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XMM-Newton EPIC observations of stellar clusters and star forming regions ⋆

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Abstract. We report on observations of open clusters (OCs) and star forming regions (SFRs) obtained with the EPIC camera as part of the Mission Scientist Guaranteed Time on XMM-*Newton*. These observations provide a powerful tool to investigate the evolution of coronal activity in late-type convective stars and its dependence on magnetic field generation by dynamo processes. We discuss the motivations for this program and present some results for the SFRs σ Orionis (∼2−5 Myr) and Taurus-Auriga (∼1−10 Myr) as well as for the OCs IC 2602 (∼30 Myr), α Persei (∼50 Myr), Praesepe (∼600 Myr) and the Hyades (∼600 Myr). We discuss imaging and spectral data provided by the EPIC MOS and PN detectors focussing on the determination of the cluster X-ray luminosity function and of the temperature structure, chemical abundances and time variability of cluster stars.

Key words. stars – coronae – X-rays – open clusters – star forming regions

1. Why observing stellar clusters in X-rays

Open clusters constitute homogeneous samples of stars with approximately the same age, distance and chemical composition. Because of this, they are fundamental tools to study stellar structure and evolution as well as the dependence of chromospheric and coronal activity on stellar rotation and dynamo-generated magnetic fields. Observations show that the X-ray emission of late-type stars in clusters is a strong function of magnetic activity as measured, e.g., by the Rossby number (a combination of rotation and convective zone properties that is believed to measure the efficiency of the dynamo process). Since late-type convective stars suffer magnetic braking during their evolution on the main-sequence (MS), the level of coronal X-ray emission is expected to be a decreasing function of age through the influence of stellar rotation on the efficiency of the dynamo process. Early observations by *Einstein* and ROSAT have by and large confirmed these expectations, but they have also shown that the relationship between activity, age and rotation may be much more complex that hitherto suspected (Jeffries 1999, Randich 2000, and references therein). The more sen-

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⋆ Based on observations collected with the ESA mission XMM-*Newton* as part of the Mission Scientist (R. Pallavicini) Guaranteed Time sitive observations now possible with *Chandra* and XMM-*Newton* are allowing us to investigate also the dependence of coronal spectral properties on age, as well as to study in much more detail the variability of cluster sources on both short and long timescales. Finally, observations of X-ray sources in SFRs and in young OCs have proved to be a unique way to identify pre-main sequence (PMS) stars and cluster members, which is essential for an unbiased cluster census and for the determination of the cluster mass function.

We have observed with the EPIC camera on XMM-*Newton* several OCs and SFRs spanning the age interval from a few Myr to the age of the Hyades (~600 Myr). In this paper we present an overview of this program carried out as part of the Guarateed Time of a Mission Scientist (R. Pallavicini). The reported results include: i) the detection of an X-ray flare from the hot star σ Ori E, that we attribute, on the basis of the preflare quiescent spectrum, to an unseen late-type companion of the hot star; ii) the discovery of rotational modulation in a K star belonging to the same cluster; iii) the detection of very-low mass stars (later than M6) in the σ Ori cluster, including the brown dwarf candidate S Ori 25 and (perhaps) the planetary mass object S Ori 68; iv) the determination of the temperature structure of the classical T Tauri star SU Aur and the discovery of frequent flaring from the same source; v) the finding that the X-ray luminosity distribution function of solar-type stars in the core of the Praesepe cluster is consistent with that of the Hyades, at variance with previous ROSAT results which covered a much larger area of Praesepe (thus giving support to the suggestion that Praesepe may result from two merged clusters of different ages); vi) the detection of X-ray flares from the Hyades stars VB 50 and VB 72 and from the M dwarf star VA 479 in the field of the Hyades giant θ^1 Tau; vii) the finding that long term variations of cluster stars in the Hyades, Praesepe and α Persei are generally small (within a factor of two) except for a few stars that present evidence of larger long term variations over time scales of years, possibly associated with stellar activity cycles.

