X-ray variability of cool stars: Magnetic activity and accretion

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This article provides a review of X-ray variability from late-type stars with particular focus on the achievements of XMM-Newton and its potential for future studies in this field.

1 X-ray emission from cool stars

One of the most prominent signatures of the X-ray emission observed from late-type stars is its variability. In analogy to the Sun, the bulk of the X-ray emission from cool stars is a manifestation of magnetic activity, i.e. a result of the stellar dynamo which continuously regenerates the magnetic field against dissipation. It is, thus, a genuinely dynamic process.

Since stellar dynamos require the presence of a convection zone, they are believed to operate only in the cooler half of the Hertzsprung-Russell diagram, in stars of spectral types F and later. The second key ingredient of stellar dynamos is (differential) rotation. As a consequence, in the faster rotating, younger stars magnetic activity is scaled up with respect to main-sequence (MS) stars, e.g. 10\textsuperscript{3} times higher X-ray luminosity is detected from pre-main sequence (pre-MS) T Tauri stars (TTS) with respect to MS dwarfs (Preibisch et al., 2005; Stelzer & Neuhäuser, 2001).

Similar to the Sun and late-type MS stars in general, TTS display various kinds of magnetic activity phenomena. In addition, their X-ray emission and its variability may carry the signatures of various kinds of interaction with their circumstellar environment. In fact, during the first few Myrs of their evolution late-type stars pass through several phases that are characterized by the amount of circumstellar material and its interaction with the forming star. While there are no current reports on X-ray emission from the earliest protostellar stages when the star is surrounded by an optically thick envelope and radiates mostly at sub-mm and longer wavelengths (so-called Class 0 objects), X-ray emission was seen from several of the somewhat more evolved Class I protostars. However, the X-ray properties (luminosity, plasma temperature and column density) of protostars have remained poorly constrained so far (Pillitteri et al., 2010; Prisinzano et al., 2008). In the subsequent evolutionary phase (Class II objects) the envelope has dispersed and settled into a disk from which the star generally accretes matter (classical TTS). Thanks to the superb spectral capabilities of XMM-Newton and Chandra a soft high-density X-ray component was identified in a small number of bright, accreting T Tauri stars which was ascribed to shocks at the base of the accretion flow (Kastner et al., 2002; Stelzer & Schmitt, 2004). Moreover, the spatial and spectral properties of the X-ray emission observed from some young stars have revealed X-ray emission from shocks in protostellar jets (Güdel et al., 2007). When finally all circumstellar matter is gone and only the Class III object or weak-line TTS is left, the viable X-ray emission mechanisms reduce to those based on (scaled-up) magnetic activity.

In the remainder of this article I review recent developments in studies of X-ray variability from late-type stars focusing on magnetic activity and accretion.

2 Activity-related X-ray variability

Stellar magnetic activity can produce variable X-ray emission on a vast range of time-scales from minutes to decades. Drastic brightness increases and subsequent decay to the previous emission level with typical time-scales of hours are the most prominent activity signature. These flares represent a rapid release of magnetic energy through reconnection events. At the long end of the variability time-scales are the dynamo cycles, analogs of the solar 11-year cycle which is characterized by a periodic variation of the overall X-ray output of the Sun by a factor \(\sim 100\) depending on the energy band (Orlando et al., 2001). While flares and cycles ultimately go back to intrinsic variability of the magnetic field, there are also variations related to geometric effects. In particular, inhomogeneous surface coverage with magnetically active regions together with surface rotation can be expected to lead to periodically modulated X-ray emission.

\textsuperscript{1} See e.g. Feigelson & Montmerle (1999) for details on the classification scheme of pre-main sequence stars.
reflecting the time-scale of stellar rotation. In the following, the individual phenomena are discussed in more detail.

2.1 Flares

Stellar flares are the result of magnetic reconnection in the upper atmosphere which leads to particle acceleration and plasma heating. Footpoints of magnetic loops light up in optical/UV emission lines and continuum following electron bombardment of the lower atmosphere. Intense X-ray emission goes along with such events, and is ascribed to the filling of the coronal loops with heated plasma evaporated off the chromospheric layers along the magnetic field lines ("chromospheric evaporation"; Antonucci et al. 1984).

XMM-Newton studies of flares comprise both detailed analyses of individual events on nearby stars and statistical investigations of larger samples. An interesting capability of XMM-Newton for flare science is the simultaneous availability of the Optical Monitor which enables recording the white-light flare jointly with the X-ray signal.

