AN *XMM-NEWTON* DEEP PENCIL BEAM SURVEY IN THE UPPER SCO-CEN STAR-FORMING REGION

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Abstract

As part of our long-term effort to characterize the low-mass stellar population of the Upper Sco-Cen association based on deep X-ray surveys and follow-up optical observations we present results from a pencil beam deep survey of about 0.4 sq. deg. in Upper Sco-Cen based on two *XMM-Newton* EPIC observations of 40–50 ksec each. One of the two EPIC images covers a fraction of the area previously studied by Sciortino et al. (1998) on the basis of *Einstein* and ROSAT observations. By jointly analyzing the EPIC data from the two MOS and the pn cameras with Pwdetect, the wavelet detection code developed at OAPA, we have found, down to a limiting sensitivity of 2×10^{-15} erg cm^{-2} s^{-1}, 94 sources in the same area where Sciortino et al. (1998) had previously reported 12 sources. Based on positional matching with public catalogs as well as on the available *BVRI* and 2MASS photometry, some of the new sources can be associated with very-low mass stars, likely members of Upper Sco-Cen. We present also examples of the light-curves and CCD-resolution spectra we have obtained.

Key words: Stars: pre-main sequence, Stars: coronae, X-rays: stars

1. Introduction

The identification of a complete sample of members is crucial in deriving an accurate estimate of the IMF of young clusters and associations whose possible variance across the various sites of current and recent star formation in the Galaxy is a powerful way to test the "universality" of star-formation process itself or its dependence on more "local" conditions.

One of the best place to study such a problem is Upper Sco-Cen, one the three moving groups of the nearest OB association Sco-OB2, with an age of 5 Myr, and moderate absorption ($A_V < 2$), where the star-formation process has likely been halted by a recent supernova explosion (cf. Preibisch & Zinnecker 1999). Its stellar population down to 3 $M_\odot$ has been recently investigated by de Zeuw et al (1999) on the basis of Hipparcos data, while Preibisch et al. (1998; 2001) have studied its late-type population down to $M/M_\odot \sim 0.5$–1 both by considering RASS-selected stars and by a multi-fiber spectroscopic survey of ~ 2 sq. deg. selected area.

However this latter sample (largely based on the RASS detected sources) suffers of the unavoidable bias of selecting mainly the very bright ($L_X > 10^{30}$ erg/sec) coronal emitters, i.e. those with mass of $\sim 1\,M_\odot$, missing a large fraction of low-mass stars having typically a 10–50 times lower coronal emission level. The shallow limiting flux of the RASS results in a physical bias because: 1) even in very young stars (mostly emitting close to the saturation level) in any given mass range the coronal emission shows a spread (likely due to coronal variability and different rotation rate) of about 1 dex (e.g. Flaccomio et al. 2000), 2) young active stars have saturated coronae, i.e. a maximum $\log L_X/L_{Bol} \sim -3$, hence low-mass, low L_{Bol} PMS stars have a less intense coronal emission. In order to overcome such a bias deeper X-ray surveys able to detect 10–100 times fainter coronal emitters (i.e. down to $L_X \sim 10^{28}$–10^{29}) are required and have motivated our approach of performing deeper X-ray surveys, in the past with ROSAT, and now with *XMM-Newton*. In the following we present initial result of the new *XMM-Newton* survey as well as of the shallow (waiting deeper ones now planned at ESO) photometric and spectroscopic follow-up observations.

2. *XMM-Newton* observations and data analysis

With the aim of detecting fainter, later-type Upper Sco-Cen members we observed, as part of the *XMM-Newton* GTO program, two distinct regions of Upper Sco-Cen with EPIC. Our survey covers an area of ~ 0.40 sq. deg. with exposure times ranging between 40 and 50 ksec. In this way we have reached a quite faint limiting flux (cf. Fig. 3) and have accumulated adequate quality medium-resolution X-ray spectra for the already known strong emitters. Here we report results from our ongoing analysis of one of the two observations.

