ECLIPSE MAPPING AND RELATED TECHNIQUES

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Abstract. Eclipse mapping is a technique to deduce spatial structure on very small angular scales in eclipsing cataclysmic variable stars (CVs). By analysing the eclipse light curve, information is obtained on the brightness structure of the accretion disk and of the compact mass-accreting object in these systems. This information would otherwise be well beyond the resolving power of any optical telescope. Since the development of the eclipse mapping technique by K. Horne, about one decade ago, it has now become an important tool in the study of CVs. Originally eclipse mapping was employed to construct brightness maps of accretion disks in broad spectral bands. Recently, maps of much higher spectral resolution have become available from which optical and UV spectra have been reconstructed in spatial detail across accretion disks. Such information is very important for our understanding of the physics of the accretion process.

In this paper I will describe the eclipse mapping technique and review recent results. In conjunction, I will briefly highlight other techniques related to the mapping of surface structure in CVs.

1. Introduction

Cataclysmic variable stars (hereafter abbreviated as CVs) are interacting binary systems which generally consist of a cool low-mass star and a more massive compact white dwarf. CVs are closely related to low-mass X-ray binaries in which the compact object is a neutron star or black hole; both groups of interacting binary stars have many observational and physical features in common.

CVs exhibit brightness variations of very different amplitudes and on a wide range of time scales. These variations can be regular, semi-regular, irregular, or unique, and may affect a large wavelength range. The most

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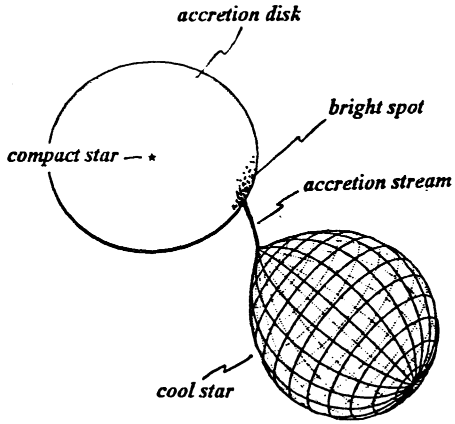

Figure 1. Representation of a cataclysmic variable star with the Roche-lobe filling secondary star, the accretion disk, and the compact white dwarf indicated.

dramatic of these brightness variations, the dwarf nova and nova outbursts, have given these binary systems their common name. The large variety of observational features, and in particular their time dependence, renders CV research into a very complex but exciting field (see La Dous 1993).

Cataclysmic variables present an advanced stage of binary star evolution in which the compact and most massive star has evolved through the giant branch, has shed a substantial fraction of its main sequence mass during the binary common-envelope phase, and is evolving further as a white dwarf. The mass of the secondary star is typically sub-solar, and this star remains close to the main sequence during evolution towards the CV stage (see e.g. de Kool 1992). The secondary star fills its critical potential Roche surface, and hence material from its atmosphere can readily overflow to the compact object. In the mass-transfer process a luminous accretion disk around the primary star is formed. Orbital periods are typically of the order of hours. A cartoon of a CV is shown in Figure 1.

The transfer of material between the binary components not only has an impact on the appearance of the binary, but it also has a profound influence on the evolution of the binary system as a whole. Under conditions of conservative mass transfer from the less massive to the more massive component (i.e. when no material and angular momentum leaves the system) the binary system would have to become wider in order to conserve orbital angular momentum. As a result the Roche lobe of the secondary star would grow, leaving this star to underfill its Roche lobe, and thus impeding the mass transfer process. Hence, mass transfer has the tendency to switch itself off (King 1988, Frank et al. 1992). From observations, however, it is clear long-lived mass transfer does take place and hence angular momentum has to be removed from the system. Magnetic braking of the cool secondary star, in combination with gravitational radiation for the short period systems are thought to be responsible for this loss of angular momentum.

