Received: 28 August 2018 | Accepted: 1 October 2018
DOI: 10.1002/asna.201913620

ORIGINAL ARTICLE

Astronomische Nachrichten

The complex phenomena of young stellar objects revealed by their X-ray variability

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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 multiwavelength observations have paved the way to our current understanding of the physical processes at work, which 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 a few selected very large flares observed with the *Chandra* Orion Ultradeep Pointing, 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.

KEYWORD
X-rays – stars: activity – stars: flare – stars: formation – stars: coronae – stars: premain sequence variability – YSO – flares – K_α 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. Because the time scales of the involved phenomena are rather different, a proper tuned study of variability can allow us to single out the many physical processes 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 multiwavelength 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 (c.f. 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 multiwavelength studies of flares and of the Fe K_α 6.4 keV line. Other interesting issues, such as accretion and outflow processes, are discussed by Argiroffi (2019).

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 typical light curve of a flare[1], which is characterized by a very fast increase of the emission (due to the rapid heating of the plasma) followed by a slow, almost exponential decay (due to the cooling by thermal conduction and radiation). Under very general conditions that are typically met by most

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

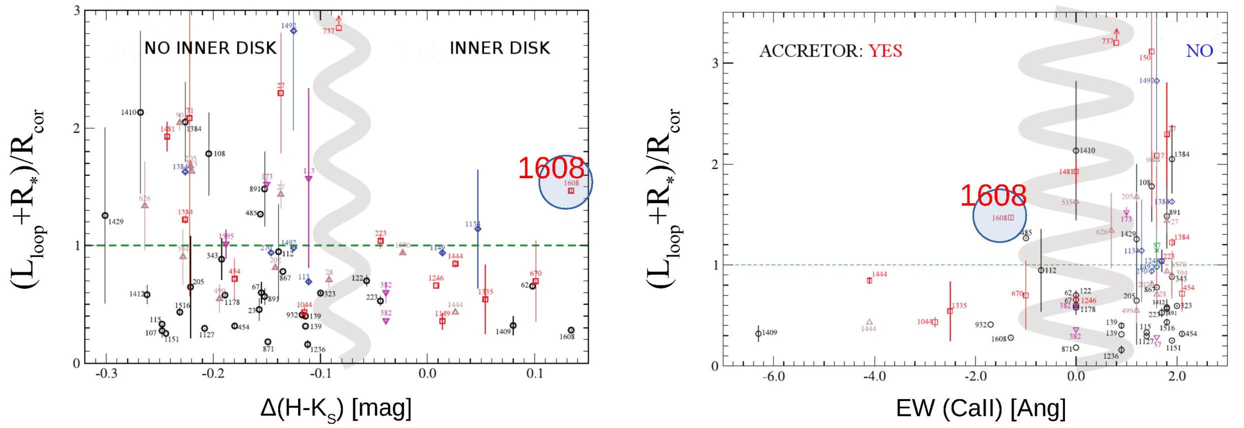

FIGURE 1 Scatter plot of $(L_{\rm loop}+R_*)/R_{\rm cor}$ vs. excess of $(H-K_S)$ color, an indicator of the presence of circumstellar disk (left). Scatter plot of $(L_{\rm loop}+R_*)/R_{\rm cor}$ vs. the EW of CaII triplet, an indicator of accretion process (right). In both panels the vertical wavy gray curve marks the transition to accreting/inner disks. COUP 1068, that is outlined, clearly behaves very differently from the rest of (most of) the other sources. COUP 332, for which the analysis derives long flaring structure, is not shown in the plots for lack of period and EW data (adapted from Getman et al. (2008b))

of the observed flares, Reale (2007) showed that the time evolution of the emission and the peak temperature (and the cooling as traced in the $\log(T)$–$\log(\sqrt{EM})$ diagram) can provide a "direct" estimate of the length of the flaring magnetic structure (arc). On the basis of this interpretative framework, Favata et al. (2005a) have analyzed a sample of 32 large flares observed on thanks to a long continuous *Chandra* observation toward Orion, nicknamed Chandra Orion Ultradeep Pointing (COUP) (PI E. Feigelson, Getman et al. 2005), concluding that in about 10 of them the length of the flaring structure is $3-5$ stellar radii (R$_*$). Similar length structures have never been "seen" in more evolved normal stars. Favata et al. (2005a) note that structures of such extent, if anchored on the stellar surface, should suffer of major stability problem due to the centrifugal force because 1–2-Myr old YSOs are fast rotators with a rotation period, P ∼ 3–6 days. Hence long loops anchored only on the star would be ripped open. As a solution to this problem, they conclude that, because the corotation radius of those YSOs is typically at 4–5 R_*, it is very likely that the loop, on which the flare occurs, is connecting the star and the disk (at the corotation radius). It is worth noticing that the existence of such magnetic "funnels" in class I–II YSOs is postulated by magnetospheric accretion scenario (e.g., Hartmann 1998 and references therein cited).

