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Rotational Modulation of X-ray Emission from T Tauri Stars

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Abstract. We have modeled the rotational modulation of X-ray emission from T Tauri stars assuming that they have isothermal, magnetically confined coronae. By extrapolating surface magnetograms we find that T Tauri coronae are compact and clumpy, such that rotational modulation arises from X-ray emitting regions being eclipsed as the star rotates. Emitting regions are close to the stellar surface and inhomogeneously distributed about the star. However some regions of the stellar surface, which contain wind bearing open field lines, are dark in X-rays. From simulated X-ray light curves, obtained using stellar parameters from the Chandra Orion Ultradeep Project, we calculate X-ray periods and make comparisons with optically determined rotation periods. We find that X-ray periods are typically equal to, or are half of, the optical periods. Further, we find that X-ray periods are dependent upon the stellar inclination, but that the ratio of X-ray to optical period is independent of stellar mass and radius.

Key words. Stars: pre-main sequence – Stars: magnetic fields – Stars: coronae – Stars: activity – Xrays: stars – Stars: formation

1. Introduction

One of the results from the Chandra Orion Ultradeep Project (COUP) was the detection of significant rotational modulation of X-ray emission from low mass pre-main sequence stars. The detection of such modulation suggests that the coronae of T Tauri stars are compact and clumpy, with emitting regions that are inhomogeneously distributed across the stellar surface, and confined within magnetic structures that do not extend out to much beyond a stellar radius (Flaccomio et al. 2005). There is also evidence for much larger magnetic loops, possibly due to the interaction with surrounding circumstellar disks (Favata et al. 2005; Giardino et al. 2006). A model already exists for T Tauri coronae, where complex magnetic field structures contain X-ray emitting plasma close to the stellar surface, whilst larger magnetic loops and open field lines are able to carry accretion flows (Jardine et al. 2006; Gregory et al. 2006a).

We use surface magnetograms derived from Zeeman-Doppler imaging to extrapolate the coronae of T Tauri stars (Fig. 1) using stellar parameters taken from the COUP dataset (Getman et al. 2005). The method for extrapolating the magnetic field is described

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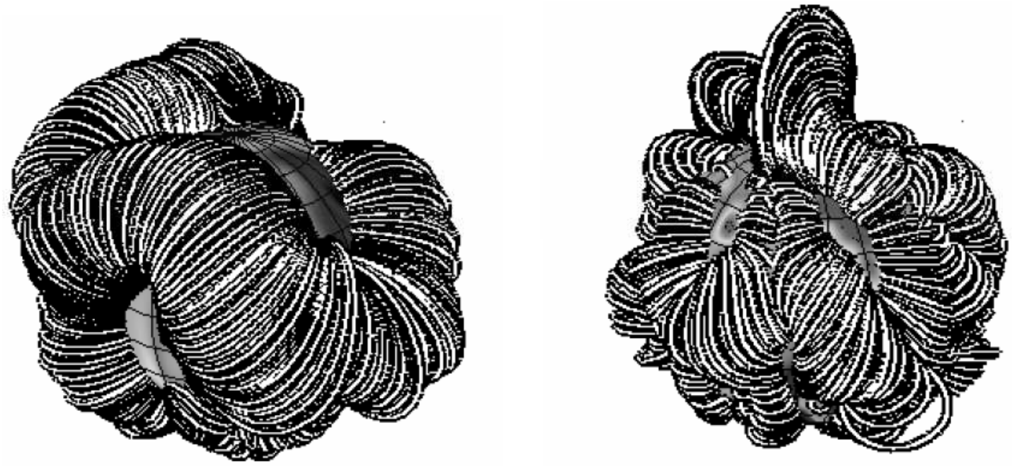

Fig. 1. Closed coronal structures showing field lines which contain X-ray emitting plasma, extrapolated from surface magnetograms of LQ Hya (left) and AB Dor (right). The magnetic structures are compact and inhomogeneously distributed about the stellar surface.

by Jardine et al. (2006) and Gregory et al. (2006a). By considering isothermal coronae in hydrostatic equilibrium we have simulated X-ray light curves, for a range of stellar inclinations, and calculated X-ray periods using the Lomb Normalized Periodogram method (Gregory et al. 2006b). We compare our results with those of Flaccomio et al. (2005), who demonstrate that those COUP stars which show clear evidence for rotationally modulated X-ray emission appear to have X-ray periods which are either equal to the optically determined rotation period $P_X = P_{opt}$ or are half of it $P_X = 0.5P_{opt}$.

