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X-ray emission regimes and rotation sequences in the M34 open cluster

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Abstract. I report on a correlation between the saturated and non-saturated regimes of X-ray emission and the rotation sequences that have been observed in the M34 open cluster. An interpretation of this correlation in term of magnetic activity evolution in the early stage of evolution on the main sequence is presented.

1. X-ray observations of the M34 open cluster

The M34 open cluster was observed with the *XMM − Newton* space observatory on 12 February 2003. Detection was made of 189 X-ray sources that are listed in the *XMM − Newton* Serendipitous Source Catalog (Watson *et al.* 2009). This list of X-ray sources was correlated with lists of M34 cluster members with known rotation periods established by Meibom *et al.* (2011), Irwin *et al.* (2006), and James *et al.* (2010). In total, 41 single stars in the M34 open cluster have been found that have known rotational periods and detected X-ray emissions (Gondoin 2012).

X-ray fluxes were derived from the source count rates using energy conversion factors (ECF) calculated in the 0.5-4.5 keV range (Gondoin 2006). The X-ray fluxes were converted into stellar X-ray luminosities assuming a distance of 470 pc (Jones & Prosser 1996). The X-ray luminosity distribution of the sample stars rolls off at luminosities lower than $L_{\rm X} \approx 10^{29}$ erg s^{-1}, which provides a sensitivity limit estimate of the *XMM − Newton* observation. The mass of the sample stars ranges from 0.4 $M_\odot$ to 1.3 $M_\odot$ and reaches a maximum around 0.8 $M_\odot$. Their rotation periods are between 0.49 days and 11 days.

Recent studies have shown that stars tend to group into two main sub-populations that lie on narrow sequences in diagrams where the measured rotation periods of the members of a young stellar cluster are plotted against their B − V colors. Figure 1 (left) shows the rotational periods P of the sample stars as a function of their reddening corrected $(\rm B-V)_0$ indices. The color-period diagram also displays the I and C rotational sequences of M34 along the form established by Barnes (2007) and Meibom *et al.* (2011). The proximity of the M34 data points to these curves was used to determine their membership to the I sequence, to the C sequence or to the gap. Figure 1 (right) displays the X-ray to bolometric luminosity ratio $L_{\rm X}/L_{\rm bol}$ of the sample stars as a function of their Rossby number ($Ro = P/\tau_{\rm c}$) distinguishing members of the I sequence, of the C sequence and of the gap.

Figure 1 shows a correlation between the X-ray activity regimes and the rotation sequences. Indeed, members of the C sequence have small Rossby numbers ($Ro < 0.1$), and an X-ray to bolometric luminosity level close to the 10^{-3} saturation level. Members of the I sequence, in contrast, have larger Rossby numbers ($Ro \geqslant 0.17$), and an X-ray to bolometric luminosity ratio significantly smaller than the saturation limit. Remarkably,

