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# Magnetic activity of interacting binaries

**Colin A. Hill**

Université de Toulouse / CNRS-INSU, IRAP / UMR 5277, F-31400, Toulouse, France
email: chill@irap.omp.eu

**Abstract.** Interacting binaries provide unique parameter regimes, both rapid rotation and tidal distortion, in which to test stellar dynamo theories and study the resulting magnetic activity. Close binaries such as cataclysmic variables (CVs) have been found to differentially rotate, and so can provide testbeds for tidal dissipation efficiency in stellar convective envelopes, with implications for both CV and planet-star evolution. Furthermore, CVs show evidence of preferential emergence of magnetic flux tubes towards the companion star, as well as large, long-lived prominences that form preferentially within the binary geometry. Moreover, RS CVn binaries also show clear magnetic interactions between the two components in the form of coronal X-ray emission. Here, we review several examples of magnetic interactions in different types of close binaries.

**Keywords.** stars: novae, cataclysmic variables, stars: activity, stars: spots, stars: imaging, stars: magnetic fields, stars: binaries (including multiple): close, techniques: spectroscopic

## 1. Introduction

Interacting binaries provide unique parameter regimes in which to test stellar dynamo theories, and to study the resulting magnetic activity. Cataclysmic variables (CVs) are semi-detached binaries (typically) consisting of a lower main-sequence secondary star that is overflowing its Roche-lobe, transferring material to a white dwarf (WD) primary star. These systems typically have orbital periods of $P_{orb} < 10$ hr, with the tidal distortion (due to the companion star) forcing the secondary to synchronously rotate (on average) with the binary (i.e. $P_{rot} = P_{orb}$). This co-rotation means that magnetic braking (where charged particles stream along open field lines, removing angular momentum) does not slow the rotation period, but instead acts to shrink the orbit of the system, driving it to shorter orbital periods and sustaining the mass transfer. Furthermore, as the secondary stars may be massive enough to possess large radiative cores, they also have very low Rossby numbers (Ro$=P_{rot}/\tau_c < 0.003$) despite being significantly evolved. Moreover, Doppler imaging of the secondary stars has revealed that they are highly magnetically active, with starspots covering a large fraction of their surfaces, with evidence to suggest that magnetic flux tubes may preferentially emerge facing the companion star. The secondary stars in this class of binary have also been found to harbour large prominences (extending out to several stellar radii), that may also be influenced by the close companion star.

Thus, close binaries such as CVs (and related objects) provide excellent laboratories in which to test stellar dynamo theories, to study the resulting magnetic activity, and to observe the magnetic interactions between the two components. Indeed, these interactions may mirror those found between a planet and its host star, and so the phenomena observed in stellar binaries has far reaching applications.

## 2. Magnetic activity of the cataclysmic variable AE Aqr

As an example of the type of magnetic activity that may be observed in close binaries, we present our studies on the CV, AE Aqr. This bright CV (V mag ∼11.6) consists of a WD primary star with a K4V-type secondary, with $P_{rot} = 0.41$ d (1.5% that of the Sun). By using the technique of Roche tomography (analogous to Doppler imaging, but adapted specifically for close binary systems) we have constructed brightness maps of the surface, showing the highly spotted nature of this rapidly rotating star (see Figure 1).

Comparing two spot maps taken 9 days apart (labelled 2009a and 2009 in Figure 1), we determined that the surface of the secondary star in AE Aqr is differentially rotating, with a shear rate $d\Omega$ around 40% that of the Sun (Hill *et al.* 2014). This surprising result overturned the decades-old assumption held by theorists and observers (e.g., Scharlemann 1982) that tides raised on the secondary star by the WD act to suppress differential rotation in tidally locked systems (such as CVs), forcing the stellar envelope to co-rotate on average, and shows that CV secondaries are not necessarily tidally locked.

Given that differential rotation is thought to play a crucial role in amplifying and transforming initially poloidal magnetic field into toroidal field through dynamo processes (the so-called $\Omega$ effect), one may test dynamo theories in such stars with further measurements of differential rotation in tidally distorted systems, thus disentangling the most important parameters (period, stellar type, mass-ratio, Roche-lobe filling-factor) driving the stellar dynamo and influencing tidal dissipation efficiency. Furthermore, such studies may also lead to a better understand of why close-in exoplanets are preferentially misaligned with the stellar rotation axis around hot stars (>6250 K), and are aligned around cool stars (<6250 K, see Brothwell *et al.* 2014). Given that the outer convective envelope is responsible for tidal interactions, is a change in internal structure the cause of this transition? Tests of tidal dissipation efficiency in interacting binaries (of different spectral types) may help to answer this question.

