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Stream Eclipse Mapping with 'Fire-Flies'

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Abstract. We apply a new method of eclipse mapping to the light curves of eclipsing polars. The technique aims to locate the bright emission associated with the accretion stream, using a technique that makes the fewest prior assumptions about the location of the accretion stream material. We have obtained data of EP Dra and HU Aqr with the S-Cam 2 superconducting tunnel junction camera using the William Herschel Telescope. The location of emission regions in both systems show that previously assumed trajectories are consistent with those found using our technique. Most of the emission is located in a region where we expect material to be confined to magnetic field lines, particularly for HU Aqr, while there appears to be a lack of emission from where we conventionally expect material to follow a ballistic trajectory from the L_1 point.

1. Introduction

Eclipse mapping is an inversion technique that can be used to reconstruct the distribution of bright material in the accretion streams of eclipsing polars. The eclipsing nature of these systems means that for a short duration the stream is the dominant contributor to the observed brightness, the white dwarf and accretion region being hidden from view by the secondary. The technique of eclipse mapping was first applied to accretion disks in the early 1980s, and the method was later applied to the bright eclipsing polar HU Aqr by Hakala (1995). Because it was found that the accretion stream contributed around half the optical emission in HU Aqr, this system was ideal for the application of eclipse mapping to determine the distribution of this bright stream material in the binary system.

Hakala (1995) developed this method assuming a one-dimensional stream confined to the orbital plane. This was represented as an arc connecting the inner Lagrangian point (L_1) to the white dwarf. Developments to this method included a two part trajectory, and models using this have been successfully applied to the eclipse light curves of the bright eclipsing polars HU Aqr and UZ For (Bridge et al. 2002; Vrielmann & Schwope 2001; Harrop-Allin, Potter & Cropper 2001; Kube, Gänsicke & Beuermann 2000; Harrop-Allin et al. 1999b). This trajectory comprises a ballistic free-fall component from the L_1-

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point (Lubow & Shu 1975), followed at some distance from the white dwarf by a magnetically confined component. The confined part of the trajectory originates in the threading region from where the stream material is channeled by the field lines to the white dwarf surface. The field lines are assumed to have a dipolar geometry and be centred on the white dwarf. However, such a clear division between two trajectories is likely to be an inadequate assumption (e.g. Heerlein, Horne & Schwope 1999) and the assumption of a ballistic free-fall component may not be appropriate in all cases (e.g. the low state of HU Aqr; Harrop-Allin et al. 2001). A further development is a move to three-dimensional streams (Vrielmann & Schwope 2001; Kube et al. 2000), thus attempting to include the effects of uneven heating of the stream and features related to the eclipse by the stream of the white dwarf and accretion region.

All these previous model techniques have the common feature that the stream trajectory is fixed prior to the application of the model. Hakala, Cropper & Ramsay (2002) introduced a technique which makes no assumptions about the location of the stream material prior to the modeling process. In principle, emission is allowed from anywhere within the Roche lobe of the white dwarf. They have successfully applied this technique to synthetic data sets, but here we apply it to observed light curves for the first time.

We model the 'white' light curves of the eclipsing polars EP Dra and HU Aqr (see Bridge et al. 2002, 2003 for a discussion of the light curves), observations of which were obtained with the superconducting tunnel junction (STJ) camera S-Cam 2 (see e.g. Perryman et al. 2001). The S-Cam 2 camera records the location on the array, time of arrival and energy of each incident photon. This allows the study of the energy dependence of short timescale variations observed in polars.

2. Model technique

We discuss briefly here the main points of the model (for a detailed discussion see Hakala et al. 2002). The model consists of a number of 'fire-flies', where each fly is an individual bright emission point. A fly is created with an initially random location within the Roche lobe of the white dwarf, but is subsequently free to move during the evolution of the model. The fly has a brightness (F_{fly}) which varies with the angle α between the observer, the fly and the white dwarf. This is defined as $F_{fly}(\alpha) = F_0 + Acos(\alpha)$ where F_0 is the minimum brightness of a fly and A is the amplitude of angular dependence. The brightness of those flies not eclipsed by the secondary at each phase are summed to form the model light curve. Many swarms of such flies are created and for each a model light curve can be generated.

