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X-ray rotational modulation of a supersaturated star in IC 2391

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Abstract. We present evidence of X-ray rotational modulation on VXR45, a young fast rotator star, member of IC 2391. It is a dG9 spectral type star whose rotational period and X-ray luminosity make it a supersaturated star. Our X-ray observation, made with EPIC/PN on XMM-Newton, covers about two photometric rotational periods. The detection of X-ray rotational modulation implies the presence of structural inhomogeneities. Possible interpretations are presented and discussed.

Key words. Open clusters and associations - individual: (IC2391) - stars: coronae - stars: late-type - stars: rotation - X-ray: stars

1. Introduction

Rotational modulation by a factor of two, due to the non-uniform distribution of emitting regions, is observed in solar coronal emission at any phase of the solar cycle. Since we cannot resolve stellar coronal structures, rotational modulation is one of the main methods to find evidence of non-uniform distribution of emitting stellar coronal regions and to investigate geometrical and physical properties of stellar coronal structures. Therefore, detection of X-ray rotational modulation on a very active star is particularly important to gain some insight into the physical mechanisms which operate on these stars. Observational data have shown that the most active stars, rotating above $\sim$ 15-20 km/s, reach a maximum X-ray luminosity such that L_x/L_{bol} saturates at $\sim 10^{-3}$, where L_{bol} indicates the star's bolometric luminosity (e.g. Vilhu, 1984). Saturation lacks a clear interpretation: it could be the effect of dynamo saturation, or rather could correspond to the total filling of the star's surface by active regions, as originally suggested by Vilhu (1984). Furthermore ROSAT observations have shown that very fast rotators ($v \sin i > 100$ km/s) exhibit a level of X-ray luminosity a factor of 3-5 below the saturated level (Randich, 1998). The origin of this phenomenon, named supersaturation by Prosser et al. (1996) is still unexplained and several hypotheses have been formulated. Supersaturation could be the result of an overall decrease of dynamo efficiency at very high rotation rate or the consequence of the redistribution of the radiative output due to the lower stellar gravity because of the enhanced rotation (Randich, 1998). A different explanation is that very rapid rotation could lead to a higher coronal temperature and to the shift of the X-ray emission out of the ROSAT passband (Randich, 1998). Stępień et al. (2001) suggested a common explanation for the supersaturation both in ultra fast rotators stars (UFRs) and in W UMa binaries via a decreased coverage of the stellar surface by X-ray emitting regions, although they noted that the physical mechanisms leading to such a decreased coverage can be different for the two star classes. For UFRs they proposed strong polar updrafts within a convection zone, driven by nonuniform heating from below. Thanks to the high sensitivity and broad bandpass of XMM-Newton, we can now test some of these hypotheses. However presently there is no consensus on phenomena occurring in a stellar corona either in the saturated or in supersaturated regime.

There have been several attempts to observe rotational modulation of stellar coronal emission in fast rotating stars (e.g. Collier Cameron et al., 1988; Vilhu, 1992; Agrawal & Vaidya, 1988; Kürster et al., 1992; Drake et al., 1994; Guedel et al., 1995; Kürster et al., 1997; Audard et al., 2001; García-Alvarez et al., 2003) in order to find a possible signature of non-uniform distribution of emitting coronal regions. In most cases the results were affected by frequent superimposed flares or poor sampling over more than one rotation period (e.g. Collier Cameron et al., 1988; Vilhu, 1992). Probably one of the best examples of X-ray rotational modulation is that reported by

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Guedel et al. (1995): X-ray flux variations within a factor of two in the ROSAT All-Sky Survey light-curve of EK Draconis, a dG0 star with an optical rotation period of 2.7-2.8 day, just slightly too long for the star to be in the saturation regime. Guedel et al. (1995) found that the X-ray light curve is significantly variable in the ROSAT energy band with the emission from the cooler plasma being responsible for the rotational modulation but with the hot plasma approximately constant. On the other hand Kürster et al. (1997) find only a partial evidence of X-ray rotational modulation of the X-ray flux implying structural inhomogeneities in the saturated star AB Dor. Similar results are found in BeppoSAX observations of AB Dor by Franciosini et al. (2002). On the contrary Guedel et al. (2001) find no evidence for X-ray rotational modulation in a XMM-Newton observation of AB Dor. Analogously also Singh et al. (1999) find no indication of X-ray rotational modulation both in the saturated fast rotators HD197890, of similar spectral type of VXR45, and in Gl890, observed with ASCA.

