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Hard X-ray view of nearby Star Forming Regions

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Abstract. *Chandra* and *XMM-Newton* have surveyed several nearby star forming regions and have greatly advanced our knowledge of X-ray emission from Young Stellar Objects (YSOs). After briefly reviewing it I discuss the advancements in this research field that could be possible with Simbol-X unique imaging capability in the hard X-ray bandpass.

Key words. Stars: pre-main-sequence – Stars: flare – Xrays: stars

1. Introduction

In the last decade thanks to the new space and ground instrumentations the study of star formation and early stellar evolution has gained a great impulse becoming a vibrant research field.

The role of X-rays, that likely trace, and are connected to, the magnetic fields at work in the interaction region between the pre-main sequence star and its surrounding disk, has started to be recognized as one of the relevant elements to deal with for understanding star formation and early evolution. Henceforth the X-ray observational window has gained an increasing interest by the specialists in this research field.

In the last few years the X-ray emission from Young Stellar Objects (YSOs) has been the subject of many *Chandra* and *XMM-Newton* studies that have surveyed several nearby Star Forming Regions (SFRs) and have performed deep observations of topical objects. Given the extent of the available literature it is impossible to review it in the space of this contribution, however most of our knowledge has largely advantaged of the results of *COUP* (*C*handra *O*rion *U*ltradeep *P*roject, cf. Getman et al. 2005), of *XEST* (*X*MM-Newton *E*xtended *S*urvey of *T*aurus, cf. Güedel et al. 2007) and, more recently, of *DROXO* (*D*eep *R*ho *O*phiuchi *X*MM-Newton *O*bservation, cf. Sciortino et al. 2006).

Very synthetically our current knowledge on the YSO X-ray emission can be summarized as follows: a) YSOs are X-ray luminous, at 1 M_{sun} their typical X-ray emission is in the log(L_X [erg/sec]) = 30−31 range. For comparison the typical value for the Sun is log(L_X [erg/sec]) = 26.5−27.5. b) The emitting plasma is very hot. Plasma at several 10^7 K is always present and its temperature increases up to 10^8 K during flares. For comparison, in the Sun plasma with temperature up to 10^7 K is present only during flares. c) The emission is highly variable and, at the same time, can be present stochastic variability, big flares (with intensity variations up to 100 times), as well as

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rotational modulation. d) The typical X-ray luminosity of Class I/II YSOs is 2−3 times lower than that of Class III YSOs. e) Class II YSO X-ray spectra show emitting plasma often with low metal abundances. f) Class I/II YSO have hotter X-ray spectra than Class III YSOs, but a soft (0.2-0.3 keV) component can be present. This latter component is associated to accretion shocks due to disk material "falling" on the surface of the central accreting PMS star.

Seen in the perspective offered by Simbol-X, with its unique capacity to obtain, for the first time, real images of the X-ray sky in the 10−60 keV bandpass, our current knowledge naturally brings to identify key open issues in YSO studies, such as: i) the still controversial X-ray emission in Class 0 YSOs, i.e. in the early protostars with a lifetime of just $\sim 10^4$ yr; ii) the existence of quiescent hard X-ray emission from Class I-III YSOs and its possible explanation in terms of continuous micro-flares; iii) the occurrence of non-thermal hard X-ray emission during intense flares in YSOs and its possible analogy to the case of solar flares. All the above are connected to the general theme of the role played by high-energy radiation on star formation and early evolution. Other related issues are the channeling and regulation of accretion onto YSOs and the effects of the high-energy radiation on the chemistry and early evolution of proto-planetary disks, as well as on the formation of complex molecules.

2. X-rays from Class 0 YSOs

After many years of search, the X-ray emission from Class 0 YSOs is still controversial. Either it is weak or rare or it is extremely difficult to discover due to the conspicuous amount of intervening absorbing material. While X-rays are quite penetrating – indeed the absorption at 2 keV and at 2 μm are similar – Class 0 sources can be subject to extinction up to 100 magnitudes (and even higher) preventing the escape of any X-rays. One of the most (if not the most) stringent upper limit to the intrinsic X-ray luminosity of Class 0 has been obtained thanks to a 100 ksec *Chandra* observation toward the Serpens SFR (Giardino et al. 2007a). By staking data taken at 6 known Class 0 positions it has been possible to determine that the Serpens Class 0 intrinsic X-ray luminosity is lower than 4 10^{29} erg/s (assuming emission from an optically thin isothermal plasma with kT = 2.3 keV seen through an absorbing column with $N_H = 4\ 10^{23}$ cm^{-2}). The X-ray luminosity implyed by this upper limit is still a dex higher than the X-ray luminosity of the active Sun. Future deep observations with Simbol-X will make it possible to take advantage, for the first time, of the penetrating power of hard X-ray to really advance our knowledge on this subject. I feel this important because with COUP we have discovered in Orion a deeply embedded population (cf. Fig. 2), that has been shown to locally dominate the ionization level within a molecular cloud (cf. Lorenzani et al. (2007) and Fig. 3). However, as of today, we do not know when intense X-ray emission from YSOs develops and starts to affect – for example by determining the effectiveness of ambipolar dif-