Some of the notable case studies carried out with XMM-Newton regard huge flares on our nearest stellar neighbor, Proxima Cen (Güedel et al. 2004) and on the nearby M star CN Leo (Liefke et al. 2010). The high photon statistics of these events allowed to establish a density increase during the flare through a time-resolved analysis of the high-resolution RGS spectrum. The changing profile of the O VII triplet during these flares indicates a temporary increase in the electron density during phases which correspond to peaks in the X-ray luminosity.

For some X-ray flares, including the above-mentioned events, the optical counterpart has been caught thanks to the simultaneous observation carried out with the Optical Monitor onboard XMM-Newton. A time-lag of few tens of seconds was determined by Stelzer et al. (2006) between the peaks of the V band and the EPIC/pn lightcurves for a giant flare on a late-M star. Such observations have substantially increased our knowledge of stellar flare physics, and have confirmed some essential points in the canonical picture of a solar flare (Cargill & Priest, 1983), providing support for the solar-stellar analogy.

One point where the analogy of solar and stellar flares hits shaking ground regards the size of the X-ray emitting loop structures. The length of flaring plasma loops can be inferred by adapting hydrodynamical (HD) models (Reale et al. 1997) to the observed time-evolution of X-ray temperature and emission measure. Contrary to the case of the Sun where magnetic loops cover only a small fraction of the surface (Reale, 2010), coronal loops on the order of a stellar radius have been derived for M dwarf stars (e.g., Stelzer et al. 2006). Contrasting results have been presented from Chandra and XMM-Newton observations of flares on pre-MS stars: next to loops of regular size (e.g., Franciosini et al. 2007), very large structures were derived for some flares and it was suspected that they represent magnetic loops that connect from the star to the circumstellar disk (Favata et al. 2005). However, after the evolutionary stage of the individual objects was better constrained with the help of Spitzer data, the evidence for X-ray emitting star-disk loop structures has weakened (Aarnio et al. 2010, Getman et al. 2008). As an independent method to determine flare loop sizes, López-Santiago et al. (2016) applied a wavelet-based analysis to brightness oscillations seen during some X-ray flares of TTS. Such oscillations had first been discovered in XMM-Newton observations of the M dwarf AT Mic (Mitra-Kraev et al. 2005). Under the assumption that the oscillation is caused by a wave within a magnetic flux tube, the observed period is through the sound speed directly connected with the loop length. This analysis confirmed the large values obtained previously with HD models from the same data. A drawback of this method is that it is applicable only to the small subset of flares which display detectable oscillations.

Given the low occurrence rate of large flares (~ 1/yr for events of $E_F > 10^{34}$ erg for the Sun; Schrijver et al. 2012), statistical studies of stellar X-ray flares require access to a (possibly) homogeneous database comprising large numbers of stars. Such data, potentially, allow to characterize the number distributions of flares which are a crucial diagnostic for the importance of nano-flares in the coronal heating process. Flare energy number distributions have been extensively studied for the Sun across a wide wavelength range from the UV to the hard X-ray band (see e.g. references in Aschwanden, 2014), but are much harder to come by for other stars. Lately, the XMM-Newton Serendipitous Source Catalog (Rosen et al. 2016) has revealed to represent a valuable source for such studies. Using this database, Pye et al. (2015) have identified ~ 130 X-ray flares on stars comprising spectral types F to M. A critical point in such studies is to take proper account of the survey incompleteness which is difficult to assess in a non-uniform database. Here, studies of flares from pre-MS stars offer an advantage, as X-ray observations in star forming regions naturally provide data for many stars in one shot and all stars are observed at the same flux limit. Representative systematic investigations in various star forming regions suggest that the X-ray flare energies of TTS follow a power-law with spectral index $\approx 2$ (Albacete Colombo et al. 2007, Caramazza et al. 2007, Stelzer et al. 2007), similar to the case of the Sun. However, applying this result to the regime of nano-flares requires an extrapolation over many orders of magnitude in flare energy, since the pre-MS X-ray flare energy distributions are complete only for energies $\gtrsim 10^{35}$ erg/s.

