Mon. Not. R. Astron. Soc. **355,** 1066–1072 (2004) doi:10.1111/j.1365-2966.2004.08391.x

The changing corona of LQ Hya

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Accepted 2004 September 3. Received 2004 September 2; in original form 2004 May 17

ABSTRACT

We have used Zeeman–Doppler maps of the surface magnetic field of the rapidly rotating ($P_{\rm rot}$ = 1.61 d) K2 star LQ Hya to extrapolate the coronal field, assuming it to be potential. Using the data sets from the observations in 2000 December and 2001 December, chosen for their excellent phase coverage, we show how the global structure of the magnetic field can change drastically in the space of one year. In 2000 December the large-scale field resembled a tilted dipole, with most of the open field emerging in two mid-latitude regions separated by 180° of longitude. One year later, most of the open field emerged at the pole, and the large-scale field most closely resembled an aligned dipole albeit with a significant contribution from many smaller scale east–west arcades of magnetic field-lines. This appears to be quite different from what is seen on the Sun, where the emergence of many east–west bipoles occurs towards cycle maximum, when the large-scale heliosphere field resembles a tilted, not an aligned, dipole. We have also modelled the X-ray emission (assuming an isothermal corona) and find that, despite the changes in the field structure, the magnitude and the rotational modulation of the emission measure ($10^{51.15}$ cm^{-3}) are largely unchanged. While the emission measure is close to observed values, the density ($10^{9.8}$ cm^{-3}) is somewhat lower.

Key words: stars: activity – stars: coronae – stars: imaging – stars: individual: LQ Hya – stars: spots.

1 INTRODUCTION

The changes in the Sun's magnetic field over its cycle are well known and have been studied for many years. In the case of solar-like stars, however, observations of the surface distribution of flux are much more difficult to obtain. The technique of Doppler imaging allows us to map the surface brightness of rapidly rotating stars, revealing spot patterns across the stellar disc. In contrast to what is observed on the Sun, these spots can be found at all latitudes, even up to the rotation pole (Strassmeier 1996). These observations have been explained by the emergence of flux tubes at high latitudes due to the strong Coriolis forces present in rapid rotators acting on the flux tubes in the convective interior (Schuessler & Solanki 1992). While the distribution of spots may be very different from that on the Sun, in many cases the latitudinal differential rotation is surprisingly similar, even on stars rotating much more rapidly than the Sun (Donati & Collier Cameron 1997).

More complete information on the nature of stellar magnetic fields has become available with the advent of Zeeman–Doppler imaging (ZDI). This is a technique which uses high-resolution circularly polarized spectra to map the magnetic flux distribution of rapidly rotating stars (Semel 1989). Stars that have been studied to date, AB Dor ($P_{\rm rot}$ = 0.514 d), LQ Hya ($P_{\rm rot}$ = 1.6 d) and the subgiant component of the RS CVn binary HR 1099 ($P_{\rm rot}$ = 2.8 d), show patterns unlike that of the Sun with flux at all latitudes, and a strong azimuthal field that can form a unidirectional ring at high latitudes (Donati & Collier Cameron 1997). Jardine, Collier Cameron & Donati (2002a) have used maps obtained from Zeeman–Doppler images to extrapolate the coronal topology of the star AB Dor based on data acquired in 1995 December and 1996 December. This revealed that the large-scale field structure was dominated by a north–south arcade that extended right across the rotation pole. This arcade separated two large open field regions of opposite polarity centred at mid- to low latitudes. This work assumed that the coronal field was potential. An extension of this to non-potential fields, however, showed broadly the same field structure (Hussain et al. 2002). In turn, Jardine et al. (2002b) followed this with a model of the X-ray emission of the star based on the extrapolated coronal field. This model reproduced the observed densities and the magnitude of the X-ray emission, and showed that much of the X-ray emission would be expected to come from high latitudes where it would remain in view as the star rotated. Thus the X-ray emission would show very little rotational modulation. This is consistent with the *BeppoSAX* observation of two flares on AB Dor (Maggio et al. 2000), which showed no rotational self-eclipse of the flaring plasma during the flare decay phase which lasted for more than one rotation cycle.

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The other single star for which maps of the surface magnetic field are available is LQ Hya. This star is similar in mass to AB Dor ($1\,M_{\odot}$ for AB Dor and $0.95\,M_{\odot}$ for LQ Hya), and both stars are about 40 to 50 Myr old. Both stars have a convective zone that is about 30 per cent of the stellar radius (Kitchatinov, Jardine & Donati 2000). Where these stars do differ, however, is in their rotation rate, with AB Dor spinning 3.4 times more quickly than LQ Hya. In 1982 the star was found by Eggen (1984) and Fekel et al. (1986) to be photometrically variable. Since then, long-term photometric studies have been carried out by Jetsu (1993) and Cutispoto, Messina & Rodonò (2001). The observed variability of LQ Hya is caused by its magnetic activity, which has been well established by the detection of widespread surface magnetic fields (Basri & Marcy 1994; Donati & Collier Cameron 1997). Photometric studies of LQ Hya show spotted regions to occupy up to 23 per cent of the total stellar surface (Alekseev & Kozlova 2003). These studies have shown star-spots to be localized at medium latitudes, $24°$–$48°$, confirming results from Doppler imaging which show the existence of medium-latitude spots as well as near-polar star-spots (Donati et al. 2003).