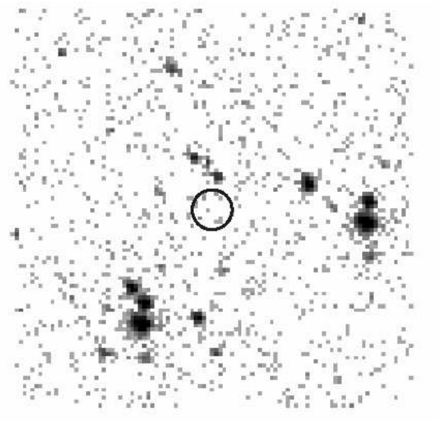

Fig. 1. The staked image obtained by adding ACIS events in the 0.5-8.0 keV range from six regions of 200 × 200 pixels centered on the position of the 6 known Class 0 sources in the surveyed region. The circular region in the center is 5", corresponding to positional uncertainties of the mm/submm sources. No X-ray excess is present within this area indicating that the surveyed Serpens Class 0 YSOs are unlikely to be X-ray sources with intensities just below the detection threshold (adapted from Giardino et al. 2007a).

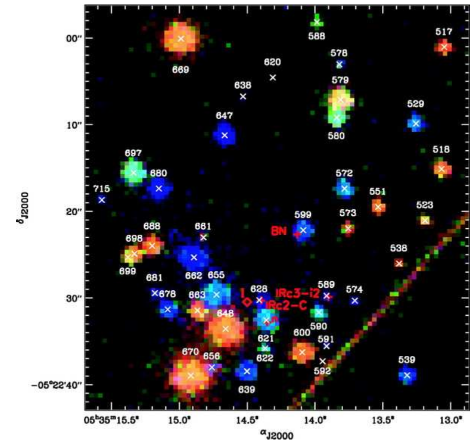

Fig. 2. A COUP color coded (red = 0.5-1.7 keV, green = 1.7-2.8, blue= 2.8-8.0 keV photons) view of the BN-KL region. Red crosses mark the positions of luminous mid-infrared sources. The red diamonds shows the radio position of source I with no X-ray counterpart. Note the large population of deeply embedded (blue) COUP sources (adapted from Grosso et al. (2005)).

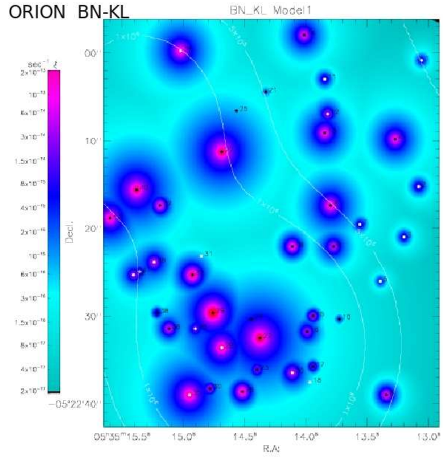

Fig. 3. A two dimensional projection of a model computation of the ionization rate as function of position for the BN cloud core in the OMC 1 region. Across the entire core the (color coded) value of ionization rate is higher than the typical value due to cosmic rays (2 10^{-17} s^{-1}). Around each of the embedded X-ray emitting YSOs develops a Röntgen sphere where the X-ray induced ionization rate is several orders of magnitude higher than the background level. (courtesy of A. Lorenzani and F. Palla.)

fusion – the further evolution of star formation process. As a result we do not know yet if this effect is just a small adjustment of the current interpretational scenario(s) or a major change is required if X-rays start acting at very early (Class 0) times.