The description above in a nutshell sets the scene against which this review paper attempts to describe efforts to map surface structure in CVs. The rather small physical sizes of these systems, in combination with the appreciable distance of even the brightest CVs would require micro-arcsecond resolution to resolve their structure directly. Such small angular scales are well beyond the possibilities of direct imaging techniques, now and in the forseeable future. Hence, indirect techniques are the only way to deduce structural information on the surface of CVs.

Alternative techniques to resolve surface structure have been developed during the past decade and have opened up new avenues of research which allow a much closer interaction between observation and theory. The following section present a brief introduction to the physics of accretion processes, and how accretion processes are observed in CVs. How surface structure of the accretion disk can be mapped is described in Section 3 and 4. Mapping of surface structure on the white dwarf and on the secondary star in CVs is discussed in Section 5. Finally, a forward look in the field of mapping of surface structure is presented in Section 6.

2. Accretion disks

When in a binary system material flows from the secondary Roche-lobe filling star towards the compact star, that material has to shed part of its angular momentum before it can accrete onto the compact object. If a particle would retain its angular momentum it would follow a Keplerian orbit, but it would not accrete. The accretion disk is nature's answer to the problem of how angular momentum is removed and matter is allowed to accrete. Viscosity in the disk is the key to angular momentum transport; it allows material in some orbit to give off angular momentum to material in wider orbits, allowing it to move to a narrower orbit, which eventually will lead to accretion onto the central object.

Although this principle of accretion is generally accepted, there is still no consensus on the nature of the viscous process. Molecular viscosity is orders of magnitudes too small to be of importance in accretion disks (Frank et al. 1992). Alternative sources of viscosity have been proposed of which currently the most promising is a form of magnetic turbulence (Balbus & Hawley 1991, Hawley et al. 1995). Since viscosity is responsible for accretion of material it also determines how the disk is heated, and hence is relevant to the detailed appearance of the disk, as well as to how the disk evolves with time (see Cannizzo 1993, and references therein). In spite of the uncertainty regarding the nature of viscosity, standard accretion disk theory is able to provide some fundamental characteristics of disks which are *independent* of viscosity. For instance, the effective temperature as a function of radial distance R from the center of an accretion disk in steady state is given by:

$$T_{\rm eff}^4(R) = \frac{3GM_{\rm wd}\dot{M}}{8\pi R^3\sigma}\left[1-\left(\frac{R_{\rm wd}}{R}\right)^{1/2}\right]$$

where $\dot{M}$ is the mass-transfer rate through the disk, and $R_{\rm wd}$ and $M_{\rm wd}$ are the radius and mass of the white dwarf (Frank et al. 1992). This formula can be approximated as $T_{\rm eff} \propto \dot{M}R^{-3/4}$ for radii well in excess of the white dwarf radius. This important result shows that, assuming conservative mass transfer (i.e. $\dot{M}$ independent of R), the radial temperature dependence is fixed, and that the mass accretion rate sets the overall brightness of the disk.

The description above refers to radial dependences only, but deviations from axial symmetry do also occur. At the outer edge of the disk the accretion stream from the secondary star strikes the disk which gives rise to local heating and brightening. This disturbance is fixed in the co-rotating frame of the binary orbit. From observations we also know that disks can become highly unstable, for instance during dwarf nova outbursts when a large amount of material accretes on a short time scale. Furthermore, resonances in the disk due to the periodic gravitational pull from the secondary star can result in deviations from symmetry and may trigger so-called super outbursts of dwarf novae, resulting in a dramatic release of energy (Osaki 1994). This paper, however, considers only disks in a steady state in order to avoid complications caused by time-dependent phenomena. For an overview of accretion disk theory and observations see the book by Frank et al. (1992) and the monograph by La Dous (1993).

