

# What can we learn from Accretion Disc Eclipse Mapping experiments?

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**Abstract.** The accretion disc eclipse mapping method is an astrotomographic inversion technique that makes use of the information contained in eclipse light curves to probe the structure, the spectrum and the time evolution of accretion discs in cataclysmic variables. This paper presents examples of eclipse mapping results that have been key to improve our understanding of accretion physics.

**Key words:** binaries: close – binaries: eclipsing – novae, cataclysmic variables – stars: imaging

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## 1. Introduction

Cataclysmic Variables (CVs) are close interacting binaries in which mass is fed to a white dwarf (the primary) by a Roche lobe filling companion star (the secondary) via an accretion disc, which usually dominates the ultraviolet and optical light of the system (Warner 1995). Accretion discs in CVs cover a range of accretion rates,  $\dot{M}$ , from the low-mass transfer dwarf novae (the discs of which show recurrent outbursts on timescales of weeks to months) to the high-mass transfer nova-like variables (the discs of which seems to be stuck more or less in a steady state).

One of the difficulties in studying accretion disc physics comes from the fact that the physical conditions in an accretion disc are expected to vary by large amounts with disc radius (the temperature distribution in a steady-state disc decreases as  $T \propto R^{-3/4}$ ), making the integrated disc spectrum a complex combination of light emitted from regions of distinct physical conditions (e.g., Frank, King & Raine 1992).

In this regard, CVs are excellent sites for studying accretion physics because their binary nature and relatively short orbital periods enable the application of powerful indirect imaging techniques. These techniques overcome the intrinsic ambiguities associated with the composite disc spectra by providing spatially resolved information about accretion discs on angular scales of micro arcseconds – well beyond the current direct imaging capabilities.

The Eclipse Mapping Method (Horne 1985) is one of these techniques. It assembles the information contained in

the shape of the eclipse into a map of the accretion disc surface brightness distribution. The *eclipse map* is defined as a grid of intensities centred on the white dwarf and usually contained in the orbital plane. The eclipse geometry is specified by the inclination  $i$ , the binary mass ratio  $q (=M_2/M_1)$ , where  $M_2$  and  $M_1$  are the masses of, respectively, the secondary star and the white dwarf) and the phase of inferior conjunction. Given the geometry, a model eclipse light curve can be calculated for any assumed brightness distribution in the eclipse map. A computer code then iteratively adjusts the intensities in the map (treated as independent parameters) to find the brightness distribution the model light curve of which fits the data eclipse light curve within the uncertainties. The quality of the fit is checked with a consistency statistics, usually  $\chi^2$ . Because the one-dimensional data light curve cannot fully constrain a two-dimensional map, additional freedom remains to optimize some map property. A maximum entropy procedure (e.g., Skilling & Bryan 1984) is used to select, among all possible solutions, the one that maximizes the entropy of the eclipse map with respect to a smooth default map. Details of the mathematical formulation of the problem can be found in Horne (1985) and Baptista (2001). A movie illustrating the iterations of an eclipse mapping experiment from start to convergence is available at [www.astro.ufsc.br/~bap/slide1.gif](http://www.astro.ufsc.br/~bap/slide1.gif).

## 2. A highlight of results

Early applications of the technique showed that accretion discs in outbursting dwarf novae (e.g, Horne & Cook 1985)

and in long-period novalike variables (e.g., Rutten, van Paradijs & Tinbergen 1992) closely follow the  $T \propto R^{-3/4}$  law expected for a steady-state disc, and that the radial temperature profile is essentially flat in the short-period quiescent dwarf novae (e.g., Wood et al 1989). This suggests that the viscosity in these short period systems is much lower in quiescence than in outburst, lending support to the disc instability model, and that their quiescent discs are far from being in a steady-state.