Data have been processed by us with the standard SAS V5.2 pipeline system augmented by in-house developed software. In particular, in order to minimize the background due to non-X-ray events we have retained only counts with energy in the 0.3–7.9 keV bandpass and, as a final step, we have applied a technique developed at OAPA that maximizes the statistical significance of weak sources

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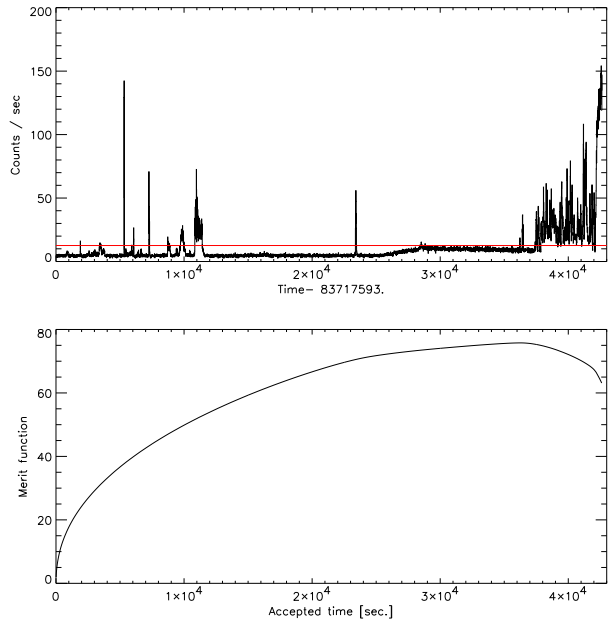

Figure 1. Top: Total EPIC-pn image rate in the 0.3–7.9 keV bandpass as a function of time from the beginning of the observation. The horizontal line marks the optical screening level. All data segments above the line have to be rejected in order to increase the attainable limiting sensitivity. Bottom: The behavior of the adopted merit function as a function of cumulative observing time. The merit function is based on the detectability of faint sources near the detection threshold.

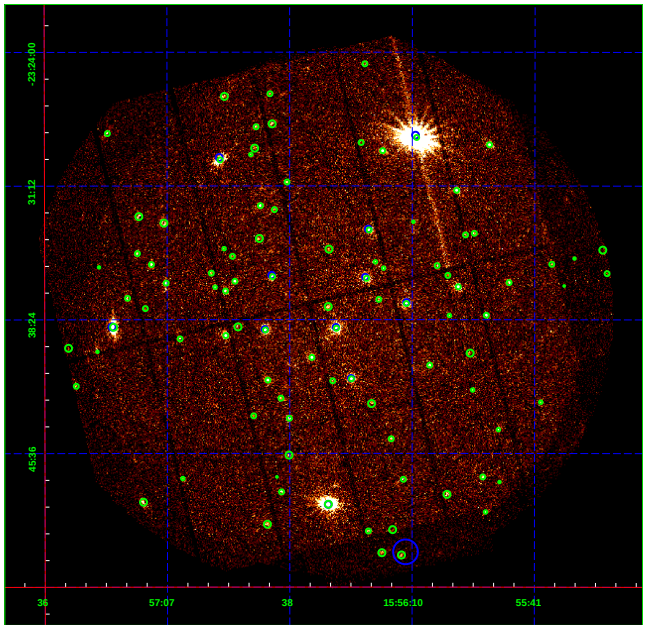

Figure 2. The summed MOS1, MOS2, and pn image in the 0.3–7.9 keV bandpass. The 94 distinct sources are indicated by green circles with radius equal to the scale of maximum source significance. The blue circles indicate the previously known X-ray sources in the region (Sciortino et al. 1998).

by identifying and removing fraction of the exposure time strongly affected by high-background episodes (cf. Fig. 2).

