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X-ray Observations of Star Formation Regions: EPIC results in L1551 and Upper Sco-Cen

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Abstract. The formation and early evolution of stellar and planetary systems is one of the present frontiers of astronomy. Results obtained in the last decade have shown that the stellar formation process contrarily to previous thoughts is not a "cool" process, but instead one where at some stage high-temperature plasma emitting X-rays is present. As a results X-rays are a powerful tracers of star forming activity, and growing evidence is accumulating that they are a crucial ingredient for understanding the complex star formation related phenomena. After briefly sketching our current view of X-ray emission from pre-main sequence stars, we will discuss some recent results obtained with XMM-Newton in the L1551 and Upper Sco-Cen star forming regions.

Key words. stars: formation – stars: pre-main sequence – stars: X-rays – open clusters and associations: individual: Upper Sco-Cen – star forming regions: individual: L1551

1. Introduction

Since the '80s the *Einstein* X-ray observations have shown that young pre-main sequence (PMS) stars are intense X-ray emitters with luminosities up to 4 dex higher than the Sun and evidence of strong X-ray variability; a review of these early results can be found in Vaiana & Sciortino (1987). The ubiquitousness and the level of the X-ray emission posed, since those early days, the question of its origin. However it is only in the last decade, first thanks to ROSAT, and now thanks to *Chandra* and *XMM-Newton* that X-ray studies of star forming regions have gained a vigorous impetus and our understanding of origin and effects of X-ray emission in pre-main sequence stars is making substantial progress. Since X-rays are a crucial ingredient of PMS evolution, today X-ray observations are not only crucial to investigate the origin of X-ray emission from PMS stars, but also an essential tool to investigate the complex physics at work in star forming regions.

In brief, there are several reasons why X-rays are so relevant for these investigations, namely: they i) peer deep into dense cores of past or ongoing star formation; ii) trace hot plasma either due to magnetic or accretion phenomena and help in discriminating among those two production mechanisms; iii) are a key way (together with infrared observations)

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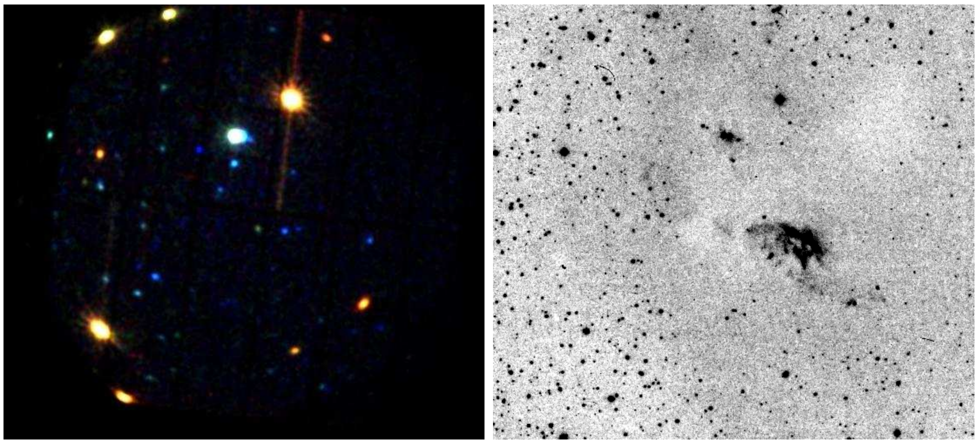

Fig. 1. Left: summed EPIC pn+MOSs image of the L1551 region, color-coded to indicate the energy of the X-ray photons. Right: the same region in the red Palomar plates. The outflow from the IRS5 embedded protostar is the bright nebulosity near the center of the latter image.

to derive as complete as possible a census of PMS population in various star-forming regions (SFRs), e.g. in different physical conditions, such as in high-mass vs. low-mass formation regions; iv) likely are an important ingredient for the large-scale evolution of giant molecular clouds; v) could have a non-negligible role in the formation and evolution of stellar and planetary system, and in evolution of atmospheres of habitable – earth-like – planets.

Let us recall that star formation is quite a rapid process, in just few million years a protostar evolves from the early in-falling protostar (known also as Class 0) phase, to the evolved protostar with a thick disk (or Class I) phase, to the classical T Tauri star (or Class II phase), to the weak-lined T Tauri star characterized by a thin disk (or Class III phase). As today we have conclusive evidence that X-ray emission is present as early as in Class I objects, while the evidence of X-ray emission from Class 0 objects is still controversial. Even the details of the X-ray emission mechanism are unclear: for the weak-lined PMS stars, a stage where the disk should not play any longer a prominent role, the X-ray emission mechanism is supposed to be similar, but scaled up, to the one at work in other, older, active stars; in the class I and II PMS stars, where signatures of a relatively massive disks are seen in the optical, UV and IR, as well as signatures of ongoing accretion, the possible role of accretion in determining the X-ray luminosity (either enhancing or inhibiting it) is still an open issue.

