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An XMM-Newton Pencil-Beam Deep Survey in Upper Sco-Cen

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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 in Upper Sco-Cen based on two *XMM-Newton* EPIC observations obtained as part of the GTO program. 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 sec^{-1} cm^{-2}, 92 sources in the same area where Sciortino et al. (1998) had previously reported 12 sources. Based on positional matching with public catalogues 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.

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 open issues, essential for the lack of reliable census of low-mass members on a large sample of open clusters and associations, is the "Galactic universality" of the IMF low-mass tail, and in particular the possible dependence of IMF shape on the presence of a large number of high-mass stars, as in the case of OB associations.

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 and 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;

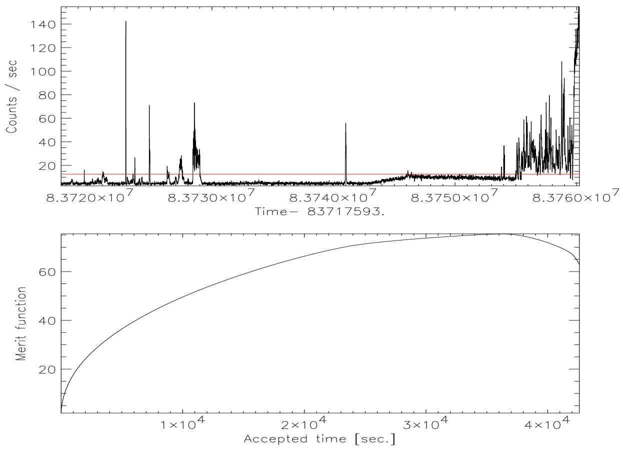

Figure 1. The top panel shows the count rate for the complete image as a function of time in the PN camera during the XMM observation we discuss. The horizontal line is the determined threshold value, time intervals during which the total rate was above this threshold are filtered out. The bottom panel shows the value of merit function which was used to determine the threshold.

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 $\sim$ 2 sq.deg. selected area.

However their sample (largely based on the RASS detected sources) suffers of the unavoidable bias of selecting only the very bright ($\log L_X > 30$ 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 reasons for such a bias are twofold: 1) at each 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 Log Lx $\sim$ 28–29) are required and have motivated the deeper X-ray surveys started by our group with pointed ROSAT observations and now with pointed XMM-Newton ones that we discuss in the following as well as with shallow (waiting deeper ones) photometric and spectroscopic follow-up observations.

Sciortino et al. (1998) have studied a region of $\sim$ 3 sq. deg. in search of low-mass, faint X-ray emitting members. Pointed *Einstein* IPC, ROSAT PSPC and HRI observations have allowed us to reach a limiting sensitivity one order of magnitude deeper than the RASS and to detect 52 sources in the entire 3 sq. deg. surveyed region. Most of these sources have to be low-mass members of Upper Sco-Cen since the predicted number of field sources (both galactic and extragalactic) is less than 10. The membership status of a (small) subsample of the counterparts of X-ray emitting sources has been confirmed by

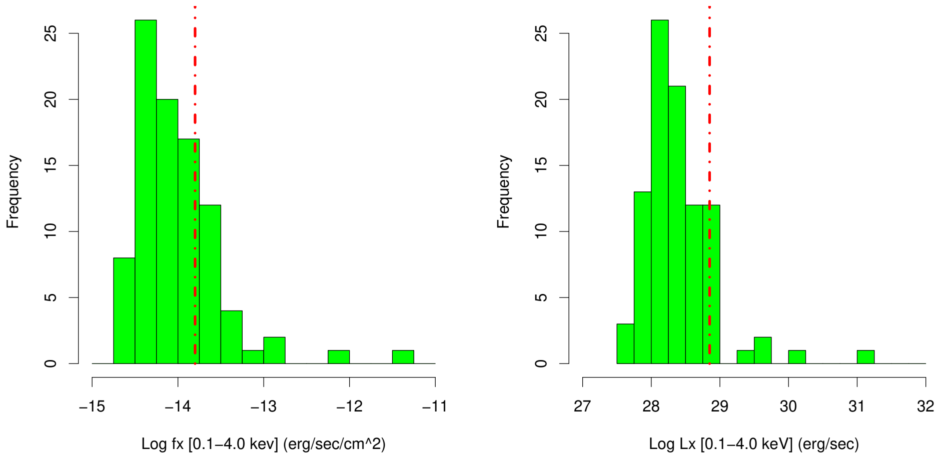

Figure 2. (left) Histogram of unabsorbed intrinsic flux for the 92 sources; the vertical dashed line marks the limiting sensitivity of the Sciortino et al. (1998) survey showing that the XMM-Newton survey is one dex deeper. (right) Histogram of X-ray luminosity for an assumed distance of 160 pc. For reference the vertical dashed line marks the median X-ray luminosity of the Pleiades dM stars.

