XMM-*Newton* OBSERVATIONS OF OPEN CLUSTERS

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ABSTRACT

We present observations of stellar clusters obtained with XMM-*Newton* as part of the Guaranteed Time program. We have obtained EPIC observations of the open clusters Praesepe, α Per, σ Ori and Hyades and of the Taurus-Auriga star-forming region. The results of the analysis are presented and discussed, with emphasis on the imaging data. In all clusters a large number of new X-ray sources with no known catalogued optical counterpart has been detected. In σ Ori three X-ray sources coincide with very-low mass members of the cluster, including a brown dwarf candidate. The Praesepe observation does not show the discrepancy with the Hyades found by *ROSAT*, supporting the suggestion that this cluster may be formed by two merged clusters of different ages.

INTRODUCTION

Open clusters provide homogeneous samples of stars with approximately the same age and chemical composition. As such, they are uniquely suited to investigate the dependence of stellar coronal activity upon rotation and age, and the evolution of dynamo activity in convective stars. X-ray observations with *Einstein* and *ROSAT* (Jeffries 1999; Randich 2000, and references therein) have demonstrated that coronal activity declines with age as the result of angular momentum loss in stars of different masses and different convective zone properties. By studying clusters of different age at a sensitivity substantially larger than that allowed by previous X-ray satellites, it is possible to further investigate the activity-age-rotation relationship over the full age range from a few million years to about 1 Gyr. Moreover, the spectral capability and larger sensitivity of current X-ray missions (*Chandra* and XMM-*Newton*) allow also the investigation of the age dependence of coronal spectral properties in late-type stars.

As part of the Guaranteed Time program on XMM-*Newton* we have observed a sample of stellar clusters and star forming regions. We have obtained EPIC observations of the open clusters Praesepe, α Persei and Hyades, of the very young cluster σ Ori in the Orion OB1 association, and of the Taurus-Auriga star forming region (P.I. R. Pallavicini, see the XMM-*Newton* WWW pages for details on the observations).

In this paper we summarize the imaging results obtained for Praesepe, α Per and σ Ori, and we present a preliminary analysis of our pointings of the Hyades and Taurus-Auriga regions.

DATA ANALYSIS

Data analysis was carried out using the standard tasks in SAS v.5.3.3. Source detection was first performed on the individual datasets using the Maximum Likelihood (ML) algorithm. After checking the relative alignment of the three EPIC cameras (MOS1, MOS2 and PN), we merged the event files into a single dataset. A combined exposure map was obtained by summing the individual exposure maps with an appropriate scaling factor for PN, derived from the median ratio of PN to MOS count rates, in order to take into account the different sensitivities of MOS and PN. Source detection was then performed on the summed dataset. The resulting count rates are MOS equivalent count rates. For cluster members with no associated X-ray source we estimated 3σ upper limits from the background count rates. Conversion factors from count