Source detection has been performed on the screened and summed pn and MOS data set with a *XMM-Newton* prototype version of the wavelet transforms detection code, Pwdetect, a multi-scale detection algorithm developed at Osservatorio Astronomico di Palermo. Source acceptance threshold has been chosen to have no more than 1 expected spurious detection per image and has been derived by running simulations of empty fields with the summed exposure map from the original data (including all the discontinuity features). Few obvious spurious sources, associated with trailing features in the vicinity of strong sources (the so called out-of-time features due to the CCD readout speed) have been removed from final list. With this procedure we have detected 94 distinct sources (cf. Fig. 2).

The distribution of X-ray fluxes and luminosities (for an Upper Sco-Cen distance of 160 pc) for the 94 sources are shown in Fig. 3. These distributions show that the *XMM-Newton* survey is one dex deeper than previous ROSAT-based ones and should allow the detection the late-type PMS association members.

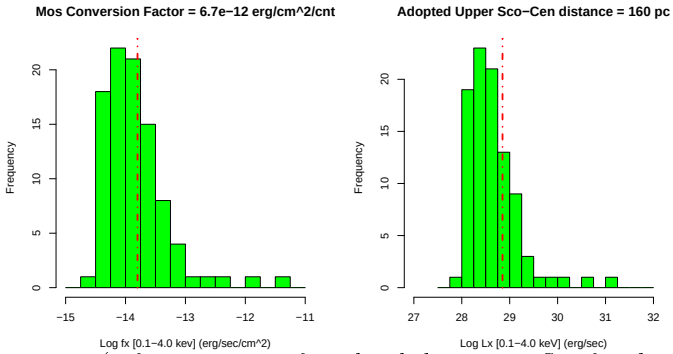

Figure 3. (Left: Histogram of unabsorbed intrinsic flux for the 94 X-ray sources; the vertical dashed red line marks the limiting sensitivity of the Sciortino et al. (1998) survey showing that the XMM-Newton *survey is one dex deeper. Right: Histogram of X-ray luminosity for an assumed distance of 160 pc. For reference the vertical dashed line marks the median X-ray luminosity of the Pleiades dM stars.*

3. Identifications

By positional matching against both optical and IR source catalogs and our own optical photometry of the region we have found possible counterparts for 37 out of the 94 X-ray sources. For 23 we have found a single counterparts, while for 14 sources we have found two or three possible counterparts in the error circle. A graphical summary of identifications based on our shallow photometry and 2MASS catalog is shown in Figs. 4 and 5. These plots show X-ray sources that have as likely unique counterparts low-mass

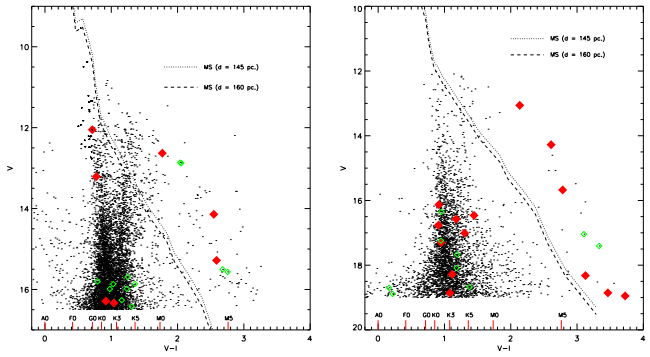

Figure 4. Left: V vs. $V-I$ diagram for the stars whose photometry was obtained at the Curtis Schmidt CTIO telescope. The lines indicate the position of the Zero Age Main Sequence (ZAMS) for two adopted distances. Stars above the ZAMS are possible members of the Upper Sco-Cen association with some contamination of foreground stars. Red filled symbols indicate unique counterparts of X-ray sources, green open ones multiple counterparts. Right: V vs. $V-I$ diagram for the stars whose photometry was obtained at the Danish 1.54 m telescope. The symbols have the same meaning as in the left panel.