As well as studying its short-term behaviour, we have also observed the long-term trends of the magnetic activity on the secondary star in AE Aqr. For this purpose, we constructed 7 brightness maps of the surface over an 8 yr period (see Figure 1). This is the first time such a campaign has carried out for a CV secondary, and our maps of AE Aqr have given us a unique insight into its magnetic activity (Hill *et al.* 2016). The first map, created with data taken in 2001, shows a high spot coverage around the polar region (due to a large high-latitude spot), as well as an increasing fractional spot coverage towards lower latitudes (∼20°, see Figure 1). However, there is a clear paucity of spots at around 45° latitude. In contrast, the 6 maps made with data taken in the years since then show a clear increase in fractional spot coverage at around 45° latitude, with a similarly high concentration of spots at 20° (see Figure 1). The emergence of this band of spots at 45° latitude in the 8 years between observations may be indicative of a solar-like magnetic activity cycle in operation in AE Aqr, where the latitude of spot formation may change in a manner that mimics the butterfly-diagram for the Sun. Furthermore, the increase in fractional spot coverage around 20° latitude may be a second band of spots that form part of a previous cycle. In the case of the Sun, the latitude of emergence of flux tubes gradually moves towards the equator over the course of an activity cycle, taking ∼11 yr, with little overlap between consecutive cycles of flux tube emergence. However, simulations by Işık *et al.* 2011 show that stronger dynamo excitation may cause a larger overlap between consecutive cycles, and given the strong dynamo excitation in AE Aqr, the presence of two prominent bands of spots may be indicative of such an overlap between cycles. Over

