Results and Perspectives of Young Stellar Object long look programs

S. Sciortino\textsuperscript{1,*}

INAF-Osservatorio Astronomico di Palermo Giuseppe S. Vaiana, Piazza del Parlamento 1, 90134 Palermo, Italy

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Both Chandra and XMM-Newton have performed long look programs for studying the YSO physics. I will discuss recent results on the controversial issue of Class 0 YSO X-ray emission, the observational evidence of magnetic funnels interconnecting the YSO with its circumstellar disk and the Fe 6.4 keV fluorescent line emission and its origin. While recent results of the XMM-Newton DROXO program challenge the "standard" interpretation of the Fe 6.4 line origin as due to photoionized fluorescing disk material, the discovery of X-ray excited Ne 12.81 \( \mu \)m line is a clear evidence of the interaction between X-rays and disk material. Future long look observations with XMM-Newton are required to clarify the X-ray effects on YSO disk.

\textsuperscript{1} Corresponding author: e-mail: sciorti@astropa.inaf.it

1 Introduction

X-ray emission likely traces, and is related to, magnetic fields at work in the interaction region between the central Young Stellar Object (YSO) and its surrounding disk. Because of their role, X-rays have started to be recognized as an important element for understanding star formation and early evolution. Since the launch of Chandra and XMM-Newton X-ray emission from YSOs has been the subject of many studies focussed on nearby Star Forming Regions (SRFs), among those are notable few selected long look programs. So far two of these programs have been performed with Chandra: i) COUP (Chandra Orion Ultradeep Project, PI: E. Feigelson, cf. Getman et al. 2005), a 850 ks long continuous observation of the Orion Nebula Cluster region which has allowed us to study the X-ray properties of known Orion YSOs as well as to discover and characterize the Orion YSO embedded population, and ii) a 450 ks long observation of the young cluster N 1893 in the external side of the Galaxy. This latter program, led by G. Micela, aims to study the IMF in the external region of the Galaxy where the environmental conditions are different than in the vicinity of the Sun. I will not discuss anymore this latter program since I will concentrate on the role of X-rays on YSO physics and evolution. In this specific realm only one long look program, led by myself, has been performed with XMM-Newton, it is nicknamed DROXO (Deep Rho Ophiuchi XMM-Newton Observation). It consists of a 500 ks long continuous observation of the \( \rho \) Oph core F region (Sciortino et al. 2006).

Thanks to XMM-Newton high throughput the DROXO time resolved spectroscopy is allowing us to study the X-ray emission of the 1 Myr old \( \rho \) Oph YSOs and its impact on YSO physics.

Another extensive program devoted to the study of YSO physics is XEST (XMM-Newton Extended Survey of Taurus, G"{u}del et al. 2007) that has adopted an observational strategy different from a long look one. The program and its results are presented in this volume by M. G"{u}del.

In the current scenario of Class I-II YSOs (Hartmann 1998) magnetically funneled accretion streams connect the central star with its circumstellar disk. In such a system X-rays could be emitted by the PMS star corona, by the funnel plasma that is shocked as it accretes on the star, by the fluorescing disk material or by gas shocked in a jet. Some of the recent observations, with crucial contributions from COUP and XEST, have shown evidence that all the above contributions can indeed be present. However from an observational point of view, we need a stronger and more compelling evidence, i.e. to find a way to distinguish, recover and study the properties of those distinct contributions. On more general ground X-rays are likely to be crucial to understand the chemistry and evolution of proto-planetary disks. In the following I will briefly discuss some of the current open issues on YSO physics.

