used in our work, and additional correlations can be found in [Gregory et al. (2016)].

The reduction in $L_X$ with substantial radiative core development may be linked to the observationally inferred transition in the large-scale magnetic field topologies of PMS stars. Zeeman-Doppler imaging observations (e.g. Donati et al. 2011a,b, 2012) have revealed that (accreting) PMS stars are born with simple and axisymmetric large-scale magnetic fields, that are well-described by a tilted dipole plus a tilted octupole component (Gregory & Donati 2011), which become more dominantly octupolar with age (Gregory et al. 2014). As PMS stars develop substantial radiative cores their large-scale magnetic fields become highly multipolar and non-axisymmetric (Gregory et al. 2012). If the large-scale magnetic field is able to contain X-ray emitting coronal plasma, then a transition from mostly low-order multipole / axisymmetric to a mostly high-order multipole / non-axisymmetric magnetic field would correspond to a decrease in the X-ray emitting volume. In turn, this reduces the volume emission measure and therefore the X-ray luminosity.

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