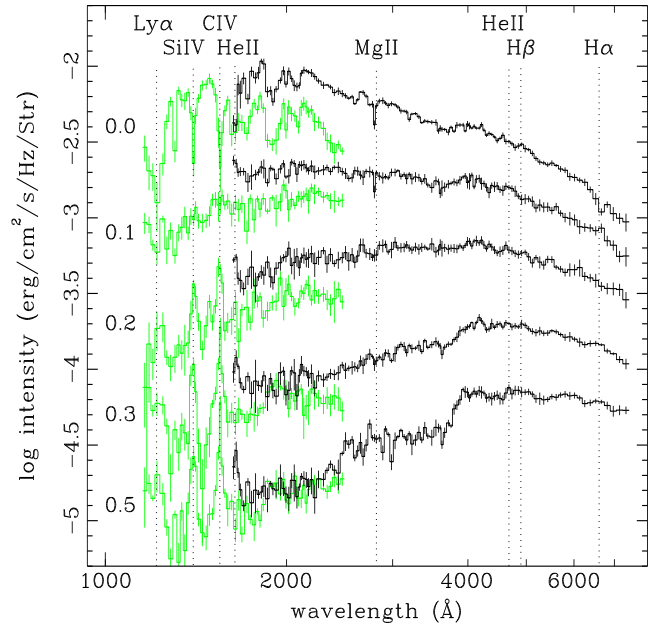
From the  $T(R)$  diagram it is possible to obtain an independent estimate of the disc mass accretion rate,  $\dot{M}$ . The diagram of  $\dot{M}$  versus orbital period (e.g., Baptista 2001) suggests a tendency among the steady-state discs of novalike variables to show larger  $\dot{M}$  for longer binary period – in agreement with current evolutionary scenarios for CVs (Patterson 1984) – and that the discs of novalike variables and outbursting dwarf novae of similar binary periods have comparable  $\dot{M}$ . The mass accretion rates in the eclipse maps of novalike variables increase with disc radius. The departures from the steady-state disc model are more pronounced for the SW Sex stars (period range 3–4 hrs). Illumination of the outer disc regions by the inner disc or mass ejection in a wind from the inner disc are possible explanations for this effect (Rutten et al 1992).

Multi-colour eclipse mapping is useful to probe the spectrum emitted by the different parts of the disc surface. Two-colour diagrams show that the inner disc regions of outbursting dwarf novae (e.g., Horne & Cook 1985) and of novalike variables (e.g., Horne & Stiening 1985) are optically thick with a vertical temperature gradient less steep than that of a stellar atmosphere, and that optically thin, chromospheric emission appears to be important in the outer disc regions. The fact that the emission from the inner disc regions is optically thick thermal radiation opens the possibility to use a colour-magnitude diagram to obtain independent estimates of the distance to the binary with a procedure similar to cluster main-sequence fitting.

## 2.1. Spectral studies

The eclipse mapping method advanced to the stage of delivering spatially-resolved spectra of accretion discs with its application to time-resolved eclipse spectrophotometry (Rutten et al 1993). The time-series of spectra is divided up into numerous spectral bins and light curves are extracted for each bin. The light curves are then analyzed to produce a series of monochromatic eclipse maps covering the whole spectrum. Finally, the maps are combined to obtain the spectrum for any region of interest on the disc surface.

The spectral mapping analysis of nova-like variables (e.g., Baptista et al 1998) shows that their inner accretion disc is characterized by a blue continuum filled with absorption bands and lines which cross over to emission with increasing disc radius (Fig. 1). The continuum emission becomes progressively fainter and redder as one moves outwards, reflecting the radial temperature gradient. These high- $\dot{M}$  discs seem hot and optically thick in their inner regions and cool and optically thin in their outer parts. The spectrum of the infalling



**Fig. 1.** Spatially resolved spectra of the UX UMa accretion disc on August 1994 (gray) and November 1994 (black). The spectra were computed for a set of concentric annular sections (mean radius indicated on the left in units of  $R_{L1}$ , the distance from disc centre to the L1 point). The most prominent line transitions are indicated by vertical dotted lines. From Baptista et al (1998).

gas stream was found to be noticeably different from the disc spectrum at the same radius suggesting the existence of gas stream “disc-skimming” overflow that can be seen down to the inner disc regions (e.g., Baptista et al 2000b).

The spectrum of the uneclipsed light in these nova-like systems shows strong emission lines and the Balmer jump in emission indicating an important contribution from optically thin gas. The lines and optically thin continuum emission are most probably emitted in a vertically extended disc chromosphere + wind (e.g., Baptista et al 2000b). The uneclipsed spectrum of UX UMa at long wavelengths is dominated by a late-type spectrum that matches the expected contribution from the secondary star (Rutten et al 1994). Thus, the uneclipsed component provides an unexpected but interesting way of assessing the spectrum of the secondary star in CVs.

