The complex phenomena of YSOs revealed by their X-ray variability

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Abstract
X-ray observations of Young Stellar Objects (YSOs) have shown several complex phenomena at work. In recent years a few X-ray programs based on long, continuous and, sporadically, simultaneous coordinated multi-wavelength observations have paved the way to our current understanding of the physical processes at work, that very likely regulates the interaction between the star and its circumstellar disk. We will present and discuss some recent results based on a novel analysis of few selected very large flares observed with the Chandra Orion Ultradeep Pointing (COUP), on the systematic analysis of a large collection of flares observed with the Coordinated Synoptic Investigation of NGC 2264 (CSI 2264) as well as on the Class I/II YSO Elias 29, in the rho Oph star forming region, whose data have been recently gathered as part of a joint simultaneous XMM-Newton and NuSTAR large program.

KEYWORDS:
X-rays, Stars: activity – Stars: flare – Stars: formation – Stars: coronae – Stars: pre-main sequence variability, YSO, Flares, Kα Fe line

1 | INTRODUCTION

Rotation, magnetism and accretion produce X-ray emission as a strong feature of young stellar objects (YSOs) yet to be fully understood. As a result high energy phenomena are key elements of the process of star formation because of the interplay, mediated by the magnetic field, between the newly born stars and their disks. Since the time scales of the involved phenomena are rather different, a proper tuned study of variability can allow to single out the many physical process at work. This has been the focus of a series of key studies in the last decade of which I will present and discuss a few selected topical examples together with a glimpse at some recent ongoing studies, in a few cases part of multi-wavelength observational campaigns, made possible by data gathered with XMM-Newton and Chandra and, very recently, with NuSTAR. Most of the recent advances have been possible thanks to long continuous observations of YSOs in nearby star forming regions, especially in Orion (Getman et al., 2005) and in ρ Oph (Pillitteri et al., 2010) or to long term monitoring programs as for the study of cycles (cf. Stelzer (2017) and reference therein cited). In the following I will mostly concentrate on what we have learned and what we can still learn from the multi-wavelength studies of flares and of the Fe Kα 6.4 keV line. Other interesting issues, such as accretion and outflow processes, are discussed by Argiroffi (2018).

2 | YSO FLARES

2.1 | Flares as a tool to trace the disk-star magnetosphere

As discussed in more detail by Reale (2007), a flare is essentially an impulsive release of energy occurring in a tenuous plasma confined in a “magnetic bottle” that loses energy by optically thin radiation and by efficient thermal conduction to the chromosphere (for an extensive discussion see Reale (2014)). The magnetic confinement is crucial for shaping the
A similar analysis has been performed for the several tens of YSOs of the ρ Oph Core F region, thanks to the data gathered with a large XMM-Newton program, nicknamed DROXO (PI: S. Sciortino, Pillitteri et al. 2010). In seven YSOs (Flaccomio, Stelzer, Sciortino, Pillitteri, & Micela, 2009) we have discovered intense flares. By means of the $log(T) - log(\sqrt{EM})$ diagram we derived the length of the flaring structure. In 2 out of the 7 flares that have been studied the derived length is several stellar radii. It is worth noting that the fraction of the very long flaring structures in ρ Oph is similar to the one observed in Orion, namely $\sim 30\%$.

Subsequently, by adopting a new flare spectral analysis technique that avoids nonlinear parametric modeling, Getman and collaborators (Getman, Feigelson, Broos, Micela, & Garmire, 2008; Getman, Feigelson, Micela, et al., 2008) analyzed the full set of COUP data of 216 flares occurring in 161 YSOs and determined the length of the flaring loop, $L_{loop}$. Based on estimation of the stellar radius, $R_*$, and disk keplerian corotation radius, $R_{cor}$\(^2\), they constructed the scatter plots of $(L_{loop} + R_*)/R_{cor}$ as a function of indicators of the presence of circumstellar disk or of on-going accretion process (cf. Fig. 1). On the basis of those scatter plots they concluded that: 1) circumstellar disks have no effect on flare morphology; 2) circumstellar disks are unrelated to flare energetics; 3) super-hot (> 100 MK) “non-standard” flares do occur in accreting YSOs (in agreement with Favata, Flaccomio, et al. 2005); 4) circumstellar disks may truncate PMS magnetospheres, i.e., $(L_{loop} + R_*)/R_{cor} < 1$. Points 1) and 4) are at odds with the findings of Favata, Flaccomio, et al. (2005) because they seem

\[^1\]The shape of light curve would be very different in the case of unconfined plasma

\[^2\]i.e. the distance from stellar surface at which the angular velocity of disk equates that at stellar surface
FIGURE 2 (Left panels) The data and the summary of the wavelet analysis results for COUP 1068. Time is measured from the beginning of the observation; the analyzed flare data segment is highlighted in yellow. The central panel shows the analyzed data segment after subtraction of the running average, while the bottom panel shows the intensity curve as function of period and time. The statistical significance maps are also shown, they allow to discriminate the statistically significant period and the duration of the periodic signal. The dashed outer region is outside the so-called “cone of influence”, delimiting the region where the analysis is meaningful. (Right panels) The analogous plots for COUP 332.

