Original citation:
Watson, C. A. et al. (2007). Imaging the cool stars in the interacting binaries AE Aqr, BV Cen and V426 Oph. Astronomische Nachrichten, 328(8), pp. 813-816
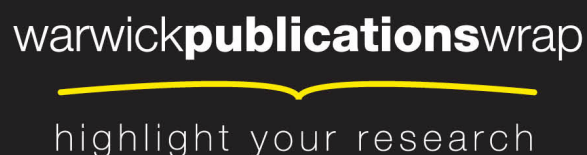
Permanent WRAP url:
http://wrap.warwick.ac.uk/48657

Publisher's statement:
'The definitive version isavailable at www.blackwell-synergy.com'.
DOI: 10.1002/asna.200710800

http://go.warwick.ac.uk/lib-publications

Imaging the cool stars in the interacting binaries AE Aqr, BV Cen and V426 Oph

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It is well known that magnetic activity in late-type stars increases with increasing rotation rate. Using inversion techniques akin to medical imaging, the rotationally broadened profiles from such stars can be used to reconstruct 'Doppler images' of the distribution of cool, dark starspots on their stellar surfaces. Interacting binaries, however, contain some of the most rapidly rotating late-type stars known and thus provide important tests of stellar dynamo models. Furthermore, magnetic activity is thought to play a key role in their evolution, behaviour and accretion dynamics. Despite this, we know comparatively little about the magnetic activity and its influence on such binaries. In this review we summarise the concepts behind indirect imaging of these systems, and present movies of the starspot distributions on the cool stars in some interacting binaries. We conclude with a look at the future opportunities that such studies may provide.

1 Introduction

Starspots, the most easily observed manifestation of magnetic activity, are a ubiquitous feature of rotating late-type stars with outer convective zones. Indeed, naked-eye observations of spots on our own Sun first took place 1000's of years ago, and subsequent telescopic observations have been undertaken almost continuously for over 3 centuries. Despite this, our understanding of how magnetic fields are produced and evolve on the Sun and other stars, and how fundamental parameters affect magnetic field generation, is still critically lacking. Since Vogt & Penrod (1983) demonstrated that starspots could be seen as bumps traversing the line profiles of HR 1099, several indirect imaging techniques have been used to map the magnetic topographies on mainly (but not exclusively) isolated rapid rotators. Since it is well known that magnetic activity increases with increasing stellar rotation rate, much of this work has focused on determining how rotation impacts starspot emergence.

Interacting binaries such as Cataclysmic Variables (CVs) contain some of the most rapidly rotating late-type stars known. CVs typically consist of a late-type main-sequence star in orbit around a more massive white dwarf. The close proximity of both components causes the late-type (or donor) star to fill its Roche-lobe and transfer mass to a white dwarf. With orbital periods as short as an hour, and tides forcing synchronous rotation of the donor, images of these systems provide excellent tests of stellar dynamo theories at ultra-fast rotation rates. In addition, such systems also allow the impact of tides on the stellar dynamo to be assessed.

Furthermore, many interacting binaries show variations in orbital periods, brightnesses, and outburst durations that have been attributed to starspots and activity cycles. Despite their obvious importance, both to understanding stellar dynamos and understanding the observed behaviour of interacting binaries, little progress in this field has been made until recently. In this review, we will describe the astro-tomographic techniques required to image starspots on the cool stars in interacting binaries, before summarising some of the recent highlights in this field. Finally, we will conclude with some future opportunities.

2 The technique of Roche Tomography

Unfortunately, interacting binaries are too small and too distant to be resolved directly, even in the worlds largest telescopes. Rutten & Dhillon (1994), however, described a technique, called Roche tomography, which uses phase-resolved spectra to reconstruct the line-intensity distribution on the donor stars. While analogous to Doppler imaging methods applied to single stars, Roche tomography differs in two important ways. First, the donor stars are tidally distorted into a Roche-lobe and are in synchronous rotation around the centre-of-mass of the binary. Second, the systems often show rapid variability due to the accretion. This means that one usually requires simultaneous photometry with which to slit-loss correct the spectra before continuum subtraction, whereas with Doppler imaging the spectra need not be slit-loss corrected and the continuum is normalised.