follow-up optical spectroscopy. In particular, 3 of the sources are early-M pre-main-sequence (PMS) stars. The analysis of deep photometric data has further enlarged the sample of possible Upper Sco-Cen members of spectral type M2-M5 (Flaccomio et al. 1999). In summary, these studies have pointed toward the existence of a substantial population of low-mass Upper Sco-Cen members down to spectral type M5.

Makarov & Urban (2000) have studied the proper motions of some of the counterparts of the sources reported by Sciortino et al. (1998), finding that they share the same proper motion direction of the better known high-mass members, but that their distances can be as large as 300 pc, suggesting that the low-mass stellar population of Upper Sco-Cen can occupy a larger volume of space than previously thought.

More recently, Preibisch et al. (2001) have conducted a multi-fiber high spectral resolution survey of stars in a region of ~ 6 sq. deg. concluding that there is no evidence of a lack of late-M members ($0.1 < M_{\odot} < 0.7$) in Upper Sco-Cen, confirming with an independent approach in a distinct area of the sky, and on a larger sample, the findings of Sciortino et al. (1998) and Flaccomio et al. (1999).

2. XMM-Newton Observations and Data Analysis

With the aim of detecting fainter (and later-type) Upper Sco-Cen members we have decided to observe, as part of the XMM-Newton GTO program, two distinct regions with the XMM-Newton EPIC CCD-based imager. The entire survey covers an area of ~ 0.40 sq. deg. and each of the two regions has been

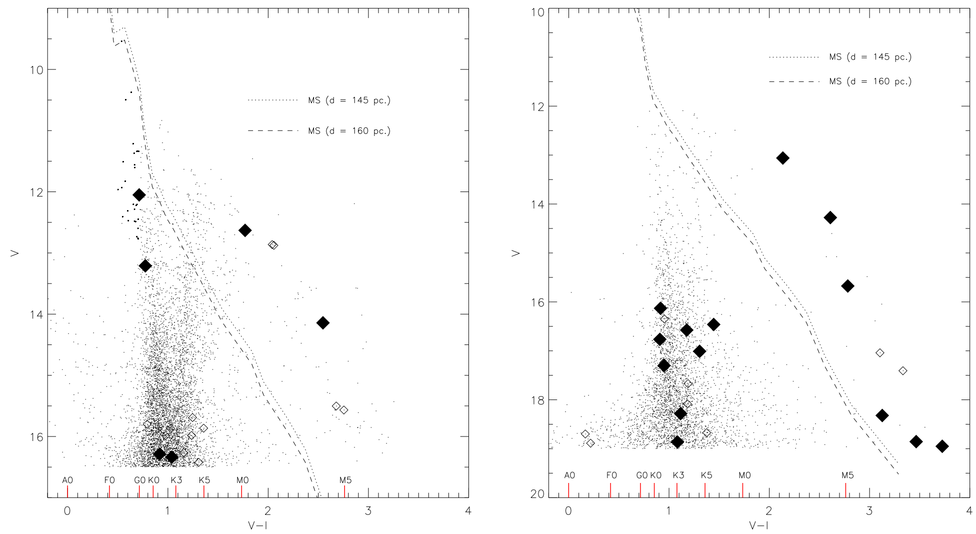

Figure 3. (left) V vs. V-I plot for the stars whose photometry was obtained at the Curtis Schmidt CTIO telescope. The lines indicate the position of the Zero Age Main Sequence (ZAMS) for two adopted distances. Stars above the ZAMS are possible members of the Upper Sco-Cen association with some contamination of foreground stars. Large filled symbols indicate unique counterparts of X-ray sources, small open ones multiple counterparts. (right) V vs. $\mathrm{V} - \mathrm{I}$ plot for the stars whose photometry was obtained at the Danish 1.54m telescope. The symbols have the same meaning as in the previous figure.

observed for about 40–50ksec in order to detect faint members and accumulate 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. In order to minimize the background due to non-X-ray events we have retained only the 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 by identifying and removing fraction of the exposure time strongly affected by high-background episodes (cf. Fig. 1).