With the advent of ZDI, maps of the three vector components of the surface magnetic field became available. These showed yearly changes in the global field structure of LQ Hya, with significant changes (such as the polarity of the high-latitude azimuthal field) possible over a time-scale of 1 yr (Donati 1999). Kitchatinov et al. (2000) presented a model for distributed dynamo activity on LQ Hya which reproduced many of these features, and demonstrated that both axisymmetric and non-axisymmetric modes may be present, with the axisymmetric mode being favoured. A similar result was found by Berdyugina, Pelt & Tuominen (2002), who analysed almost 20 years of photometric observations of LQ Hya. They found three possible cycle periods which may be associated with these different modes. They suggested that, as stars spin down from their state of rapid rotation when very young, the dominant mode changes from non-axisymmetric to the axisymmetric form that we find on the Sun. LQ Hya would represent some intermediate stage in this process.

The nature of the global field is of interest not only from the point of view of field generation by a dynamo, but also to the whole question of stellar spin-down. Open field-lines that are rooted close to the stellar rotation pole provide less efficient wind losses than lower latitude flux (Solanki, Motamen & Keppens 1997). Over the course of its cycle, the open flux of the Sun changes its location from being mainly polar at cycle minimum (when the global field is closest to a dipole) to emerging from much lower latitudes at cycle maximum (Wang, Sheeley & Lean 2002; Mackay, Priest & Lockwood 2002; Lockwood 2003) when higher order non-axisymmetric modes become apparent.

The aim of this paper is to examine the large-scale potential field structure of LQ Hya, in order to determine the locations of the open and closed flux regions. By solving hydrostatic equilibrium along the closed field-lines we can calculate, for an isothermal corona, the emission measure and the emission-measure-weighted density. These are the two quantities that can be compared with observations. We focus particularly on the changes that are apparent in the data from 2000 December and 2001 December. These maps were reconstructed with very dense phase coverage, and so provide a reliable image of the surface flux.

2 MODELLING THE CORONA

The extrapolation of the field is the same as used by Jardine et al. (2002a). Since the method is the same, we refer to the aforementioned paper for a detailed description of the calculations involved. We write the magnetic field $\boldsymbol{B}$ in terms of a flux function Ψ such that $\boldsymbol{B} = -\nabla\Psi$ and the condition that the field is potential ($\nabla\times\boldsymbol{B} = 0$) is satisfied automatically. The condition that the field is divergence-free then reduces to Laplace's equation $\nabla^2\Psi = 0$. A solution in terms of spherical harmonics can then be found:

$$\Psi = \sum_{l=1}^{N}\sum_{m=-l}^{l}\left[a_{lm}r^{l} + b_{lm}r^{-(l+1)}\right] P_{lm}(\theta)\mathrm{e}^{\mathrm{i}m\phi}, \tag{1}$$

where the associated Legendre functions are denoted by P_{lm}. The coefficients a_{lm} and b_{lm} are determined by imposing the radial field at the surface from the Zeeman–Doppler maps, and assuming that at some height R_s above the surface the field becomes radial. In order to calculate the field we use a code originally developed by van Ballegooijen, Cartledge & Priest (1998). For this particular model we choose to set $N = 31$ which is more than enough for the resolution of the surface magnetograms.

We note that, since LQ Hya is inclined at approximately $60°$ to the observer, only one hemisphere can be imaged reliably. ZDI produces flux values for all parts of the stellar surface, becoming progressively less reliable below latitudes of $-30°$. The effect of this 'missing flux' on the global field topology was investigated by Jardine et al. (2002a) for the case of AB Dor which has a similar inclination. They created an artificial surface map in which the map from 1995 December forms one hemisphere and the map from 1996 December forms the other. They concluded that the nature of the lower hemisphere flux did indeed affect the topology of the low-latitude field, where field-lines connected across the equator, but that the mid- to high-latitude field topology was unaffected. For this paper we are more interested in the change in field structure from one year to the next, and have chosen to ignore the effect of the invisible part of the stellar surface.