The goodness of fit of an individual model light curve to the observed light curve is then defined using a fitness function, R, which consists of a χ^2 term and a regularisation term: $R = \chi^2 + \lambda S_{reg}$. The best fit solution is 'bred' through a number of generations using a genetic algorithm (GA; see e.g. Charbonneau 1995 for a review) that is regulated by a self-organising map (SOM; Kohonen 1990). The regularisation places a number of sections of a smooth curve through the fly distribution (see Hakala et al. 2002), this helps to constrain the model where generally there are more degrees of freedom than data points. The two

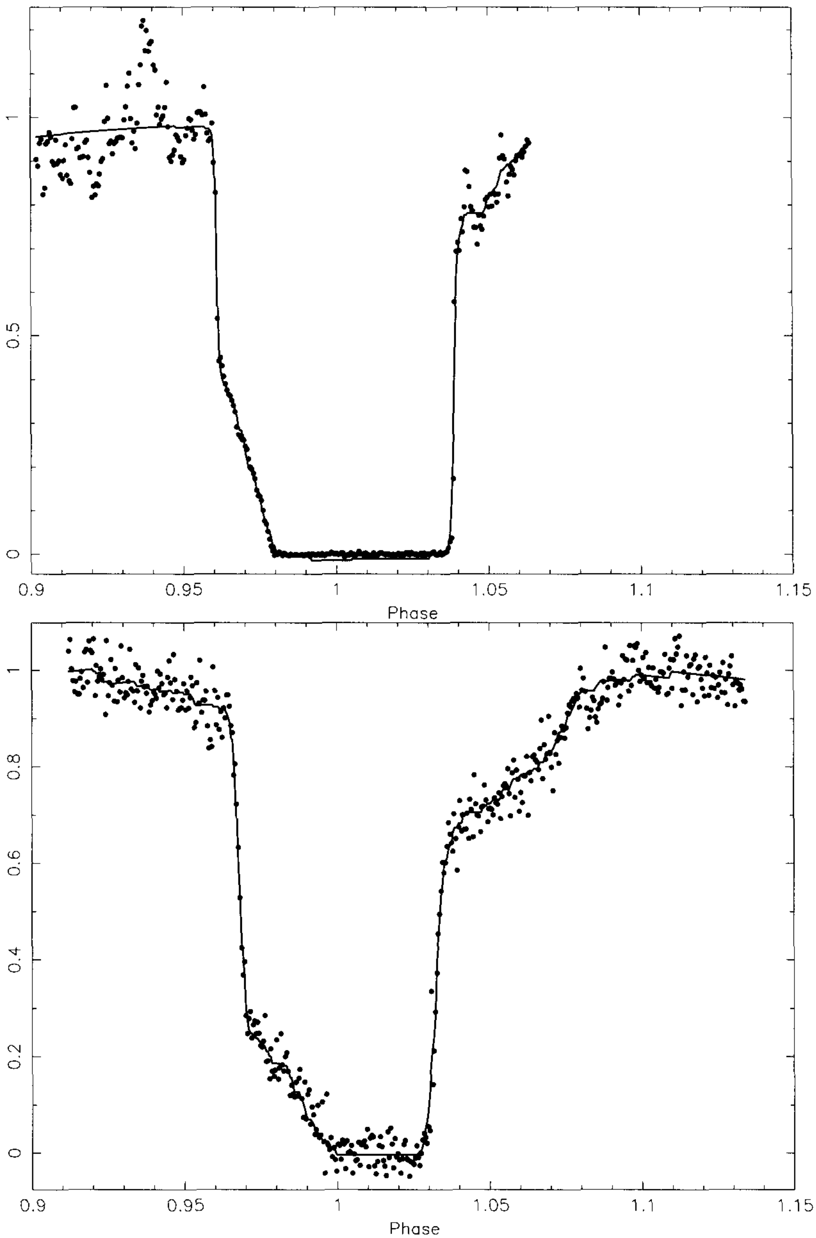

Figure 1. The model fits (solid line) to the observed light curves (dots) for HU Aqr (top) and EP Dra (bottom). The light curves are binned in 3 s intervals and normalised to 1 pre-eclipse.

end points of the curve are defined as the L_1-point and the white dwarf surface, thus providing two physically realistic constraints on the stream trajectory. The