As a result we started with a data set of 1.23 Mcnts collected during an exposure of ~ 40.1 ksec and ended with a cleaned data set of 0.39 Mcnts collected in 34.7 ksec, i.e with a judicious time and energy filtering we have been able to reduced the background level by a factor ~ 3 just rejecting 15% of the overall exposure time.

As next step we have summed the two MOS and the PN EPIC cleaned data sets, and the summed data have been searched for sources with the Wavelet Transform detection algorithm developed at OAPA (Pwdetect, Damiani et al 2001). The characteristics of the XMM-Newton version of the algorithm are inherited by the version developed for the ROSAT PSPC (Damiani et al. 1997). The overall analysis procedure follows the recipe described in more details by

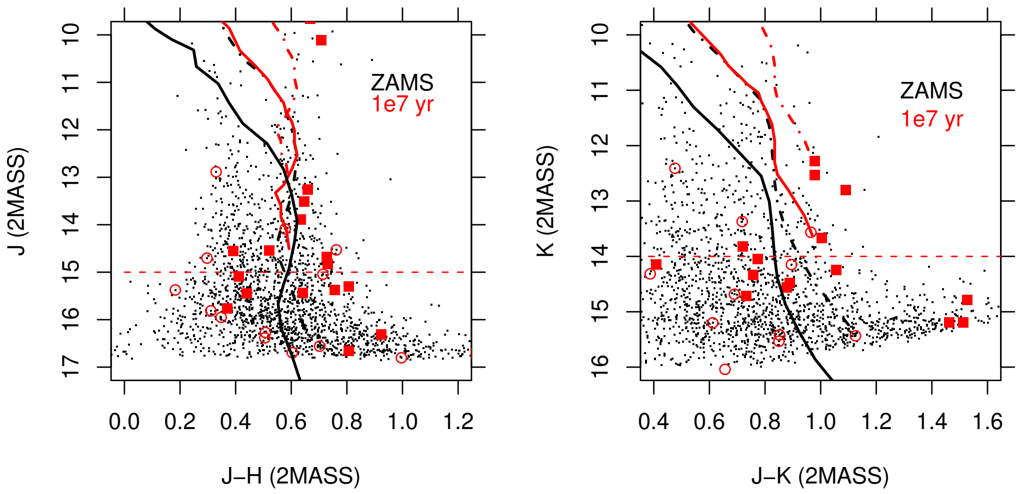

Figure 4. (left) J vs. J-K for the 2MASS stars falling in the FOV of the XMM observation. The lines indicate the position of the Zero Age Main Sequence (ZAMS) and of the 10 Myr isocrones for two adopted distances of 160 pc (dashed) and 300 pc (solid). The horizontal line marks the value of J magnitude at which the uncertainty is about 0.05 mag. Filled circles indicated single 2MASS counterparts, while open circles indicate multiple counterparts. (right) K vs. J − K plot for the same sample of stars in the left panel. The horizontal line marks the value of K magnitudes at which the uncertainty is about 0.05. The symbols have the same meaning as in the left panel. Both panels show low-mass and very low-mass stars unique counterparts of X-ray sources.

Sciortino et al. (2001). The observations have been taken with the medium filters and in such a case we have derived that the value of the relative efficiency of the PN and MOS cameras is 2.94, hence the summed data set has a MOS-equivalent exposure time of 171.4 ksec.

In order to assess the source significance threshold to adopt we have run a full set of simulations of empty fields with the same background level and the same exposure map of the summed data set we have analyzed. While this procedure reliably accounts for the spurious sources due to background fluctuations, it does not take into account yet the presence of spurious sources resulting from the so-called out of time event signatures, i.e. elongated structures due to duty-cycle of EPIC CCD reading system that become prominent near an intense source. However those spurious sources are easily recognized and few of them have been removed from our final cleaned list of 92 sources. The weakest source has a MOS-equivalent rate of 3.2 10^{-4} cnt/sec.