## 2.2. Physical parameters studies

Vrielmann, Horne & Hessman (2002a) developed a version of the eclipse mapping method that simultaneously fits a set of multi-colour light curves to directly map physical quantities in the accretion disc (in contrast to the classical mapping of disc surface brightnesses). This *physical parameter* eclipse mapping requires the assumption of a *a priori* spectral model for the disc emission relating the parameters to be mapped (e.g., temperature and surface density) to the observed surface brightness in a set of passbands. The adopted spectral model is a pure hydrogen slab of gas in LTE including only bound-free and free-free H and  $H^-$  emission. Although sim-

ple, this model is useful to distinguish between optically thin and optically thick disc regions and allows to estimate the disc surface density (for the optically thin regions).

The analysis of multicolor data of the dwarf novae HT Cas and V2051 Oph with this technique provides evidence that their discs consist of a hot, optically thin chromosphere (responsible for the emission lines) on top of a cool, dense and optically thick disc layer (Vrielandt et al. 2002a, 2002b).

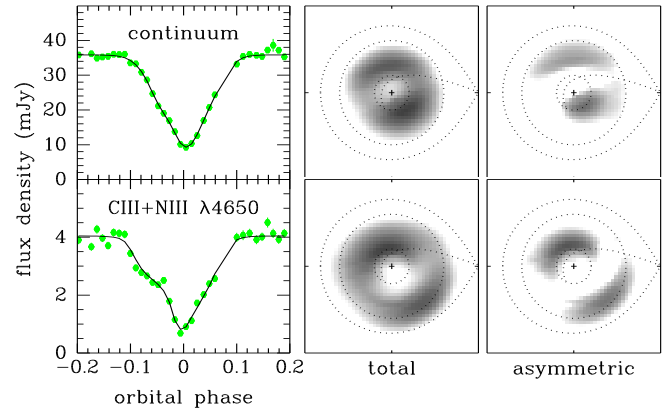
### 2.3. Spatial studies

Eclipse mapping has also been a valuable tool to reveal that real discs have more complex structures than in the simple axi-symmetric model.

Besides the normal outbursts, short-period dwarf novae (SU UMa stars) exhibit superoutbursts in which superhumps develop with a period a few per cent longer than the binary orbital period (e.g., Patterson 2001). O’Donoghue (1990) analyzed light curves of Z Cha during superoutburst with eclipse mapping techniques in order to investigate the location of the superhumps. His analysis shows that the superhump light arises from the outer disc, and appears to be concentrated in the disc region closest to the secondary star. This result helped to establish the superhump model of Whitehurst (1988), which proposed that they are the result of an increased tidal heating effect caused by the alignment of the secondary star and an slowly precessing eccentric disc.

Ultraviolet observations of the dwarf nova OY Car in superoutburst show dips in the light curve coincident in phase with the optical superhump. The eclipse mapping analysis of these data indicates the presence of an opaque disc rim, the thickness of which depends on the disc azimuth and is large enough for the rim to obscure the centre of the disc at the dip phase (Billington et al 1996). These results are consistent with a model of superhumps as the consequence of time-dependent changes in the thickness of the edge of the disc, resulting in obscuration of the ultraviolet flux from the central regions and reprocessing of it into the optical part of the spectrum.

Tidally induced spiral shocks are expected to appear in dwarf novae discs during outburst as the disc expands and its outer parts feel more effectively the gravitational attraction of the secondary star. Eclipse mapping of IP Peg during outburst (Baptista, Harlaftis & Steeghs 2000a) helped to constrain the location and to investigate the spatial structure of the spiral shocks found in Doppler tomograms (Steeghs, Harlaftis & Horne 1997). The spiral shocks are seen in the eclipse maps as two asymmetric arcs of  $\sim 90$  degrees in azimuth extending from intermediate to the outer disc regions (Fig. 2). The comparison between the Doppler and eclipse maps reveal that the Keplerian velocities derived from the radial position of the shocks are systematically larger than those inferred from the Doppler tomography indicating that the gas in the spiral shocks has sub-Keplerian velocities. This experiment illustrates the power of combining the spatial information obtained from eclipse mapping with the information on the disc dynamics derived from Doppler tomography.