The order of magnitude increase of the X-ray flux during stellar flares entails that such events can also be seen on stars with quiescent flux below the detection limits of current X-ray instrumentation. In particular this applies to the ultracool dwarfs (UCDs), objects at the faint end of the stellar sequence defined as having spectral type M7 and later which may be stars or brown dwarfs depending on the – generally unknown – age. The activity of UCDs
is gaining interest as some objects of this class have been shown to present circularly polarized radio bursts similar to those of solar-system planets (Burgasser & Putman, 2005; Hallinan et al., 2006), indicative of a transition between stellar-like and planetary-like coronal properties in the UCD regime. Based on the small sample of objects with multiwavelength measurements, X-ray flaring and radio bursting seems to be mutually exclusive suggesting the presence of two classes of UCDs harboring distinct coronal conditions (Stelzer et al., 2012). The upcoming Evolutionary Map of the Universe (EMU) to be produced by the SKA precursor ASKAP (Norris et al., 2011) will likely represent a step-change in the number of radio detections of UCDs, offering many targets suitable for XMM-Newton follow-up with the aim to examine the above-mentioned dichotomy.

2.2 Rotational modulation

Star spots are responsible for the most frequent and well-studied stellar variability phenomenon at optical wavelengths. The periodic brightness variation produced by surface spots moving in and out of the line-of-sight in the course of a stellar rotation is also an excellent means to measure stellar rotation rates (see e.g. Herbst et al., 2000). In the X-ray band, the rotational modulation associated with structured coronae – if present at all – is usually masked by much stronger irregular variability related to flaring. As a consequence only isolated reports on periodic X-ray variability from late-type stars are found in the literature: The most notable examples, both identified with XMM-Newton, are VXR 45 in the IC 2391 star cluster (Marino et al., 2003) and the benchmark young field dwarf AB Dor (Hussain et al., 2007). Interestingly, both stars have similar spectral type (late-G; early-K), age (∼ 50 Myr) and rotation rate ($P_{\text{rot}} = 0.2; 0.5 \text{ d}$). Fast rotation is known to be associated with larger optical spot amplitude (e.g. McQuillan et al., 2014; Stelzer et al., 2016). In this vein, the detection of X-ray rotational modulation exclusively on stars with short rotation period may not be surprising.

The more typical, longer rotational time-scales of late-type stars (∼ 1 – 20 d) make it generally difficult to follow a whole star spot period in the X-ray band. A few star forming regions have been observed with XMM-Newton for exposure times approaching the stellar rotational timescales (e.g. ρ Oph: Scintino et al., 2006) but no X-ray rotational modulation was reported so far. However, a systematic exploitation of these data has not yet taken place. Here, the analysis tools provided by the EXTras project may prove useful. X-ray periodogram analysis may follow the example of Flaccomio et al. (2005) who found X-ray periods in ∼ 10 % of the stellar sample in a nearly uninterrupted 13 d-long Chandra observation of the Orion Nebula Cluster (project ‘COUP’). Statistical methods examining changes of the amplitude of X-ray lightcurves throughout the phases of known periodic optical variability patterns can also be used to establish the presence of rotational modulation in the X-ray band (Flaccomio et al., 2012).

2.3 Dynamo cycles

Dynamo cycles, similar to the Sun’s 11-yr cycle, have been observed on ∼ 60 % of solar-type MS stars through variability of the Ca II H&K index (Baliunas et al., 1995). For a much smaller number of late-type stars, dynamo cycles have been identified through photometric monitoring (e.g. Oláh et al., 2009), and only four stars have established X-ray cycles. Three of the stars with X-ray cycles are binaries (see Ayres, 2014; Favata et al., 2008; Robrade et al., 2012, and references therein). All these stars have long rotation periods, estimated ages of a few Gyrs (Barnes, 2007), and intermediate to low Ca II H&K activity levels. This is in line with results from chromospheric studies, where activity cycles were found mostly among intermediate-active stars while very active stars (in terms of $R_{\text{HK}}$) tend to show irregular Ca II H&K variability (Baliunas et al., 1995).

Sanz-Forcada et al. (2013) reported the first detection of an X-ray activity cycle in a young solar analog: $\iota$ Hor has a spectral type of G0 V and an age of ∼ 600 Myr (Barnes, 2007). Its monitoring with XMM-Newton started in 2011, stimulated by the detection of a cycle in Ca II H&K emission with only 1.6 yr period (Metcalfe et al., 2010). The X-ray luminosity was soon seen to mimic the cyclic variation of the Ca II S-index but an interruption of the cycle in both diagnostics seems to have taken place in 2013 with a subsequent phase shift when the periodic behavior resumed (see Fig. 2). $\iota$ Hor can be considered a proxy for the Sun at an early evolutionary phase. Its age corresponds to the time when life developed on Earth, a process which might have been stimulated by the detection of a cycle in Ca II H&K emission (Sanz-Forcada et al., 2013) with a period of ∼ 600 Myr (Barnes, 2007).

