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Rotational modulation of X-ray emission in Orion Nebula young stars

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Abstract. We present the detection of rotational modulation of X-ray emission from the Orion Nebula Cluster (ONC) young stars. This result is obtained with the Chandra Orion Ultradeep Project (COUP) thanks to the exceptional length of the observation: 10 days of ACIS integration during a time span of 13 days. We apply the Lomb Periodogram method to the X-ray light curves; comparing the X-ray modulation periods with published rotation periods, we find that the two are statistically related. X-ray rotational modulation is often observed in stars with saturated activity levels, indicating a substantial inhomogeneity in the spatial distribution of active regions. Saturation is thus not due to the filling of the stellar surface with active regions.

Key words. stars: activity – stars: coronae – stars: pre-main sequence – stars: rotation – open clusters and associations: individual (Orion Nebula Cluster) – X-rays: stars

1. Introduction

Observations of rotational modulation of X-ray emission from low mass stars can yield information on the spatial distribution of the emitting plasma. Such observations are to date scarce because typical X-ray observations are shorter than most stellar rotation periods. Exceptions are the detection for VXR45, a fast rotating (P_{rot}=0.22d) G9 ZAMS star (Marino et al. 2003), for AB Dor (Hussain et al. 2005), a K0 ZAMS star with P_{rot}=0.5d and, possibly, for EK Dra (P_{rot}=2.7d) by Guedel et al. (1995). The COUP collaboration has obtained an almost uninterrupted 850ks long Chandra ACIS observation of the ONC (Getman et al. 2005), detecting 1616 sources in the 17'x17' FOV. We thus have the unique opportunity to study rotational modulation of X-ray emission on a large sample of PMS stars.

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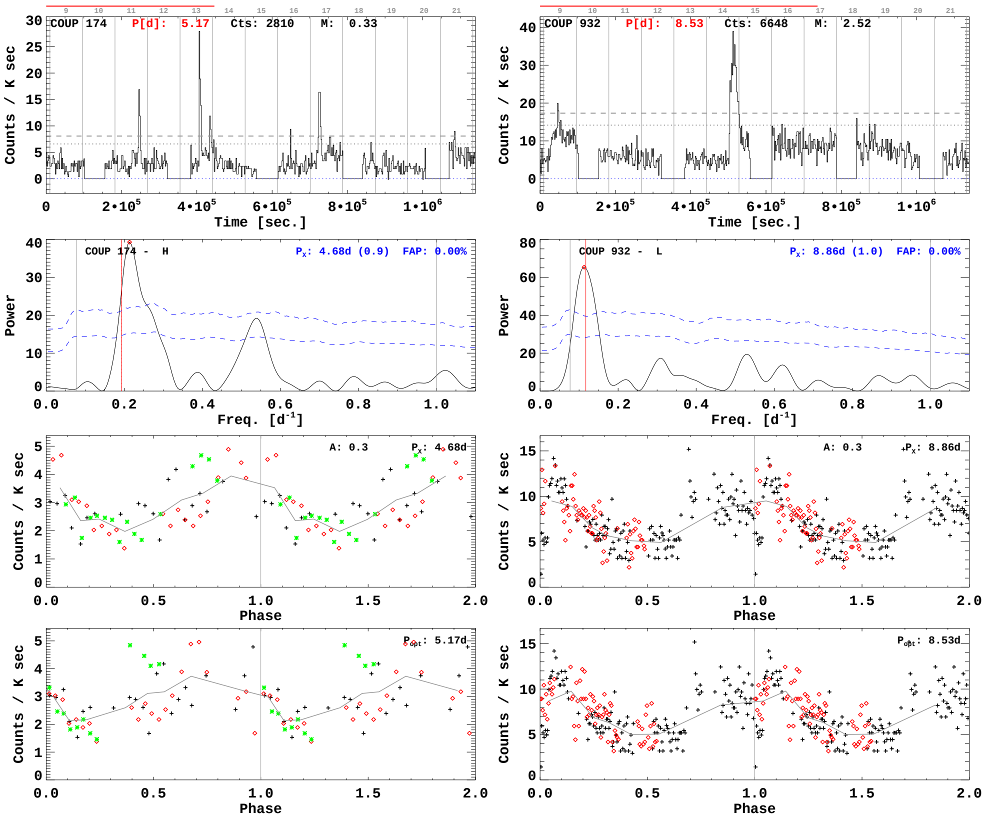

Fig. 1. Upper panels: light curves for COUP sources 174 and 932. Rotation period, extracted net counts and stellar mass are given in the upper part of the plot. Horizontal segments above the light curves indicate the length of one rotation period. Second row: periodograms. The vertical line indicates the frequency $1.0/P_{opt}$. Dashed curves indicate 1% and 0.1% FAP thresholds. The most likely X-ray period is reported in the upper right corner (with in parenthesis the ratio P_X/P_{opt}) along with the FAP. Third row: light curves folded with P_X. Different symbols indicate data-points belonging to different modulation cycles. The solid line indicates the average count-rate as a function of phase. Fourth row: light curves folded with the optically determined rotation period.