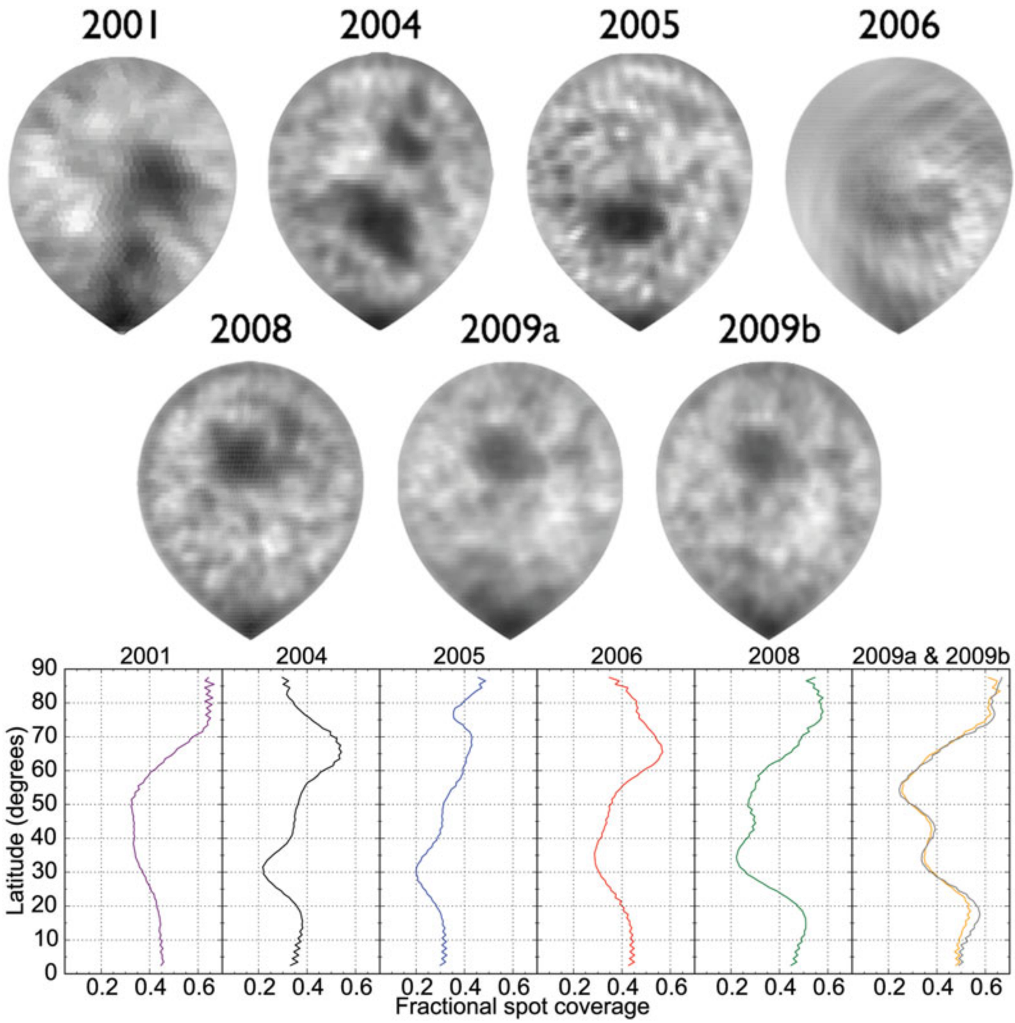


**Figure 1.** Top panel: Roche tomograms of AE Aqr, shown pole-on, where dark features are starspots, with some irradiation and gravity darkening around the L1 point (also appearing dark). Bottom panel: Fractional spot coverage as a function of latitude for the Northern hemisphere of AE Aqr for each data set (year above plot), normalized by the surface area at that latitude. Note, the absolute level of fractional spot coverage is not directly comparable between maps.

the course of such a cycle, we would expect to see the higher-latitude peak move towards lower latitudes and, as we do not clearly see this, any solar-like activity cycle in AE Aqr must take place over a timescale longer than the 8 years between our observations. Indeed, using the correlations between the duration of the magnetic activity cycle and the rotation period by Saar & Brandenburg 1999, we estimate that AE Aqr would have a magnetic activity cycle lasting ∼16–22 yr. If these correlations are also true for AE Aqr, then we may have observed less than half of an activity cycle.

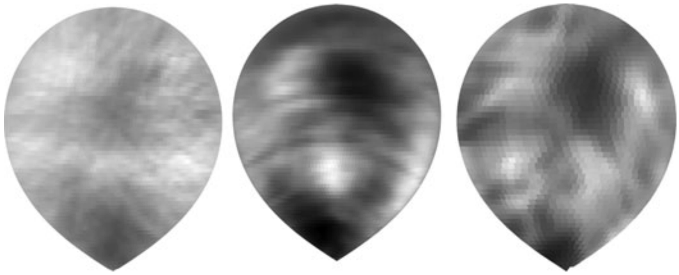

**Figure 2.** Roche tomograms of 3 CVs, all showing an increase in fractional spot coverage on the hemisphere facing the WD. Left to right, the stars are V426 Oph (Hill *et al.* in prep.), SS Cyg (Hill *et al.* in prep.) and BV Cen (Watson *et al.* 2007).

## 3. Tidal effects on magnetic ativity

As well as testing stellar dynamo theories in these rapidly-rotating, tidally-distorted stars, we may also study how the nearby companion star may influence its magnetic activity.

Figure 2 shows Roche tomograms of 3 CVs, namely V426 Oph, SS Cyg and BV Cen. For these objects, as well as for AE Aqr, we find a significant increase in spot coverage on the hemisphere facing the WD, even after accounting for the increased area (of the significantly distorted hemisphere) and the affects of gravity darkening and irradiation (both appearing dark in the maps, mimicking spots). This increase in spot coverage may suggest that magnetic flux tubes are forced to emerge at preferred longitudes, as predicted by Holzwarth & Schüssler (2003), and may possibly be related to the impact of tidal forces from the nearby compact object. If these particular spot distributions are confirmed to be long-lasting features, they would require explanation by stellar dynamo theory, and would provide evidence for the impact of tidal forces on magnetic flux emergence. In addition, since the number of starspots should change dramatically over the course of an activity cycle, the density of spots around the mass transfer nozzle may also vary (providing an explanation for the extended high and low accretion states seen in polar type CVs such as AM Her). However, further observations are required to confirm whether this higher concentration of spots is indeed altered over the course of an activity cycle.