2 X-rays from Class 0 YSOs

After many years of search, the occurrence of X-ray emission from Class 0 YSOs is still controversial. Either this emission is weak or rare or it is hidden due to the conspicuous amount of intervening absorbing material. In fact, while X-rays are quite penetrating – indeed the absorption at 2 keV and at 2 \( \mu \)m are similar (Reyter 1996)– Class 0 sources can be subject to extinction up to hundreds of magnitudes 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, i.e. by constructing a virtual \( \sim 600 \text{ ks} \) long observation, the Class 0 intrinsic X-ray luminosity has resulted to be lower than \( 4 \times 10^{29} \text{ erg/s} \) (assuming emission from an optically thin isothermal plasma with \( kT = 2.3 \text{ keV} \) seen through an absorbing column with \( N_H = 4 \times 10^{23} \text{ cm}^{-2} \)). However the best upper limit so far obtained is still a dex higher than the X-ray luminosity of active Sun. Future deep observations are needed to really advance our knowledge on this subject that could affect our understanding of star formation process. In fact with COUP we have discovered a deeply embedded population in Orion (Grosso et al. 2005), that has been shown to locally dominate the ionization level within the given molecular cloud core (cf. Lorenzani et al. 2007, and Fig. 2). Still, as of today, we do not know when intense X-ray emission from YSOs really develops likely affecting –for example by determining the effectiveness of ambipolar diffusion – the further evolution of star formation process. 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

X-ray flares are a classic tool to derive physical parameters of an emitting region (cf. Reale 2007). In fact the use of dynamical information (decay time, etc.) allows deriving physical characteristics of the flaring region. 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 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 \( 10^4 \)), both in absolute terms and with respect to the star bolometric luminosity. In most cases the observed YSO flares fall in the same category, but there are a few notable exceptions: in about 10 COUP (Favata et al. 2005a) and 2 DROXO (Flaccomio et al. 2007a) flares, the analysis results in a size of the flaring region a 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. These long structures have never been seen in more evolved normal stars. Such long structures, if anchored on the stellar surface, will suffer severe stability problem due to the centrifugal force – 1-2 Myr YOSs are fast rotators (\( P_{rot} = 1-8 \text{ days} \)) with a disk corotation radius of about 1-10 stellar radius – hence they would be ripped open. A possible alternative scenario is one in which the loop connects the star with the disk at the corotation radius. This is compatible with the currently available observational evidence. Such magnetic funnels have been predicted by magnetospheric accretion models (e.g., Shu et al. 1997) and have been shown to occur in up-to-date MHD simulations of disk-star system (eg., Long et al. 2007), but it is only thanks to the COUP and DROXO long look observations that we have gained some observational evidences of their existence.
4 The Fe 6.4 keV fluorescent line emission of YSOs

The first detection of the Fe 6.4 keV fluorescent line in a YSO has been obtained with Chandra during an intense flare on YLW16A, a Class I YSO in the Oph SFR (Imanishi et al. 2001). Thanks to COUP we have collected 134 Orion YSO good quality spectra that allows investigating the presence of the ∼6.4 keV Fe Kα line. In 7 COUP sources the 6.4 keV line (cf. Fig. 3) has been found (Tusijmoto et al. 2005) and the emission has been interpreted, following original suggestion of Imanishi et al. (2001), as due to the circumstellar neutral disk matter illuminated by the X-rays emitted from the PMS star during the intense flares observed in all those seven sources. 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). In all the above reports 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. Very recently Czesla & Schmitt (2007) have reported the results of time-resolved spectroscopy of V1489 Ori, one of the 7 COUP sources with the Fe 6.4 eV line, showing that the Kα line appears predominantly during the 20 ks rise phase of a flare. Their initial calculation suggests that the photo-ionization alone cannot account for the observed intensity of the Fe Kα line.

Thanks to DROXO it has been possible to perform, for the first time, a detailed 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 (cf. Fig. 4). Subsequently 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 observation. This behavior clearly challenges the ”standard” interpretation of the fluorescent emission being due to photo-ionizing X-ray photons (requiring an adequate flux of photons with E > 7.1 keV, that in this case seems to lack) 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. The required energy can be released by magnetic fields stressed near the corotation radius as a result of the radial gradient of rotational speed.

Further long look continuous observations will permit us to verify if the phenomenon we have discovered in Elias 29 is present/common in other YSOs. Based on further DROXO results as well as on a recent time-resolved spectral analysis of the COUP data (Flaccomio 2007) I have not the space to discuss here, I am convinced that the YSO emission of the 6.4 keV fluorescent line is a more complex phenomena that originally though and I am expecting soon further developments on this matter. On a somewhat longer time scale the next generation of imaging X-ray observatories (Simbol-X, XEUS, etc.) covering the bandpass up to ∼60 keV will allow us to directly probe the existence of a population of non-thermal electrons that is a key ingredient of the interpretational scenario proposed by Giardino and collaborators (2007b).