2. X-ray and Optical Periods

We find that X-ray emitting regions are distributed across the stellar surface, but some regions remain dark in X-rays. Emitting regions are close to the star and enter eclipse as it rotates. Clear rotational modulation of X-ray emission is apparent from plots of emission measure (EM) against rotational phase (Fig. 2). The coronal magnetic field considered in Fig. 1 (left panel) has two dominant emitting regions in opposite hemispheres. Flaccomio et al. (2005) argue that such a field structure would give rise to $P_X = 0.5P_{opt}$. For large stellar inclinations we find that this is the case, but for small inclinations, our field structure with two dominant emitting regions in opposite hemispheres, gives rise to $P_X = P_{opt}$. Thus the X-ray period depends on stellar inclination (Fig. 4), but the ratio of X-ray to optical period is independent of stellar mass and radius (Gregory et al. 2006b). By selecting inclinations at random, and using different coronal magnetic field structures (Fig. 4) we find that the amplitude of modulation strongly depends upon the stellar inclination and the distribution of X-ray emitting regions across the stellar surface. In some cases an X-ray period of $0.5P_{opt}$ is found, but in the majority of cases, T Tauri coronae are so complex that it is difficult to disentangle the exact contribution to the X-ray light curve from any particular emitting region. Therefore in the majority of cases we only recover X-ray periods which are equal to optical periods.

3. Discussion

Jardine et al. (2006) and Gregory et al. (2006a) have shown that stars which have coronae that would naturally extend to beyond the corotation radius would have their outer corona stripped by the presence of a disk. Any field

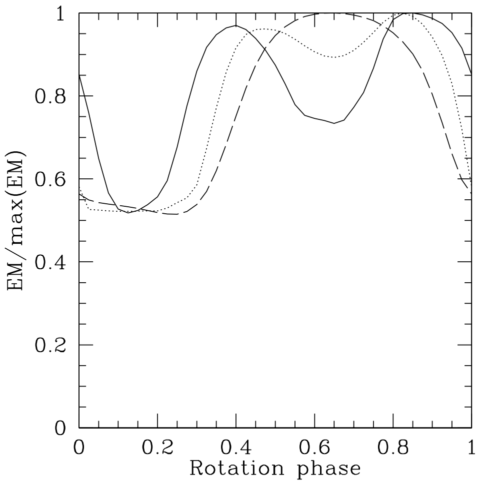

Fig. 2. The variation in X-ray emission measure (EM) with rotation phase for the LQ Hya-like coronal structure shown in Fig. 1, for inclinations of 30 ° (*dashed*), 60 ° (*dotted*) and 90 ° (*solid*). There is clear rotational modulation of X-ray emission.

line which passed through the disk at, or within the corotation radius was assumed to have the ability to carry an accretion flow and was therefore considered to be "mass-loaded" and set to be dark in X-rays. We find that the influence of a disk makes no difference to the value of P_X and very little difference to the amplitude of modulation. Therefore the presence of a disk does not influence rotational modulation of X-ray emission, however, active accretion might and should be considered in future work.

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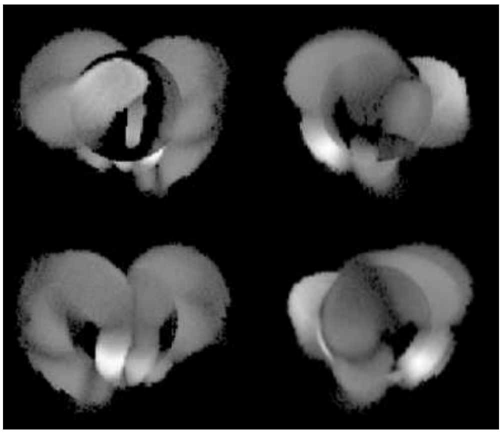

Fig. 3. X-ray images corresponding to the LQ Hya field structure at an inclination of 90 ° - brighter regions indicate more X-ray emission. *Upper left* is for a rotational phase of 0.1, where the brightest of the two dominant emitting regions is in eclipse, *upper right* 0.4, where both of the dominant emitting regions are visible, *lower left* 0.65 where the brightest emitting region is visible and *lower right* 0.85, where once again both of the dominant regions can be seen.

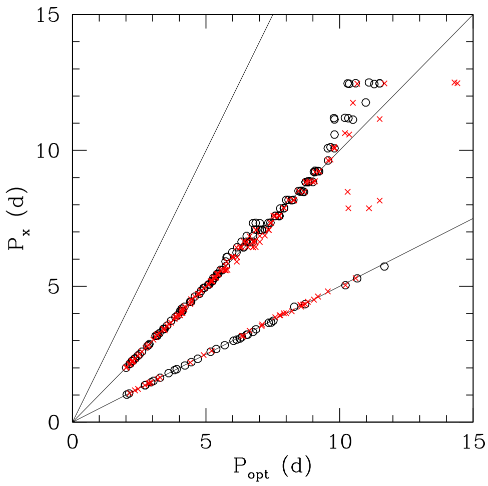

Fig. 4. Comparison between our calculated X-ray periods and observed optical periods for the coronal fields in Fig. 1 (*circles/crosses* for the LQ Hya/AB Dor-like coronal structures). X-ray periods have been calculated for COUP stars from Flaccomio et al. (2005) with randomly assigned inclinations. Lines represent $P_X = [0.5, 1, 2]P_{opt}$.