The fact that a single disk combines a large range of physical conditions, from the hot inner disk to the cool outer regions of the disk, reflects on their spectra. Understanding observed disk spectra requires complex radiative transfer models which differ substantially from stellar atmosphere models (see Hubeny 1990, Shaviv and Wehrse 1993). For example, unlike stellar atmospheres, the disk's atmosphere is heated throughout, the effective temperature varies with radius, the disk can be optically thin at some radii, strong shearing motions are present, the gravitational potential strongly varies through the disk, etcetera. As the details of the heating process are not known, the vertical temperature stratification is not easily predicted and consequently many details in the calculated disk spectra remain uncertain. A confrontation of model calculations with observations may shed light on many of these issues, but this would require spectral

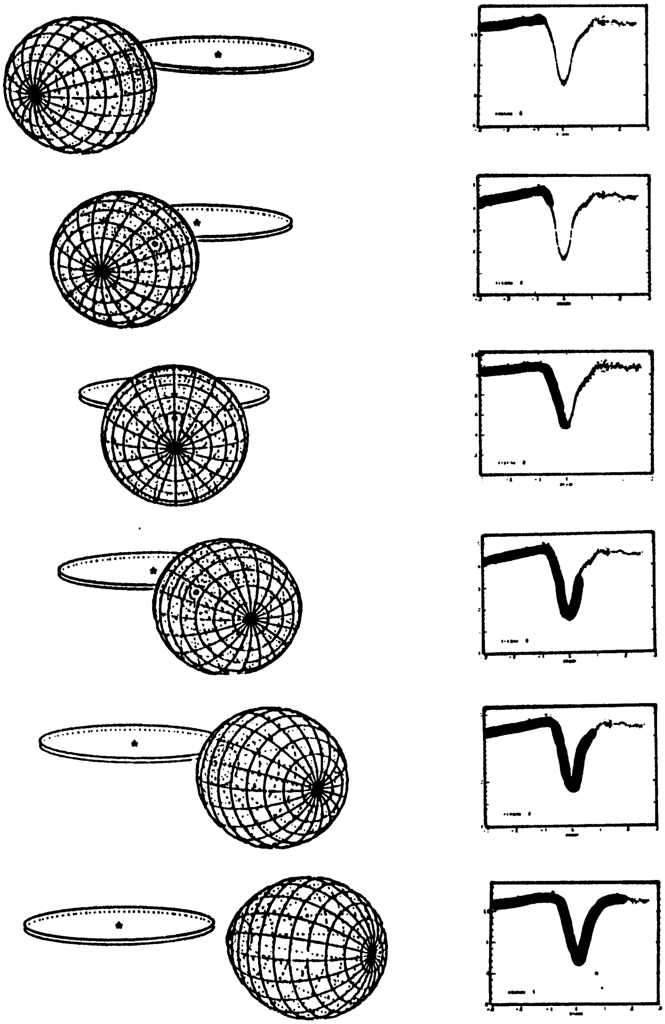

Figure 2. A series of drawings showing how the secondary star obscures the bright accretion disk, going through eclipse, and the development of the light curve.

observations that resolve the disk structure. Such detailed spectral information of the disk structure may now be obtained using techniques such as eclipse mapping and Doppler tomography which are described below.

3. Mapping accretion disk structure: eclipse mapping

Unlike many other environments in the universe where accretion disks are present, in close binary systems, and in particular in the cataclysmic variable stars, accretion disks can be studies very well. One of the reasons for this is that the disk is usually by far the brightest component in the system. Hence, photometric and spectroscopic variability can readily be used as probes for accretion physics. Also, the geometry of these binary systems, their orbital period, inclination and masses, are often well established and helps us constrain the shape, size and temperatures of accretion disks.

In spite of these advantages our understanding of accretion disks is still very limited, partly due to the fact that an accretion disk combines a wide range of physical conditions, but the different ranges could until recently not be resolved by observations. This situation often results in ambiguous results when interpreting observations. Horne (1985) greatly improved this situation with the development of the eclipse-mapping technique which uses the eclipse of the disk by the secondary star to probe the brightness distribution of the disk.

