X-RAY SPECTRAL AND TIMING PROPERTIES OF THE IC 2391 STARS

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Abstract

We present X-ray spectral and timing analysis of the young open cluster IC 2391 observed with XMM-Newton EPIC. By analysing the summed data from MOS1, MOS2 and pn detectors, we detected 99 X-ray sources; 24 of them are members, or probable members, of the cluster, spanning all spectral types. The X-ray spectral analysis of the X-ray brightest cluster stars shows that a spectral model with two thermal components (at kT1 $\approx$ 0.3-0.5 keV and kT2 $\approx$ 1.0-1.2 keV, respectively) describes well the coronal spectra of G, K and M stars, while a softer 1-T model is appropriate for F stars. The spectra of the A1 type star VXR56 and B8.5 type-star VXR46 are consistent with the hypothesis that a later type-star companion is responsible of the X-ray observed emission. Variability on short time scales is common among IC 2391 members; the Kolmogorov-Smirnov test applied to the X-ray photon time series shows that approximately 46% of the IC 2391 members are variable at a confidence level $> 99\%$. A very fast rotating star of the cluster unambiguously shows X-ray rotational modulation, while indication of rotational modulation is found in another fast rotating star and in other two stars with unknown rotational period. The comparison of our data with those obtained with ROSAT/PSPC, nine years earlier, and ROSAT/HRI, seven years earlier, shows that there is no evidence of significant variability on these time scales.

Key words: X-ray: stars – Stars: activity – Stars: early-type – Stars: late-type – Open clusters and associations: individual: IC 2391

1. IC 2391: observation and data analysis

IC 2391 is a young ($\sim$ 30 Myr) relatively nearby ($\sim$162 pc) open cluster, rich of members ranging in spectral type from B to M. Since its members have just arrived on the Zero Age Main Sequence, they include a significant number of fast rotators, in particular stars in the saturation and supersaturation regime (Prosser et al. 1996; Randich 1998; James et al. 2000).

We analysed the Guaranteed Time XMM-Newton EPIC observation centered on the core of the cluster with a "clean" exposure time of 43 ks for MOS cameras and 31 ks for the pn one. The data have been processed using the XMM-Newton Science Analysis System version 5.4.1. The sources have been detected on the summed data set in the 0.3 - 7.8 keV bandpass using the Wavelet Detection code developed at INAF - Osservatorio Astronomico di Palermo (Damiani et al. 1997).

We have detected 99 X-ray sources, 24 identified with 31 cluster members. Detections are distributed along all spectral types. The two images in Fig. 1 show the DSS image of the cluster with the 30 arcmin field of view (FOV) of XMM-Newton EPIC, and the corresponding X-ray image of our EPIC field with circles indicating the detected sources.

2. Spectral analysis

We have been able to perform fits of EPIC pn spectra for the eleven X-ray brightest cluster members. The spectra in the 0.3 - 3.5 keV band and their best-fitting models for three X-ray bright members are displayed in Fig. 2; also the lower panel of each spectrum shows the fit residuals. We have performed a spectral analysis based on global-fitting, using the APEC code (Smith et al. 2001) implemented in the XSPEC software, in order to obtain the relevant temperature components and relative Emission Measure (EM) values.

We have found that a 2-T model fits the spectra of G, K and M type stars while a soft 1-T model describes the F type stars spectra. The result that dF stars have coronae softer than the other spectral types has been reported in other clusters, as in the Pleiades ([Briggs & Pye 2003), in NGC 2516 (Micela 2001), in Blanco 1 (Pillitteri et al. 2004), suggesting a reduced efficiency of the coronal heating mechanism in dF coronae.

In all cases the hydrogen column density N_H is consistent with the photometric derived value, 3.2×10^{19} cm^{-2}, computed from the average B-V color excess E_{B-V}=0.006 $\pm$ 0.005 (Patten & Simon 1996). The 2-T model fits result in the emission measure ratio EM2/EM1, being greater than 1, indicating the presence of a significant hot component. We have found a rise of the coronal temperature going from F to M stars (with respect to the solar one). A similar trend was found by Briggs et al. 2003 for Pleiades. Our spectra are systematically fitted with "depleted" abundances with respect to the solar ones. In particular, we found Z $\sim$ 0.1-0.2 $Z_\odot$ for K-stars and M-stars, $\sim$ 0.3 $Z_\odot$