3. Flares and Magnetic Funnels

The use of dynamical information (decay time, etc.) of flares is a classic tool to derive physical parameters, including size, of emitting regions (cf. Reale 2007). This is possible because in order to have a flare with the typical decay phase the plasma **must** be confined (Reale, Bocchino & Peres (2002)). As a results the behavior of flare X-ray light curve (and the related time resolved spectra) allows measuring the size of flaring magnetic structure. In normal stars the observed flares are similar to solar ones, but sometimes much stronger (up to 10^4 times) both in absolute term and with respect to the stellar bolometric luminosity. In most cases the observed YSO flares are similar to "standard" stellar ones, but there are a few notable exceptions: in about 10 *COUP* (Favata et al. 2005) and 2 *DROXO* (Flaccomio et al 2007) flares, the deduced size of the flaring region is at least 3 times larger than stellar radius and in few cases as long as 0.1 AU, i.e. the size of the star-disk separation. This long structures have never been "seen" in more evolved normal stars. Such long structures, if anchored on the star surface, will suffer severe stability problem due to the centrifugal force since 1-2 Myr YOSs are fast rotators (P_{rot} = 1-8 days) with a disk corotation radius of about 1-10 stellar radius. A possible solution, compatible with avaliable observational evidence, is one in which the loop connects the star with the disk at the corotation radius. Such magnetic funnels have been predicted by magnetospheric accretion model (e.g., Shu et al. 1997) and have been shown to occur in up-to-date

MHD simulations of disk-star system (e.g., Long et al. 2007), but it is only thanks to the *COUP* and *DROXO* long continuous observations that we have gained some observational evidence of their existence.

Returning for a moment to the ”standard” flares, the detection of non-thermal hard X-rays during intense flares is discussed in this volume by Maggio (2007) and Argiroffi et al. (2007), to which I defer the interested readers.

4. The origin of the emission of Fe 6.4 keV K_α fluorescent line in YSOs

The first detection of a Fe 6.4 keV K_α fluorescent line emission in a YSO has been obtained with *Chandra* during an intense flare on YLW16A, a Class I YSO in the ρ Oph SFR (Imanishi et al. 2001). Thanks to COUP we have collected 134 Orion YSOs spectra of sufficient quality to allow investigating the spectra in vicinity of the Fe XXV 6.7 keV line looking for the presence of the Fe 6.4 keV K_α line. In 7 COUP sources the 6.4 keV line (cf. Fig 4) has been found (Tusijmoto et al. 2005) and the emission has been interpreted, following original suggestion of Imanishi et al. (2001), as originating from the circumstellar neutral disk matter illuminated by the X-ray emitted from the PMS star during the intense flares observed in all seven cases. A Fe 6.4 keV fluorescent line has also been seen during a relatively short XMM-Newton observation of the Class II YSO Elias 29 without any evidence of concurrent flare emission (Favata et al. 2005b). None or very limited time resolved spectroscopy has been possible due either to the *XMM-Newton* too short observation or the *Chandra* limited collecting area. Recently Czesla & Schimtt 2007 have reported time-resolved spectroscopy of V1489 Ori, one of the 7 COUP sources with the Fe 6.4 keV K_α line, showing that this line appears predominantly in the 20 ks rise phase of a flare. Their preliminary calculation suggests that the photo-ionization alone cannot account for the observed intensity of the Fe K_α line.

Thanks to *DROXO*, a XMM-Newton large program aiming to study the properties of X-ray emission of the 1 Myr old ρ Oph YSOs, it has been possible to perform, for the first time, a time-resolved study of the Fe 6.4 keV fluorescent line emission of Elias 29 (Giardino et al. 2007b). The line intensity is highly variable. It is absent at the beginning of observation, then after a quite typical flare (a factor 8 in intensity with a 6 ksec decay time) it appears with a conspicuous equivalent width, EW ~ 250 eV. Subsequentely it continues to be present with EW ~ 150 eV for the remaining 300 ksec (i.e. for 4 days!) of the observation. Apart for the flare, the, relatively soft, X-ray spectra of Elias 29 remains essentially unchanged across the entire observation, with no obvious hardening of the spectrum during the last 300 ksec of