In this *Letter* we present the unambiguous detection of X-ray rotational modulation in a fast rotating star member of IC 2391: VXR45, observed with XMM-Newton/EPIC/PN. VXR45 is a dG9 star with a very short photometric period of 0.223 days (Patten & Simon, 1996), and $v \sin i > 200$ km/s (Stauffer et al., 1997). Its $\log L_x$, as measured with ROSAT, ranges between 30.12 and 30.10 erg/s, but the range of $\log(L_x/L_{bol})$ between -3.60 and -3.62 puts the star below the saturation level, making it a supersaturated star.

2. The observation and data analysis

The observation analyzed here was dedicated to the young open cluster IC 2391 as part of EPIC/PN GTO time and it has been performed in November 20, 2001. Here we present EPIC/PN data relative to the star VXR45, located at RA (J2000) = $8^h\ 42^m\ 14.8^s$, Dec (J2000) = $-52^o\ 56'\ 01''$; it has V=10.70 and B−V=0.81.

The nominal duration of the observation is 50 ks; after the selection of the good time intervals (i.e. those of adequately low background emission) we retained $\sim$ 33 ks. The X-ray data reduction was performed with the *SAS* 5.4.1 software [1]. The star is one of the brightest in the field and it is located $3.96'$ off-axis, far from the EPIC/PN CCD gaps.

2.1. Light-curve

In order to determine the count rate, we extracted photons from a circular region centered on the source and selected so as to include $\sim$ 80% of the source photons (Ghizzardi, 2001; Saxon, 2002), corresponding to a radius of $37''$. The total number of photon counts in the 0.3 - 7.8 keV band amounts to 7431; the local background has been determined from a source-free region near VXR45 for a total of 506 counts. Fig. 1 shows the light-curves of VXR45 obtained in the 0.3 - 7.8 keV band (top) and of the corresponding background (bottom). The X-ray modulation, with a period very similar to the photometric one (0.223 days = 19.3 ksec), is clearly evident in Fig. 1. Note that other short term variability not due to X-ray rotational modulation may also be present in the light-curve but the data clearly show that the variability observed cannot be explained with individual large flares.

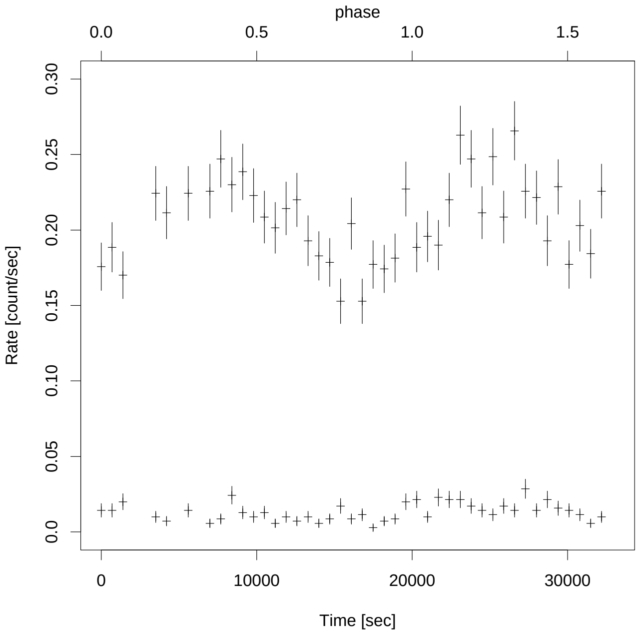

Fig. 1. X-ray light-curve of VXR45 (top) and background (bottom) as seen with EPIC/PN in the 0.3 - 7.8 keV band, time bins are 700 sec long. The photometric rotational period of $\sim$ 19.3 ksec is well visible.