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 et al. 2009), we have discovered intense flares. By means of the $\log(T)-\log(\sqrt{EM})$ diagram, we have derived the length of the flaring structure. In 2 out of the 7 flares that have been studied, the derived length is of 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 ∼30%.

Subsequently, by adopting a new flare spectral analysis technique that avoids nonlinear parametric modeling, Getman et al. 2008a, 2008b analyzed the full set of COUP data of 216 flares occurring in 161 YSOs and determined the length of the flaring loop, $L_{\rm loop}$. Based on estimation of the stellar radius, R_*, and disk keplerian corotation radius, $R_{\rm cor}$[2], they constructed the scatter plots of $(L_{\rm loop}+R_*)/R_{\rm cor}$ as a function of indicators of the presence of circumstellar disk or of on-going accretion process (cf. Figure 1). On the basis of those scatter plots they concluded that: (a) circumstellar disks have no effect on flare morphology; (b) circumstellar disks are unrelated to flare energetics; (c) super-hot (>100 MK) "non-standard" flares do occur in accreting YSOs (in agreement with Favata et al. (2005a)); and (d) circumstellar disks may truncate YSO magnetospheres, that is, $(L_{\rm loop}+R_*)/R_{\rm cor}<1$. Points (a) and (d) are at odd with the findings of Favata et al. (2005a) because they seem to imply the nonexistence of star-disk interconnecting flaring structures. However, it is worth noticing that even in the analysis of Getman et al. (2008b) there are remarkable exceptions, namely a few YSOs whose data points cannot be reconcilied with the above conclusions, notably COUP 1688 and COUP 332[3] (two of 10 YSOs with long flaring loop according to Favata et al. (2005a)), 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 because 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 us to further investigate the relevant astrophysical question of the existence of long flaring magnetically confined structures

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[2] That is the distance from stellar surface at which the angular velocity of disk equates that at stellar surface.

[3] COUP 332 has a weak near-infrared (NIR) counterpart and is not shown in the plots because of lack of period and EW(CaII) data.