**Fig. 2.** Eclipse mapping of spiral shocks in IP Peg. The light curves are shown in the left-hand panels and the eclipse maps are displayed in the middle and right-hand panels in a logarithmic greyscale. Bright regions are dark; faint regions are white. A cross marks the center of the disc; dotted lines show the Roche lobe, the gas stream trajectory, and circles of radius 0.2 and 0.6  $R_{L1}$ . The secondary is to the right of each map and the stars rotate counter-clockwise. From Baptista et al (2000a).

### 2.4. Time-resolved studies

Eclipse maps yield snapshots of an accretion disc at a given time. Time-resolved eclipse mapping may be used to track changes in the disc structure, e.g., to assess variations in mass accretion rate or to follow the evolution of the surface brightness distribution through a dwarf nova outburst cycle.

Rutten et al (1992b) obtained eclipse maps of the dwarf nova OY Car along the rise to a normal outburst. Their maps show that the outburst starts in the outer disc regions with the development of a bright ring, while the inner disc regions remain at constant brightness during the rise. The flat radial temperature profile of quiescence and early rise changes, within one day, into a steep distribution that matches a steady-state disc model for  $\dot{M} = 10^{-9} M_{\odot} \text{ yr}^{-1}$  at outburst maximum. Their results suggest that an unclipped component develops during the rise and contributes up to 15 per cent of the total light at outburst maximum. This may indicate the development of a vertically-extended (and largely unclipped) disc wind, or that the disc is flared during outburst.

Eclipse maps covering the full outburst cycle of the long-period dwarf nova EX Dra (Baptista & Catalán 2001) show the formation of a one-armed spiral structure in the disc at the early stages of the outburst and reveal how the disc expands during the rise until it fills most of the primary Roche lobe at maximum light. During the decline phase, the disc becomes progressively fainter until only a small bright region around the white dwarf is left at minimum light. The evolution of the radial brightness distribution suggests the presence of an inward and an outward-moving heating wave during the rise and an inward-moving cooling wave in the decline. The radial temperature distributions shows that, as a general trend, the mass accretion rate in the outer regions is larger than in the inner disc on the rising branch, while the opposite holds

during the decline branch. Most of the disc appears to be in steady-state at outburst maximum and, interestingly, also during quiescence. It may be that the mass transfer rate in EX Dra is sufficiently high to keep the inner disc regions in a permanent high viscosity, steady-state. A movie with the sequence of eclipse maps of EX Dra along its outburst cycle is available at [www.astro.ufsc.br/~bap/slide2.gif](http://www.astro.ufsc.br/~bap/slide2.gif).

## 2.5. Flickering mapping

A long standing unsolved problem in accretion physics is related to the cause of flickering, the intrinsic brightness fluctuation of 0.1-1 magnitudes on timescales of seconds to minutes considered a basic signature of accretion. Eclipse mapping of flickering light curves (e.g., Welsh & Wood 1995) is starting to shed light on this subject by spatially-resolving the flickering sources in CVs.

The orbital dependency of the flickering is obtained by measuring the random variations due to flickering with respect to the mean flux level in a set of light curves as a function of the orbital phase. Baptista & Bortoletto (2003) applied complementary techniques (e.g., Bruch 2000) to construct separate light curves of low- and high-frequency flickering of the dwarf nova V2051 Oph. Their eclipse mapping analysis reveals that the low-frequency flickering is associated to the bright spot and gas stream (suggesting that it is caused by inhomogeneities in the mass transfer from the secondary star) whereas the high-frequency flickering seems spread over the surface of the disc with a radial distribution similar to that of the steady light (suggesting it reflects variability intrinsic to the disc such as convection and/or magnetic turbulence).