In order to confirm that modulation of the X-ray emission is due to rotation we have folded the X-ray light-curve with the photometric rotational period as shown in Fig. 2. Phase-related variability is clearly evident; the X-ray variations in the light-curve are $\sim$ 30% of the average count rate. Using a radius of 0.9 $R_\odot$ adequate for the star's age and spectral type (Siess et al., 2000) and knowing P_{rot} and $v \sin i$, we obtain an inclination angle close to 90^o. This makes the star an ideal target to detect rotational modulation due to a longitudinal structure. In order to explore if differences exist between modulation of cool and hot plasma as in EK Dra (Guedel et al., 1995) we show in Fig. 3 the ratio between the hard count rate (1.5 - 3.5 keV) and the soft count rate (0.3 - 1.5 keV) versus the time [2]. There is no strong evidence of spectral changes in the soft and hard passbands, and the χ^2 test applied to the hard/soft count-rate ratio confirms that the variations observed are those expected in a random sample. We tried

[1] available at http://xmm.vilspa.esa.es/sas

[2] The break point 1.5 keV separates the line-dominated Fe L shell + *NeIX/X* + *MgXI/XII* region from the part dominated by bremsstrahlung continuum. Hence the adopted ratio maps on temperature.

different energy boundaries in soft and hard bands definition and the result does not change. The lack of modulation in the hard (1.5 - 3.5 keV)/soft (0.3 - 1.5 keV) ratio is consistent with the hypothesis that hotter and cooler plasmas are co-spatial. On the contrary the X-ray rotational modulation of EK Dra (Guedel et al., 1995) was detected predominantly in the soft ROSAT band (0.1 - 0.4 keV), that in practice is outside the XMM-Newton bandpass, while it was approximately constant in the hard ROSAT band (0.4 - 2 keV).

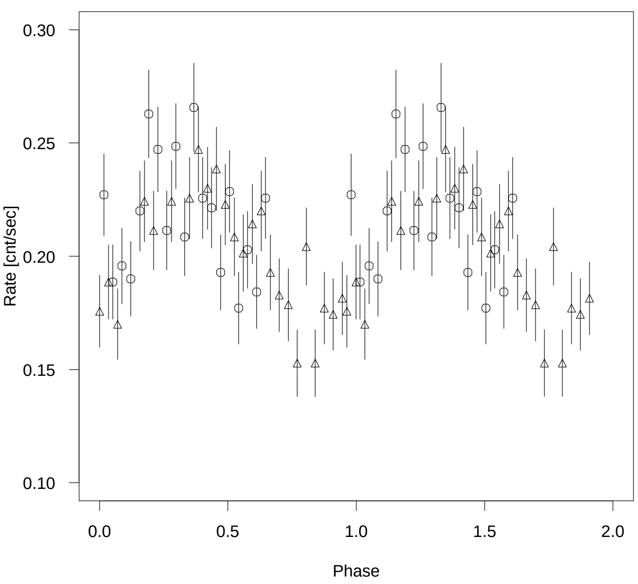

Fig. 2. X-ray data of Fig. 1 folded with the rotational period vs. phase. Circles are points observed at t < 0.223 days (the photometric period) since the observation start and triangles those observed at t > 0.223 days. For clarity we report two photometric periods.

2.2. Count Rate, Flux and Luminosity

We extracted the spectrum of the single and doubly flagged PN events with energy in 0.3 - 3.5 keV band that contains the essential part of the source (Fig. 4). We found that a 2-T APEC spectral model provides the best fit to the data, as measured with a χ^2 test (χ^2_ν=1.01 for 189 degrees of freedom). The N_H value was fixed to $10^{19.5}$ cm^{-2} (Patten & Simon, 1996). The two temperatures in the model, as well as the corresponding emission measures and the abundance Z were allowed to vary as free parameters in the fitting process. We obtained temperatures of 0.61 keV and 1.19 keV, with a ratio of emission measure of $EM_{cold}/EM_{hot} \approx 1.42$, and $Z \sim 0.27 Z_\odot$. The spectral fit yielded an X-ray flux, in the 0.3 - 3.5 keV band, of 4.77 $\times$ 10^{-13} ergs cm^{-2} s^{-1} corresponding to an average X-ray luminosity of 1.50 $\times$ 10^{30} erg/s adopting a distance of 162 pc (Patten & Simon, 1996) and $\log(L_x/L_{bol}) = -3.54$. Assuming that the spectrum does not change, as suggested