As well as surface features, one may observe clear signs of magnetic interaction between binary components in the form of slingshot prominences. Here, a magnetic structure (rooted on the secondary) is pulled towards the WD, causing the loop to expand. Plasma is confined at the top of the loop by magnetic tension, and is illuminated by the disk and secondary star. This results in an emission source that co-rotates with, but is well separated from, the secondary star, and is seen in emission at 0 kms$^{-1}$. Figure 3 shows several examples of this phenomena, as seen in the CVs BV cen (Watson *et al.* 2007), IP Peg and SS Cyg (Steeghs *et al.* 1996). Although prominences may (in principle) appear anywhere on the secondary, the material is loosely bound at the inner hemisphere, and as the effective potential decreases as one approaches the WD, one only requires surface fields of $\sim$1 kG to produce such prominences seen in these systems.

In other work by Parsons *et al.* 2016, large prominences were also seen in the pre-CV, QS Vir ($P_{orb}$ = 3.62 h). Here, the highly magnetically-active M dwarf (that almost fills its Roche lobe) features long-lived spots that remain in fixed locations, preferentially found on the hemisphere facing the WD (see Figure 4). The system also displays three large prominences that cross the line of sight, with one passing in from of both stars (allowing is position to be well constrained, see Figure 5). Furthermore, despite showing small variations on a time-scale of days, they persist for more than $\sim$1 yr. Indeed, one of