The pressure structure of the corona is calculated by assuming it to be isothermal and in hydrostatic equilibrium. Thus the pressure at any point is

$$p = p_0 \exp\left[(m/kT)\int g_s\,\mathrm{d}s\right], \tag{2}$$

where the path of integration, s, is along an individual field-line and m is the mean particle mass. $g_s = (\boldsymbol{g}\cdot\boldsymbol{B})/|\boldsymbol{B}|$ is the component of gravity along the field and

$$g(r,\theta) = (-GM_{\star}/r^2 + \omega^2 r\sin^2\theta,\ \omega^2 r\sin\theta\cos\theta), \tag{3}$$

with ω the stellar rotation rate. The plasma pressure p_0 at the footpoint of each field-line is scaled to the local magnetic pressure such that $p_0 = KB_0^2$ where K is a constant. The plasma pressure is set to zero within any volume element if the field-line through that element is open, or if the plasma pressure exceeds the magnetic pressure. This is to mimic the effect of having closed field-lines forced open by high gas pressure, i.e. where $\beta > 1$. For short-time-scale effects on the field such as coronal mass ejections, we would see supersonic velocities for the gas flow which would certainly have a strong effect on the structure of the field. A potential field model, however, represents the lowest energy configuration for the magnetic field, and as such does not allow any such reconnection events. Stationary flows like stellar wind could still result in the bending of open field-lines for this model. The flows required to bend the field-lines significantly would need to be supersonic. Since we are concerned with a corona closed out to heights of $2.5R_{\star}$, which lies well below the sonic point, we have ignored any effect that the ionized gas flow might have on the field structure. From the pressure, the density of

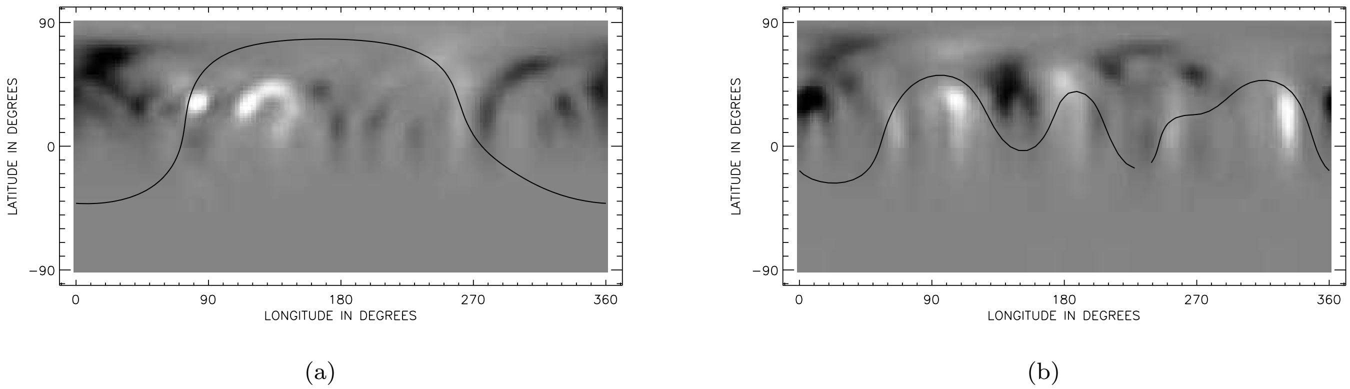


Figure 1. Radial field maps at the surface of LQ Hya for (a) 2000 December and (b) 2001 December. The black line represents the neutral polarity at a height of $2R_\star$. White represents +500 G, while black represents −500 G.

the corona can then be calculated assuming it to be an ideal gas. Using a Monte Carlo radiative transfer code we can then determine the X-ray emission.

For a given coronal temperature, this model has two free parameters: the radius of the source surface which determines the magnetic field structure, and the constant K which scales the coronal pressure and density. K is set to a value of 10^{-5} in order to give an emission measure consistent with observations (Sanz-Forcada, Brickhouse & Dupree 2003a). In the previous models of the corona of AB Dor (Jardine et al. 2002a) the source surface was chosen to be at about 3.4 stellar radii. The reason for this is that large slingshot prominences are observed mainly around the corotation radius which lies at $2.7R_\star$, indicating that much of the corona is closed out to these heights. In the case of LQ Hya the choice of source surface seems more arbitrary because of the lack of observable phenomena. We can obtain an upper limit on the source surface by determining, for a dipolar field, the point at which the ratio β of the plasma pressure to the magnetic pressure reaches unity. To do this we take the simplest solution of (1), which is a dipole aligned with the rotation axis with $l = 1$ and $m = 0$, and impose the boundary conditions

$$B_r(r = R_\star) = 2M \cos\theta / R^3, \tag{4}$$

$$B_\theta(r = R_s) = 0, \tag{5}$$

where $M = B_r(r = R_\star, \theta = 0)R_\star^3/2$ is the dipole moment. Choosing a dipole field to find the height where β reaches unity ensures that for all other higher order terms in the spherical harmonic expansion $\beta < 1$, since for all these terms the magnetic field drops off more quickly with radial distance.