The new very deep observations with *Chandra* and *XMM-Newton* are allowing us to investigate many of the above open issues.

A more detailed discussion of the above points can be found in a recent review on the topic of X-ray emission and star formation by Feigelson & Montmerle (1999); however, the field is growing very vigorously and the interested reader is urged to follow the recent developments and results based on the new *Chandra* and *XMM-Newton* observations (a non exhaustive list includes Getman et al. 2002; Feigelson et al. 2002a,b, 2003; Flaccomio et al. 2003a,b,c,d; Preibisch 2003a,b; Preibisch & Zinnecker 2002; Preibisch, Stanke & Zinnecker 2003).

In the following we will present and discuss new exciting findings from *XMM-Newton* observations taken as part of the Guarantee Time (GTO) programme.

2. The L1551 Star Forming Region

L1551 is a nearby ($d \sim 140$ pc; Kenyon et al. 1994) SFR, that in the recent years has been

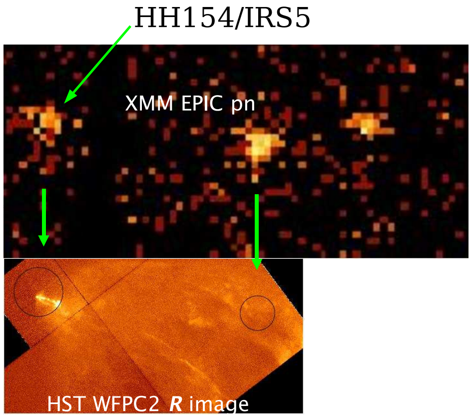

Fig. 2. The region of L1551 IRS5 seen in X-rays with the *XMM-Newton* pn EPIC camera (top), compared with (part of) the same region seen in a 1800 s R-band CCD image obtained with the Hubble Space Telescope WFPC2 camera. The vertical arrows indicates the position of the X-ray sources in the HST FOV. The X-ray sources associated with HH 154/IRS5 is also indicated.

extensively studied (cf. Favata et al. 2003 and reference therein) and whose PMS population has been well characterized. As a results we know that the L1551 cloud hosts most of the phenomena related to low-mass star formation, including highly embedded sources (such as IRS5), CTTSs, WTTSs, and proto-stellar outflows, including a number of Herbig-Haro objects (shocked, ionized regions in the outflows).

As part of the *XMM-Newton* GTO program, L1551 has been observed with EPIC for ∼ 57 ksec starting on Sep. 9 2000 at 19:10 UT. All three EPIC cameras were active at the time of the observation, in full-frame mode, with the medium filters. The background level during the observation shows only two strong enhancement (removed following the approach of Sciortino et al. 2001) whose removal leave a clean data set of 250 kcnt collected in ∼ 50 ksec. The cleaned MOS and PN data have been summed (cf. Fig. 1) and searched for sources with a Wavelet Transform Detection algorithm, developed at the Osservatorio Astronomico di Palermo by F. Damiani and collaborators, resulting in the detection of 81 X-ray sources (Favata et al. 2003), including IRS5/HH154 and XZ Tau (discussed below). Based on their X-ray colors 13 of the bright sources are likely to be of extragalactic nature; their number is in good agreement with expectation based on known $\log N$-$\log S$ (Hasinger et al. 2001).

The analysis of the XMM-Newton observation has allowed us to detect (Favata et al. 2002) for the first time X-ray emission associated with the protostellar jet (HH 154) emanating from the L1551 IRS5 protostar (cf. Fig. 2). The pn count rate is 0.8 cnt/ksec, and given the length of the observation, it has been possible to accumulated a weak, yet usable, X-ray spectrum (cf. Fig. 3) whose analysis has shown that the spectrum can be represented by a single temperature absorbed thermal model with $T \sim 4 \times 10^6$ K, and N_H corresponding to an obscuration of 7 magnitudes. The derived emission measure of emitting plasma is 10^{52}cm^{-3}, and the derived L_X is 3×10^{29} erg/sec.