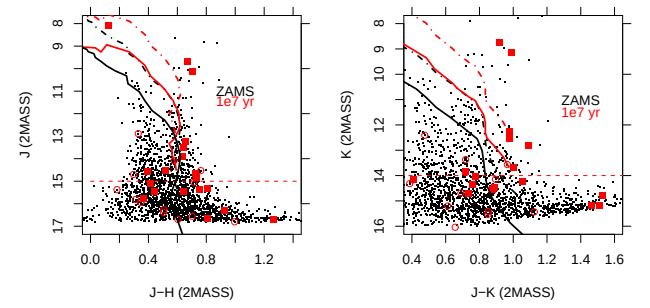

Figure 5. Left: J vs. $J-K$ for the 2MASS stars falling in the FOV of the XMM observation. The lines indicate the position of the Zero Age Main Sequence (ZAMS) and of the 10 Myr isocrones for the two adopted distances of 160 pc (dashed) and 300 pc (solid), as recently reported for some Upper Sco-Cen members (Makarov & Urban 2000). The horizontal line marks the value of J magnitude at which the uncertainty is about 0.05 mag. Filled squares indicated single 2MASS counterparts (by positional matching in a 10 arcsec identification circle), while open circles indicate multiple counterparts. Right: K vs. $J-K$ diagram as in the left panel. The horizontal line as in the left panel but for of K magnitudes. The symbols have the same meaning as in the left panel.

and very low-mass stars. For the X-ray sources without a catalog identification the inspection of the DSS-2 red plate has allowed to conclude that the majority of them have a possible faint counterpart ($V > 19$) but still well visible on the plates (i.e. with $V < 21$–22).

Taking advantage of the sensitivity map computed by PWdetect we have estimated the number of X-ray sources that can be explained by field objects. We have adopted the published shapes of the $\log N$–$\log S$ source distribution (Giacconi et al. 2001; Tozzi et al. 2001) and have assumed that source intrinsic spectra can be described with a power law with slope $\alpha = 1.5$. Given the patchy nature of absorption toward the imaged region, we have assumed that the minimum source hydrogen column density is $N_{\rm H} = 5 \times 10^{21}$ cm^{-2}. On this basis we predict that the number of (mostly extragalactic) field sources is at most ~ 45. Hence we conclude that a large number of the 94 detected sources have to be associated with likely Upper Sco-Cen late-type members.

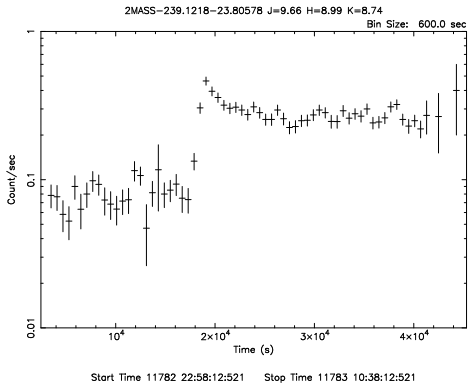

Figure 6. An example of X-ray variability in a source identified with a 2MASS star.

4. Light curves and spectra

Strong variability has been detected in some of the Upper Sco-Cen members; examples of X-ray light curves are shown in Figs. 6 and 7. This latter case is particularly intriguing since early A stars are not considered coronal X-ray sources. Most likely the flare takes place on an unseen (and unknow) low-mass companion. The ratio between the quiescent and the peak flare X-ray luminosity is more than 2 orders of magnitude, larger than previously observed in other PMS stars. We have studied this flare in detail and the results are summarized in graphical form in Fig. 8. Our analysis show that the flare long decay time ($\tau \sim 21$ ksec) is dominated by sustained heating.

It is worth to add a final caveat: while the general features of our analysis are clearly established, given the (yet) non-final nature of the calibration files we had available at the time of this writing, the detailed values of fitted parameters could slightly change once we adopt the final (or improved) calibrations.