If a cataclysmic binary system is viewed under high inclination the secondary star obscures the bright accretion disk once every orbital cycle. Such an eclipse results in a dip in the light curve which can be several magnitudes deep because the disk is so bright relative to the secondary star, and the star can obscure a large part of the disk. The shape of the light curve depends on many parameters such as the shape and brightness of the secondary star, the orbital inclination, and the shape and brightness structure of the disk itself. Figure 2 outlines how an eclipse arises and how the eclipse light curve results.

If the geometry of the binary system is reasonably well constrained through spectroscopic and photometric observations, it is easy to calculate which part of the accretion disk is obscured at any time during the eclipse. Hence, if we would know the brightness structure throughout the disk it would be easy to predict what the light curve would look like. In practice, however, we find ourselves in the opposite situation where the light curve is known from observations and it is the disk brightness structure we want to deduce, so the inverse problem has to be solved. The classical method of fitting such light curves involves building a model assuming a certain functional dependence of the brightness across the face of the accretion disk. The model parameters (e.g. some parameterization of the radial temperature profile) can then be fitted so that the observed light curve is reproduced. The disadvantage of such method is that one enforces a certain physical model which is not necessarily correct, and often these models have difficulty explaining eclipse light curves satisfactorily.

An alternative method of fitting eclipse light curves, known as eclipse-mapping (Horne 1985) uses a grid in the orbital plane around the compact object on which each grid element is assigned some intensity. By adjusting the intensities of all elements the eclipse light curve is reproduced, resulting in a brightness map of the accretion disk without the necessity to enforce

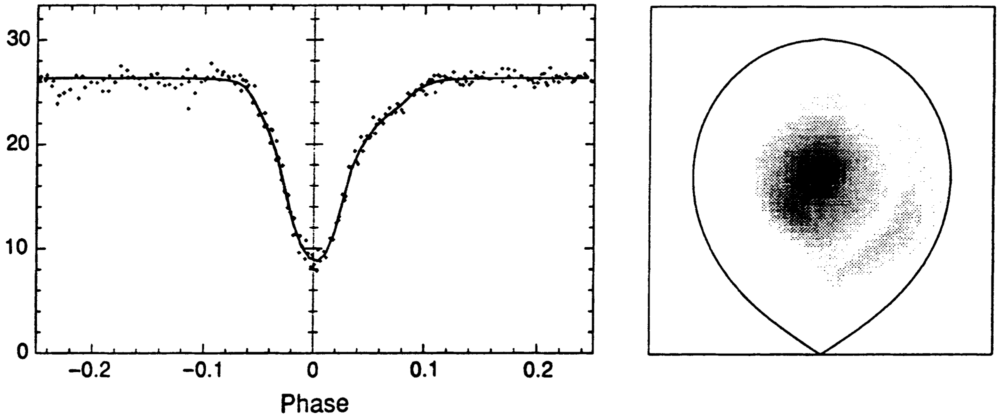

Figure 3. Left: eclipse light curve of UX UMa. The smooth line represents the fit to the data obtained by the eclipse mapping technique. Right: eclipse mapping reconstruction of the disk in UX UMa. The image is displayed on an inversed linear grey scale. The thin curve outlines the shape of the Roche lobe in the orbital plane. Note the asymmetric structure, the bright spot, indicates the area where the mass accretion stream from the secondary star collides with the disk.

some physical model for the disk's brightness distribution. Obviously, since the grid usually contains many (thousands) elements and the intensity on each element acts as a free parameter this is a complex problem to solve. There is no unique solution to this problem; many different disk brightness distributions reproduce the light curve equally well, to within the errors of the observations; an additional constraint is required which is obtained in the entropy measure. This entropy measure is a function of the shape of the disk brightness and is measured against some smooth disk shape (the default map). Maximizing the entropy function is equivalent to picking the smoothest possible solution, but provided the solution reproduces the eclipse data. In practice, the procedure is a constrained minimization problem where the reduced χ^2 of the fit is brought to unity while the entropy function is maximized in an iterative fashion. (For details on different optimization schemes see Skilling and Bryan 1984, Horne 1985, Baptista and Steiner 1993, Spruit 1994). This method assumes that the disk's brightness distribution does not change, at least during the eclipse, and that the disk is geometrically thin. An example of a disk reconstruction is shown in Figure 3 for the well known nova-like cataclysmic variable UX UMa.