X-ray emission from Herbig-Haro (HH) objects has so far been reported in just two cases, HH 154 itself and HH 2 (Bally et al. 2003), so at present we do not know if it is a common feature of HH objects or instead occurs in some of them under some very specific circumstances. It is important to point out that where this X-ray emission is present, it has an intensity, $L_X \sim 10^{29}$-10^{30} erg/sec, comparable

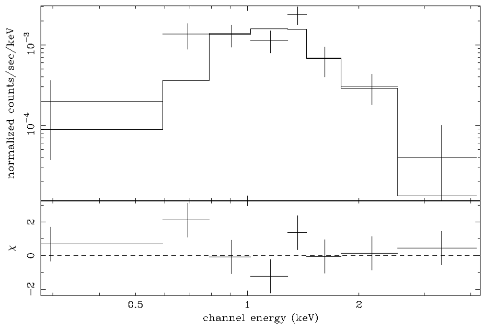

Fig. 3. The background-subtracted EPIC pn X-ray spectrum of the X-ray source associated with the L1551 IRS5 jet. The solid continuous line shows the best-fit single temperature ("MEKAL") spectrum.

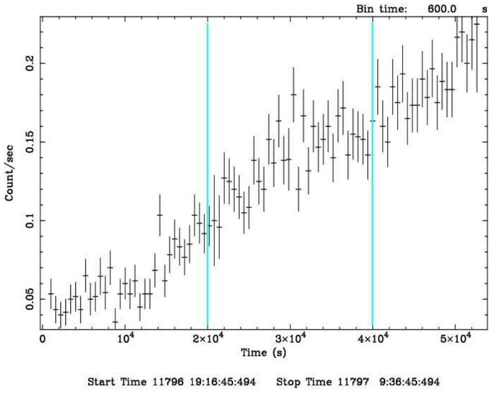

Fig. 4. The EPIC pn X-ray light curve of XZ Tau. The vertical lines mark the three time-segments in which distinct X-ray spectra have been accumulated and analyzed. The resulting best fit N_H values are 1.06 ± 0.06, 0.49 ± 0.11 and 0.26 ± 0.02 ($\times 10^{22}$cm^2), from the highest to the lowest rate bins.

to the intrinsic emission from PMS stars. Given that it illuminates the circumstellar disk under a much more favorable view angle than the emission coming from putative coronal loops anchored to the surface of PMS star, it is very likely that the X-ray emission from HH objects strongly affects the ionization of matter in the disk, hence the overall viscosity of disk itself. This X-ray emission should therefore influence disk evolution and likely the formation of planets. Clearly further observations are required to investigate the frequency of X-ray emission from HH objects in order to evaluate its relevance in the scenario just depicted.

The EPIC survey of the L1551 star forming regions has allowed us to investigate the properties of the X-ray spectra of several L1551 members, both in the WTTS (Class III) and CTTS (Class I/II) phases. The spectra of the two samples show quite distinct characteristics with the CTTSs having a narrow range of metallicities clustering at $Z/Z_\odot \sim 0.2$ and an anomalous high value of Ne abundance, while the WTTSs shown a large spread of Z and have normal Ne abundance. Such a difference is in agreement with other differences discovered by comparing CTTS and WTTS stars in other star forming regions (cf. Flaccomio et al. 2003c,d and reference therein cited) and strongly indicates an intrinsic physical difference in the X-ray emission mechanisms at work in CTTS and WTTS pre-main sequence stars. A further indication comes from the time-resolved EPIC spectroscopy of XZ Tau, a M3 CTTS in L1551, that shows a long-term variability (cf. Fig. 4) characterized by a distinct anti-correlation between the X-ray emission level and the N_H value (as deduced from fits to EPIC spectra). If one considers that XZ Tau is known to possess a large photometric hot spot, the latter X-ray finding can be explained in terms of shadowing from the stream of spatially concentrated accreting material flowing along magnetic field lines, ending in the hot photosphere accretion spot. The observed variation of X-ray luminosity in such a scenario would be simply explained as an effect of the stellar rotation (Favata et al. 2003). In order to test such an interpretation additional X-ray observations with EPIC, taken at proper times, have been approved, and are already scheduled for March 2004.

3. Upper Sco-Cen

Upper Sco-Cen is the nearest OB association (145 pc), with an age of about 5 Myr. Notwithstanding being very young, the measured absorption is modest, $A_V < 2$, likely because a supernova explosion has swiped out the cloud material, so that the star formation process has stopped. Because of the above characteristics it is a very convenient place to study the Initial Mass Function (IMF). Previous studies have shown that low-mass and B members have the same age (Preibisch & Zinnecker 1999; Preibisch et al. 2001) with the low mass members being well known intense X-ray emitters (Walter et al. 1994). This association has been the target of a ROSAT All-Sky Survey study and of follow-up optical studies that has allowed to select members with $\log L_X > 30$ (Preibisch et al. 1998), a deeper ROSAT PSPC and HRI pointed X-ray survey has allowed selecting low-mass members down to M type (Sciortino et al. 1998).