to imply the non-existence of star-disk interconnecting flaring structures. However it is worth noticing that even in the analysis of Getman, Feigelson, Micela, et al. (2008) there are remarkable exceptions, namely a few YSOs whose data points cannot be reconciled with the above conclusions, notably COUP 1688 and COUP 332\(^3\) (two of 10 YSOs with long flaring loop according to Favata, Flaccomio, et al. (2005)), at this two Orion YSOs we have to add also DROXO 63 and DROXO 67, the two ρ Oph showing firm evidence of very long flaring loops. In summary, the issue of the existence of star-disk interconnecting flaring arch has been matter of debate over the last decade. The issue is particularly interesting since, depending on the actual occurrence of those large flares, they can affect the early evolution of circumstellar disks with far reaching effects even on the formation of planetary systems.

Recently a novel analysis technique has allowed to further investigate the relevant astrophysical question of the existence of long flaring magnetically confined structures very likely interconnecting the circumstellar disk and the central star. First of all Flaccomio, Micela, & Sciortino (2012) has performed a sophisticated time resolved analysis of all available COUP data showing that disk-bearing stars are definitively more X-ray variable than disk-less ones, and proposed that this can be easily explained as due to the effect of time-variable absorption by warped and rotating circumstellar disks.

Even more relevant is a novel analysis of the light curves based on the so-called Morlet wavelet (eg. López-Santiago (2018) and references therein cited) of some of the big COUP flares studied by Favata, Flaccomio, et al. (2005). Wavelet analysis has demonstrated to be a powerful way to reveal oscillations in the light curve of stars during coronal flares. Indeed its application to some of the COUP big flares has shown the existence of oscillations during the flare decay phase. This has allowed an accurate derivation of the oscillation period from which, on the basis of simple physical argument, it is possible to derive the length of the flaring structure where the oscillating X-ray emission comes from (López-Santiago et al., 2016). More recently, on the basis of the wavelet analysis, Reale, Lopez-Santiago, Flaccomio, Petralia, & Sciortino (2018) have reported the detection of large-amplitude (∼20%), long-period (∼3 hr) pulsations in the light curve of two day-long flares observed with COUP. Detailed hydrodynamical modeling of two flares observed on V772 Ori (shown in Fig. 5) and OW Ori shows that these pulsations track the sloshing of plasma along a single elongated magnetic tube, triggered by a heat pulse whose duration (∼1 hr) is much shorter that the sound crossing time along the loop. From this simple and robust modeling Reale et al. (2018) concluded that the involved magnetic tubes are ∼20 solar radii long, and, very likely, connect the stars with their surrounding disks.

\(^3\)COUP 332 has a weak NIR counterpart and is not shown in the plots because of lack of period and EW(CaII) data.
3 | MULTI-WAVELENGTH STUDIES

The multi-wavelength coordinated simultaneous observations are certainly an interesting territory, but poorly explored so far because of the factual difficulties of organizing those programs, as they require to access at the same time several observing facilities from space and from the ground. The most notably coordinated simultaneous observations that have been pursued till today are i) CSI (Coordinated Synoptic Investigation) of NGC 2264 based on COROT, Chandra and Spitzer simultaneous observations (eg. Cody et al. (2014); Cody, Stauffer, Micela, Baglin, & CSI 2264 Team (2013); Stauffer et al. (2016)) of which some recent results, mostly based on the X-ray data, will be illustrated in the following, ii) Kepler/XMM-Newton observations of the Pleiades, where about a dozen of flares have been detected and studied in detail (Guarcello 2018a, 2018b), ii) Few more selected interesting individual sources (e.g. AB Dor, V4046 Sgr, V2129 Oph, etc.), some of which are YSOs.

**Systematic study of YSO flare energetics:** Flaccomio et al. (2018) have performed a detailed analysis of all the flares observed in the NGC 2264 YSOs during the CSI program and have compared the light curves obtained in X-rays (with Chandra), in optical (with COROT), and in the infrared (with Spitzer). This analysis allows deriving few conclusions, namely, i) the flare peak luminosity measured in the optical, IR and X-ray band-passes are tightly correlated, with a small scatter, a similar relation (with a similar amplitude scatter) holds also for the flare energy released in the optical, IR and X-ray band-passes; ii) the relationship holds over more than 3 orders of magnitude with little (.3 dex) scatter. This is somehow surprisingly given the available data and analysis assumptions; iii) the flare energy emitted in soft X-rays (i.e. in the XMM-Newton bandpass) is about 10% to 20% of the flare energy emitted in the optical band; iv) the flare energies are up to ~ 5 dex higher than those of the brightest solar flares, and the simple extrapolation of solar flares to this extreme regime requires some cautions. As an example, the data seem to indicate that the flare photospheric temperature is significantly lower than 10⁴ K, that is the typical solar value; v) finally there is evidence of a strong IR excesses for flares in stars with circumstellar disks: likely as a result of the direct response (heating) of the inner disk to the optical/X-ray flare.