The maximum-entropy eclipse mapping technique was first used on broad-band photometric observations of eclipsing CVs by Horne (1985; for later work see also, for example, Wood et al. 1986, Baptista and Steiner 1993, Rutten et al. 1992, and Warner et al. 1988). The short duration of

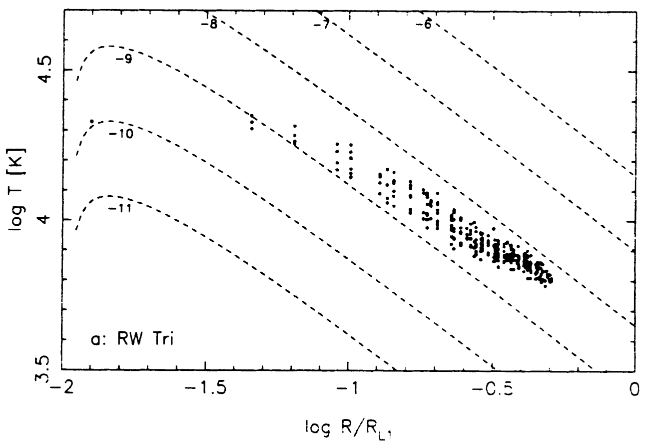

Figure 4. Radial temperature profile of the accretion disk of the system RW Tri. The dashed lines represent the relationship given by the standard steady-state accretion theory (see Section 2), for different values of the mass accretion rate $\dot{M}$ (labels indicate log$\dot{M}$ in solar masses per year). Note the good agreement between observations and theory.

eclipses, typically ranging from just a few minutes to about one hour, in combination with the required high quality of the photometric data renders such measurement demanding. Disk maps deduced from broad-band light curves, such as the one shown in Figure 3, can be used to obtain the disks' radial temperature profile which provides a direct observational test of predictions from the standard accretion disk theory. From such comparisons it became clear that in several cases the theoretical relationship $T_{\rm eff} \propto R^{-3/4}$ is indeed a fair representation of the observations (see Figure 4).

The observation that some eclipses are clearly asymmetric points towards the fact that disks are asymmetric. As can be seen from the light curve and the eclipse map of UX UMa in Figure 3, an asymmetry in the light curve results in an asymmetric disk map. The most prominent asymmetry arises from the area at the disk rim where the accretion stream from the secondary star impacts onto the disk and causes heating locally which shows up as a bright spot.

In principle eclipse mapping can be used on narrow-band light curves just as well as on broad-band light curves, but obviously high signal-to-noise is more difficult to obtain. Rutten et al. (1993) showed that eclipse mapping can be employed successfully at much higher spectral resolution when using spectrophotometric measurements. In this way not only the spectral continuum can be mapped in much greater detail, but also images in the light of individual spectral lines can be reconstructed. Spectral eclipse mapping was first used on the accretion disk of the object UX UMa in more than 100 independent pass bands covering the near UV to the near