Footnote 2: Exploring the X-ray Transient and variable Sky (EXTras), funded within the EU seventh Framework Programme, is aimed at the thorough characterization of the variability of X-ray sources in archival XMM-Newton data; De Luca et al. (2014).
have been affected by the Sun’s high-energy radiation (see e.g. Chosen et al. 2007). Clearly, differences between X-ray cycles of young and old stars are relevant for our understanding of the early evolution of the Earth. Whether the violent X-ray and Ca II cycle of ι Hor is typical for dynamo activity of young Suns, therefore, is to be demonstrated through studies of other, similarly young stars.

Evidently, decade-long monitoring is not easily feasible in the X-ray band. The four known X-ray cycles have been constructed on the basis of repeated snapshot observations over the years, sometimes combining data from different instruments. As described e.g. by Avret (2009) this requires careful cross-calibration, and a long-term timeseries of a single instrument is certainly preferable. The lifetime of XMM-Newton now extends over the typical duration of stellar activity cycles and is perfectly suited for a systematic search of the associated X-ray variability.

Next to the stars for which dedicated long-term monitoring campaigns are already ongoing, indirect evidence for cycles may be collected from sparser multi-epoch observations. Rosen et al. have reported on this conference that multiple visits of XMM-Newton are available for > 70000 sources, with individual cases having up to ~ 50 observations. A preliminary sample based on positional matching with the CDS SIMBAD database yields a total of ~ 600 cool stars among the XMM-Newton sources having at least three separate observations; ~ 10% of these show flux variations of a factor of ≥ 5 between different observations and in many cases there is no discernible contribution from short-term variability (Pye et al. 2016; J.P. Pye priv. comm.).

3 X-ray variability from YSO environments

Observations with XMM-Newton and Chandra led, in the early days of their operation, to the discovery that Young Stellar Objects (YSOs) can produce X-rays not only through their vigorous coronae but also in shocks associated with disk accretion and protostellar jets. Since in- and outflows are dynamic processes, variability of the associated X-ray emission can be expected. Next to intrinsic variations, geometric effects may play a role in the observable (X-ray) emission as accretion streams or structures in the protostellar disk rotate in and out of the line-of-sight.

X-ray signatures associated with the YSO environment are superposed on the – often much stronger – features produced by magnetic activity. Thanks to the great leap in spectral and spatial resolution provided by the instruments onboard XMM-Newton and Chandra it became possible to disentangle these different X-ray emission mechanisms.

3.1 Accretion

High-resolution X-ray spectra with the gratings onboard both satellites allowed for the first time to examine individual emission lines in the soft X-ray band on a star other than the Sun. This gave access to the flux ratios of helium-like triplet which represent a diagnostic for the density of the X-ray emitting plasma in cool stars (see e.g. Ness et al. 2001). XMM-Newton emission line measurements provided evidence for high densities (\(n_e \sim 10^{13} \text{ cm}^{-3}\)) in a handful of classical (i.e. accreting) TTS (see Sect. 1) and indications for an extra soft X-ray component in these stars (Güdel & Telleschi 2007). Both phenomena represent the typical conditions in accretion shocks on low-mass stars.

Few studies of X-ray accretion diagnostics have been carried out in the time-domain. Only for the prototypical classical TTS TW Hya some evidence for temporarily enhanced mass accretion has been identified in soft X-ray emission lines observed with Chandra and likely produced in the accretion shock (Dupree et al. 2012). The observed variability supports the picture of an “accretion-fed corona” where the stellar X-ray emission is enhanced as a result of heating by the accreting matter (Brickhouse et al. 2012).