A test height was deliberately overestimated at $6R_\star$. By selecting a closed field-line that stretches out to this test height, the change in the ratio β along this field-line can be followed. We find that, for a base pressure of 1 Pa, a temperature of 10^7 K and a field strength at the pole of 400 G, β rises rapidly with distance from the stellar surface, reaching unity at around $r = 2.5R_\star$. Placing the test height further out (say, to 10 $R_\star$) has little effect on the height at which $\beta = 1$. Dropping the temperature to 2×10^6 K has a much more dramatic effect, pushing the height where $\beta = 1$ to about $r = 4.7R_\star$. Dropping the base pressure to 0.01 Pa at this temperature pushes the β-point out even further, close to the Keplerian corotation radius that lies at about $6R_\star$. It seems that a slight variation of the parameters can have a considerable effect as to where β will reach unity. For the purposes of this paper we are going to choose the source surface to be at $r = 2.5R_\star$, which gives good agreement with observations of the emission measure by Sanz-Forcada et al. (2003a) In Section 5 we discuss the implications that moving the source surface has on the X-ray emission and open flux, which of course is linked to the amount of angular momentum loss of the star.

3 CHANGES IN MAGNETIC TOPOLOGY

The changes in the surface magnetic field of LQ Hya from 2000 to 2001 have already been described by Donati et al. (2003), who noted the growth of the higher order modes with time. This can be seen clearly in the radial field maps shown in Figs 1(a) and (b) by noting the structure of the neutral polarity contour. In 2000, the surface map shows that one set of longitudes (from 80° to 270°) were of predominantly negative polarity, while the others were of positive polarity. This is very similar to the global field structure for AB Dor, and results in a large north–south arcade running over the pole (Fig. 2a). Clearly, in the spherical harmonic decomposition of equation (1) the $m = 1$ mode must be strong. One year later, however, the field structure has changed. The neutral polarity contour shows a more complex structure, with many more changes of polarity along a line of latitude. This results in a more complex global field structure, with many more north–south arcades (Fig. 2b). Clearly, modes of higher m-value have been excited (Donati 1999). Although AB Dor has been observed on an almost yearly basis, such a dramatic change in the magnetic topology has not been seen (Jardine et al. 2002a).

To see this change in context, we can compare it to changes in the Sun's magnetic field over the course of its cycle. At cycle minimum, the field most closely resembles an aligned dipole with most of the open field emerging from the polar regions. As the cycle progresses and more east–west bipoles emerge, the higher order modes become stronger and the coronal holes (which contain the large open field regions) extend down from the poles towards lower latitudes. While on small scales this behaviour is very complex, on the largest scales a simpler pattern emerges. The changes in the heliospheric field can simply be described as a dipole that is aligned with the rotation axis at cycle minimum, but rotates down into the equatorial plane at maximum (Smith et al. 2003).

These changes in the Sun's large-scale field have been studied both observationally and theoretically (Lockwood, Stamper & Wild 1999; Solanki, Schüssler & Fligge 2002). The contribution to the total field of the axisymmetric (or aligned) dipole and the non-axisymmetric (or tilted) dipole over the cycle have received much attention (Wang, Lean & Sheeley 2000; Mackay, Priest & Lockwood 2002). We define the total contribution of flux from the aligned

Figure 2. Closed field regions for LQ Hya calculated from Zeeman–Doppler maps in (a) 2000 December and (b) 2001 December. The image is viewed from a longitude of 180° and a latitude of 30° consistent with the stellar inclination of 60°. Note that, because of the stellar inclination, only the upper hemisphere is totally in view and so can be imaged reliably. We have therefore plotted only field-lines in this hemisphere. The surface radial maps are painted on to the stellar surface in each case.

dipole component ($l = 1, m = 0$) at the stellar surface as

$$\Psi_{10}(R_\star) = \int \Psi_{10}(R_\star, \theta, \phi) \mathrm{d}\Omega/4\pi \tag{6}$$

and that from the tilted dipole component ($l = 1, m = 1$) as

$$\Psi_{11}(R_\star) = \int |\Psi_{11}(R_\star, \theta, \phi)| \mathrm{d}\Omega/4\pi. \tag{7}$$

Mackay et al. (2002) used a model of flux emergence and transport to study the behaviour of the solar field over many cycles. They looked in particular at the evolution of the first two modes from this expansion for full solar cycle simulations. It was found that the flux from the aligned dipole component (Ψ_{10}) increased as the flux from the tilted dipole (Ψ_{11}) decreased, with this latter component reaching a maximum at solar maximum.