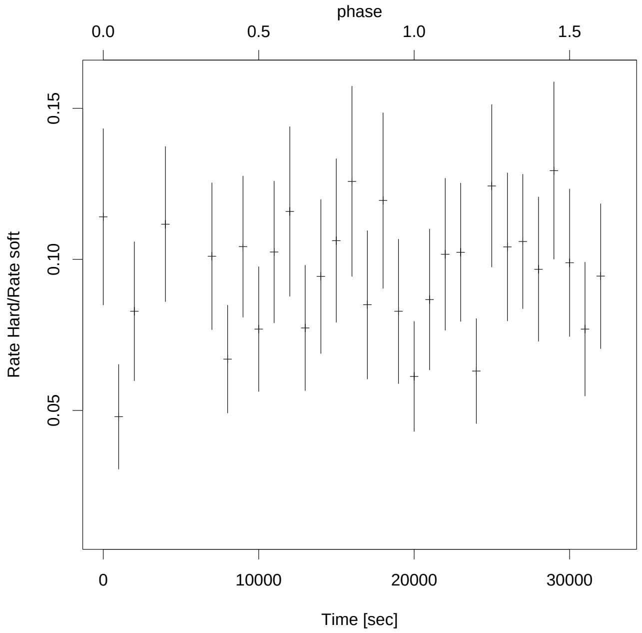

Fig. 3. Ratio of hard count rate (1.5 - 3.5 keV) to soft count rate (0.3 - 1.5 keV) vs. time for VXR45, time bins are 1000 sec long. There is no evidence for modulation of the ratio.

by Fig. 3, the peak to peak variations of $\log(L_x)$ are 30.04 - 30.28 and $\log(L_x/L_{bol})$ ranges between -3.44 and -3.68. These intervals include the values observed with ROSAT.

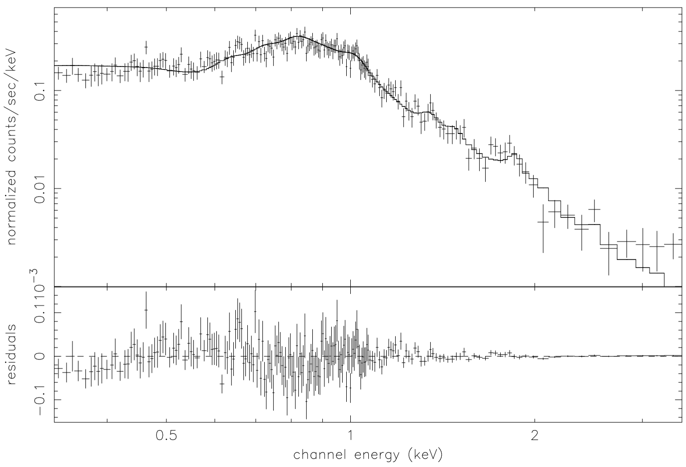

Fig. 4. X-ray spectrum of VXR45 with the best fit model superimposed.

3. Discussion and conclusions

Notwithstanding the wealth of available data, X-ray rotational modulation is very hard to detect in active stars, as discussed in the Introduction. We observed VXR45 a fast rotator member of IC 2391, with XMM-Newton/EPIC/PN for $\sim$ 33 ks, corresponding to $\sim$ 2 photometric rotational periods. We find unambiguous evidence of X-ray rotational modulation from a supersaturated star with a level of X-ray emission $\sim$ 100 times larger than the solar one. We note that we detect X-ray rotational modulation in the 0.3 - 7.8 keV energy band while the X-ray rotational modulation of EK Dra (Guedel et al., 1995), was detected in the softer and smaller ROSAT energy band (0.1 - 0.4 keV); furthermore VXR45 is a dG9 supersaturated star located on the left of the $\log L_x/L_{bol}$ vs. P_{rot} plot (being a very fast rotator) (Randich, 1998) while EK Dra is a dG0 with a similar $\log(L_x/L_{bol})=-3.53$ but a rotation period 10 times slower that puts it on the right side of the same plot and just before the saturated regime [3]. On the other hand X-ray rotational modulation has been detected in at least some observations in AB Dor, a star in the saturated regime, while it has not been detected in other saturated stars (HD 197890, Gl890).

VXR45 was extensively observed with ROSAT, but an analysis of the PSPC observations of those IC 2391 cluster members whose photometric rotational period was known (including VXR45), failed to detect X-ray rotational modulation in any of the X-ray light-curves (Patten & Simon, 1996). These authors note that the segments of their observations were not optimally spaced for this kind of analysis. Furthermore, they studied the time variations of the PSPC VXR45 light-curve, with several statistical tests but obtaining contradicting results.

The new XMM-Newton observation allows us to detect X-ray rotational modulation thanks to the quasi-continuous time coverage, spanning twice the photometric period. The detection of X-ray rotational modulation, implying the presence of non-uniformly distributed active regions on the star, is in some sense surprising, since bright coronae variations are typically due to flares.