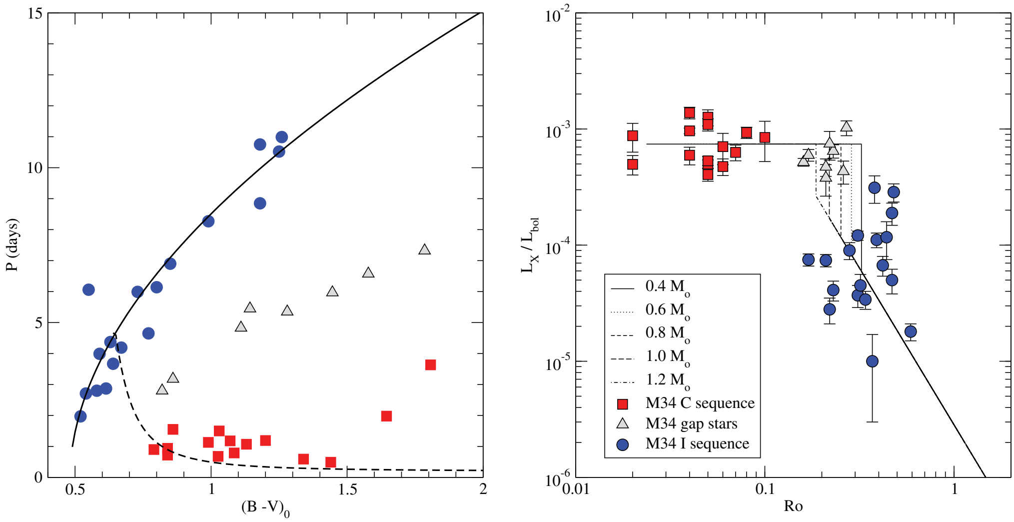

Figure 1. Left: rotation periods vs. (B−V) indices of the M34 sample stars. The solid line and the dashed lines represent the I and the C sequence, respectively. The proximity of the M34 data points to these curves was used to determine their membership to the I sequence (blue circles), to the C sequence (red square) or to the gap (grey triangles). Right: X-ray to bolometric luminosity ratio vs Rossby number of the sample stars compared models of X-ray activity evolution for stars with masses between 0.4 and 1.2 $M_{\odot}$ having an initial period of rotation of 1.1 days on the ZAMS.

gap stars occupy an intermediary position with Rossby numbers in the same range as those of some I sequence stars but with X-ray to bolometric luminosity ratio similar to those of C sequence stars, i.e., close to the saturation level.

2. A model of X-ray activity evolution

Based on this correlation, I derived a model of X-ray activity evolution (Gondoin 2013) assuming that stars on the C sequence and in the gap emits X-rays at the saturation level while I-sequence stars exhibit a power-law dependence of the X-ray to bolometric luminosity ratio as a function of the Rossby number. This model can be expressed as

$$\frac{L_{\rm X}}{L_{\rm bol}} = \begin{cases} R_{\rm X,sat} & \text{if star} \in \text{C sequence or gap,} \\ C^{st} \times Ro^{\beta} & \text{if star} \in \text{I sequence.} \end{cases} \tag{2.1}$$

Barnes (2010) proposed one particularly simple formulation of the rotation period evolution on the main-sequence star as a function of the convective turnover time $\tau_{\rm c}$ and the initial period of rotation on the ZAMS P_0,

$$t = \frac{\tau_{\rm c,B}}{k_{\rm C}} \times \ln\left(\frac{P(t)}{P_0}\right) + \frac{k_{\rm I}}{2\tau_{\rm c,B}} \times (P(t)^2 - P_0^2). \tag{2.2}$$

The combination of Eq. 2.1 and 2.2 provides a time evolution model of the stellar X-ray emission on the main sequence. The dependence of the X-ray luminosity on stellar mass is implicitly contained in the bolometric luminosity and in the convective turnover time. A parameterisation of the convective turnover time as a function of stellar mass has been provided by Wright *et al.* (2011). The bolometric luminosity is related to stellar mass on the main sequence by $M/{\rm M}_{\odot} = (L_{\rm bol}/{\rm L}_{\odot})^{1/4}$ (e.g. Duric 2003).

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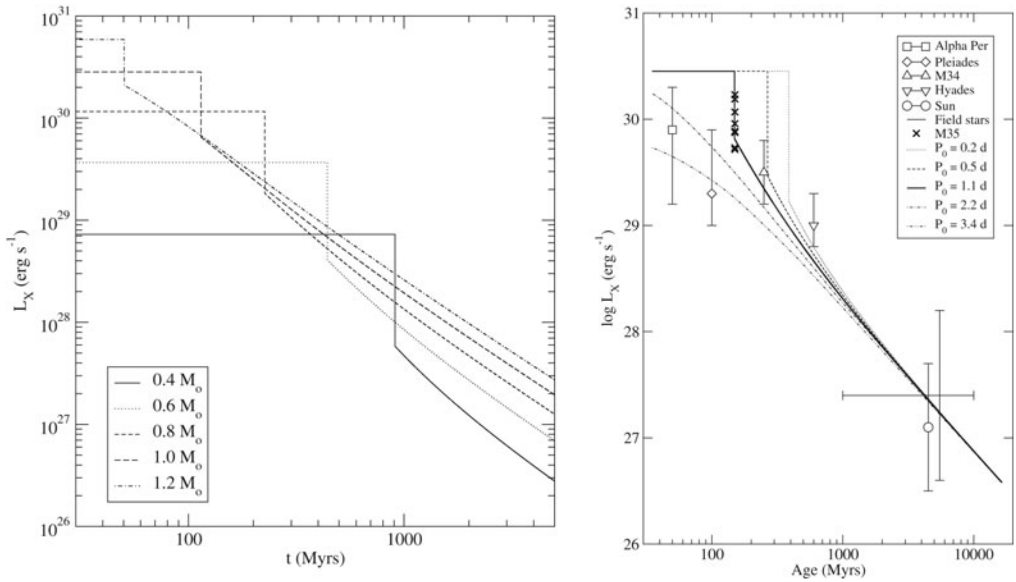