This simple sinusoidal pattern for the Sun's cycle is not what we see for LQ Hya. At first sight, LQ Hya shifts from a dominant tilted dipole field in 2000 ($\Psi_{10}/\Psi_{11} = 0.7$) to a strong aligned dipole field in 2001 ($\Psi_{10}/\Psi_{11} = 4.3$). This explains the open field structure that we can see in Figs 3(a) and (b), but does not explain the abundance of closed east–west field that is seen in Fig. 2(b). This field is related to the strength of the higher modes from the spherical harmonic expansion. On inspection of the higher order modes, we find that ($l = 3$, $m = 3$) is the strongest mode in the spherical harmonic expansion in 2001, and has a contribution nearly twice that of the aligned dipole mode to the overall flux function (1). This mode is directly responsible for the arcades of loops that we see in this year (Fig. 2b). This is a very different picture from what we see on the Sun, where the higher harmonic modes never dominate over the north–south axisymmetric dipole or the east–west non-axisymmetric dipole. We can see that open flux is spread across mid-latitudes in 2000 (Fig. 3a) with little flux near the pole. In contrast, Fig. 3(b) shows the open field to be mostly concentrated around the polar region. Zeeman–Doppler images of the polar regions in both 2000 and 2001 show weak signal at the pole, despite the obvious large spot found in brightness maps (Donati et al. 2003). It is therefore possible that the large change in structure of the open field could be over-emphasized as a result of the missing flux at the poles. McIvor et al. (2003), however, showed that for the similar dwarf star AB Dor the presence of polar field had almost no noticeable effect on the global coronal field structure. In one case, where a unipolar spot was placed at the pole, the coronal field was influenced, but this model was ruled out because of the extremely large X-ray modulation values. The location and amount of open field at the surface will have strong implications for the stellar wind and hence the angular momentum loss. Owing to the short lever arm of the field-lines at high latitudes, there is significantly less angular momentum lost in these winds (Solanki et al. 1997). Fig. 4 shows the change in open flux with latitude. Ignoring the southern hemisphere where very little Zeeman signal could be detected, we can clearly see a shift in the latitude where the open flux is strongest between the years 2000 and 2001.

The effect of changing the position of the source surface from the value of $2.5R_\star$ used elsewhere in this paper can also be seen. Moving the source surface closer to the star increases the amount of open flux, but has little effect on its distribution with latitude.

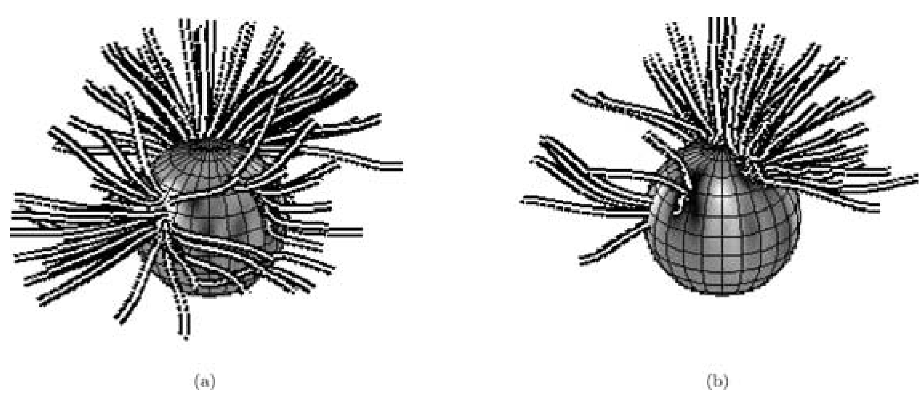


Figure 3. Open field regions for LQ Hya calculated from Zeeman–Doppler maps in (a) 2000 December and (b) 2001 December. As in Figs 2(a) and (b), we have plotted only upper hemisphere field-lines. The surface radial maps are painted on to the stellar surface in each case.