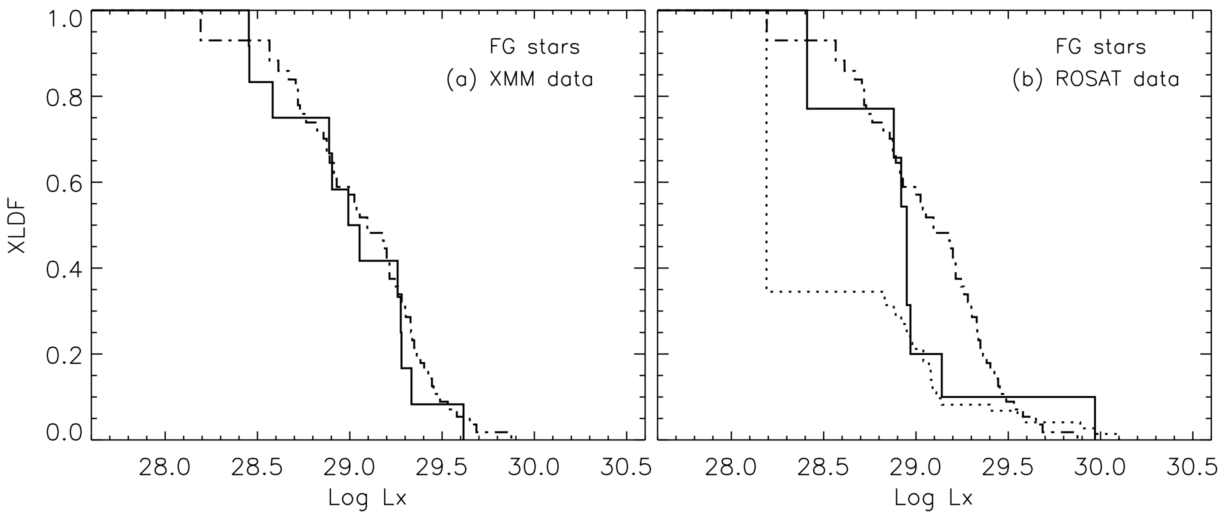

Fig. 1. Comparison of the X-ray luminosity distribution function (XLDF) of Praesepe (solid line) and the Hyades (dash-dotted line) for F-G dwarf stars in the colour range $0.50 \leq (B-V)_{\circ} \leq 0.81$. In panel (a) we show the Praesepe XLDF obtained from the present XMM-*Newton* data. Panel (b) shows the XLDF derived, for the same sample of stars, from the previous *ROSAT* observations; for comparison, we also show the Praesepe XLDF derived from the entire *ROSAT* sample (dotted line). The Hyades XLDF was derived from the *ROSAT* observations by Stern et al. (1995)

rate to flux in the *ROSAT* band ($0.1-2.4$ keV) have been derived assuming a Raymond-Smith plasma with $\log T = 6.8-7.0$ and the appropriate column density for each cluster.

PRAESEPE

The Praesepe open cluster (age $\sim$ 660 Myr, $d = 180$ pc) represents a puzzle since it has about the same age as the Hyades, and only slightly different metallicity, yet previous *ROSAT* observations (Randich & Schmitt 1995, hereafter RS95) resulted in a detection rate of cluster sources significantly lower than for the Hyades, implying that the bulk of the population of Praesepe solar-type stars was considerably less X-ray luminous than the Hyades. The discrepancy does not appear to be due to contamination of the Praesepe X-ray sample by non-members (Barrado y Navascues et al. 1998) or to different distributions of rotation rates in the two clusters (Mermilliod et al. 1997) or to significantly different metallicities. This finding casts doubts on the universality of the activity-rotation-age paradigm, i.e. on the assumption that a cluster of a given age is representative of all clusters of the same age.

In order to further address this problem, we have performed a 47 ksec observation of the central region of the Praesepe cluster with XMM-*Newton* (centered at $\alpha = 08^{\rm h}39^{\rm m}58^{\rm s}$, $\delta = 19^{\circ}\,32'\,29''$, J2000). The combined EPIC image is shown in Figure 2; the merged dataset has an equivalent MOS exposure time of 279 ksec. The sensitivity in the center of the field is $L_{\rm X} \sim 5 \times 10^{27}$ erg sec^{-1}, i.e. a factor ~ 4 higher than the previous *ROSAT* observations.

Source detection resulted in 183 sources with $ML > 10$ (4σ) on the combined dataset, and 16 additional sources above the same significance level on the single instrument datasets, giving a total number of 199 sources. Of these sources, 46 have a cluster member counterpart within $10''$, including the two giants; 24 additional sources have been identified with cluster non-members. The remaining 129 sources have no known optical counterpart.

We detected all solar-type stars ($0.5 \leq (B-V)_{\circ} \leq 0.81$) included in the field of view, 10 of the 11 K-dwarfs (91%), and 12 of the 20 M dwarfs (60%). We mention the detection of the very low-mass star WRS4 which, with an estimated mass of $0.13\,M_{\odot}$, is well below the fully convective boundary. For this star we derived an X-ray luminosity $L_{\rm X} = 2.37 \times 10^{28}$ erg sec^{-1}.

The comparison of the XLDF of the Praesepe solar-type members in our field of view with the Hyades does not confirm the discrepancy found by RS95 (Figure 1a); the median luminosity ($\log L_{\rm X} = 28.99$) as