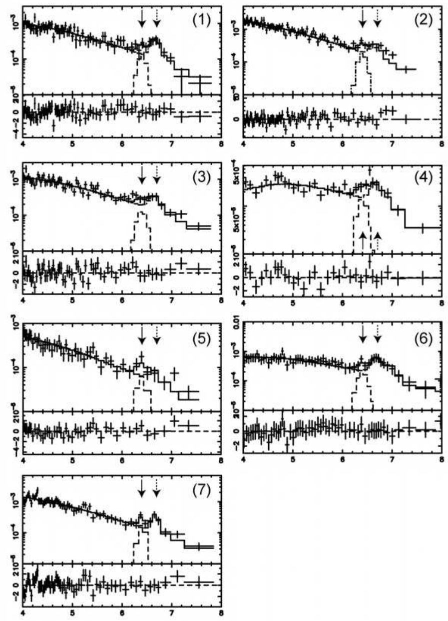

Fig. 4. (Upper panels) Observed spectra (pluses) and best-fit models (solid steps) of the 7 COUP YSOs showing the Fe fluorescent 6.4 keV line. The Fe 6.4 keV line Gaussian component is shown by dashed steps. The 6.4 and 6.7 keV lines are indicated by solid and broken arrows, respectively. Photon energy in keV is on the abscissa, while the ordinate is the spectral intensity as counts s^{-1} keV^{-1}. (Lower panels) Residual to the fit in unit of χ values (adapted from Tusijmoto et al. 2005).

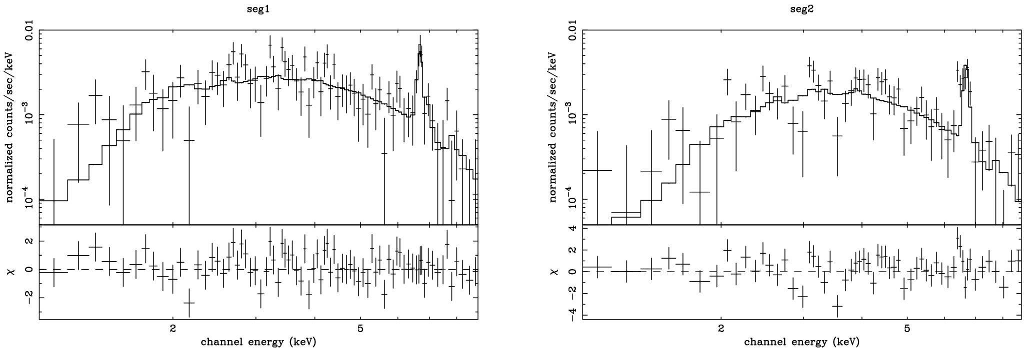

Fig. 5. Spectra and spectral fit to the *DROXO* data of Elias 29 before the flare (left) and after the flare (right). The spectra are very similar in overall shape, intensity, and resulting best fit model parameters. After the flare, however, a significant excess of emission at 6.4 keV is present which is not visible in the data before the flare (adapted from Giardino et al. 2007b).

observation. This behavior clearly challenges the "standard" interpretation of the fluorescent emission as due to photo-ionizing X-ray photons (requiring an adequate flux of photons with E > 7.1 keV) and suggests an alternative scenario in which the line is collisionally excited by beams of electrons due to reconnections of magnetic field lines occurring in the accretion funnels connecting the accreting pre-main-sequence star with its circumstellar disk. The required energy can be released by magnetic fields stressed near the corotation radius as a result of the radial gradient of rotational speed.

A deep Symbol-X observation will offer a unique opportunity to test this alternative scenario since the presence of non-thermal electrons should be detectable through their bremsstrahlung radiation in the hard (Simbol-X) X-ray bandpass (while being invisible in the XMM observation). This is shown by the detailed simulations presented in this same volume by Micela et al. (2007).

5. The quiescent hard X-ray emission of YSOs

Another issue that could be explored with Simbol-X is the quiescent hard X-ray emission of YSOs and its origin and nature.

To set the framework let me remember that i) the analysis of the COUP light-curves of the

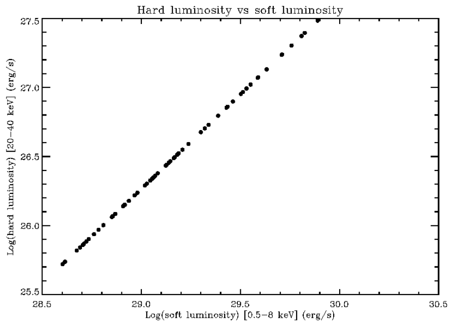

Fig. 6. Predicted Hard (20-40 keV) vs. Soft (0.2-8.0 keV) X-ray luminosities for the putative YSOs similar to those found in ONC but at the typical distance (~ 150 pc) of a nearby star forming region. The predicted hard X-ray emission allows the detection of those YSOs with Simbol-X.