Here we present some initial results based on one of two EPIC observations toward Upper

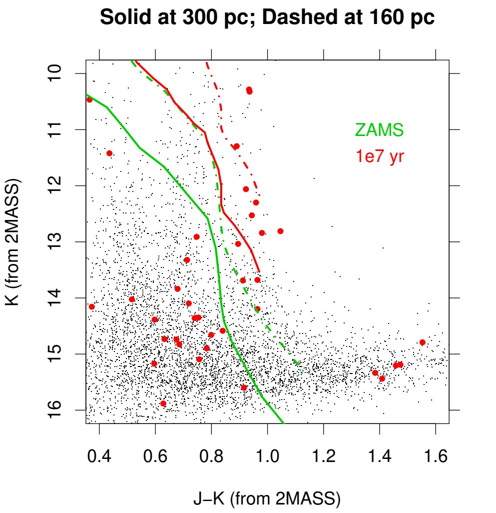

Fig. 5. K vs. $J - K$ color-magnitude diagram for the 2MASS stars falling in the FOV of the XMM observation of the Upper Sco-Cen region. The lines indicate the position of the Zero Age Main Sequence (ZAMS) and of the 10 Myr isochrones for two adopted distances of 160 pc (dashed) and 300 pc (solid). Filled circles indicate the 56 2MASS counterparts to the X-ray sources (in a matching radius of 10 arcsec), 39 of them being unique.

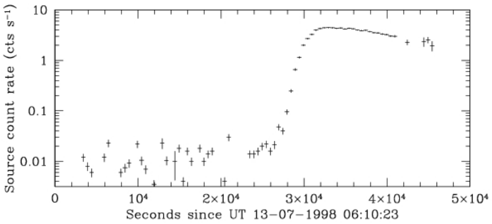

Fig. 6. EPIC-pn X-ray light curve of the large flare observed on the A2 star HD 142578 in Upper Sco-Cen.

Sco-Cen we have obtained and are analyzing. With a 45 ksec observation we have reached the limiting sensitivity log $L_X = 27.7$, detecting 98 X-ray sources, only 12 of which were previously known. In order to understand their nature we have looked for counterparts in the 2MASS survey finding, with a matching radius of 10 arcsec, 56 possible counterparts for 47 out of the 98 sources, with 39 of them unique. Based on the position on a color-magnitude diagram (cf. Fig. 5), about 15 of them are likely Upper Sco-Cen members.

During the EPIC observations we have found one source that shows a quite remarkable variation of its X-ray intensity (cf. Fig. 6). This source has been identified with the A2 Upper Sco-Cen member HD 142578. While this star is not known to be a binary, yet the kind of observed flare-like variability strongly suggests that the emission comes from an unseen low-mass companion. Given its age, if such a companion is a solar mass stars its radius at the age of Upper Sco-Cen should be $R = 3.5\,R_\odot$. The observed variability is such that the X-ray count rate increases by a factor 100 in 7 ksec, the X-ray luminosity, as deduced by detailed fit, increases by about 3 dex in the same time, while the decay phase is characterized by a decay time of 21 ksec. A detailed analysis with the Reale & Micela (1998) approach shows that sustained heating is present during the decay phase, and allow deriving that the flaring loop has a length of 1.7 $R_\odot$, i.e. about 0.5 stellar radii. Notwithstanding its somehow exceptional intensity, yet the flare occurs in a somehow compact region.

In light of other intense flares discovered in other young pre-main sequence stars one intriguing question is their frequency and if they can affect disk evolution. In this respect we have to remember that the recombination time for disk material is about 30 yr, hence emission from strong flare, even if occurring every few years, will dominate over 'quiescent' coronal emission and likely affect PMS accretion disk evolution.

In few cases we have collected enough counts to be able to perform spectral fits of Upper Sco-Cen members. The initial results indicate a patter similar to that found in the case of L1551 PMSs we have previously discussed.

4. Summary and Conclusions

The recent XMM-Newton (and Chandra) observation of star forming regions allow us to derive a series of on-going conclusions:

- A new class of X-ray sources associated with HH objects has been found. Their X-ray emission may have a non-negligible influence on disk evolution and planetary system formation.
- CTTS and WTTS spectra are different. This and other evidences (different L_X/L_{bol} and variability of CTTSs vs. WTTSs) point toward differences in the X-ray emission mechanism between these two classes of PMS stars. Accretion may play a role in the CTTS stars (e.g. XZ Tau), and the determination of its relevance requires further investigations of properly planned data.
- Very strong flares, with L_X at peak 2–3 dex higher than quiescent emission, occur on PMS stars. Even if they are not very frequent their X-ray emission dominates over the 'quiescent' one and can affects disk evolution. More detailed model studies are required to better quantify this effect.

In the next coming years, more and more exciting results will come out from the EPIC (and *Chandra* ACIS) observations of star forming regions, … *stay tuned on this channel*…

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