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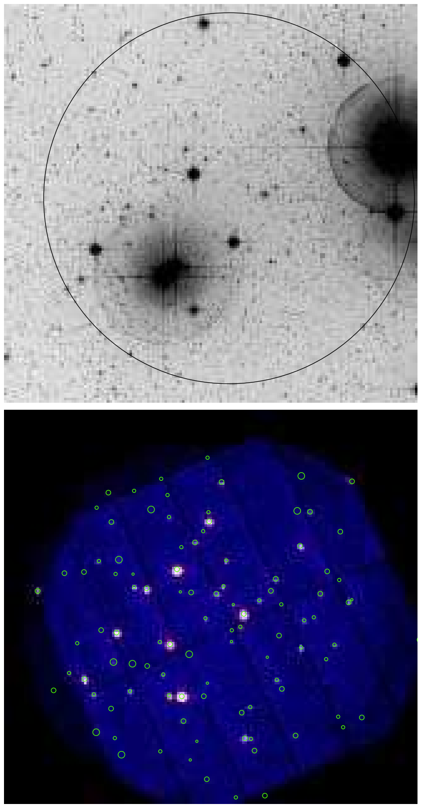

Figure 1. On top: the EPIC's 30 arcmin FOV in the IC 2391 DSS optical image. on the bottom: MOS1 + MOS2 + pn X-ray image of our EPIC field; circles show the detected sources.

for the G-star VXR45 and $\sim 0.5\ Z_\odot$ for the F-stars. Indications of subsolar abundances with a a similar trend of Z with spectral type have been found also for Pleiades by Briggs & Pye (2003).

The stellar structure models predict that stars earlier than A7 lack of, or have very thin, convective zones (required to generate magnetic activity), and hence lack of one key ingredient for an α-Ω dynamo. Therefore one expects no X-ray emission from these stars. Usually, for the binary systems unresolved in the X-ray band, the emission is attributed to late companions. This could be the case of the two IC 2391 early-type stars, detected in the field of view (Fig. 3). In particular, VXR46 is a B8.5 spectral type star flagged as single star by Patten & Simon (1996), but that could have a faint unknown companion, and VXR56, an A1 star flagged as spectroscopic binary by Patten & Simon (1996). Spectra of both VXR46 and VXR56 are fitted with a 1-T, low Z model, quite similar to the best-fit of later X-ray spectra, consistent with the hypothesis that X-ray emission came from later companions.

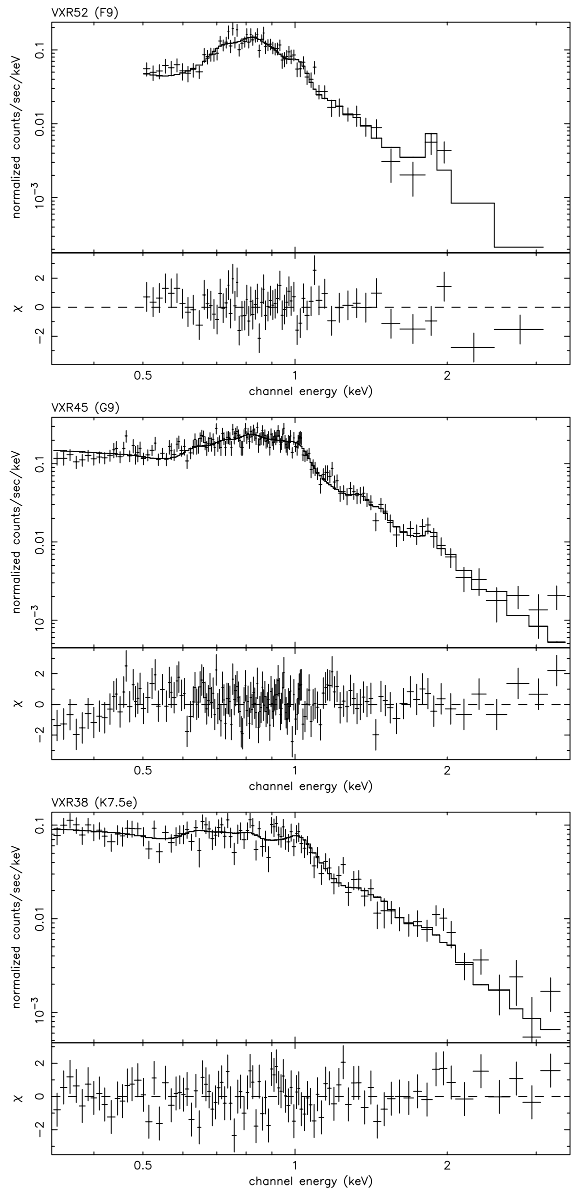

Figure 2. Spectra of three X-ray bright IC 2391 members in the XMM-Newton EPIC pn field. Each spectrum is labeled with the source name and its spectral type. The model and the residuals are also displayed.