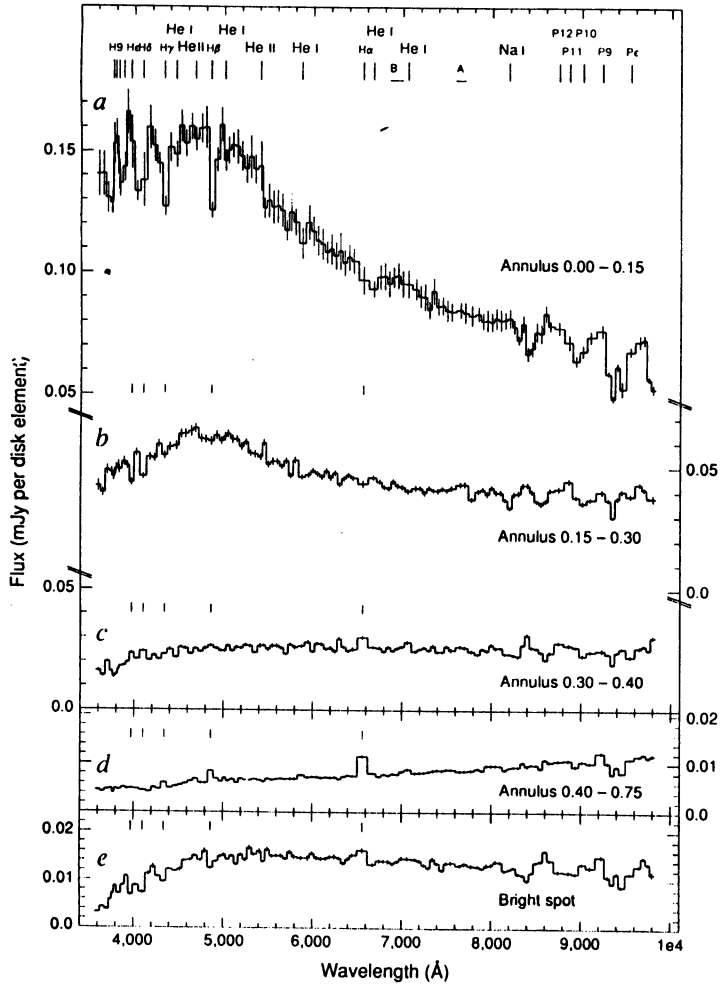

Figure 5. Reconstructed spectra for selected parts of the disk in UX UMa. From top to bottom spectra are plotted of annuli going out to progressively larger radii in the disk. The bottom spectrum represents the bright spot.

IR (Rutten et al. 1993). From all these semi-monochromatic maps it was possible to reconstruct spectra from any part of the disk, by recombining the fluxes from selected disk areas as is shown in Figure 5. These spectra for the first time showed the radial changes throughout the disk, from the hot optically thick inner disk with Balmer lines in absorption, towards the much cooler, red, and optically thin outer disk where Balmer lines are seen in emission. Also, these reconstructed spectra showed that the bright spot, where the accretion stream from the secondary star strikes the disk, is optically thick and fairly hot, in contrast with other parts of the disk at the same radial distance from the disk center. More recently, spectral eclipse mapping was conducted in the UV by Baptista et al. (1995) using time-resolved spectra obtained with the *Hubble Space Telescope*.

Such novel information contained in these disk spectra allows much more detailed probing of the accretion disk structure. It offers a way to compare theoretical spectral models with observations, with a much reduced problem of ambiguity resulting from lack of spatial information. A confrontation of radiative transfer models with observations is currently under way.

4. Mapping velocity structure: Doppler tomography

Eclipse mapping of the disk brightness structure, as described in the previous section, can only be carried out on a small fraction of the CVs since the system must be eclipsing. Another mapping technique, called Doppler tomography, can be used to map the brightness distribution of spectral lines for a much larger set of binary systems since it does not require an eclipse.

Material in the disk whirls around at ever greater velocities as it accretes, reaching velocities up to thousands of kilometers per second. Line emission coming from the disk reflects these large velocities through their width. The line wings are formed close to the disks center, where velocities are high, while the line core is mainly formed in the outer parts of the disk.

The observed line shape at some orbital phase reflects the velocity field where the line is formed. Spectra taken at some orbital phase may be regarded as a projection in velocity space of the line brightness in a specific direction corresponding to that phase, Doppler tomography, a technique first developed by Marsh and Horne (1988), reconstructs an image of the binary system in velocity space in the co-rotating frame of the binary from the phase dependent line changes.

Figure 6 shows an example of phase-dependent spectra together with the corresponding Doppler tomogram, a map of the spectral line brightness in velocity space of the Hβ line in the system U Gem (Marsh et al. 1990). The large ring shape corresponds to the accretion disk, where the outer regions in velocity space corresponds to high-velocity material and thus originate close to the disk center, and visa-versa. Also visible is a bright area in velocity space; this area corresponds to the secondary star, which fills a well confined spot in velocity space, and the accretion stream.