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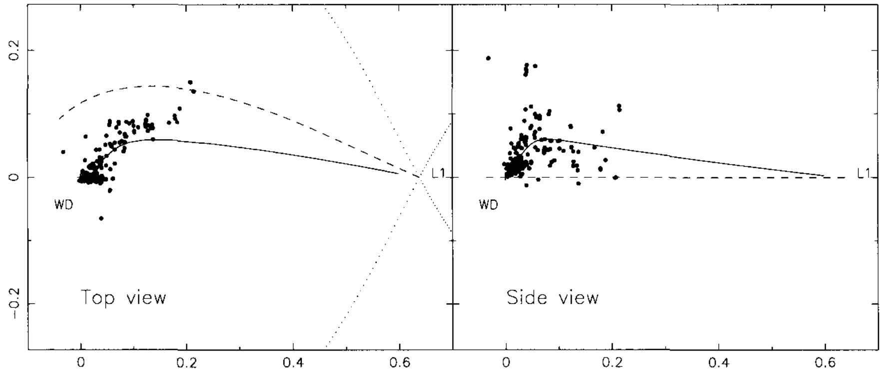

Figure 2. The fly distribution for HU Aqr defining the emission region. The left-hand panel shows the x-y plane looking down onto the orbital plane, while the right-hand panel shows the view parallel to the orbital plane. The dotted line illustrates the Roche lobe, the dashed line a ballistic trajectory and the solid line the regularisation curve.

model then prefers those swarms with minimal distance to the curve, resulting in smooth tube-like fly distributions. Hakala et al. (2002) also demonstrated the use of the technique with no regularisation term. Here, there is no computational pressure on the flies to create any form of tube and they are not constrained to lie between the white dwarf and the L_1-point. In this case the model will define those regions of the Roche lobe volume where emission can and cannot be.

3. Results

The light curves were obtained in October 2000 at the William Herschel Telescope, La Palma. Preliminary results for fits to the 'white' light curves of EP Dra and HU Aqr are shown in Figure 1, the light curves are binned into 3 s time intervals, with the model fits superimposed as a solid line. We used 500 swarms each with 200 flies, and the models are run for 500 generations. This provides a sufficient number of swarms to produce a unique solution and enough iterations to reach convergence. Figures 2 and 3 show the corresponding fly distributions.

The fitting process is necessarily a trade-off, mediated by the value of λ, between fitting real gradient changes and avoiding statistical noise features. The presence of noise in the data will have the effect of broadening the fly distribution, but we can attempt to minimise this by binning the data, and also by adjusting the λ term to place more emphasis on the regularisation. However, while increasing λ has the effect of smoothing the distribution of flies into a more tube-like structure, we must be careful not to place too much emphasis on λ as this will have the effect of smoothing out any real brightness variations.

Figures 2 shows that the emission points in HU Aqr are located mostly out of the orbital plane. The extent in volume of the emission points, and location at different distances in the z-direction may indicate that material is threaded

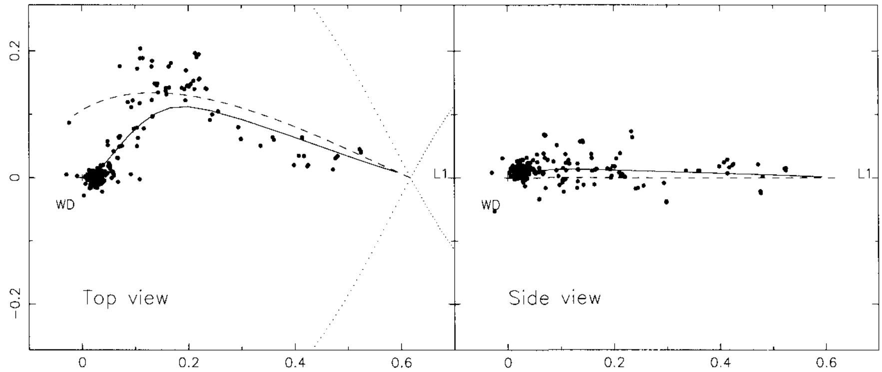

Figure 3. As for Figure 2 but for EP Dra.

along many different field lines, and may be the cause of the lack of evidence for a bright threading region at any one place in the orbital plane. In contrast to HU Aqr, the emission points in EP Dra are located close to the orbital plane, possibly indicating accretion along field lines that meet the white dwarf surface at low latitudes. The emission in EP Dra is also distributed over a larger volume than HU Aqr, particularly the region where we expect coupling to field lines to occur. To some extent this is a product of a noisier light curve, but it could also indicate material located in a large stagnation region, where it collects before coupling to the white dwarf field lines.