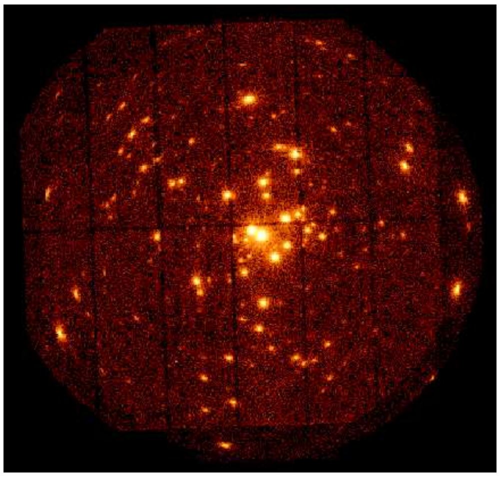

Fig. 1. Composite EPIC image of the σ Ori cluster

2. The σ Orionis cluster

The σ Ori cluster, discovered by ROSAT around the O9.5V star σ Ori AB, belongs to the OB1b association and is located at a distance of ~350 pc; it contains ~100 likely PMS stars within 30′ of σ Ori AB. Optical and IR photometric and spectroscopic surveys have detected several very low mass cluster candidates, including brown dwarfs and planetary-mass objects. 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 1; the merged dataset has an equivalent MOS exposure time of 217 ksec. The sensitivity at the center of the field is $L_X \sim 2.5 \times 10^{28}$ erg sec^{-1}.

We detected 240 sources with maximum likelihood (ML) >10. We have identified 86 sources with at least one possible cluster counterpart within 10″ of the X-ray position. Of the detected members, 5 are early-type stars, including σ Ori AB and σ Ori E. We have identified 7 sources with very-low mass stars of spectral type later than M6, including S Ori 68, a planetary-mass object of spectral type L5.0. However 4 of these sources (including the one identified with S Ori 68) have another possible counterpart within 10″, therefore their identifi-

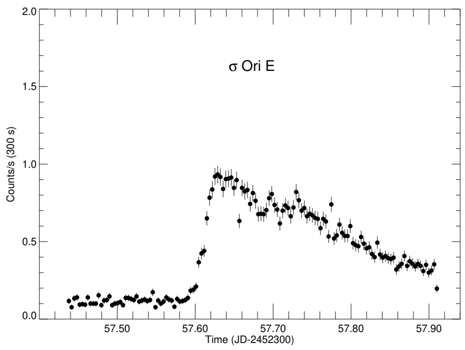

Fig. 2. X-ray flare from the hot star σ Ori E

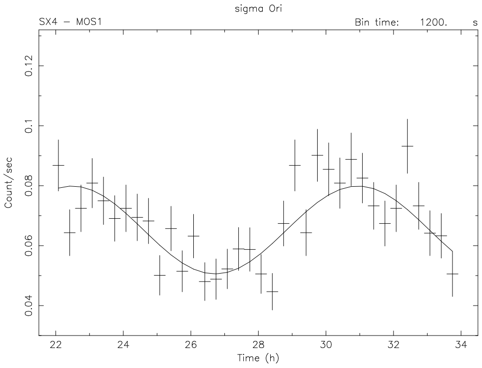

Fig. 3. X-ray rotational modulation of a K-type star in the σ Ori cluster

cation is ambiguous. The latest member with a certain X-ray detection is the brown dwarf candidate 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}.

Our pointing at the σ Ori cluster was centered on the hot star σ Ori AB in order to obtain a high resolution RGS spectrum of this source. The RGS spectrum is contaminated by nearby sources, whose contribution needs to be subtracted in order to get a clean spectrum of the central source (Sanz-Forcada et al. 2003). The three sources that contribute more to the contamination are the B2Vp star σ Ori E and two nearby K-type dwarfs. They are all quite interesting in the EPIC data. An X-ray flare has been detected during this observation from the hot star σ Ori E (Figure 2): a flare from the