**Unveiling circumstellar disks by time resolved X-ray spectroscopy:** The main mechanisms responsible for the YSO X-ray variability are variable extinction, unsteady accretion, and rotational modulation of both hot and dark photospheric spots and X-ray-active regions. In stars with disks, this variability is related to the morphology of the inner circumstellar region (≤ 0.1 AU) and that of the photosphere and corona, all impossible to be spatially resolved with present-day techniques. Thanks to the CSI data Guarcello et al. (2017) have studied the X-ray spectral properties during optical bursts and dips in order to unveil the nature of these phenomena occurring on disk bearing YSOs. They have analyzed simultaneous CoRoT and Chandra/ACIS-I observations to search for coherent optical and X-ray flux variability. In stars with variable extinction, they have looked for a simultaneous increase of optical extinction and X-ray absorption during the optical dips; in stars with accretion bursts, they have searched for soft X-ray emission and increasing X-ray absorption during the bursts. Guarcello et al. (2017) have found evidence for coherent optical and X-ray flux variability among the stars with variable extinction. In 38% of the 24 stars with optical dips, they observe a simultaneous increase of X-ray absorption and optical extinction. In seven dips, it is possible to calculate the \( N_H / A_V \) ratio in order to infer the composition of the obscuring material. In 25% of the 20 stars with optical accretion bursts, they observe increasing soft X-ray emission during the bursts arguably associated to the emission of accreting gas. It is not surprising that these properties have been observed only in a fraction of YSOs with dips and bursts, since favorable geometric configurations are required. The observed variable absorption during the dips is mainly due to dust-free material in accretion streams. In stars with accretion bursts we observe, on average, a larger soft X-ray spectral component not seen in non-accreting stars.

4 | IRON Kα 6.4 KEV FLUORESCENCE LINE

Fe Kα 6.4 keV line from “cold” material (with EW > 100 eV) has been found in tens of YSOs, mostly in Orion and ρ Oph but the relation between line with EW > 100 eV and flare is quite controversial: in YLW16A in ρ Oph the line has been seen during an intense X-ray flare (Imanishi, Kovama, & Tsubo, 2001); in 7 YSOs in Orion the line has been seen during flares (Tsujimoto et al., 2005); in Elias 29 in ρ Oph the line has been seen during quiescence and flaring periods (Favata, Micela, Silva, Sciortino, & Tsujimoto, 2005; Giardino et al., 2007), the same is true for many other YSOs in Orion (Czesla & Schmitt, 2010).

If photoionized, then the EW is ≤ 100 eV in the case of a corona exciting “photospheric material” (Drake, Ercolano, & Swartz, 2008) and the EW is ≤ 150 eV for an AGN disk excited by a power law source (George & Fabian, 1991; Matt, Perola, & Piro, 1999). A Fe Kα line with with EW > 100 eV has never been seen in “normal” stars while the Fe Kα line with EW below 100 eV has been seen in a few “active” stars.
We have to face the unsolved question of “how can the Fe Kα EW be > 100 eV and even > 800 eV?”. As matter of fact the current data leave open the scenarios where photo-ionization alone could be insufficient to explain such a strong fluorescent emission and collisional excitation is required. [Drake et al. (2008)] have considered the Fe Kα fluorescent line emission in the relatively few cases known at the time concluding that there was not compelling evidence for a collisional excited fluorescence from high energy electrons. They have proposed 4 different possible explanations, namely: 1) Super-solar Fe abundance in disk material, but an extremely high abundance of Fe is required and the EW rapidly saturates at ∼ 800 eV [Ballantyne, Fabian, & Ross (2002)]; 2) Disk Flaring where a favorable geometry results in a source solid angle > 2π, but this can increase line intensity by, at most, a factor two or three; 3) Line emission due to an “unseen” flare obscured by stellar disk. This implies that the evaluation of the exciting continuum is grossly underestimated, but a very ad-hoc geometry is required; 4) Excitation due to high energy non-thermal electrons, but this requires a substantial amount of energy stored in the impinging particles [Ballantyne & Fabian, 2003].