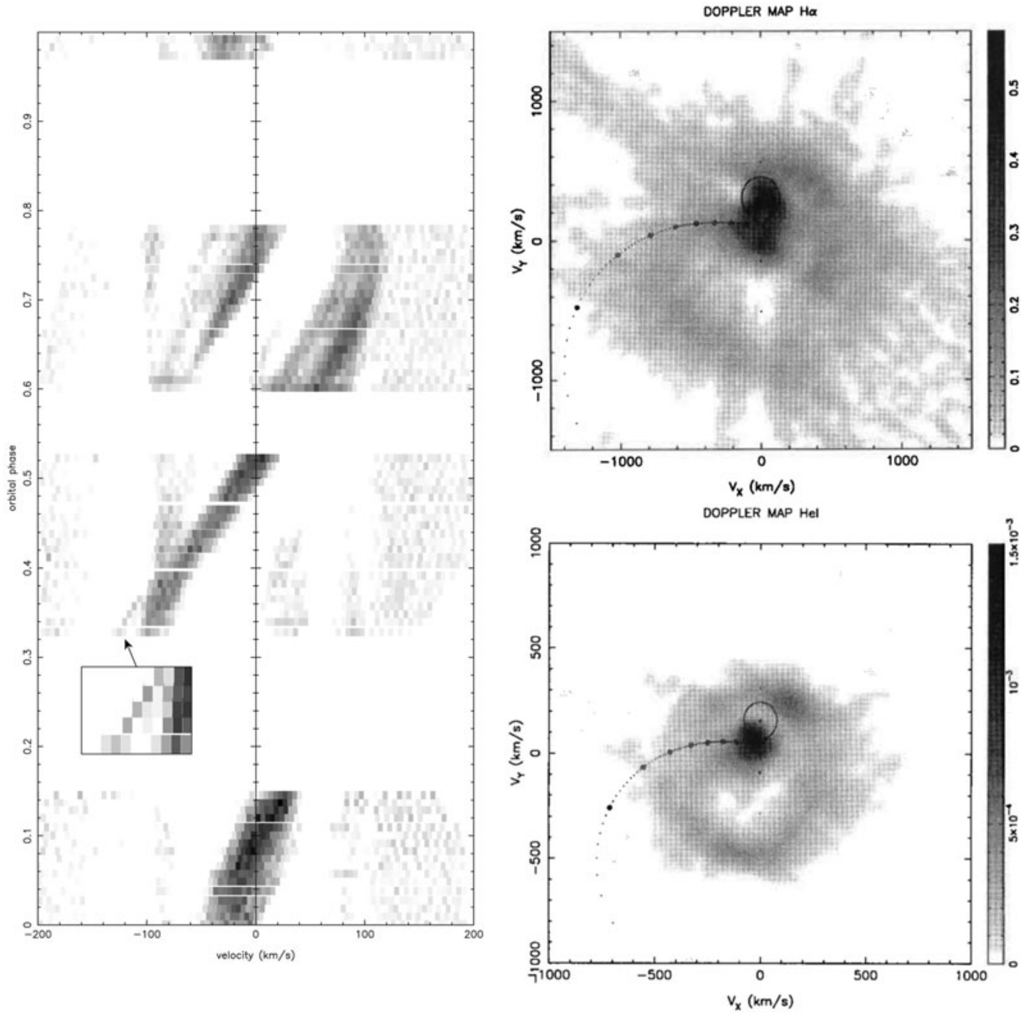


**Figure 3.** Left: A dynamic spectra the least-squared deconvolved line profiles of BV Cen, where the orbital motion has been removed, and the profiles have had a theoretical line profile subtracted. Features due to starspots and irradiation appear dark, with a slingshot prominence appearing as a narrow feature (indicated with an arrow and shown enlarged) lying off the blue edge of the stellar limb at phases 0.328–0.366. Top-right: A Doppler map of the H$\alpha$ emission in IP Peg. Bottom-right: A Doppler map of the He I (6678 Å) emission in SS Cyg. For both Doppler maps, the Roche lobe and gas stream are additionally plotted, the centre of mass is denoted by a cross, and the WD is plotted as a point. For both IP Peg and SS Cyg there is significant emission at zero velocity, indicative of slingshot prominences.

these prominences may have been detected (as a sharp absorption feature) in a spectra taken ~11 yr previously, and so these features may last decades. Moreover, the heavily spotted regions may well be related to these prominences; since the prominences appear to be stable on a time-scale of years, they must still be anchored to the surface of the M star by its magnetic field, and starspots are likely to form near these anchor regions, as is seen in solar coronal loops.

Lastly, magnetic interactions between binary stars have also been observed in the RS CVn, AR Lac (Siarkowski *et al.* 1996). Here, coronal X-ray emission was found to be concentrated on the hemispheres facing the companion star, with evidence that extended

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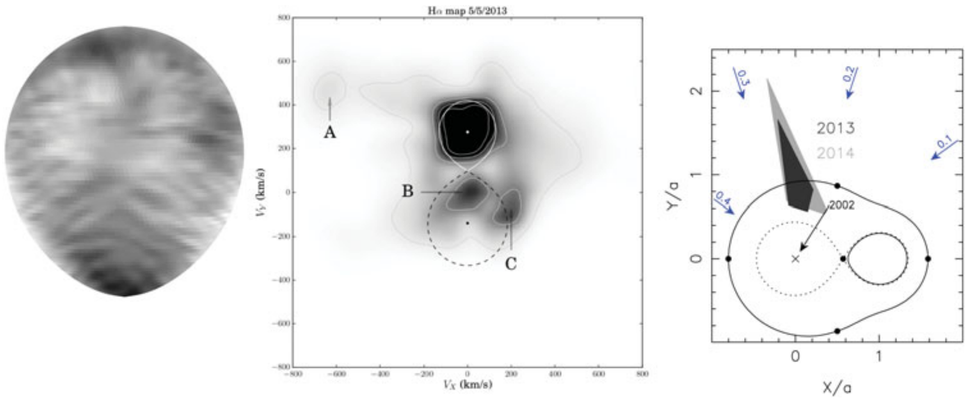


**Figure 4.** Left: A Roche tomogram of QS Vir, where dark grey scales indicate the presence of starspots or the impact of irradiation. Centre: A Doppler map of the Hα line, where the Roche lobes of the WD and M star are highlighted with a black dashed line and solid white line, respectively. Contours are also plotted to highlight the additional emission features against the strong emission from the M star. Three emission features that do not originate from either star are also labelled. Right: Top-down view of the binary indicating the location of the large prominence feature in 2013 and 2014 (orbital phases shown in blue). Dotted lines indicate the Roche lobes, a solid line shows the M star radius. The arrow indicates the viewing angle to the WD during a 2002 observation in which prominence material was also observed. The WD is marked with a cross and the black dots indicate the 5 Lagrange points. The outer solid black line indicates the effective 'co-rotation' radius of the binary.