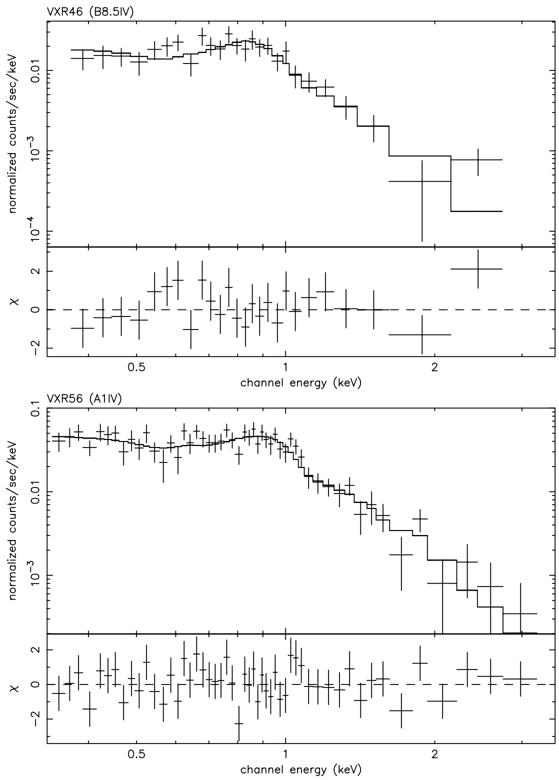

Figure 3. As in Fig. 2 for two early-type stars of the cluster.

3. Timing analysis

We have obtained light-curves in the (0.3-7.8) keV bandpass of the pn detected sources of which three examples are shown in Fig. 4 and Fig. 5. Variability on short-time scale is common among IC 2391 members, with various characteristics: flare-like variations, slow decreases and indication of rotational modulation in a few cases. The best evidence of rotational modulation has been observed in the dG9 star VXR45 for which the optical period is known. The X-ray light-curve (see Fig. 5 top panel) indicates a period of 20 ksec, to be compared with the optical period of 19 ksec, that makes VXR45 one of the fastest rotators in the supersaturated regime. The folding of the X-ray light-curve with the optical period (Fig. 5 bottom panel) confirms that we are observing rotational modulation (Marino et al. 2003a). The detection of X-ray rotational modulation implies an inhomogeneous distribution of coronal emitting structures. Also in other three stars, light-curves suggest that rotational modulation could be present (e.g. VXR38 in Fig. 4).

The Kolmogorov-Smirnov variability test (K-S) gives that on short-time scales, approximately 46% of the sources are variable at a confidence level greater than 99%. A summary of K-S test results is given in Table 1.

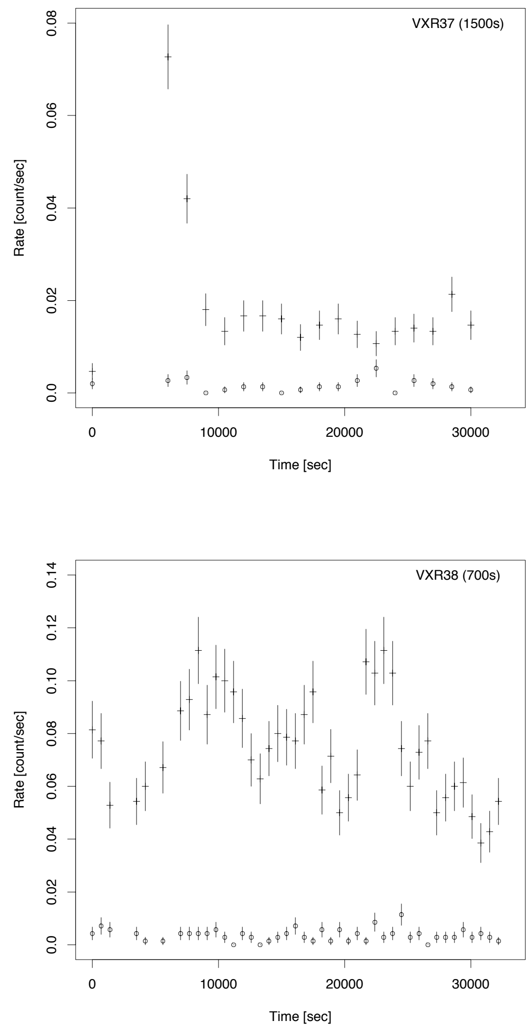

Figure 4. Light-curves of two X-ray bright IC 2391 members: VXR37 a dM star and VXR38 a dK7.5 star.