Otherwise, the concept of Roche tomography is relatively straight forward. Given the binary parameters, the donor's surface can be defined to lie on the critical surface

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of equal gravitational potential given by the Roche approximation at the point where Roche-lobe overflow occurs. The surface can then be modelled as a series of tiles lying on this critical surface. Each tile is then assigned a copy of the local specific intensity profile (which may either be Gaussian or taken from a spectral-type standard) and convolved with the instrumental resolution. One can then assign an intensity to each tile which scales its contribution to the total profile. Each tile's contribution is then integrated over the visible surface of the star taking into account limb-darkening, foreshortening and the radial-velocity of the elements.

Roche tomography essentially carries out the reverse of the process just described. The contribution of each element is iteratively varied until a map is obtained which predicts data consistent with the observed data. The goodness of fit is measured using the reduced χ^2 statistic. Unfortunately, the reduced χ^2 constraint alone is not sufficient to select a unique map as there are many maps that can fit the data equally well, and so we also adopt an additional *regularisation* statistic. Following Horne (1985), we adopt the map of *maximum entropy*, which can loosely be thought of as the smoothest map, or map containing the least information, with respect to a *default map* which may contain some a priori information about the surface intensity distribution across the donor star. Generally, we assume a uniform default map whose pixels are set to the average value in the reconstructed map, and the default map is updated after each iteration. An efficient algorithm for maximising entropy subject to a χ^2 constraint has been implemented by Skilling & Bryan (1984) in the FORTRAN package MEM-SYS.

3 Roche Tomography highlights

The earliest work using Roche tomography concentrated on reconstructing surface maps of CV donors using either single absorption or emission lines obtained using intermediate resolution spectrographs. The maps clearly showed the varying impact of irradiation from the compact object and accretion regions on these stars. While interesting in their own right, these results have been covered in several papers and reviews already and, instead of repeating the findings here, we refer the reader to the work by Watson et al. (2003). Instead, we shall focus on some of the more recent results showing the starspot distribution on a number of CV donors.

3.1 AE Aqr – the first image of starspots on a CV donor star

Early, single line CV studies failed to reveal the presence of cool starspots on CV donors since they neither had the resolution nor the signal-to-noise to detect the small, faint signatures of starspots. (One should consider that most CVs have $m_v > 11$, generally about 2–4 mags fainter than most stars that have been Doppler imaged). The first of these problems can be solved by employing a high resolution echelle spectrograph. Simply moving to a larger aperture telescope, however, does not solve the signal-to-noise problem.

Fortunately, the wide wavelength coverage of an echelle spectrograph allows 1000's of stellar lines to be observed in one spectrum. One can then apply a technique known as *Least Squares Deconvolution* (LSD – see Donati et al. 1997) which effectively combines all the lines to form one 'average' stellar absorption line of greatly increased signal-to-noise. Typically, this technique provides a multi-plex gain in signal-to-noise of $\sim$30. To put this in perspective, using LSD on an 8-m class telescope is the equivalent of attempting a single line study on a 40-m class telescope!

Armed with this technique, we obtained two nights echelle spectroscopy with the 4.2-m William Herschel Telescope (WHT) on La Palma on AE Aqr as part of a pilot study. This target was chosen as it is the brightest CV in the Northern sky, and the donor star contributes a large fraction ($\sim$ 70%) to the total system light. AE Aqr also has a relatively long-orbital period of 9.87-hrs which meant that reasonably long exposures could be used before the donor's orbital motion started to smear out the line profiles. Application of LSD to this dataset resulted in a multi-plex gain in signal-to-noise of $\sim$26 over single-line studies.

The Roche tomogram of AE Aqr is published in Watson et al. (2006), and can be viewed as a movie on AN's webpages. Representative frames are displayed in Figure 1 and show several dark starspot features. The most prominent of these is a large, high latitude spot most clearly visible at orbital phase ϕ=0.25. This spot is centred on a latitude of $\sim$65°, in stark contrast to our Sun where few spots are seen above latitudes greater than $\sim$35°. Such a high latitude feature on AE Aqr is, however, consistent with Doppler images of rapid rotators which often show the presence of polar spots.