3. Results and Discussion

In order to evaluate source intrinsic fluxes in the [0.1-4.0] keV bandpass we have assumed 1-T Raymond-Smith thermal emission model with kT=0.86 keV and log N_H = 20.65 resulting in a conversion factor of 5.78 10^{-12} erg cm^{-2} cnt^{-1}

for the MOS camera. Over an ample range of source parameters the conversion factor does not vary more than 20%. The attained limiting sensitivity is $\sim 2\ 10^{-15}$ erg sec^{-1} cm^{-2} (cf. right panel of Figure 2), 10 times deeper than the deep pointed survey of Sciortino et al. (1998). The histogram of source intrinsic luminosity (cf. Figure 2) shows that, if the sources belong to Upper Sco-Cen, the new XMM-Newton observation have allowed us to sample X-ray luminosity, L_X, well below the median L_X of young (Pleiades-age) low-mass stars. Hence we are confident that the vast majority of Upper Sco-Cen pre-main-sequence members in the surveyed region have been detected. The question is how many of the 92 X-ray sources are likely not associated with Upper Sco-Cen members. Taking advantage of the sensitivity map produced by Pwdetect we have estimated the number of X-ray sources than can be explained with typical field (galactic and extragalactic) objects based on the recent analysis of deep X-ray surveys (Giacconi et al. 2001, Tozzi et al. 2001). These surveys have permitted to derive the shape of Log N - Log S at faint X-ray fluxes, showing that the typical spectrum of faint extragalactic sources has a power-law shape with $\Gamma \sim 1.4$ with evidence of increasing local absorption, in excess of $N_H \sim 10^{22}$cm^{-2}, going toward fainter sources. Considering also the somewhat patchy nature of the absorption in the area we have surveyed (as shown in the DSS2 image) we can safely assume that the *minimum* source hydrogen column density is $N_H = 5\ 10^{21}$ cm^{-2} and that extragalactic source spectra are power-law with $\alpha = 1.5$, resulting in a conversion factor from rate (in the 0.3-7.9 keV bandpass) to flux (in the 0.5-2 keV bandpass) of 5.6 10^{12} erg sec^{-1}cm^{-2}. Adopting the published forms of Log N - Log S (Giacconi et al. 2001, Tozzi et al. 2001) we estimate that the expected numbers of X-ray sources is 33–43. The predicted number will further reduce if a large fraction of source are more heavily absorbed than we are assuming. So, at the *minimum* we predict that 49–59 of the 92 sources are likely to be associated with Upper Sco-Cen members in a region of $\sim$ 0.2 sq. deg.

As a step in source identification we have searched published catalogs and have taken advantage of the medium-deep BVRI photometry we have obtained at CTIO Curtis-Schmidt and ESO 1.54m Danish telescopes. As results of our search in Simbad with a cross-matching radius of 20", we have found counterparts for 12 X-ray sources; 2 of the counterparts are NTTS stars, one is an A2IV/V member of Upper Sco Cen, one is a likely M5-6 star, candidate member of Upper Sco-Cen (Ardila et al. 2000), and 7 are previously known ROSAT sources.

Our Curtis-Schmidt photometry covers the entire XMM-Newton FOV down to V $\sim$ 17, while our Danish photometry covers only a fraction of the surveyed region but down to V $\sim$ 19. Positions have been derived using as reference GSC-1 stars and their absolute accuracy is better than $\sim$ 1". Taking into account the 90% X-ray positional uncertainty region (as derived by Pwdetect) and optical positional uncertainties we have positionally cross-matched the 92 X-ray sources with the stars in the surveyed region, obtaining both single and multiple matches (cf. Figure 3 and its caption).

We have also searched the 2MASS catalogue for possible counterparts of the X-ray sources with a cross-matching radius of 10". The currently available 2MASS second release cover only $\sim$ 70% of the XMM FOV, specifically the

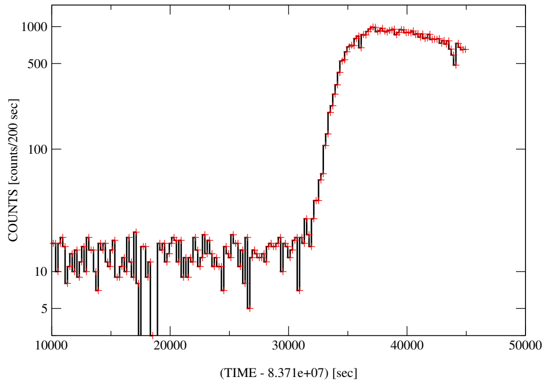

Figure 5. An extreme example of variability is shown by this light-curve observed on an A2IV/V star, member of Upper Sco-Cen. The source count-rate increases by more than a factor 100 in few ksec and then starts to slowly decay. The available data allow us to follow only the early phase of the flare decay.

eastern part of the FOV. Within this area where fall 69 X-ray sources we have found 39 possible counterparts for 31 distinct X-ray sources.