The changing visibility of magnetically channeled, accreting matter streams throughout a stellar rotation expected from magneto-hydrodynamic simulations (Romanova et al. 2008; Kurosawa et al. 2008) suggests that the observable X-ray accretion signatures of pre-MS stars vary across a rotation cycle. However, due to the considerable observing time investment required to follow accreting stars during a full rotation, little is known on this end from the observational perspective. A notable exception is V4046 Sgr, a binary composed of two young, accreting solar-mass stars in a synchronized 2.4 d orbit. With a 360 ks-long XMM-Newton/RGS pointing (Argiroffi et al. 2012) discovered the flux of the cool (accretion-driven) X-ray emission lines to vary periodically across the orbital/rotational cycle. The

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1 http://www.cosmos.esa.int/documents/332006/1018949/5Rosen.pdf
2 Proceedings 19th Cambridge Workshop on Cool Stars, Stellar Systems and the Sun, https://doi.org/10.5281/zenodo.58834
maxima were aligned with orbital phases in which the binary was seen in quadrature, indicating that the X-ray emitting accretion streams are located in the interbinary space. A clear periodic X-ray signal on a single accreting star was observed so far only on the Class I protostar, V1647 Ori, an EX Or type variable. From multiple epochs of X-ray data involving Chandra, XMM-Newton and Suzaku observations, Hamaguchi et al. (2012) modelled the phase-folded X-ray lightcurve with emission from accretion hot spots.

EXOr and FUOr phenomena are sporadic and poorly understood brightness bursts (up to 4−5 mag in optical light), considered to represent the most extreme accretion events during the YSO phase and responsible for assembling a significant amount of the final stellar mass. These events are classified according to the timescales of the outbursts as FU Ors (duration of decades; Hartmann & Kenyon, 1996) or as EX Ors (duration of months and recurrent; Herbig, 1989). Both types of outbursts are ascribed to drastic accretion rate increases ($M_{\text{acc}} \sim 10^{-3}−10^{-4} M_\odot/\text{yr}$), but the physical mechanisms triggering the outburst are still debated; see Audard et al. (2014) for a recent review. While the number of known EXOr and FUOr events is small by itself, even fewer have been observed in X-rays and less than a handful have multiple epoch X-ray data. Several snapshots over the course of recent outbursts on V1118 Ori and EX Lup involving both XMM-Newton and Chandra CCD cameras showed that the soft X-ray spectral component evolved towards lower flux, as expected while accretion was fading, but the X-ray temperatures are too high for emission from accretion shocks (e.g. Audard et al., 2010, Teets et al., 2012).

The number of known young eruptive stars is rapidly increasing as manifested by the large number of ATel notifications produced by programs such as EXORCISM (Lorenzetti et al., 2009). This provides high potential for X-ray identifications of newly discovered events and for follow-up during their evolution with repeated XMM-Newton pointings on months to years time-scales, shedding light on the X-ray production mechanism during violent accretion events on YSOs.

### 3.2 6.4 keV line emission

Among the most prominent feedback phenomena between stellar high-energy emission and the circumstellar matter is the 6.4 keV Fe Kα line. This line, observed in some dozens of YSOs so far, can not be attributed to highly ionized coronal material (e.g. Tsuimoto et al., 2005). In the Sun the 6.4 keV emission represents Kα fluorescence of neutral iron in the photosphere irradiated with X-rays from the solar corona during flares (Bai, 1979). In YSOs this line is usually attributed to fluorescence from neutral iron in the disk following X-ray illumination from the star’s corona. In some cases the line equivalent widths were shown to be incompatible with fluorescence calculations (Czesla & Schmitt, 2007; Giardino et al., 2007). Electron impact ionization in star-disk magnetic tubes was suggested as an alternative excitation mechanism for the line. Another possible scenario that might explain large observed equivalent widths without the need to invoke collisional excitation is the (partial) occultation of the illuminating continuum flux, e.g. a stellar flare behind the limb (Drake et al., 2008).

The identification of the origin of the Fe Kα line in YSOs can greatly benefit from time-resolved spectroscopy that enables a direct evaluation of the continuum emission visible at the moment when the line is produced. Several tens of ks exposure time with XMM-Newton are typically required to obtain enough signal in the high-energy tail of a YSO X-ray spectrum for a detection of the Fe Kα line which is partly blended with the coronal line complex produced by highly ionized iron. Time-resolved studies of the 6.4 keV line have been carried out for the Orion Nebula cluster based on the Chandra ‘COUP’ project (Czesla & Schmitt, 2010) and for ρ Oph based on XMM-Newton’s ‘DROXO’ project. For the case of DROXO, Stelzer et al. (2011) showed that higher equivalent widths are measured for the Fe Kα line in time-resolved analysis as compared to the time-averaged study (see Fig. 3). One question to follow up in future X-ray studies regards the indications for 6.4 keV emission in Class III objects, i.e. TTS that are believed to be devoid of circumstellar material such that the origin of the line remains unclear.

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