Another feature of note is the dark region surrounding the L_1 point, which we have interpreted as irradiation of the inner face by the white dwarf and/or accretion regions. Such irradiation zones in similar locations in CV donors have been mapped previously (e.g. Davey & Smith 1996; Watson et al. 2003). There does, however, appear to be a chain of spots extending from the polar regions down to the irradiated L_1 point, making longitudes of the star facing the white dwarf companion appreciably more spotted than elsewhere. Indeed, in the Doppler image of the pre-CV V471 Tau, Hussain et al. (2006) also found that the side of the star facing the white dwarf was heavily spotted. This may well be due to tidal forces, which have been predicted to cause spots to emerge at preferred longitudes (e.g. Holzwarth & Schüssler 2003).

In total, Watson et al. (2006) estimated that 18 per cent of AE Aqr's Northern hemisphere was covered with spots, providing the first conclusive evidence that these systems were magnetically active. This put the canonical theory of CV evolution (which required strong magnetic fields on the donors in order to drain angular momentum from the binary
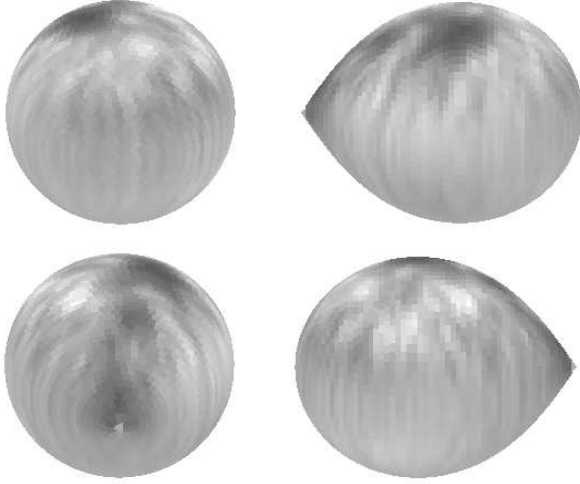
Fig. 1 The Roche tomogram of AE Aqr. The panels (clockwise from top-left) show the cool donor star at orbital phases ϕ=0 (inferior conjunction of the donor), ϕ=0.25, $\phi = 0.75$, and finally ϕ=0.5 (superior conjunction of the donor star). Dark greyscales indicate regions that are either covered in starspots or are irradiated. The system is plotted as the observer would view AE Aqr at an orbital inclination of $i = 66°$.
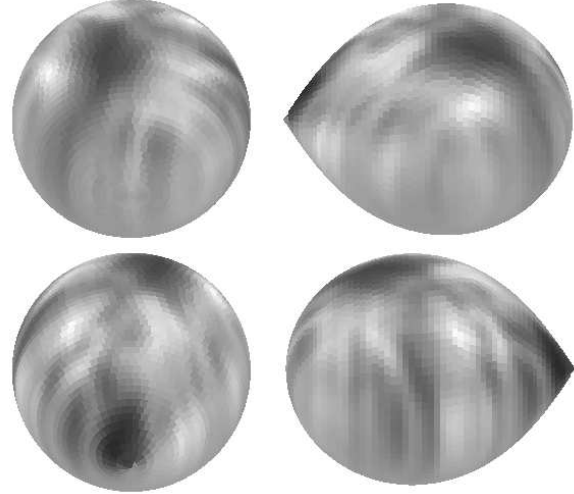
Fig. 2 The same as Fig. 1, but for BV Cen and assuming an orbital inclination of $i = 53°$. While BV Cen clearly has a larger spot coverage than AE Aqr, the similarities in the surface distribution of spots between BV Cen and AE Aqr is striking.

and drive the systems to shorter orbital periods) on a more secure observational footing.

3.2 BV Cen – starspots and slingshot prominences

Based on the success of the AE Aqr pilot study we began a campaign on the 6.5-m Magellan Clay telescope situated in Chile to map other CV donors. The larger aperture, wider spectral coverage and higher throughput of the Magellan setup compared to the WHT allowed systems 2 or 3 magnitudes fainter then AE Aqr to be imaged. The second CV we observed was the $\sim$14.7 hour period system BV Cen. A movie of BV Cen, reconstructed after applying LSD, is available on the AN website and some snapshots are shown in Figure 2.