In summary by positional matching we have found possible counterparts for 37 out of the 92 X-ray sources. For 23 sources we have found a single counterparts, while for 14 sources we have found two or three possible counterparts in the error circle. For the majority of the other X-ray sources the inspection of the DSS-2 red plates has allowed to conclude that a large fraction of them have a possible faint counterpart (V $>$ 19) but still well visible on the plates (i.e. with V $<$ 21–22).

A sizable fraction of the 92 sources are clearly variable and in several cases the variability is clearly associated with a flare. We have detected a giant flare (cf. Figure 5) from an A2V (surprisingly) star characterized by an increase of emission level by more then a factor $\sim$ 100 and an e-folding decay time of $\sim$ 20 ksec (cf. Favata et al. 2001). We note that the intense variability we have found is an additional element suggesting the pre-main-sequence nature of a fraction of the 92 sources.

For a number of sources we have obtained CCD-quality X-ray spectra, that allow us to investigate the properties of stellar coronae of Upper Sco-Cen low mass stars. Our initial results indicate that two-temperature *MEKAL* model are typically adequate to describe the collected XMM-EPIC PN spectra. In most of the cases we have considered so far we have found that to obtain reasonable fits the coronal metallicity, as derived from *MEKAL* implementation within XSPEC V11.1, should be significantly lower than solar. As an example of such a spectra we show in Fig. 6 the observed spectrum and the best fit model (together with derived best fit parameters) for the Upper Sco-Cen M0 PMS star NTTS 155421-2330.

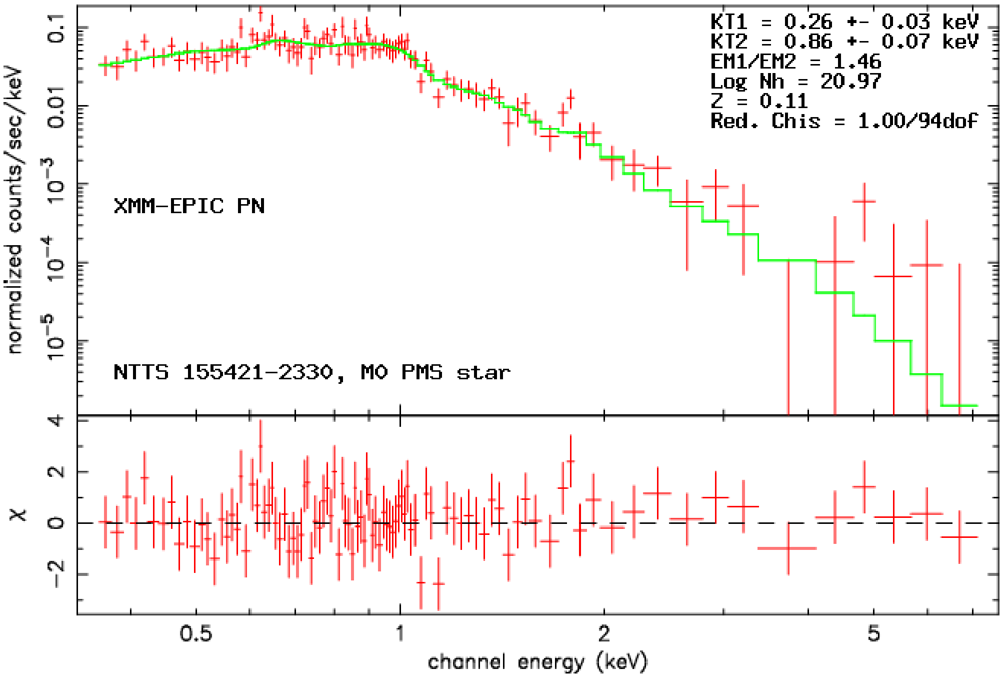

Figure 6. An example of the X-ray CCD spectra we have obtained: the EPIC PN spectrum of the PMS M0 star NTTS 155421-2330, one of the Upper Sco-Cen low-mass members. The spectrum is fitted with a double temperature *MEKAL* model, with metallicity, Z, significantly lower than solar. The best fit parameters are summarized in the upper left of the top panel. The lower panel shows the best fit residuals expressed in term of χ^2.

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