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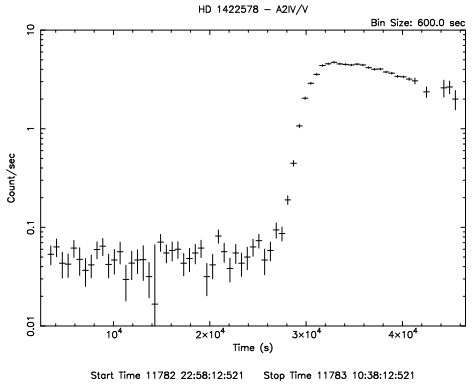

Figure 7. An intense X-ray flare (nominally) occurred on the A2IV/V pre-main sequence (PMS) star HD 142578 whose proper motion and distance are compatible with membership of the Upper Sco-Cen association.

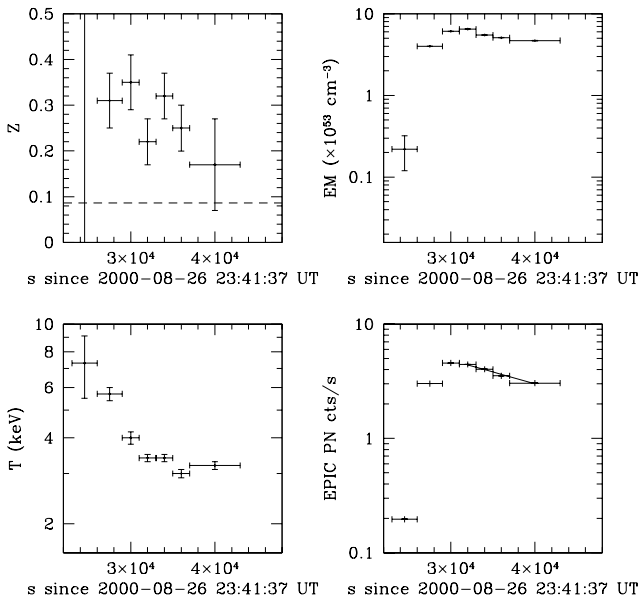

Figure 8. The time evolution of the spectral parameters of the flare observed on HD 142578, as determined by the fits of an absorbed MEKAL *model to the EPIC-pn spectra. The top-left panel shows the plasma metal abundance (with the horizontal dashed line representing the pre-flare value), the bottom-left one the plasma temperature, the top-right one the emission measure, and the bottom-right one the flare light curve.*

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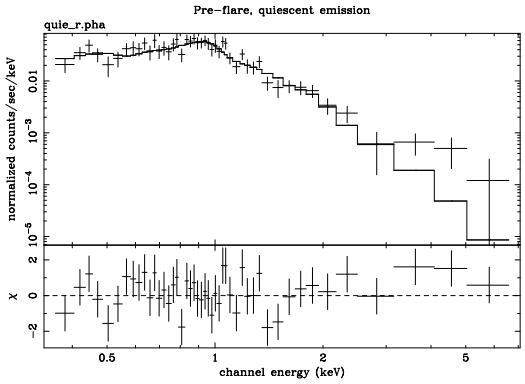

Figure 9. The EPIC-pn spectrum of the quiescent emission of HD 142578 and the best fit single temperature MEKAL *model with $kT = 0.8$ keV and $Z = 0.1\,Z_\odot$ (with a reduced $\chi^2 = 0.98$).*

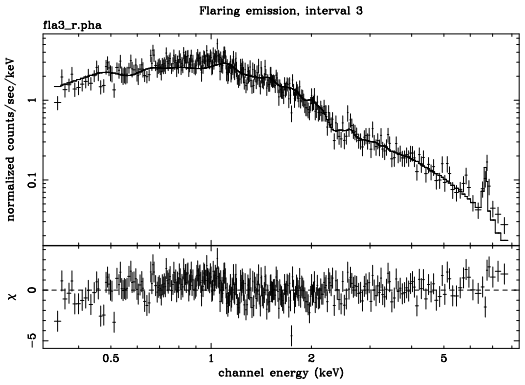

Figure 10. The EPIC-pn spectrum at the peak of the X-ray flare on HD 142578 and the best fit single temperature MEKAL *model with $kT = 4.0$ keV and $Z = 0.35\,Z_\odot$ (with a reduced $\chi^2 = 1.17$).*

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