Thanks to the broad energy bandpass of XMM-Newton, we can exclude the hypothesis that this supersaturated star has higher coronal temperature that may cause most of the X-ray emission to be outside the ROSAT passband. The detection of X-ray rotational modulation indicates that the star is not completely covered by active regions. Furthermore, as shown in Fig. 3 there is no strong evidence for spectral variations in the soft and hard passbands. This is consistent with the hypothesis that the modulation we observe is mainly due to a longitudinal concentration of X-ray emitting material, and that at all times the emission is largely due to the same mixture of emitting structures. The average surface X-ray flux, derived from the X-ray luminosity divided by the stellar surface is 3.0×10^7 erg s^{-1} cm^{-2} and ranges between 3.9×10^7 and 2.2×10^7 erg s^{-1} cm^{-2}. These surface X-ray fluxes values are a bit higher than those of solar active regions (Orlando et al., 2001) but intermediate between active regions and solar flares (Reale et al., 2001), and the X-ray temperatures are also intermediate between solar active regions and the flares.

[3] L_x/L_{bol} has been obtained taking $L_x = 10^{29.92}$ erg/s (Guedel et al., 1995) and $L_{bol} = 2.70 \times 10^{33}$ erg/s computed using the transformations by Flower (1996).

Our finding of a incomplete coverage of supersaturated stellar surface are qualitatively in agreement with the explanation proposed by Stępień et al. (2001). A possible scenario is that a large polar region is always present and another region at lower latitude is responsible for the observed modulation, albeit other scenarios are possible. Observations of other saturated and supersaturated stars will help in clarifying this picture.

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References

Agrawal, P. C. & Vaidya, J. 1988, MNRAS, 235, 239
Audard, M., Güdel, M., & Mewe, R. 2001, A&A, 365, L318
Collier Cameron, A., Bedford, D. K., Rucinski, S. M., Vilhu, O., & White, N. E. 1988, MNRAS, 231, 131
Drake, J. J., Brown, A., Patterer, R. J., et al. 1994, ApJ, 421, L43
Flower, P. J. 1996, ApJ, 469, 355
Franciosini, E., Pallavicini, R., Maggio, A., Cutispoto, G., & Tagliaferri, G. 2002, in 1st Potsdam Thinkshop on Sunspots and Starspots; Poster Proceedings of the Meeting, Potsdam, Federal Germany, 2002, p. 53.
García-Alvarez, D., Foing, B. H., Montes, D., & et al. 2003, A&A, 397, 285
Ghizzardi, S. 2001, "EPIC-MCT-TN-011", Tech. rep., EPIC Milano Calibration Team
Guedel, M., Audard, M., Briggs, K., et al. 2001, A&A, 365, L336
Guedel, M., Schmitt, J. H. M. M., Benz, A. O., & Elias, N. M. 1995, A&A, 301, 201
Kürster, M., Schmitt, J. H. M. M., Cutispoto, G., & Dennerl, K. 1997, A&A, 320, 831
Kürster, M., Schmitt, J. H. M. M., & Fleming, T. A. 1992, in ASP Conf. Ser. 26: Cool Stars, Stellar Systems, and the Sun, 109
Orlando, S., Peres, G., & Reale, F. 2001, ApJ, 560, 499
Patten, B. M. & Simon, T. 1996, ApJS, 106, 489
Prosser, C. F., Randich, S., Stauffer, J. R., Schmitt, J. H. M. M., & Simon, T. 1996, AJ, 112, 1570
Randich, S. 1998, in ASP Conf. Ser. 154: Cool Stars, Stellar Systems, and the Sun, 501
Reale, F., Peres, G., & Orlando, S. 2001, ApJ, 557, 906
Saxon, R. D. 2002, "XMM-CCF-REL-116", Tech. rep., XMM-SOC
Siess, L., Dufour, E., & Forestini, M. 2000, A&A, 358, 593
Singh, K. P., Drake, S. A., Gotthelf, E. V., & White, N. E. 1999, ApJ, 512, 874
Stauffer, J. R., Hartmann, L. W., Prosser, C. F., et al. 1997, ApJ, 479, 776
Stępień, K., Schmitt, J. H. M. M., & Voges, W. 2001, A&A, 370, 157
Vilhu, O. 1984, A&A, 133, 117
Vilhu, O. 1992, in IAU Symp. 151: Evolutionary Processes in Interacting Binary Stars, 61