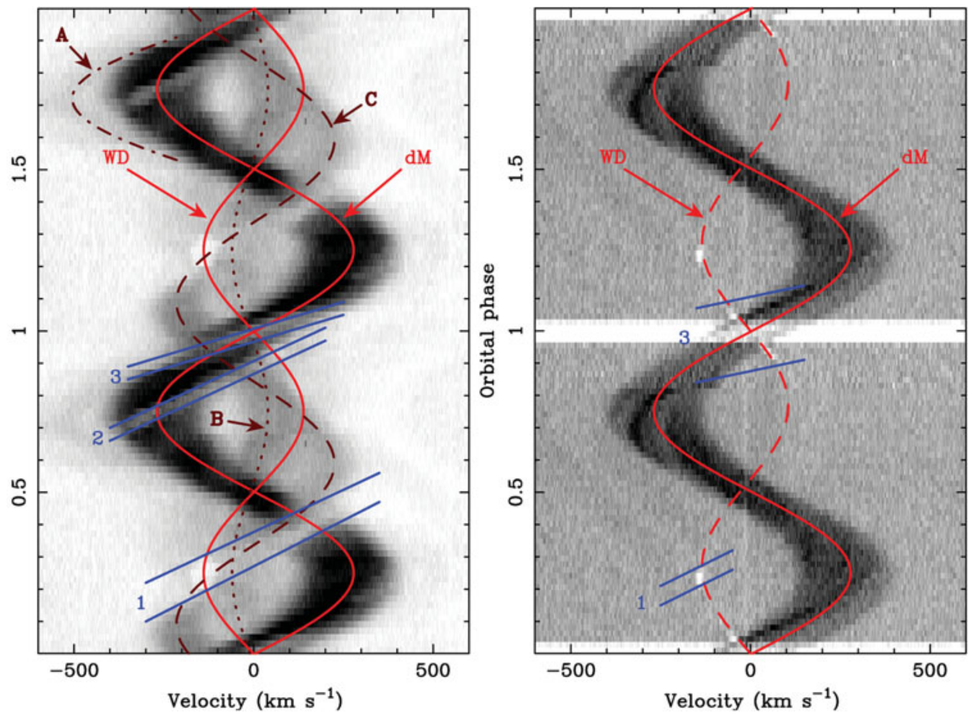


**Figure 5.** Trailed spectrogram of the Ca II 3934 Å (left) and Hα  Å (right) lines with the main features labelled. The velocities of the two stars are indicated by the bright red sinusoids. In blue, we highlight three clear absorption features that cross one of both of the stars (only two are visible in the Ca II trail). We also highlight three other emission components in the Hα trail with dark red lines.

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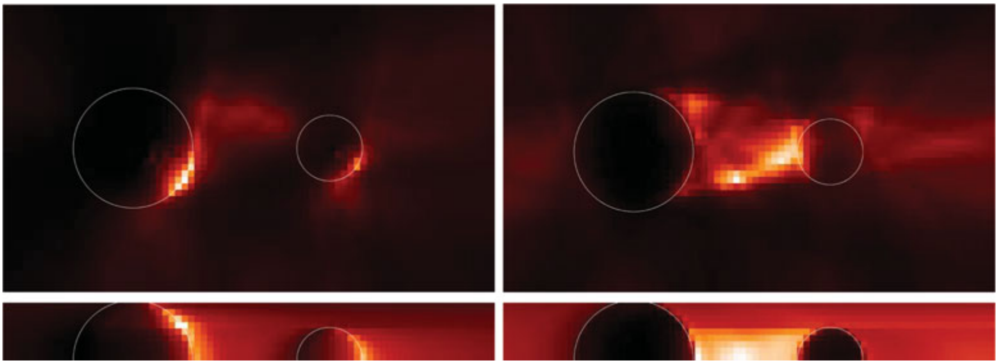

**Figure 6.** Comparison of the coronal structure (determined from X-ray emission) of AR Lac at two epochs, separated by an interval of 9 yr. The left panel from Siarkowski 1992, right panel from Siarkowski *et al.* 1992. Each panel shows a top view and a side view (at phase 0.25)

regions may connect the K and G-type stars (see Figure 6), with the pattern of the coronal emission showing clear variation over the 9 yr separation between observations.

## 4. Conclusions

There is clear evidence of magnetic interactions between the components in close binaries, such as preferential emergence of flux tubes, hot spots on facing hemispheres and extended coronal X-ray emission in RS CVn binaries, and large prominences that preferentially form due to the binary geometry, perhaps lasting over a decade. Furthermore, as stellar binaries show scaled-up interactions that may also take place in a planet-star system, as has been seen for hot Jupiters (see other author's work in this volume), understanding these systems may have far reaching consequences. In particular, one could test tidal dissipation efficiency in star-star binaries, with implications for both CV and planetary evolution.

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