A Doppler tomogram such as the one shown in Figure 6 is an invaluable aid to isolate contributions from the disk, the accretion stream, the bright spot, and the secondary star, which would otherwise be extremely difficult to separate from the complex phase-dependent spectral line shape. From these contributions it can be studied, amongst other things, how the

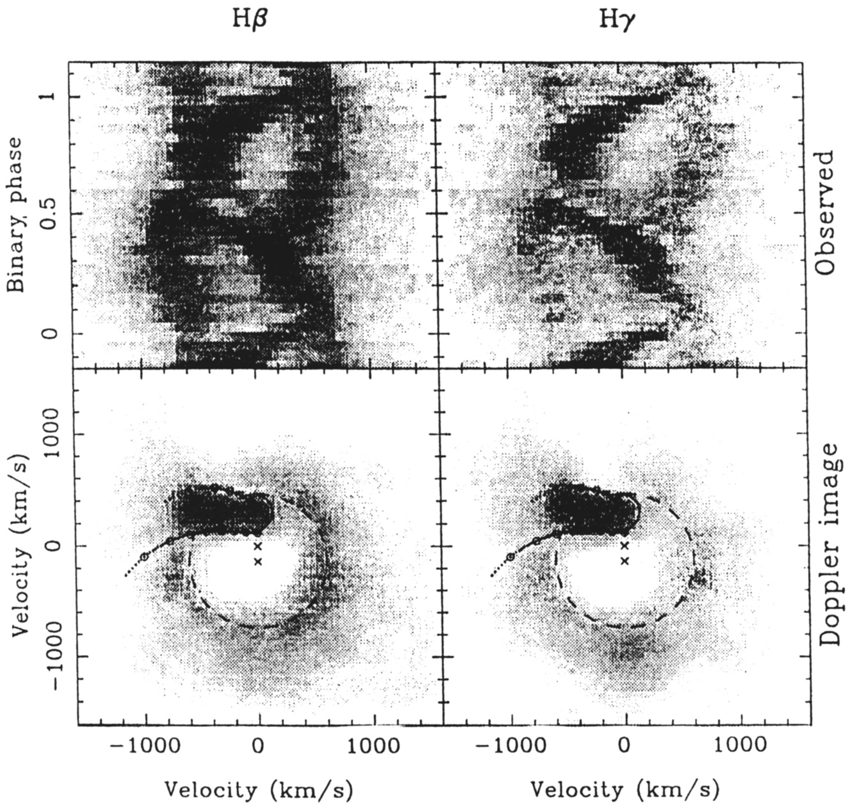

Figure 6. Trailed spectrum (top) and corresponding Doppler tomogram (bottom) of the Hβ and Hγ line in the system U Gem (adapted from Marsh et al. 1990).

line strength varies over the disk, whether the disk's velocity field behaves as predicted by theory, and whether the secondary star is irradiated by the disk. An interesting, but yet unexplored possibility is to combine spectral line eclipse maps, such as discussed in Section 3, with corresponding Doppler tomograms. This could in principle put firm constrains on the true velocity field of the accretion disk, at least in the line-forming region of the disk's atmosphere.

5. Mapping the secondary star: Roche tomography

A complete understanding of CVs is impossible without understanding the cool secondary star (typically a K or M-type dwarf). From studies of the

