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Stellar flares: from PMS to evolved cool stars

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Abstract. Taking advantage of the high sensitivity of XMM-EPIC instruments, we perform time resolved spectral analysis during the flares from mainsequence (MS) and evolved cool stars. The temporal and spectral characteristics of observed flares in stars on MS and giant branch are found to be similar to solar arced flares. Loop length derived for the flaring structure are much less than the stellar radius (length L < $R_\star$) for MS and evolved late-type stars. However, for most of the pre-mainsequence (PMS) stars loop length is found to be much larger than the stellar radius (length L ≥ $R_\star$). The temperatures at flare peak are often very high, with most of the flares in the sample showing temperatures in excess of 100 MK.

Keywords : stars: late-type – stars: X-ray – stars: flares – stars: binary

1. Introduction

The cool half of H-R diagram is dominated by stars with outer convection zones. Many of these have inner radiation zone. In these stars, an interaction of convection with rotation produces a magnetic dynamo at the base of convection zone, which is responsible for various magnetic activities in or above the stellar photosphere (e.g. star spots, thin chromosphere, extended coronae). Stellar flares are a result of magnetic reconnection at coronal heights, in which large amount of energy is released in small interval of time. Observationally flares revel in all frequencies of the electro-magnetic spectrum. The flares produced by cool stars are usually detected only in the UV or X-rays. These UV and X-ray flares show extreme luminosities and very hot temperatures ($\gtrsim$ 10MK). Flares from these stars present many analogies with the solar flares. However, they also show significant differences, such as the amount of energy released. Modeling the dynamic behavior of X-ray flares allows us to constrain the properties of magnetic loops in ways that cannot be done from analysis of quiescent coronae

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that provide only a spatial and temporal average over some ensemble of structures. The study of stellar flares is a thus a valuable tool for understanding stellar coronae; these are dynamical events, which embody different information than available from static, time-averaged observations (e.g. Pandey & Srivastava 2009; Pandey & Singh 2008, 2012). The level of magnetic activity decreases with star's age. The stars on MS and giant branch are less magnetically active than the PMS stars. Therefore, the flare study is important to derive the coronal structure in each evolutionary stage of the star. The data for this study were taken from XMM-Newton archive.

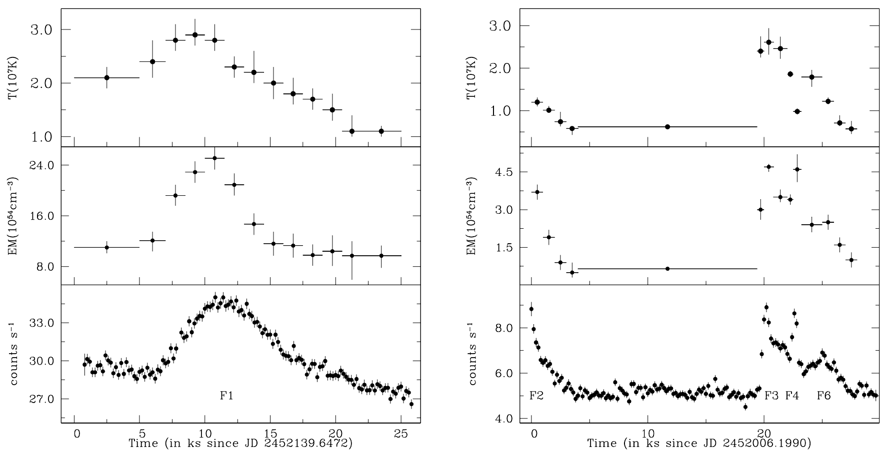
2. Spectral evolution of flares

In the bottom panels of Figures 1 (a) and 1(b), we show the X-ray light curves of the stars V711 Tau (an evolved RS CVn binary) and V368 Cep (a MS star) in the energy band 0.3-10.0 keV observed with PN detector of XMM-Newton satellite. One flare, F1, was observed from V711 Tau and four flares marked as F2, F3, F4 and F5 were observed in the X-ray light curve of the star V368 Cep. The exponential decay times (τ_d) of the flares from these two stars were found to be in the range from 0.5 to 6.3 ks. The Luminosity at the peak of the flares from the star V368 Cep were found to be of the order of $10^{29.5-30}$ erg s^{-1}. However, the luminosity at the peak of the flare from V711 Tau is $10^{30.95}$ ergs s^{-1}.