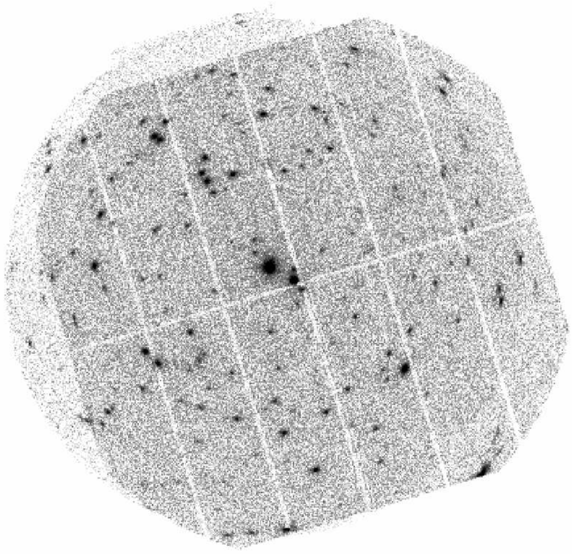

Fig. 2. Composite EPIC image of the Praesepe field

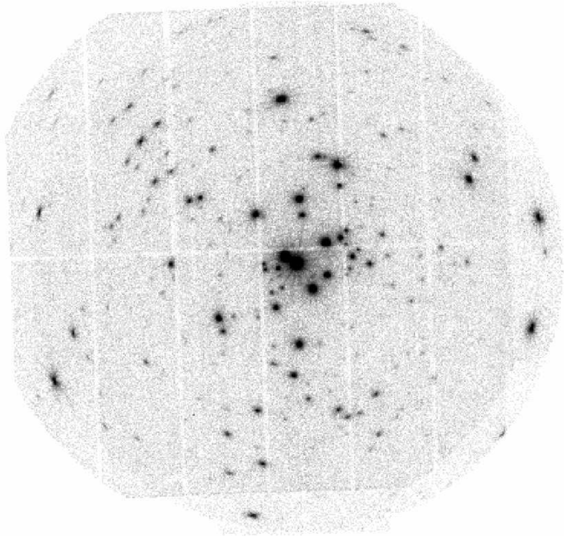

Fig. 3. Composite EPIC image of the σ Ori field

well as the 25th and 75th percentiles ($\log L_{\rm X}$ = 29.28 and 28.58, respectively) are only slightly lower than those of the Hyades ($\log L_{\rm X}$ = 29.07, 29.33 and 28.74, respectively).

Our results for solar-type stars seem to contradict the previous results by RS95 based on the *ROSAT* raster scan survey of Praesepe. However if one considers only the subsample of Praesepe stars in the survey of RS95 in common with the present sample, the disagreement between the XMM-*Newton* and *ROSAT* results is considerably reduced (Figure 1b). The difference in the detection rates is due to the different sensitivities of the two surveys, while the overall discrepancy between the X-ray properties of the Hyades and Praesepe pointed out by RS95 seems mostly due to X-ray faint Praesepe members outside our XMM-*Newton* field of view.

Holland et al. (2000) made the hypothesis that Praesepe is formed by two merged clusters. They found that the X-ray brightest sources are almost exclusively located in the "main" cluster and suggested a difference in age between the main cluster and the subcluster as an explanation for the *ROSAT* based results. Our XMM-*Newton* observation indeed covers a small area of the main cluster and thus presumably includes the X-ray brighter cluster population.

σ ORIONIS

The σ Ori cluster, discovered by *ROSAT* (Walter et al. 1997; Wolk 1996) around the O9.5V star σ Ori, belongs to the OB1b association and is located at a distance of 352 pc; it contains $\sim$ 100 likely pre-main sequence stars within $30'$ of σ Ori. Subsequent photometric and spectroscopic surveys have detected several very low mass cluster candidates, including brown dwarfs and planetary-mass objects (Béjar et al. 1999; Zapaterio Osorio et al. 2000; Béjar et al. 2001). The estimated age of the cluster is $2-5$ Myr.

The combined EPIC image of our XMM-*Newton* observation of the σ Ori cluster is shown in Figure 3; the merged dataset has an equivalent MOS exposure time of 217 ksec. The sensitivity in the center of the field is $L_{\rm X} \sim 2.5 \times 10^{28}$ erg sec^{-1}.

We detected 215 sources with $ML > 10$ on the combined dataset, and 26 additional sources on the single datasets, for a total of 241 sources. We have identified 86 sources with at least one possible cluster member counterpart within $10''$ of the X-ray position. Of the detected members, 5 are early-type stars, including components AB and E of the σ Ori system. We have identified 7 sources with very-low mass stars of spectral type later than M6 (see Table 1), including S Ori 68, a planetary-mass object of spectral type L5.0 (Béjar et al. 2001). However 4 of these sources (including the one identified with S Ori 68) have another possible counterpart within $10''$, therefore their identification is ambiguous. The latest member with a certain X-ray