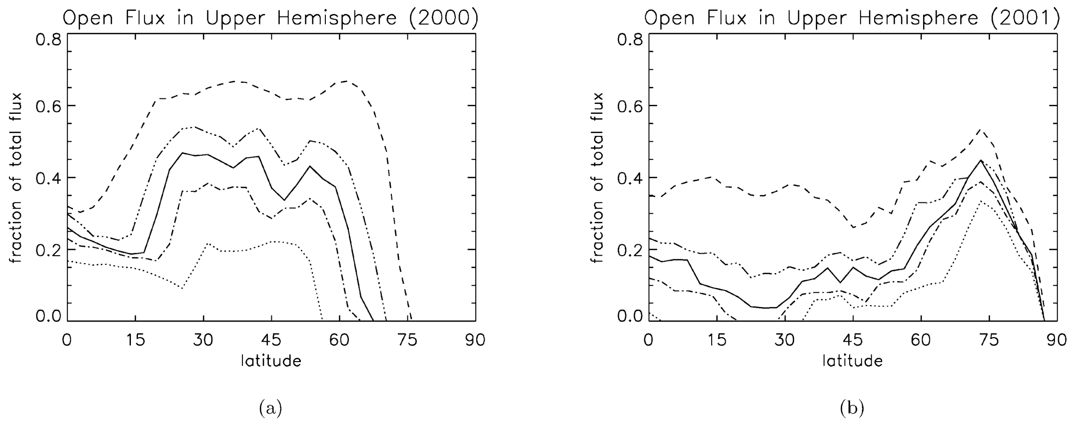


Figure 4. The fraction of the total flux that is open as a function of latitude in (a) 2000 December and (b) 2001 December. Different line styles denote different source surface radii: $R_{ss}/R_\star = 1.5$ (dashed), 2.0 (triple-dot–dashed), 2.5 (solid), 3.4 (dot–dashed) and 5.8 (dotted) which is approximately the Keplerian corotation radius for LQ Hya. While the fractional contribution of the open flux to the total flux increases as the source surface moves closer to the stellar surface, the distribution with latitude is qualitatively unchanged. There is a significant difference, however, between the distributions in 2000 and 2001, with the peak of the distribution moving to much higher latitudes in 2001.

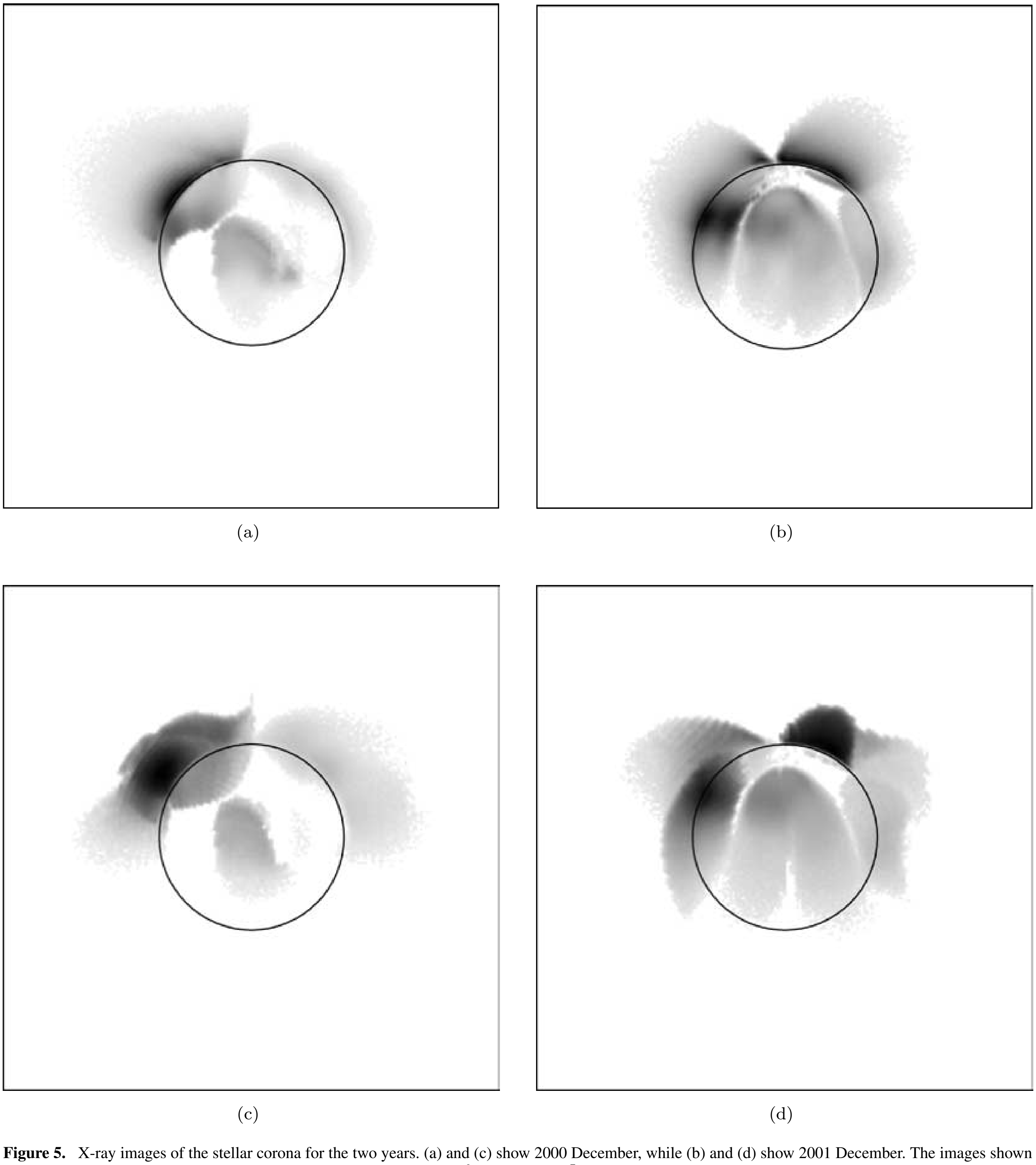
4 CHANGES IN X-RAY EMISSION MEASURE AND DENSITY