2. Sample and analysis method

We restrict our study of X-ray rotational modulations to 233 stars with more than 100 detected X-ray photons, with rotational period P_{opt} known from optical studies (Herbst et al. 2002; Carpenter et al. 2001; Herbst et al. 2000; Stassun et al. 1999) and with $P_{opt} > 2$ days.

We apply the Lomb Normalized Periodogram (LNP) method (Scargle 1982) to binned X-ray light curves. In an attempt to exclude flares, we analyze both the original light curves and light curves that are trimmed above a count-rate threshold determined from the distributions of count-rates. We search the LNPs for peaks in the period range 2-13 days and we compute False Alarm Probabilities (FAPs) taking into account non-rotational variability (e.g. flares) with a timescale < 8 hour.

3. Results and conclusions

Figure 1 illustrates two cases in which modulation is detected with X-ray periods similar to P_{opt}. We show, from top to bottom: ACIS light-

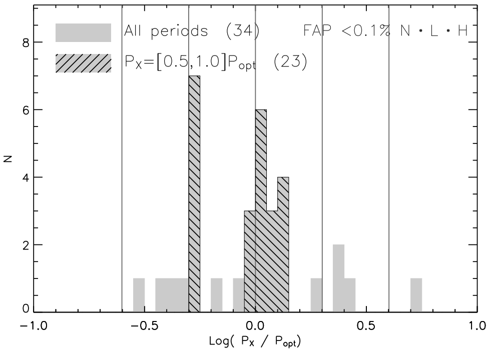

Fig. 2. Distribution of the logarithm of the ratio between X-ray and optically determined periods for X-ray periods with FAP < 0.1%. Vertical lines indicate ratios of 1/4, 1/2, 1, 2 and 4.

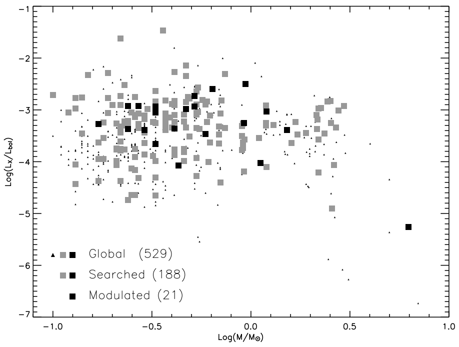

Fig. 3. Log(Mass) vs. $Log(L_X/L_{bol})$ for for all COUP sources with >100 ACIS counts (*global*), for the sample for which we performed the period analysis (*searched*) and for the subsample of this latter of "bona fide" X-ray modulated stars (*modulated*).

curves, periodograms and light curves folded with both P_X and P_{opt}.

Figure 2 shows the distribution of the logarithm of the ratio between X-ray and optically determined periods for the 34 sources for which our analysis yielded an X-ray period with FAP<0.1% both for flare-filtered and unfiltered light curves. Two peaks are visible, corresponding to $P_X \sim P_{opt}$ and to $P_X \sim 0.5P_{opt}$. We interpret this plot as evidence that X-ray periods are indeed related to the optically determined rotation periods, even though we often observe aliases of the real period. Several X-ray periods do not lie in one of the two main peaks of the P_X/P_{opt} distribution; extensive Monte Carlo simulations of light curves that include flares, analyzed with our method, indicate that these are likely spurious detections due to the presence of non-rotational variability (e.g. flares) that was not fully removed or taken into account in the calculation of FAPs. We thus define a "bona fide" sample of stars with rotationally modulated X-ray emission that includes only stars whose P_X/P_{opt} falls in one of the two main peaks as depicted by the hatched area in Fig. 2.

Figures 3 shows the L_X/L_{bol} vs. mass scatter plot for all the ONC members with > 100 ACIS counts, the stars considered in the present study (i.e. those with P_{rot} >2d) and our "bona fide" subsample of modulated stars. We note that: 1) the modulation is observed at all masses; 2) we detect modulation in saturated stars (i.e. $L_X/L_{bol} \sim 10^{-3}$). We note moreover (not shown) that the modulated sample is biased toward the most X-ray active stars. We interpret this as an onservational bias. Based on the observation of rotational modulation in $\sim$ 10% of our search sample, our main conclusions are: *i*) X-ray emitting plasma is inhomogeneously distributed in longitude; *ii*) dominant emitting structures are likely compact with sizes $\lesssim$ $R_\star$; *iii*) saturation of activity, $L_X/L_{bol} \sim 10^{-3}$, is not due to the filling of the stellar surface with active region.

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