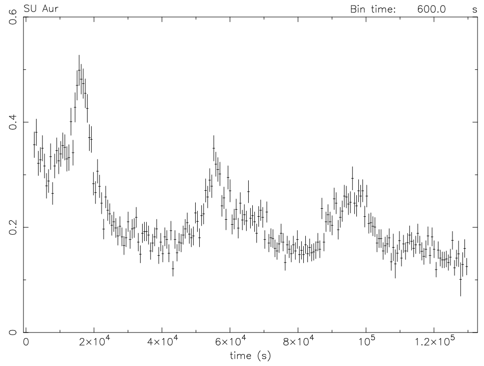

Fig. 4. High X-ray variability from the classical T Tauri star SU Aur

same source, detected by ROSAT, was reported recently by Groote & Schmitt (2003) who attributed it to the hot star. However, because of the unusually (for a hot star) high temperature of the quiescent preflare corona determined by us with EPIC, we believe it is more likely that the flare originated from an unseen late-type companion. One of the other contaminating sources, identified with a K3 dwarf, shows rotational modulation of its X-ray emission, with a period of ~9 hours (Figure 3). The observed modulation, with an amplitude of ~25%, can be attributed to the inhomogeneous distribution of active regions over the surface of the star.

3. The Taurus-Auriga region

We have obtained two observations of the Taurus-Auriga SFR centered respectively on the weak-line T Tauri star HD 283572 and on the classical T Tauri star SU Aur. While the pointing of HD 283572 was contaminated by high background and thus resulted in poor RGS and EPIC spectra for the central source, the other pointing was more interesting in EPIC, although only the MOS detectors were operative at the time of the observation. About 130 sources, mostly PMS stars, have been detected in the MOS exposures which had a nominal duration of 128 ksec. The light curve of the central source (SU Aur) is highly variable with frequent flares (see Figure 4). A 3-temperature fit of the MOS spectrum (shown in Figure 5) gives components with $T_1 = 0.67$

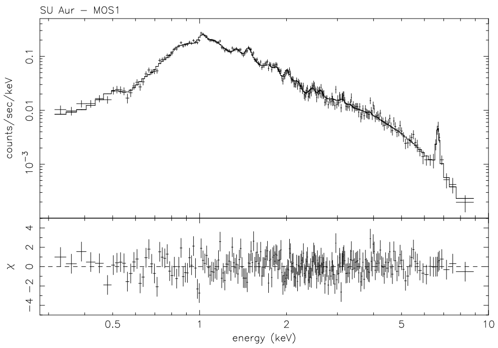

Fig. 5. EPIC MOS spectrum of SU Aur

keV, $EM_1 = 1.02 \times 10^{53}$ cm^{-3}, $T_2 = 1.67$ keV, $EM_2 = 2.24 \times 10^{53}$ cm^{-3}, $T_3 = 4.75$ keV, $EM_3 = 1.64 \times 10^{53}$ cm^{-3}, and Fe abundance 0.6 solar. The Taurus region will be observed much more extensively with XMM-*Newton* in AO-3 as part of a large program covering ~ 5 deg^2 in ~ 20 EPIC exposures of 30 ksec each.

4. The Praesepe cluster

The Praesepe open cluster (age $\sim$ 600 Myr, d=180 pc) represents a puzzle since it has about the same age as the Hyades and only slightly lower metallicity, yet previous ROSAT observations resulted in a detection rate of cluster sources significantly lower than for the Hyades, implying that the bulk of the population of solar-type stars in Praesepe was considerably less X-ray luminous than the Hyades (Randich & Schmitt 1995). The discrepancy could not be explained as due to contamination of the Praesepe X-ray sample by non-members, or to different distributions of rotation rates in the two clusters, or to the slightly different metallicity. This finding casted 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 investigate this problem, we have performed a 47 ksec observation of the Praesepe cluster with XMM-*Newton*. The combined EPIC image has an equivalent MOS exposure time of 279 ksec (see Figure 6). The sensitivity in the center of the field is $L_X \sim 5.6$