Orion Nebula Cluster (ONC) low mass YSOs has shown that their entire X-ray emission can be explained as due to continuous flaring with flare intensities following a power law distribution characterized by a unique power law index (Caramazza et al. 2007) and ii) a recent analysis of both solar (RHESSI archive data) and few stellar flares has allowed to derive a scaling law relation between soft thermal and hard non-thermal X-ray emission (Isola et al. 2007a). This relation holds over several dexs (see the figures in Isola et al. (2007b) in this volume).

Combining these two empirical evidences we can predict the expected non-thermal hard X-ray flux as a function of the soft X-ray flux for YSOs like those studied in ONC by Caramazza et al. (2007): with a long Simbol-X observation (300-500 ksec) it would be possible to detect the hard X-ray emission due to the source continuous flaring. Assuming that similar sources will be hosted in nearby, ~ 150 pc away, SFRs we can predict their expected hard X-ray luminosity (cf. Fig. 6). Since the vast majority of YSOs have soft X-ray luminosity in the 10^{29}-10^{30} erg/s range (or even higher) we expect that these putative sources would be detectable with the foreseen Simbol-X performances.

6. Conclusions

Long look observations of few selected SFRs with Simbol-X will offer the unique opportunity to find whether Class 0 YSOs, ie. the very young (10^4 yr, still accreting) protostars, actually emit X-rays. Their emission, if present at a level comparable to those of older Class I-III YSOs, could have a significant impact on star formation and early evolution, and may be also on the earliest stages of planetary formation (e.g. large grains, planetesimals). These observations will also allow us to study the origin of the quiescent (if any) hard X-ray emission of YSOs. Finally, Symbol-X will open the possibility to study the MHD acceleration process in X-ray luminous YSOs that will offer a new, nearby, laboratory for the study of other magnetic/shock related processes.

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References

Argiroffi, C., Micela, G., Maggio, A. 2007, Mem. Sait, in this volume
Caramazza, M., Flaccomio, E., Micela, G., Reale, F., Wolk, S. J., Feigelson, E. D. 2007, A&A, 471, 645
Czesla, S., Schmitt, J. H. H. M. 2007, A&A, 470, L13
Favata, F., Flaccomio, E., Reale, F., Micela, G., Sciortino, S., et al., 2005a, ApJS, 160, 469
Favata, F., Micela, G., Silva, B., Sciortino, S., Tsujimoto, M. 2005b, A&A, 433, 104
Flaccomio, E., Stelzer, B., Pillitteri, I., Micela, G., Reale, F., Sciortino, S. 2007, in Proc. of the "Cool Stars 14-th", (L. Rebull & J. Stauffer, eds.), in press.
Giardino, G., Favata, F., Micela, G., Sciortino, S., Wiston, E. 2007a, A&A, 463, 275
Giardino, G., Favata, F., Pillitteri, I., Flaccomio, E., Micela, G., & Sciortino, S. 2007b, A&A, in press
Grosso, N., Feigelson, E. D., Getman, K. V., et al. 2005, ApJS, 160, 530
Getman, K. V., Flaccomio, E., Broos, P. S., et al. 2005, ApJS, 160, 319
Güedel, M.,Briggs, K. R., Arzner, K., et al. 2007, A&A, 468, 353
Imanishi, K., Koyama, K., Tsuboi, Y. 2001, ApJ, 557, 747
Isola, C., Favata, F., Micela, G., Hudson, H. 2007, A&A, 472, 261
Isola, C., Favata, F., Micela, G., Hudson, H. 2007, Mem. Sait, in this volume
Long, M., Romanova, M. M., & Lovelace, R. V. E. 2007, MNRAS, 374, 436
Lorenzani, A., Palla, F., Feigelson, E.D., Grosso, N. 2007, in preparation
Maggio, A. 2007, Mem.Sait, in this volume
Micela, G., Favata, F., Giardino, G., Sciortino, S. 2007, Mem.Sait, in this volume
Reale, F. 2007, A&A, 471, 271
Reale, F., Bocchino, F., Peres, G. 2002, A&A, 383, 952
Sciortino, S., Pillitteri, I., Damiani, F., et al. 2006, in Proc. of the "The X-ray Universe 2005", A. Wilson, (ed), ESA SP-604, 111
Shu, F. H., Shang, H., Glassgold, A. E., Lee, T. 1997, Science, 277, 1475
Tsuijmoto, M., Feigelson, E. D., Grosso, N., et al. 2005, ApJS, 160, 503