The X-ray images (Fig. 5) which are determined from the closed field regions also exhibit an obvious change in the structure. Observations based on a single rotation cannot distinguish between a transient X-ray brightening (flare) and the rotational modulation of a quiescent stable structure. Hence detecting such a change from year to year would require long-term monitoring such as the 5-year *ROSAT* observations of AB Dor (Kuerster et al. 1997). Unfortunately, unlike AB Dor, this modulation in X-ray emission is not available for LQ Hya as yet. Despite obvious changes in the structure of the magnetic field from one year to the next, the models show little difference in the total emission measure. The observed total emission measures for LQ Hya are $10^{49.8}$ cm^{-3} for 10^6 K and $10^{51.15}$ cm^{-3} for 10^7 K (Sanz-Forcada et al. 2003a). For the models shown in Fig. 6 this corresponds to densities of $10^{9.4}$ and $10^{9.8}$ cm^{-3} for 10^6 and 10^7 K respectively. For the models at 10^6 K a small variation in emission between the years can be seen, but it would most likely be undetectable in observations. In both years at 10^7 K the corresponding densities are almost indistinguishable. It should be noted that values of emission at 10^6 K as quoted from Sanz-Forcada et al. (2003a) are uncertain owing to the few lines that occur in the temperature region. Looking at similar stars where there are more lines at this temperature, however, does paint a general picture of the emission at 10^6 K being somewhat less than that at 10^7 K. Owing to the way in which we observe the X-ray emission from a star, it is not possible to differentiate between the emission from flares and the emission in quiescence. It has been proposed (Maggio et al. 2000) that the observed emission which corresponds to these high densities could be due to the continuous presence of flares. This is far from what we observe on the Sun, but flaring has been detected through X-ray emission and in some cases for the entire duration of one rotation period of the star (Maggio et al. 2000).

The densities here are far higher than that of the Sun, but are close to that observed for the similar star AB Dor where line ratios indicate densities of $10^{10.8}$ cm^{-3} (Sanz-Forcada, Maggio & Micela 2003b). For LQ Hya, similar line ratios at 10^7 K indicate densities greater than 10^{12} cm^{-3} (Sanz-Forcada et al. 2003a). Such high densities do not agree with current loop models, where it is believed that any loops forming in regions with such high gas pressure would be blown open and hence not contribute to the X-ray emission of the star. For the models used here, densities as high as this would result in a reduction of the emission measure, as we can see in Fig. 6 where the emission for the 10^7-K models falls off below that of the 10^6-K models at higher densities. Imposing a cut-off in the emission when the plasma pressure exceeds the magnetic pressure causes a reduction in the emission measure at higher densities because the emitting volume of the corona shrinks.

For the models of years 2000 and 2001, the rotational modulation showed little change between the two years despite the obvious change in the global field structure. In 2000 the rotational modulation at 10^7K was calculated to be 21 per cent and in 2001 it was calculated to be 26 per cent. The corona is much more confined at 10^6K owing to the effect of temperature on the density scaleheight. This causes a drop in the overall emission measure but increases the rotational modulation. At this temperature there is almost no difference from year to year in the modulation, with values of 44 per cent for both years. These values are not noticeably affected by changes in density. In both years we are seeing a relatively high modulation. For the 10^6-K model this is easily explained by the fact that the emitting region is much more compact as a result of the higher densities, and as such is self-eclipsed as the star rotates. At 10^7K the reduction in modulation compared with the 10^6-K model is because of higher latitude emitting regions that remain in view for longer periods of time as the star rotates.

This result is reflected in the distribution of open flux, an important feature when we come to consider the rate of loss of angular momentum. In 2001 where we have a marginally higher modulation, this is accompanied by more open field at higher latitudes which does not contribute to the X-ray emission. The dominance of the higher order mode in the spherical harmonics expansion ($l = 3, m = 3$) plays an important role in the balance of the X-ray modulation from one year to the next. If the dipole mode were the dominating mode this year then there would be a greater amount of open flux at the pole and it would most likely extend further down in latitude. Owing to the inclination of this star, this would decrease the amount of closed flux that would remain constantly in view and thus the rotational modulation would increase.



(a) (b) (c) (d)

Figure 5. X-ray images of the stellar corona for the two years. (a) and (c) show 2000 December, while (b) and (d) show 2001 December. The images shown here are for X-ray emissions calculated for a coronal temperature of 10^6 K (top) and 10^7 K (bottom). We can see how much more extended the emitting region of the corona is in the 10^7-K model than in the 10^6-K one. Surprisingly, there is little change in the emission measure between the two years, despite obvious structural changes in the corona. The black circle superimposed on the images represents the stellar disc.