The maps of BV Cen and AE Aqr (Figure 1) make for interesting comparison. Again, BV Cen shows a high latitude spot at $\sim$65°. Interestingly, the high latitude spot in both systems are displaced in the same direction towards the trailing hemisphere of the star (the side facing away from the orbital motion of the star). While we believe that the prominent dark region near the L_1 point is due to irradiation, we also see a chain of spots extending from the polar regions down to the L_1 point similar to that seen on AE Aqr. This provides some evidence that a mechanism is at work, perhaps tidal and/or Coriolis forces, that is forcing flux tubes to arise at these locations.

The fact that regions near the L_1 point seem heavily spotted, combined with the fact that low latitude spots are seen near the L_1 point, has interesting implications for the accretion dynamics of these systems. Many accreting binaries show sudden dips in their lightcurves, and it has been

suggested that this is caused by starspots moving across the L_1 point and quenching the mass transfer, leading to a dimming in the system's brightness. In their modelling of the mass transfer history of AM Her, Hessman, Gänsicke & Mattei (2000) concluded that if starspots were to cause such dips then regions near the L_1 point would most likely be unusually heavily spotted, with a spot-filling factor around 50%. Certainly, both AE Aqr and BV Cen appear to be more densely spotted on the hemisphere facing the white-dwarf. Indeed, we have calculated that, for BV Cen, the spot-filling factor reaches 40% at longitudes near the L_1 point, which seems to support the conclusions of Hessman et al. (2000).

In addition to the presence of starspots in BV Cen, which we calculated covered some 25% of the Northern hemisphere, we also detected a transient narrow emission feature at zero velocity. Such emission has been seen previously in other CVs (see e.g. Steeghs et al. 1996), also situated at zero velocity, and have been interpreted as 'slingshot prominences' from the donor star sitting near the centre-of-mass of the binary. The preference for prominences to be seen at this location may be a combination of two things. First, prominences erupting from near the L_1 point will be more subject to illumination from the accretion regions, making them more visible to us. Second, it appears from the Roche tomograms of BV Cen and AE Aqr that spots are more likely near the L_1 point, which may increase the probability of a prominence erupting in these active regions. Furthermore, with such a strong concentration of activity near the L_1 point, magnetic fragmentation of the accretions stream may be responsible for the 'blobby' accretion seen in some CVs (e.g. Meintjes 2004; Meintjes & Jurua 2006).
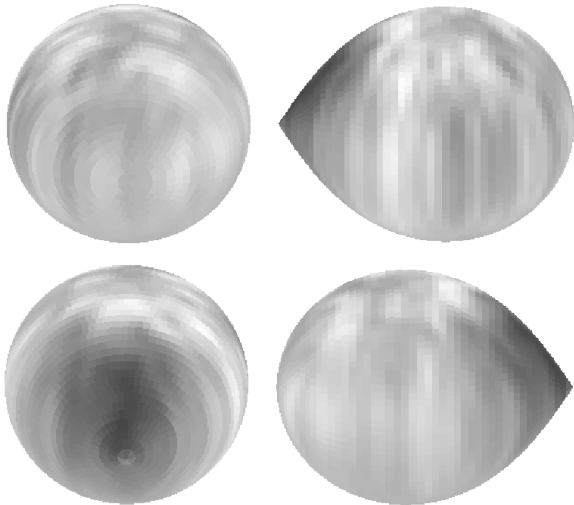
Fig. 3 The same as Figures 1 and 2 but for V426 Oph, assuming an orbital inclination of $63°$.

3.3 V426 Oph – caught during a prolonged low-state

Finally, we present a preliminary Roche tomogram of V426 Oph, again as a movie with some representative frames shown in Figure 3. With an orbital period of $\sim$6.85 hrs this is, to our knowledge, the fastest rotating star on which starspots have been imaged to date, the previous record being 7.44 hrs (RXJ1508.6 – Donati et al. 2000).