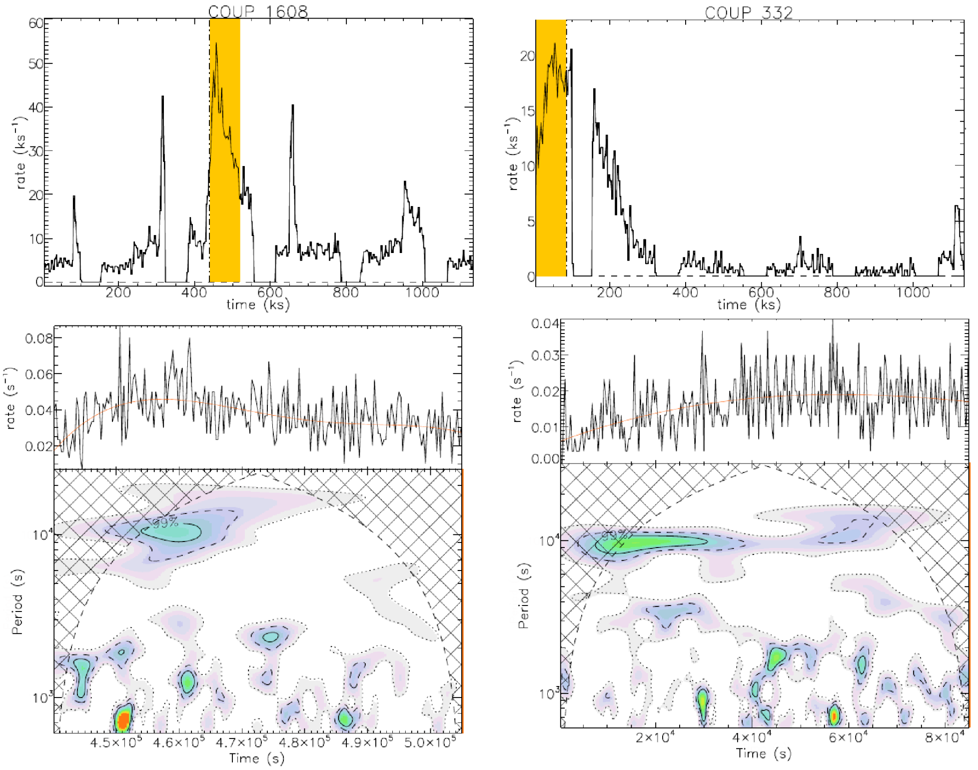

FIGURE 2 The data and the summary of the wavelet analysis results for COUP 1068 (left panels). Time is measured from the beginning of the observation; the analyzed flare data segment is highlighted in yellow. The central panel shows the analyzed data segment after subtraction of the running average, 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. The analogous plots for COUP 332 (right panels)

very likely interconnecting the circumstellar disk and the central star. First of all, Flaccomio et al. (2012) have 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 (e.g., López-Santiago (2018) and references therein cited) of some of the big COUP flares studied by Favata et al. (2005a). 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 (Figure 2). 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 et al. (2018) have reported the detection of large-amplitude (~20%), long-period (~3 hr) pulsations in the light curve of 2-day-long flares observed with COUP. Detailed hydrodynamical modeling of two flares observed on V772 Ori (shown in Figure 3) 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.

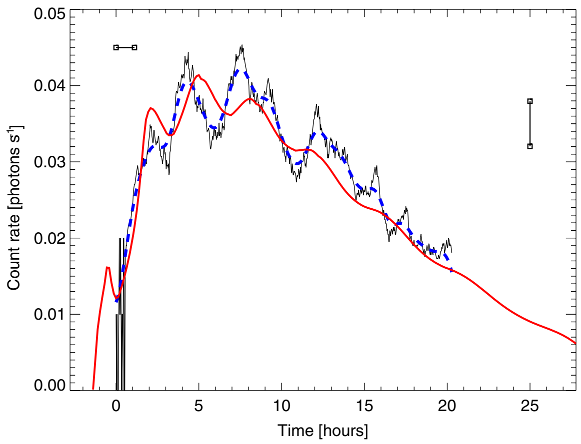

FIGURE 3 The smoothed and running average subtracted light curve of V772 Ori flare (black line) showing the oscillation of X-ray emission is compared with the hydrodynamical model synthetized light curve in the case of a short-duration heating pulse (blue dashed line) and of a long-duration heating (red line) on the same long length flaring structure. Only a long loop with a length of about 10–20 R_{*} and a short heating pulse are able to reproduce the observed oscillations both in intensity and period

3 | MULTIWAVELENGTH STUDIES

The multiwavelength 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 (a) Coordinated Synoptic Investigation (CSI) of NGC 2264 based on convection, rotation and planetary transits (COROT), *Chandra,* and Spitzer simultaneous observations (Cody et al. (2013, 2014); Stauffer et al. (2016)) of which some recent results, mostly based on the X-ray data, will be illustrated in the following, (b) Kepler/*XMM-Newton* observations of the Pleiades, where about a dozen of flares have been detected and studied in detail (Guarcello 2018, Guarcello et al. 2019), (c) a few more selected interesting individual sources (e.g., AB Dor, V4046 Sgr, V2129 Oph, etc.), some of which are YSOs.

3.1 | 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 a few conclusions, namely, (a) the flare peak luminosity measured in the optical, infrared (IR), and X-ray band-passes is 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; (b) 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; (c) the flare energy emitted in soft X-rays (i.e., in the *XMM-Newton* bandpass) is about 10–20% of the flare energy emitted in the optical band; (d) 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 10^4 K, that is the typical solar value; (e) 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.

3.2 | 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 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 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 with 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 nonaccreting stars.

4 | IRON K_α 6.4 KEV FLUORESCENCE LINE

Fe K_α 6.4 keV line from "cold" material (with equivalent width (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 et al. 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 et al. 2005b; 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 et al. 2008) and the EW is ≤150 eV for an active galactic nuclei (AGN) disk excited by a power law source (George & Fabian 1991; Matt et al. 1991). A Fe K_α line with EW > 100 eV has never been seen in "normal" stars while the Fe K_α 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 K_α EW be >100 eV? and even >800 eV? ". As a matter of fact, the current data leave open the scenarios where photoionization alone could be insufficient to explain such a strong fluorescent emission and collisional excitation is required. Drake et al. (2008) have considered the Fe K_α

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 four different possible explanations, namely: (a) Supersolar Fe abundance in disk material, but an extremely high abundance of Fe is required and the EW rapidly saturates at ∼800 eV (Ballantyne et al. 2002); (b) Disk Flaring where a favorable geometry results in a source solid angle $>2\pi$, but this can increase line intensity by, at most, a factor two or three; (c) 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; (d) Excitation due to high-energy nonthermal electrons, but this requires a substantial amount of energy stored in the impinging particles (Ballantyne & Fabian 2003).