Figure 2. Left: simulated evolution of the X-ray luminosity of main-sequence stars with masses between 0.4 and 1.2 $M_\odot$ that have an initial period of rotation of 1.1 days on the ZAMS. Right: X-ray luminosity evolution models of solar mass stars with initial rotation periods on the ZAMS ranging from 0.2 to 3.4 days compared with median luminosities of stars with similar masses in the α Per, Pleiades, M34, and the Hyades. The vertical error bars indicate the 25 % and 75 % quartiles of the distributions (Micela 2002).

One graphical representation of the model is shown in Fig. 1 (right). It displays the X-ray to bolometric luminosity ratio as a function of Rossby number for stars with $0.4 \leqslant M/M_\odot \leqslant 1.2$ and $P_0 = 1.1$ days on the ZAMS. One interesting output of the model is that the hypothesis of a correlation between rotation sequences and X-ray emission regimes leads to a transition from the saturated to the non-saturated regime of X-ray emission in a range of Rossby number between 0.32 and 0.19 for stars with $0.4 \leqslant M/M_\odot \leqslant 1.2$ and $P_0 = 1.1$ day. Figure 1 (right) shows that gap stars in M34 are located in this domain.

Using the above model, I calculated the time evolution of the X-ray luminosities of Sun-like stars with a range of initial rotation periods observed in young stellar clusters. These stars are assumed to reach the ZAMS at an age of 35 Myrs, approximately equal to the Kelvin-Helmholtz timescale of a one solar mass star. Figure 2 (right) compares the simulated evolutionary track of their X-ray emissions with the measured X-ray luminosities of Sun-like stars in various open clusters. The model shows, in agreement with the measurements, a large dispersion of X-ray luminosities among young Sun-like stars. This large dispersion in the early phase of evolution on the main sequence occurs because fast rotating Sun-like stars emit X-ray in the saturated regime while slower rotators with similar masses already operate in the non-saturated regime of X-ray emission.

3. Physical interpretation

Numerical simulations (e.g. Käpylä *et al.* 2009) indicate that large-scale dynamos are excited in rapidly rotating convection, i.e. in the absence of shear. Such turbulent dynamos probably operate in young stars providing that their rotation is rapid enough. The transition from the C to the I rotation sequence appears to be associated with a sharp

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decrease of the X-ray to bolometric luminosity ratio. Since this ratio is a lower limit of the ratio between the surface magnetic flux and the outer convective flux, its steep decrease around $Ro \approx 0.14$ - 0.4 is indicative of a significant drop in dynamo efficiency possibly associated with a quenching of the turbulent dynamo in rapidly rotating stars as their rotation rate decays due to rotational braking by stellar winds.

The evolution model of X-ray activity (see Fig. 2 left) provides an estimate of the age $t_{\rm sat}$ at which a star changes from the saturated to the non-saturated regime of X-ray emission. This age can be compared with the age $t_{\rm gap}$ taken by a star to evolve through its C rotation phase, and to reach the nominal rotational gap g marking the onset of the I rotation phase. The comparison shows that $t_{\rm sat} \gg t_{\rm gap}$. The transition from saturated to non-saturated X-ray emission thus occurs well after the stellar evolution through the rotational gap between the C and I sequences, which corresponds to a maximum of the rotation deceleration. If the associated redistribution of angular momentum is the result of a nascent interface dynamo due to a developing gradient in angular velocity at the base of the convection zone, the model suggests that during the time interval between the rotation sequence transition and the X-ray regime transition two different dynamo regimes operate simultaneously within the interior of Sun-like stars.

According to the above scenario, the angular momentum redistribution mechanism responsible for the transition from the C to the I rotation sequence results in a changing mixture of two dynamo processes occurring side by side, i.e. a boundary-layer interface dynamo and a convective envelope turbulent dynamo. This last process dominates in rapidly rotating young stars. As the shear between the fast spinning radiative interior and the convective envelope increases, another process strengthens in which dynamo action occurs in the boundary region between the radiative core and the convective envelope. This dynamo process relies on differential rotation, but also induces important redistributions of angular momentum. As the rotation of the convective envelope decays, the turbulent dynamo is quenched and the interface dynamo becomes dominant, decreasing progressively at later stages of evolution when rotation dies away.

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