We have explored long-term variability of the late-type stars of IC 2391, comparing our data with published ROSAT data. We find that most of the stars have variations less than a factor of two on seven (HRI data) and on nine (PSPC data) year time scales. Since variability does not increase with longer time scale, it possible that stars much younger than the Sun (i.e. at ages < 1 Gyr) do not have long-term cycle or their cycle amplitudes are much smaller than the solar one. Similar indications have been found in other young open clusters observed with ROSAT, CHANDRA and XMM (e.g. Gagnè et al. 1995, Marino et

Table 1. Results of the K-S test

Confidence level[1]	Number of identified sources
>99%	**11 (46%)**
90%-99%	6 (29%)
≤90%	7 (25%)

[1]Confidence level for the rejection of the constant source hypothesis.

al. 2003b, Pillitteri et al. 2004). On the other hand, thanks to XMM-Newton, we have now growing evidence that cycle activity is present in other stars with age comparable to the solar one (Favata et al. 2004).

4. Summary

We have analysed the IC 2391 open cluster observed with XMM-Newton EPIC camera. We detected 31 out of the 42 members, or probable members of the cluster in the FOV, corresponding to 24 X-ray sources.

The spectral analysis of the X-ray brightest cluster members shows that a 2-T model fits the spectra of G to M type stars while a soft 1-T model describes the F type stars spectra. The early type stars VXR56 and VXR46 are consistent with the hypothesis that a later-type companion is responsible for the observed X-ray emission.

Variability on short time scales is common among IC 2391 members: the Kolmogorov-Smirnov test shows that approximately 46% of the sources are variable at a confidence level greater than 99%. Furthermore, a very fast rotating star of the cluster unambiguously shows X-ray rotational modulation, while indications of rotational modulation are found in other three stars of the cluster. Comparing our data with published ROSAT data, we do no find evidence for long-term variability analogous to the solar activity cycle, suggesting that cyclic variability is absent or very weak at cluster age (∼ 30 Myr).

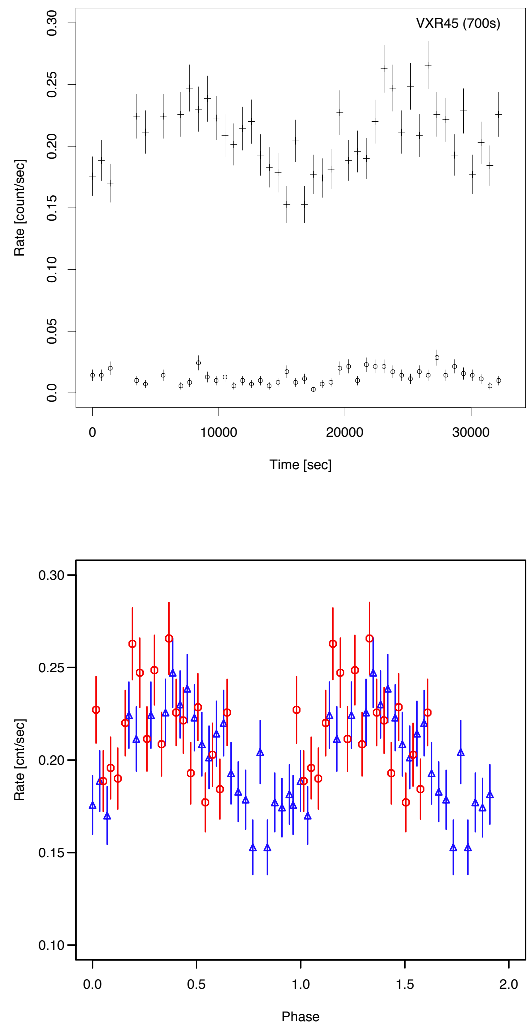

Figure 5. Light-curve (top) and X-ray data of VXR45 folded with the rotational period vs. phase (bottom). In the bottom, red circles are data points observed for t<19 ks since the observation start and blue triangles those observed for t>19 ks.

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