It is worth noticing that (a) only solution n. 4) may, in principle, explain the EW of ∼1400 eV found in V1486 Ori (Czesla & Schmitt 2007) and (b) 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 require, to be adequately fitted, the presence of the Fe K_α 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. Because 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 nonthermal population of electrons responsible for the excess of fluorescence of a disk-bearing YSO were 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 ks 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 nonthermal 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 of explaining its origin. The interested reader will found all the details of the analysis performed and a detailed account of results in Pillitteri et al. (2019). 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 with 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.

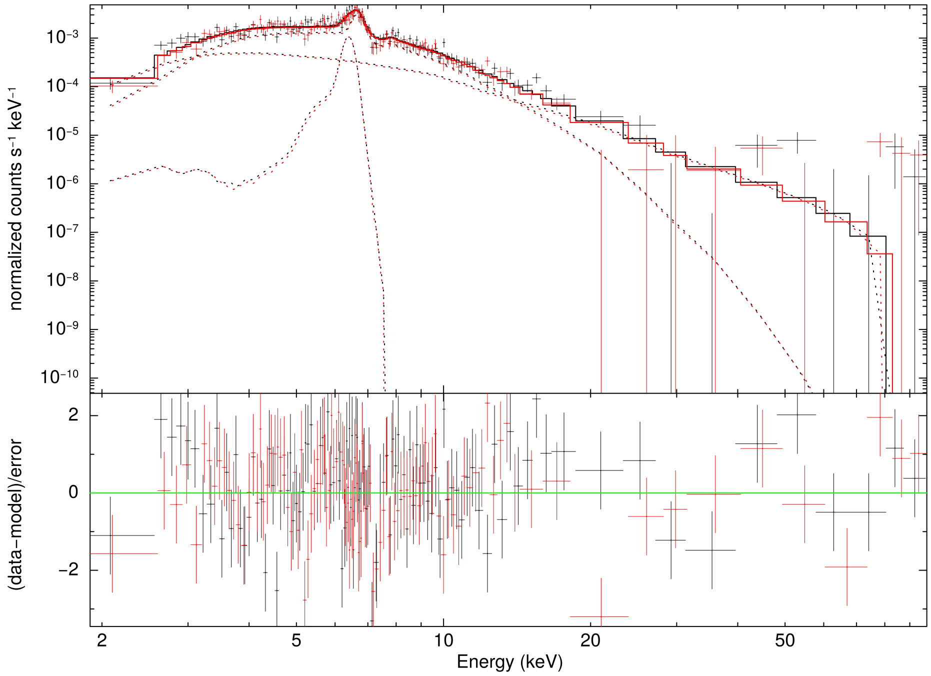

FIGURE 4 *NuSTAR* FPM A and B spectra of Elias 29 with the best fit model. The model is composed of an absorbed 1 T APEC thermal component plus a Gaussian line at 6.4 keV and a power law to model also the region above 20 keV. While the emission up to ∼20 kev is well described from the derived *XMM-Newton*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

We have also investigated if the available *XMM-Newton* spectra do allow us to trace possible time variation of the centroid of the Fe fluorescent line. We have performed 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 show that, if the source spectrum contains, in the 5–8 keV range, more than 500 counts and if $EW > 300$ eV, then it is extremely unlikely that the fitted line centroid is above 6.5 keV. Because 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 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 et al. (2004) a centroid at ~6.5 keV would imply, if ionization equilibrium conditions 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: (a) 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. (b) 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 corotation radius. (c) Simultaneous coordinate observations have shown to be crucial to improve our understanding of the nature of YSO flares and their effects on disk evolution. (d) Strong and variable Fe K_α 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 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 us to answer all those and many more questions in the field of star formation and evolution (Sciortino et al. 2013).

ACKNOWLEDGMENTS

We acknowledge modest financial contribution from the agreement ASI-INAF n.2017-14.H.O. IP acknowledges support from the ASI and the Ariel Consortium.

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How to cite this article: Sciortino S, Flaccomio E, Pillitteri I, Reale F. The complex phenomena of young stellar objects revealed by their X-ray variability. *Astron. Nachr.* 2019;1–6. https://doi.org/10.1002/asna.201913620