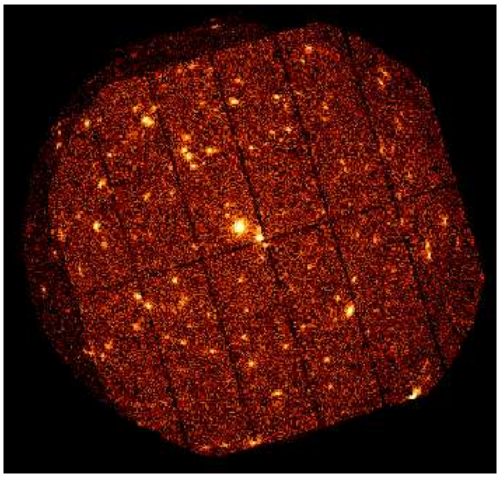

Fig. 6. Composite EPIC image of the core of the Praesepe cluster

$\times 10^{27}$ erg sec^{-1}, i.e. a factor $\sim$ 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, 48 have a cluster member counterpart within 10″, including two giants; 24 additional sources have been identified with cluster nonmembers. The remaining 127 sources have no known optical counterpart.

The comparison of the X-ray luminosity distribution function of the Praesepe solar-type members in our field of view with the Hyades does not evidence the discrepancy found by Randich & Schmitt (1995). The median luminosity ($\log L_X = 28.99$) as well as the 25th and 75th percentiles ($\log L_X = 29.28$ and 28.58, respectively) are only slightly lower than those of the Hyades ($\log L_X = 29.07$, 29.33 and 28.74, respectively). However, if one considers only the subsample of Praesepe stars in the ROSAT survey in common with the present sample, the disagreement between the XMM-*Newton* and ROSAT results is considerably reduced (see Franciosini et al. 2003 for details): the difference in the detection rates is due to the different sensitivities of the two surveys, while the overall discrepancy between the X-ray prop-

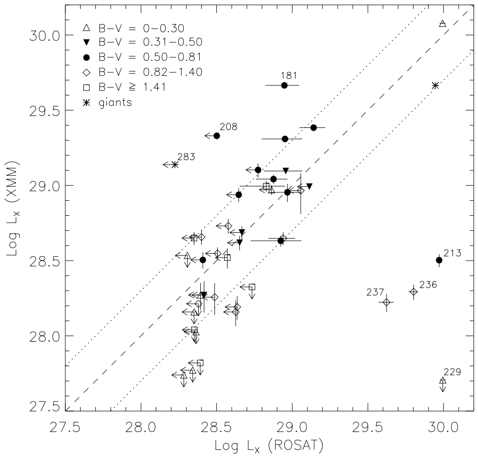

Fig. 7. XMM vs. ROSAT X-ray luminosities for members of the Praesepe cluster

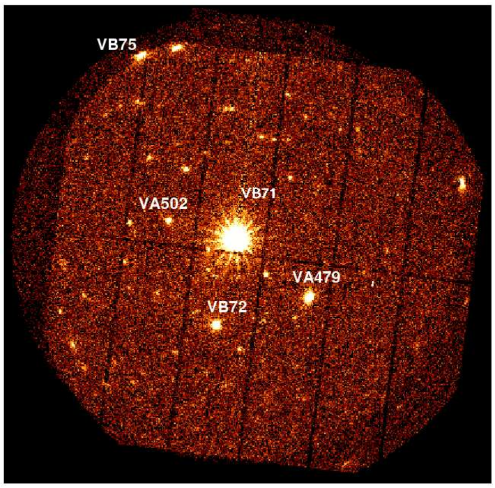

Fig. 8. Composite EPIC image of a Hyades field centered on VB 71 (θ^1 Tau)

erties of the Hyades and Praesepe found by Randich & Schmitt (1995) seems mostly due to X-ray faint Praesepe members outside our XMM field of view. This gives support to an early suggestion by Holland et al. (2000) that Praesepe might result from two merged clusters of different ages, with the brightest sources almost exclusively located in the younger cluster. Our XMM pointing covers indeed only a small area of the latter cluster and thus presumably includes the X-ray brighter cluster population.