5 CHOICE OF SOURCE SURFACE

The effects of the source surface must be considered. The potential field extrapolation for these models is partly determined by the choice of source surface, which is simply an artificial boundary to help us calculate the structure of the coronal field. We choose this boundary based upon the fact that, at some height above the star, the field will open up as a result of the magnetic pressure being overpowered by the gas pressure, i.e. $\beta > 1$. As can be seen from Fig. 4, the overall amount of open flux does depend on the choice of source surface, but there seems to be little effect on the distribution in latitude. It would have been possible to calculate the emission measure

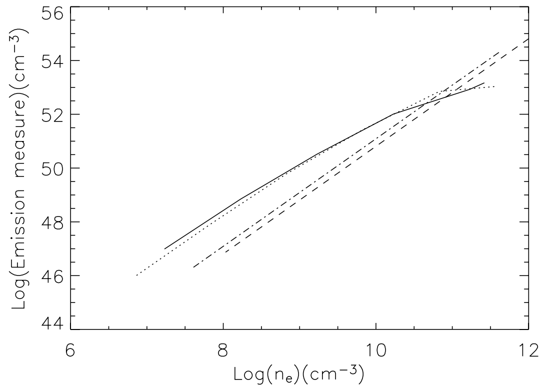


Figure 6. Total emission measure as a function of the emission measure weighted coronal density for a source surface at $2.5R_\star$. Models for the year 2000 at 10^7 K (solid) and 10^6 K (dashed) as well as for 2001 at 10^7 K (dotted) and 10^6 K (dot–dashed) are shown. The reduction in the emission measure for very high densities is due to the plasma pressure exceeding the magnetic pressure and forcing field-lines to open.

for a range of densities and source surfaces and then compare these with the observed densities and emission measures to obtain a choice of source surface based on real observations. The emission measure, however, is fairly insensitive to the choice of source surface, as is the density. Only for source surfaces less than $1.5R_\star$ is a drop seen in the emission measure. This clearly shows that most of the X-ray-emitting corona is confined close to the stellar surface. Moving the source surface further out also increases the coronal volume where we have $\beta > 1$. The potential field extrapolation does not account for this, and any closed field-lines that lie in a region where $\beta > 1$ are likely to be unphysical as they would be blown open by the gas pressure.

6 CONCLUSIONS

Using Zeeman–Doppler images to calculate the coronal magnetic field of LQ Hya, we have shown that the structure of the global magnetic field has changed considerably over the space of one year, and this is clearly illustrated in both the closed field (Figs 2a and b) and open field (Figs 3a and b) topologies. In 2000, the large-scale field resembled a tilted dipole, with the open field emerging at low to mid-latitudes. One year later the open field is mainly at the pole and the large-scale field more closely resembles an aligned dipole, albeit with a significant contribution from higher order modes.

This significant and obvious change in the structure is very different from that of the Sun. On the largest scales, the Sun's magnetic field does indeed show a gradual change over its cycle, from being mainly an aligned dipole at cycle minimum to more like a tilted dipole at cycle maximum (Smith et al. 2003). On the Sun, however, the growth of the higher order modes signals the transition from minimum, where there are few east–west bipoles, to cycle maximum, where there are many bipoles. A strong contribution from higher order modes is therefore associated with the phase of its cycle when the large-scale field most closely resembles a tilted dipole. This is just the opposite of what we see on LQ Hya.

The change in the distribution and magnitude of the open flux seen in the models over the two years is an interesting feature when we consider the loss of angular momentum of the star. On making the simple assumption that more angular momentum will be lost from field-lines nearer the equator than at the pole, because of the larger lever arm, we would expect to see a drop in the angular momentum lost over the two years. Without more information on the nature of the magnetic cycle, however, it is impossible to determine the extent to which the changing latitude of the open field regions will influence the angular momentum loss.

Intriguingly, even though the field structure changes significantly in the course of one year, the densities and emission measures that we derive are very similar, as is the rotational modulation in X-rays. At temperatures of 10^7 K, the emission measures of $10^{49.8}$ cm^{-3} for 10^6 K and $10^{51.15}$ cm^{-3} for 10^7 K are consistent with the observed values although the derived densities of $10^{9.4}$ and $10^{9.8}$ cm^{-3} are somewhat lower (Sanz-Forcada et al. 2003a). This suggests that X-ray observations alone are not sufficient to provide detailed information on coronal structure. With the advent of new polarimeters (such as ESPADONS on the Canada–France–Hawaii Telescope), however, our ability to produce Zeeman–Doppler images of stars will be greatly enhanced.

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