It is worth to notice that i) only solution n. 4) may, in principle, explain the EW of ∼ 1400 eV found in V1486 Ori (Czesla & Schmitt, 2007) and ii) that solutions n. 2 and 3, requiring “ad-hoc” geometries, are unsatisfactory when the fluorescent emission becomes quite common, as the accumulated data clearly indicate.

4.1 | Elias 29: DROXO main results

One of the most intriguing results obtained with the DROXO, 500 ks long, observations, of the ρ Oph core F, is the fact that in Elias 29, a class I/II YSO that is seen almost face-on, we have found period of “quiescent” as well as of “flaring” emission and have found that the XMM-Newton spectra requires, to be adequately fitted, the presence of the Fe Kα line at (about) 6.4 keV. The line equivalent width, EW, does vary with time, as time resolved spectroscopy with a “resolution” of about 60 ks has clearly shown. Since Elias 29 is the strongest YSO showing this phenomenon it is clearly a key target for any further investigation.

4.2 | Elias 29: the new XMM-Newton and NuSTAR joint program

Before the availability of XMM-Newton and NuSTAR simultaneous observations to test for the presence of a non thermal population of electrons responsible for the excess of fluorescence of a disk-bearing YSO was not possible. NuSTAR has offered for the first time the opportunity to perform this investigation. In this context we have obtained joint and simultaneous XMM-Newton+NuSTAR 300 ksec long observations of Elias 29 devoted to acquiring spectra from soft (XMM-Newton band 0.3-8.0 keV) to hard (NuSTAR band 3-80 keV) X-rays. Our main aims were to detect any non thermal hard X-ray emission from Elias 29, to study any time variability that could occur and to relate these features to the fluorescent emission with the aim to explain its origin. The interested reader will found all the details of the analysis performed and a detailed account of results in Pillitteri et al (2018). Here we will just provide a summary of the relevant findings. We have found evidence of an excess of likely “non-thermal” emission above 20 keV in the NuSTAR spectra (Figure 4). The presence of the excess does not seem to be associated to the occurrence of flares and we confirm the presence of a line emission at about 6.4 keV whose EW does vary with time and that does not peak at the maximum flare intensity.

![Figure 4](image_url)

**FIGURE 4** NuSTAR FPM A and B spectra of Elias 29 with the best fit model. The model is composed by an absorbed 1T APEC thermal component plus a Gaussian line at 6.4 keV and a power law in order to model also the region above 20 keV. While the emission up to ∼ 20 keV is well described from the derived XMM-Newton best fit model, it is clear the presence of a statistically significant “non-thermal” excess above 20 keV.

We have also investigated if the available XMM-Newton spectra do allow to trace possible time variation of the centroid of the Fe fluorescent line. We have performed an extensive sets of simulations and have explored a range of accumulated counts and of EWs of the fluorescent line. The input spectrum is the best fit model spectrum of Elias 29 plus a Gaussian line with a centroid at 6.4 keV. The simulations shows that, if the source spectrum contains, in the 5-8 keV range, more than 500 counts and if the EW > 300 eV then it is extremely unlikely that the fitted line centroid is above 6.5 keV. Since the fitted line centroids are above 6.5 keV in a number of data segments with more than 500 counts we conclude that there is a convincing evidence that a non-negligible fraction of the material emitting the fluorescent line is not in a neutral state. As calculated and
discussed by Kallman, Palmeri, Bautista, Mendoza, & Krolik (2004) a centroid at $\sim 6.5$ keV would imply, if ionization equilibrium condition are met, that emitting Fe is at $10^5$ K.

5 | CONCLUSIONS

Over the last decade our knowledge of high energy phenomena occurring in YSOs has greatly advanced. From the many painstaking efforts we have learned some general lessons and from observational efforts we have shed light on some controversial issues while others still remain unsolved and will require further investigations. Limiting ourselves to the issues we have discussed we can conclude that: 1) Long (> 100 ks) continuous observations catch many kind of variability at work in YSOs and allow us to unveil the nature of the physical processes behind them. 2) Novel studies of big flares in YSOs firmly confirm that very elongated (arch-like) structures exist and are involved in those flares. Due to simple considerations on the effect of centrifugal force it is likely that those structures connect the star and the disk at the co-rotation radius. 3) Simultaneous coordinates observations have shown to be crucial to improve our understanding of the nature of YSO flares and their effects on disk evolution. 4) Strong and variable Fe Kx line is a common feature of disk-bearing YSOs. Both the nature of the excitation mechanism and the physical state of emitting matter remain far from being clear. There is a growing evidence that the ionization stage of the emitting gas is different from being mainly neutral.

We are confident that in the next decade the ATHENA observatory (Barcons et al. 2017) with its high throughput and X-IFU high spectral resolution (Barret et al. 2016) will allow to answer all those and many more questions in the field of star formation and evolution (Sciortino et al. 2013).

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