Table 1. Very-low mass members of the σ Ori cluster detected by XMM-*Newton*

Name	offset ($''$)	I	R-I	J	log L_X	Other possible ID
S Ori 3	3.92	15.16	2.15	13.21	29.642	2MASS J0539215-023039 (9.03$''$) J=16.8
S Ori 5	3.83	15.40	1.86	13.62	28.525	
S Ori 6	6.70	15.53	2.00	13.46	28.619	
S Ori 25	2.53	17.16	2.17	14.70	28.671	
J053926.8-022614	4.42	18.66		16.29	29.326	GSC2 S02003217532 (4.81$''$) R=15.8
S Ori 43	5.60	19.05	2.38		29.439	r053814-0235 (5.15$''$) I=14.87, non member
S Ori 68	4.54	23.78		20.18	29.002	2MASS J0538388-022801 (3.11$''$) J=15.3

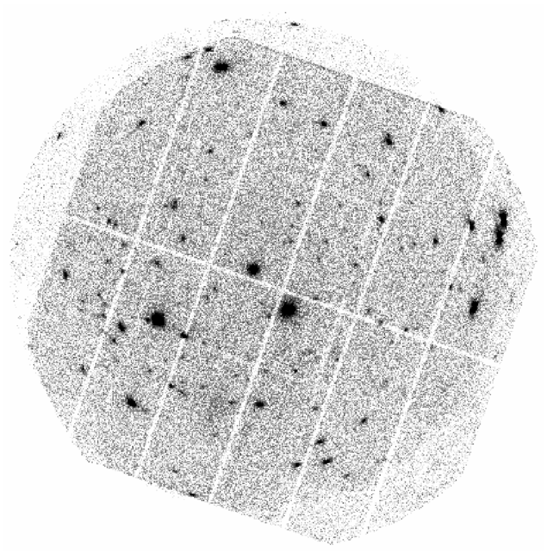

Fig. 4. Composite EPIC image of the α Per field

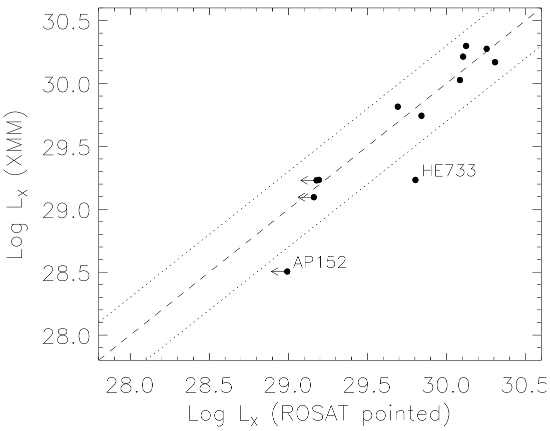

Fig. 5. Comparison of the X-ray luminosities of α Per members derived from XMM-*Newton* and from the *ROSAT* pointed observations by Prosser et al. (1996). Dotted lines mark a factor of 2 differences in L_X

detection is the candidate brown dwarf S Ori 25, which has a spectral type M6.5 and an estimated mass of $0.05 - 0.13\ M_\odot$; its X-ray luminosity is 4.7×10^{28} erg sec^{-1}.

α PERSEI

The α Per cluster is a young ($\sim$ 50 Myr) open cluster located at a distance of $\sim$ 190 pc. This cluster was observed by *ROSAT* in a raster scan and in a pointed observation (Randich et al. 1996; Prosser et al. 1996): optical follow-up of the unidentified X-ray sources allowed the identification of $\sim$ 70 new solar-type and low-mass cluster members which had not been identified in previous photometric and spectroscopic surveys (Prosser & Randich 1998; Prosser et al. 1998).

α Per was observed by XMM-*Newton* for a total of 60 ksec. In Figure 4 we show the combined EPIC image; the equivalent MOS exposure time of the merged dataset is 275 ksec. The sensitivity in the center of the field is $L_X \sim 7 \times 10^{27}$ erg sec^{-1}, which represents an improvement of one order of magnitude with respect to the previous *ROSAT* observations.