Let me conclude by adding another piece of (controversial ?) evidence. The existence of an X-ray excited Ne 12.81 µm IR line has been predicted (Glassgold et al. 2007) and its detection has been reported in 4 YSOs (Pascucci et al. 2007). Using Spitzer archive spectra this line has been detected also in 4 ρ Oph YSOs observed in X-rays, for 3 of which we have DROXO EPIC spectra (Flaccomio et al. 2007b). The X-ray brightest of them shows also the 6.4 keV Fe fluorescent line. Fig. 5 shows a summary of the Pascucci et al. (2007) and of the new ρ Oph data together with the model prediction. The ρ Oph Ne IR luminosities are more than one dex higher than those of the somewhat older YSOs studied by Pascucci et al (2007). As of today we have no explanation to offer for this fact except to note the different age between the two groups of YSOs.
Fig. 4  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).

Fig. 5  Scatter plot of 12.81 µm IR line vs. X-ray luminosity of ρ Oph YSOs. The data point from Pascucci et al. (2007) and the model prediction of Glassgold et al. (2007) are also shown.

5 Summary and Perspectives

There is growing evidence of interactions between X-rays and YSO circumstellar disks: big flares and the inferred long magnetic structures, the Fe 6.4 keV fluorescent line, the X-ray excited Ne 12.81 µm line, etc..

Our understanding of the formation mechanism(s) of Fe 6.4 keV line is still limited and controversial. DROXO time-resolved spectroscopy of the Fe line challenges the standard Fe 6.4 keV formation scenario involving a direct interaction between the X-rays and disk material, but at the same time the detection of Ne (IR) line requires such an interaction.

More long look observations and time-resolved spectroscopy are needed; 2-3 such XMM-Newton programs on nearby SFRs of, at least, 0.5 Msec each will serve this scope.

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References

Czesla, S., Schmitt, J. H. H. M.: 2007, A&A 470, L13
Favata, F., Flaccomio, E., Reale, F., Micela, G., Sciortino, et al. 2005a, ApJS 160, 469
Favata, F., Micela, G., Silva, B., Sciortino, S., Tsujimoto, M.: 2005b, A&A 433, 104
Flaccomio, E.: 2007, private communication
Flaccomio, E., Stelzer, B., Pillitteri, I., Micela, G., Reale, F., Sciortino, S.: 2007a, in Proc. of the ”Cool Stars 14-th”, (L. Rebull & J. Stauffer, eds.), in press.
Flaccomio, E., Stelzer, B., Pillitteri, I., Micela, G., Reale, F., Sciortino, S.: 2007b, in Proc. of the ”Star-disk interactions in young stars (IAU Symposium 243)”, (J. Bouvier & I. Appenzeller, eds.), in press
Getman, K. V., Flaccomio, E., Broos, P. S. et al.: 2005, ApJS 160, 319
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
Glassgold, A. E., Najita, J. R., Igea, J.: 2007, ApJ 656, 515
Grosso, N., Feigelson, E. D.; Getman, K. V., et al.: 2005, ApJS 160, 530
Güdel, M., Briggs, K. R., Arzner, K., et al.: 2007, A&A 468, 353
Hartmann, L.: 1998, in ”Accretion processes in star formation”, Cambridge University Press, ISBN 0521435072.
Imanishi, K., Koyama, K., Tsuboi, Y.: 2001, ApJ 557, 747
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
Pascucci, I., Hollenbach, D., Najita, J., et al.: 2007, ApJ 663, 383
Reale, F.: 2007, A&A 471, 271
Reale, F., Bocchino, F., Peres, G.: 2002, A&A 383, 952
Reyter, Ch. E.: 1996, Astrophysics and Space Science, 236, 285
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
Tsujimoto, M., Feigelson, E. D., Grosso, N. et al.: 2005, ApJS 160, 503