In order to trace the spectral changes during the flares, we have analysed the spectra at different time intervals of the light curves. To study the flare emission only, we have performed 1-temperature spectral fit of the data, with the quiescent emission taken into account by including its best-fitting 2-temperature/3-temperature model as a frozen background contribution. This is equivalent to considering flare emission above the quiescent level and allows us to derive one effective temperature and one emission measure (EM) of the flaring plasma. Top and middle panels of Figs. 1 (a) and 1(b) show the temporal evolution of the temperature and the EM of the flares respectively, observed from V711 Tau and V368 Cep. Both the temperature and EM show well-defined trends i.e. the changes in temperature and EM are correlated with the variations observed in the light curves during flares. In these flares either both the emission measure and the temperature peaked simultaneously or the temperature evolved before the emission measure. This is probably due to an impulsive flare event, in which a loop does not reach equilibrium conditions, and the density begins to decay later than the temperature.

3. Stellar loop modeling

By an analogy with solar flares and using flare loop models, it is possible to infer the physical size and morphology of the loop structures involved in a stellar flare. Reale et al. (1997) presented a method to infer the geometrical size and other relevant physical parameters of the flaring loops, based on the decay time and on evolution



(a) V711 Tau (b) V368 Cep

Figure 1. Bottom, middle and top panels are X-ray light curve, evolution of emission measure and evolution of temperature for the stars (a) V711 Tau, and (b) V368 Cep. The temporal bin of light curves is 200s.

of temperature and the EM during the flare decay. It includes both plasma cooling and the effect of heating during flare decay. The semi-loop length as derived from hydrodynamic model (Reale et al. 1997) is

$$L = \frac{\tau_d \sqrt{T_{max}}}{3.7 \times 10^{-4} F(\zeta)} \tag{1}$$

where L is the loop half-length in cm, and T_{max} is the flare maximum temperature (K). $F(\zeta)$ is function of slope ζ of density-temperature diagram. Both T_{max} and $F(\zeta)$ are calibrated for XMM-Newton EPIC instrument (see Reale 2007).

Maximum temperatures at the peak of flare F1 from V711 Tau and flare F2 from V368 Cep were found to be 59±5 MK and 25.5±2.5 MK, respectively. The $EM^{1/2}$ was taken as a proxy of density to determine the slope ζ in density-temperature diagram. The values of ζ for the first flare of V368 Cep and the flare from V711 Tau were 0.72 and 1.0, respectively, indicate the presence of sustained heating during decay. The loop length derived using equation (1) for the flare F1 and F2 were 6.5×10^{10} and 6.0×10^{9} cm, respectively. For the flares F3 and F5 the loop lengths were derived to be 2.0×10^{10} and 10^{10} cm, respectively. Once the loop length has been derived, it is possible to infer additional physical parameters of the flaring plasma. These parameters could be electron density, flaring volume, maximum pressure and minimum magnetic field to confine the plasma (for detail see Pandey & Singh 2008). The electron densities for these flares were derived to be of the order of 10^{11} cm^{-3}. However, the pressure and magnetic filed were derived to be of the order of 10^{3} dyne cm^{-2} and fifty Gauss respectively.

We have done similar analysis for a sample of the twenty four flares from MS and evolved stars. The exponential decay times of flares from MS and evolved stars were found to be in the range from few minutes to few hours, sometimes a day. However, the exponential decay times for flares from PMS stars are in the range from few hours to few days (see Favata et al. 2005, Getman et al. 2008). The peak flare temperature is found in the range of 20 - 200 MK for all the flares from PMS to evolved cool stars (see also Favata et al. 2005 for PMS stars). The temperature at the peak of the flares from MS stars are found to be less than that from PMS and evolved stars. The loop lengths derided for the flares from MS stars are found to be of the order of 10^9 cm, which is in generally less than that of flares from PMS and evolved cool stars. The loop length of the flares from MS stars are also found to be less that of the stellar radius ($R_\star$). In case of the flares from evolved cool stars, loop lengths were derived to be comparable to stellar radii, but in general $L < R_\star$. However, L was found to be more than the $R_\star$ for majority of the flares observed from PMS star.

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