We detected in total 154 sources with $ML > 10$ (139 on the combined dataset, and 15 on the single

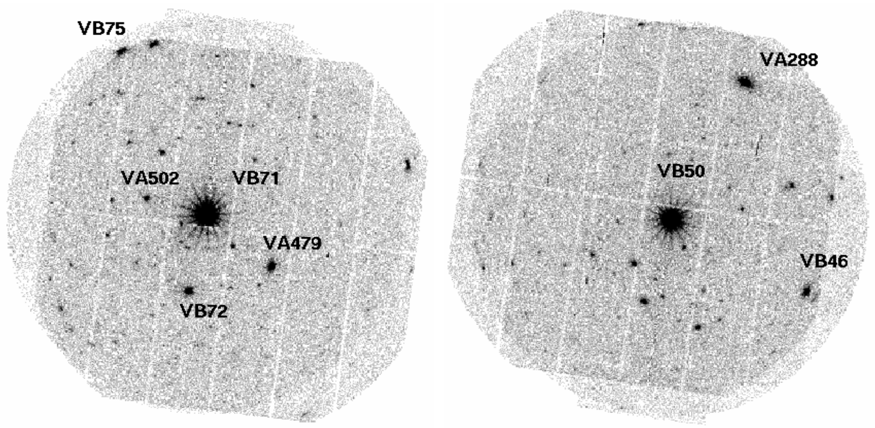

Fig. 6. Composite EPIC image of the Hyades fields around VB71 (θ^1 Tau, *left panel*) and VB50 (*right panel*). Labels mark detected Hyades members

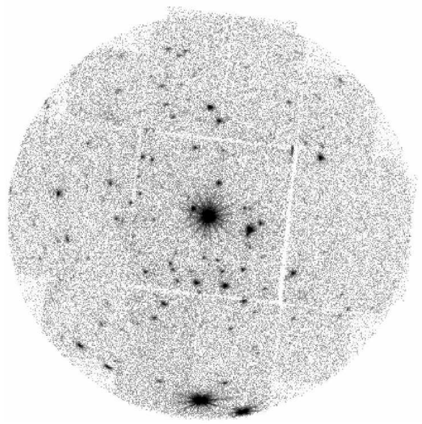

Fig. 7. Composite MOS image of the field around SU Aurigae

datasets). The XMM-*Newton* field of view contains only 13 previously known members (spectral types F to M): all except one M-type star have been detected. X-ray luminosities of the cluster members are generally in good agreement with those derived from *ROSAT* data (Figure 5). Six additional sources are identified with cluster non-members. We have cross-correlated the list of the remaining 136 sources with other optical catalogues, finding at least one possible counterpart for 58 of them; the other 78 sources have no known optical counterparts.

HYADES AND TAURUS-AURIGA

We have obtained two observations of the Hyades cluster centered respectively on the giant star VB71 $= \theta^1$ Tau and on the main-sequence star VB50 (Figure 6), and an observation of the Taurus-Auriga star-forming region centered on the classical T Tauri star SU Aur (Figure 7). A preliminary source detection yielded ~ 135 sources in the VB71 field and ~ 100 sources in the VB50 field. Detected Hyades members are marked in each image; their X-ray luminosity is consistent, within a factor of 2, with the luminosity derived from *ROSAT* observations (Stern et al. 1995). The SU Aur field contains ~ 130 X-ray sources. For the central sources, RGS spectra are also available: their analysis as well as spectral analysis of other EPIC sources in the field of view will be presented elsewhere.

CONCLUSIONS

- Our XMM-*Newton* observation of Praesepe shows that the X-ray properties of our sample of Praesepe solar-type stars are in good agreement with the Hyades; the discrepancy between Praesepe and the Hyades previously found by *ROSAT* apparently shows up only when considering a much larger area of the Praesepe cluster than the one covered by the XMM-*Newton* field of view. This gives support to the suggestion that Prasepe may be formed by two merged clusters of different ages.

- Thanks to the higher sensitivity of XMM-*Newton* with respect to previous satellites, we have detected in all clusters a large number of new X-ray sources with no known catalogued counterpart. Optical follow-up photometric and spectroscopic observations will be required to ascertain their nature and whether part of them are previously unknown members of the cluster.

- In σ Ori we have detected 7 X-ray sources spatially coincident with very-low mass members of the cluster. For 4 of these sources the identification is ambiguous owing to the presence of another possible counterpart within $10''$; for the other 3, including the brown dwarf candidate S Ori 25, the identification seems firm. Another very-low mass star (WRS4) below the fully convective boundary has been detected by us in Praesepe.

- The sources at the center of our pointings of the Hyades, Taurus-Auriga and σ Ori are sufficiently strong to give high-resolution RGS spectra. These spectra, together with lower-resolution EPIC spectra obtained for a number of sources in each field, will be presented elsewhere (for the two Hyades stars see Franciosini et al. (2002); for σ Ori see Pallavicini et al. (2002); for SU Aur the RGS spectrum is surprisingly weak with respect to the simultaneous EPIC spectrum).

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