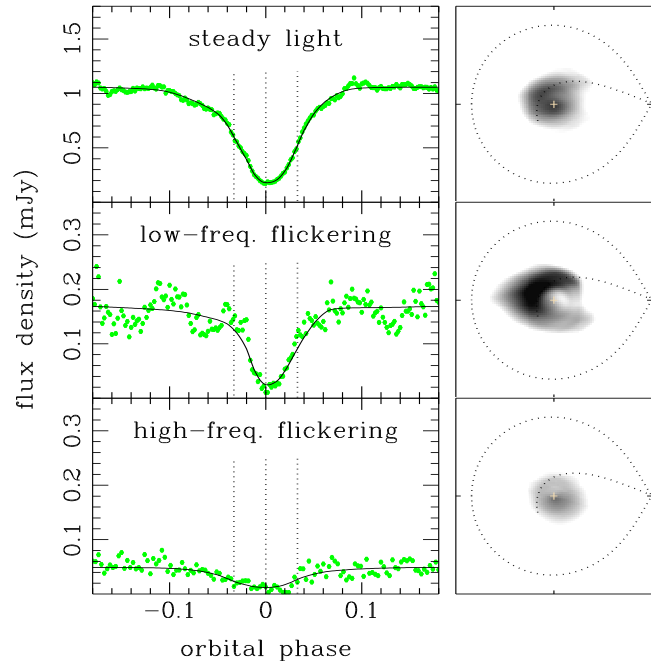
## 3. Summary and future prospects

Eclipse mapping is a powerful tool to probe the radial and vertical disc structures, as well as to derive the physical conditions in accretion discs. Partly thanks to the many experiments performed over the last two decades, our picture of accretion discs was enriched with an impressive set of new details such as gas outflow in disc winds, gas stream overflow, flared discs with azimuthal structure at their edge, chromospheric disc line emission, ellipsoidal precessing discs, sub-Keplerian spiral shocks, and moving heating/cooling waves during disc outbursts.

Additional interesting eclipse mapping results are expected in the near future. For example, fitting state-of-the-art disc atmosphere models to the spatially-resolved spectra is an obvious next step to the spectral mapping experiments and will allow estimates of fundamental physical parameters of accretion discs, such as gas temperature, surface density, vertical temperature gradient, Mach number and viscosity, setting important additional constraints on current disc models.

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**Fig. 3.** Flickering mapping of V2051 Oph. Top: steady-light. Middle: low-frequency flickering ( $f < 100$  mHz). Bottom: high-frequency flickering ( $f > 6$  mHz). The notation is the same as in Fig. 2. Vertical dotted lines mark mid-eclipse and the ingress/egress phases of the white dwarf. The two flickering maps are in the same brightness scale. From Baptista & Bortoletto (2003).

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## Slide captions

**Slide 1.** Left: Data (green dots with error bars) and model (solid line) light curves. A horizontal line depicts the uneclipsed component to the total light. Vertical dotted lines mark white dwarf ingress, egress and mid-eclipse phases. Labels indicate the number of iterations and the value of  $\chi^2$  in each case. Right: the corresponding eclipse map in a logarithmic greyscale (dark regions are brighter). The lower panel shows the asymmetric part of the eclipse map. Dotted lines show the primary Roche lobe, the gas stream trajectory and a circle of radius  $0.6 R_{L1}$ . A cross mark the centre of the disc. The slide shows the eclipse mapping run for nine iterations from close to start (niter=10) up to convergence (niter= 241). The double-stepped, smooth asymmetric eclipse shape map into two asymmetric arcs in the eclipse map (see also section 2.3).

**Slide 2.** Sequence of light curves and eclipse maps of the dwarf nova EX Draconis along its outburst cycle. Top left: the radial intensity distributions A dotted vertical line indicates the radial position of the bright spot in quiescence. Large vertical ticks mark the position of the outer edge of the disc and short vertical ticks indicate the radial position of a reference intensity level. Bottom left: The radial brightness temperature distributions. Steady-state disc models for mass accretion rates of  $\log \dot{M} = -7.5, -8.0, -8.5, \text{ and } -9.0 M_{\odot} \text{ yr}^{-1}$  are plotted as dotted lines for comparison. The dot-dashed line marks the critical temperature above which the gas should remain in a steady, high- $\dot{M}$  regime. The numbers in parenthesis indicate the time (in days) from the onset of the outburst. Top right: sequence of light curves in quiescence (h), rise to maximum (a-b), during maximum light (c), through the decline phase (d-f), and at the end of the eruption (g), when the system goes through a low brightness state before recovering its quiescence level. Bottom right: the corresponding eclipse maps in a logarithmic blackbody false color scale. Dotted lines show the primary Roche lobe and the gas stream trajectory. From Baptista & Catalán (2001).