Unlike the Roche tomograms of AE Aqr and BV Cen, V426 Oph does not show such a prominent high latitude spot, though there is still a hint of a weak polar feature, again displaced slightly towards the trailing hemisphere. V426 Oph also shows spots appearing at lower latitudes. With a rotation rate almost 90 times solar, this is at odds with the models of Schüssler et al. (1996) which predict that magnetic flux tubes should only break the surface at high latitudes due to Coriolis forces and magnetic buoyancy.

Although the reason for the lack of a high latitude spot is unknown, one possibility is that we caught it at an unusual stage in its activity cycle. Interestingly, data from the AAVSO indicates that V426 Oph was undergoing some unusual behaviour at this time – being both dimmer during 2005 (when this data was taken), and exhibiting far fewer outbursts compared to other years. Was V426 Oph in an unusual state of activity, and is this responsible for its unusual behaviour during 2005? Further observations are required if any such link is to be made, or if we are to determine whether V426 Oph simply lacks a polar spot at all times.

Other than that, the inner face of V426 Oph appears to be quite uniformly irradiated (giving the star a darker appearance in the Roche tomograms at Φ=0.5). Within the irradiated zone, however, individual starspots are still visible near the L_1 point, and V426 Oph also appears to exhibit a less distinctive chain of spots extending from high latitudes down to the L_1 point. Given the preliminary nature of the analysis presented here, we are hesitant to draw any more conclusions at this time.

4 Future opportunities

While we are now beginning to reveal in some detail the magnetic nature of CVs, a sustained campaign is required to investigate whether these systems show solar type activity cycles, and to what extent such a cycle impacts on the observed behaviour of the binary. We are currently undertaking a monitoring campaign to determine whether AE Aqr displays any solar-like activity cycle.

Another interesting question is whether the donor stars in interacting binaries display an appreciable level of differential rotation. Scharlemann (1982) suggests that tidal forces should weaken, but not suppress, differential rotation. The fact that we see very similar spot distributions on AE Aqr and BV Cen suggests that the spot distribution may essentially be fixed. In turn, this suggests that differential rotation on these systems may be weak, perhaps even suppressed. Given that differential rotation is a key ingredient in stellar dynamo models, amplifying and transforming initial poloidal field into toroidal field, any suppression of differential rotation may provide a challenge to dynamo theory. Thus measurements of the differential rotation rate, via cross-correlation of latitude strips from images taken 1 or 2 weeks apart, is essential. Such studies on binaries have a unique advantage over those conducted on single stars in that the *sense* of the differential rotation can be deduced since the actual mean rotation period is known from the orbital period of the binary, allowing the corotation latitude of the donor star to be determined.

Finally, it would be interesting to prove that starspots can affect the accretion dynamics of interacting binaries by suppressing mass transfer. An observation of a starspot crossing the L_1 point, combined with a dip in the luminosity of the system, would be compelling evidence for such a scenario. It is quite comforting to see that, in the case of V426 Oph, we can still identify starspots even if they lie within irradiated regions. In summary, such work promises to reveal much about both the behaviour of binaries, and of the stellar dynamo under the most extreme conditions.

References

Davey, S.C., Smith, R.C.: 1996, MNRAS, 280, 481

Donati, J.-F., Mengel, M., Certer, B.D., Marsden, S., Collier Cameron, A., Wichmann, R.: 2000, MNRAS, 316, 699

Donati, J.-F., Semel, M., Carter, B.D., Rees, D.E., Cameron, A.C.: 1997, MNRAS, 291, 658

Horne, K.: 1985, MNRAS, 213, 129

Meintjes, P.J.: 2004, MNRAS, 352, 416

Meintjes, P.J., Jurua, E.: 2006, MNRAS, 372, 1279

Rutten, R.G.M., Dhillon, V.S.: 1994, A&A, 288, 773

Skilling, J., Bryan, R.K.: 1984, MNRAS, 211, 111

Steeghs, D., Horne, K., Marsh, T.R., Donati, J.-F.: 1996, MNRAS, 281, 626

Watson, C.A., Dhillon, V.S.: 2001, MNRAS, 326, 67

Watson, C.A., Dhillon, V.S., Rutten, R.G.M., Schwope, A.D.: 2003, MNRAS, 341, 129

Watson, C.A., Dhillon, V.S., Shahbaz, T.: 2006, MNRAS, 368, 637