4. Discussion

We have applied this more objective technique to real data in an attempt to make the least number of assumptions about the location of bright material in these eclipsing binary systems. We find that previous assumptions are largely consistent with our results. For both EP Dra and HU Aqr most of the emission is located in the region where we expect material to be confined to the magnetic field lines of the white dwarf. In particular both models show an enhanced concentration of emission points towards the white dwarf. This may be indicative of where stream material is heated by X-ray emission from the accretion region on the white dwarf. However, the contribution from the accretion region, seen as the large amplitude change at ingress and egress, is fixed for the duration of the model. Therefore, if the input value is too low the model will assign flies to the white dwarf to boost the contribution at the ingress and egress of the accretion region. The number of flies near to the white dwarf may be indicative of this effect, rather than a real stream brightness enhancement.

An important advantage of placing no constraint on the stream trajectory, is the lack of sensitivity to input parameters. The HU Aqr data presented here have been previously modelled with a version of the technique of Harrop-Allin et al. (1999a). This method was found to be acutely sensitive to the exact value chosen for the distance to the threading region, and also the location of

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the accretion region on the white dwarf surface, which fixes the geometry of the magnetic field lines. This meant that the application to the data was restricted, and results had to be interpreted accordingly. As this new technique does not rely on the choice of initial parameters for the stream trajectory, we remove these uncertainties.

The stream trajectory used previously by Bridge et al. (2002) to model the HU Aqr data is consistent with that found from this new technique. The results of this modeling identified brightness enhancements towards the white dwarf and in the threading region. However with this new technique we do not see any enhancements where we expect material to be threaded by the field lines. The technique of Harrop-Allin et al. (1999a) was also applied to other observations of HU Aqr (Harrop-Allin et al. 1999b). They found that there was generally enhanced brightness towards the white dwarf and in the threading region, and for some cycles the threading region was significantly brighter. By comparison to both these methods, Vrielmann & Schwope (2000) did not find any enhancement towards the white dwarf, but did identify a brighter threading region. However, caution should be exercised as they used line emission only, while here we use the total emission (line and continuum). The results from modeling different light curves of HU Aqr may indicate some evolution of the stream brightness with time. However, the results of applying different models to the same data indicate that the results may be dependent upon the model parameters, as found for the technique of Harrop-Allin et al. (Bridge et al. 2002).

In HU Aqr we see no evidence for emission from where we would expect material to be following a ballistic trajectory. In EP Dra however, there is some indication that there is emission from along a ballistic trajectory (in Figures 2 and 3 the dashed curve represents the ballistic trajectory, seen most clearly in the left-hand panels). The location of material close to the orbital plane in EP Dra causes accretion at low latitude and is consistent with the suggested location of the accretion region from the cyclotron models of Schwope & Mengel (1997). Low latitude accretion may be indicative of a more complicated magnetic field geometry, with a quadrupole more likely to cause accretion at lower latitudes (Wu & Wickramasinghe 1993).

5. Summary and further work

While the previous techniques all assumed a stream trajectory, here we use a less constrained model that makes few *a priori* assumptions about the location of material. This shows that the trajectory is largely as expected, with the model providing good fits to the light curves of HU Aqr and EP Dra. The different results obtained from modeling the same data imply some dependence upon the technique, although this new technique is less sensitive to input parameters than that of Harrop-Allin et al. (1999a). A more detailed investigation of the effects of the input parameters and the regularisation curve are needed to fully understand any effects. We see most of the emission from material close to the white dwarf in both systems, and it is unclear why we see no emission from where we expect material to be following a ballistic trajectory in HU Aqr.

The colour information available from S-Cam 2 means that we can use the model to determine the colour dependence of the stream emission. In particular this will help explore the temperature variations along the stream by emphasising which parts of the stream are brightest at bluer wavelengths, and therefore hotter, and where the stream is redder and hence cooler. We can also apply this model to the consecutive cycles of HU Aqr and EP Dra, to see any evolution of the stream structure and temperature.

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