For the stars detected by both the ROSAT and XMM-*Newton* observations, it is possible to investigate time variability over time scales of years. Figure 7 shows the comparison of XMM and ROSAT X-ray luminosities for Praesepe stars of different colours. For most of the sources the difference is small (within a factor of 2), but there is a group of stars significantly brighter in ROSAT, and another one significantly brighter in XMM. While the former stars can be explained by confusion in lower spatial resolution ROSAT PSPC observations (cf. Franciosini et al. 2003), the stars brighter in XMM evidence long-term variations possibly associated with stellar activity cycles.

5. Other open clusters

We have observed with EPIC two nearby young clusters, IC 2602 and α Persei, with ages of, respectively, ~30 and ~50 My. These clusters provide information on the evolution of coronal activity between the age of SFRs and that of the Pleiades (~100 Myr). α Per was observed for a total of 60 ksec with both the MOS and PN detectors. The equivalent MOS exposure time of the combined EPIC image is 275 ksec. The sensitivity at 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 have detected in total 154 sources with ML >10. The XMM field of view contains only 13 previously known cluster members (spectral types F to M): all except one M-type star have been detected. The X-ray luminosities of the cluster members are generally in good agreement (within a factor of 2) with those derived from the ROSAT data. 6 additional sources are identified with cluster nonmembers. 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.

We have obtained two observations of the Hyades cluster centered respectively on the clump giant VB 71 = θ^1 Tau (see Figure 8) and on the G-type dwarf VB 50. The two central sources are bright enough for high-resolution RGS spectra (Franciosini et al. 2002). A preliminary source detection on the EPIC fields yielded ∼135 sources in the VB 71 field and ∼100 sources in the VB 50 field but only a few detected sources in each image are actual Hyades members. The X-ray luminosities of the cluster members in the field of VB 71 are consistent, within a factor of 2, with those derived from previous *Einstein*, ROSAT and ASCA observations, except for VB 72, which was a factor $\sim 4-5$ brighter during the ASCA observation, and VA 502, which was previously undetected and has a luminosity $L_X \sim 9\times 10^{27}$ erg sec^{-1}, a factor 2−3 lower than the sensitivity limit of previous Hyades surveys. The EPIC light curve of the Hyades member VB 72 shows significant variability and a flare with duration of ∼1000 sec and a factor of 3 increase in the count rate. A much stronger flare (a factor ∼30 increase) was detected from the source VA 479, which has been rejected as a Hyades member and is probably a background M-type star. Significant variability and two small flares were also detected from VB 50.

6. Conclusions

Although the results reported here can give only the flavour of what XMM-*Newton* can do in the area of OCs and SFRs, it is clear that these observations are providing new important insights into the physics of magnetic activity in stars. With its combination of high sensitivity and good spectral resolution, EPIC (together with the RGS for the brightest sources) allows the investigation of the coronal properties of stars over a wide range of ages, from a few million years to nearly 1 Gyr. The GT observations discussed in this paper, together with those of other GT and GO programmes, are starting to cover the full age-metallicity plane for open clusters and shall allow addressing the question whether a cluster of a given age can be taken as representative of all clusters of the same age. To reach these aims it is important to observe clusters of various ages as well as more than one cluster at any given age. In addition to the clusters discussed above, XMM-*Newton* has already acquired (or will acquire shortly) data on the open clusters IC 2391, M 34, NGC 6475, the Pleiades, Blanco 1, NGC 2516, NGC 6633 as well as on a number of nearby SFRs (see for instance the large program on the Taurus Molecular Cloud mentioned above). These data will allow studying in great detail the coronae of cool stars over the full age range from ∼1 Myr to ∼1 Gyr. Moreover, provided enough time is devoted to these observations, XMM-*Newton* and EPIC are sensitive enough to extend these studies to clusters older than the Hyades, as is being demonstrated by observations of solar-type stars in the ∼2 Gyr old cluster NGC 752 (Tagliaferri et al., in preparation).

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