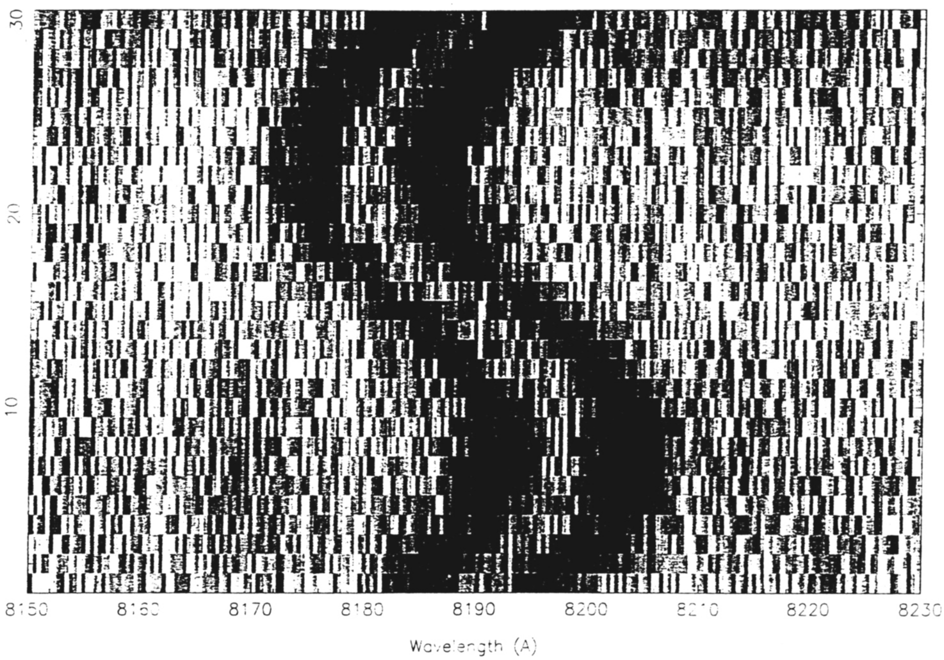

Figure 7. Phase-dependent 'trailed' spectrum of the Na I absorption line doublet for the dwarf nova IP Peg. The orbital motion is obvious from the Doppler shift in the lines. More subtle are the variations in line strength and width which contain information on the brightness distribution of the line across the face of the star.

secondary star insight may be obtained into, for example, the binary star parameters, magnetic activity on its surface, on the mass-transfer process, and the disk's radiation field through effects of irradiation. This makes detailed study of the secondary stars worth while, although their faintness in comparison to the usually much brighter accretion disk renders them difficult objects to study.

The secondary stars in CVs reveal themselves through the presence of ellipsoidal variations and spectral features such as the TiO absorption bands and the Na I doublet at λ 8190 Å. Many other spectral features that are often used to identify cool stars, such as the Ca II H and K lines and the IR triplet lines are less suitable for the study of cool stars in CVs because of confusion with line radiation from the accretion disk. Spectral lines arising predominantly from the surface of the secondary star, such as the Na I doublet, however, can be used to map the star's surface brightness in the following way (see Rutten and Dhillon 1994). The observed spectral line profile from the star at a given orbital phase is the sum of line contributions from all visible parts of its surface. The orbital motion of the Roche-lobe

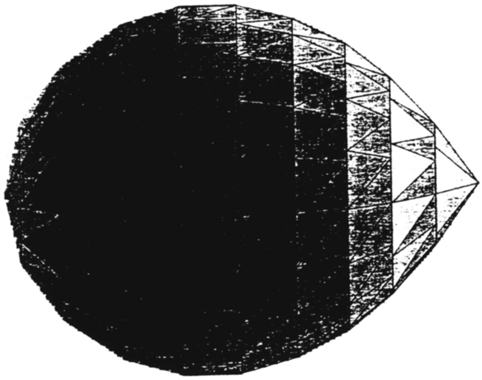

Figure 8. Reconstruction of the brightness distribution of the Na I line doublet on the surface of the Roche-lobe filling secondary star of IP Peg.

filling star introduces Doppler shifts of the line feature as a whole, and changes in the strength and shape of the spectral lines, as is shown for example in Figure 7 for the secondary star in IP Peg. Uneven strength of the line over the stellar surface will produce specific signatures in the line shape as a function of orbital phase. By modeling the observed line shape as a function of orbital phase, information is deduced as to how the line strength varies over the stellar surface; this is Roche tomography. It is interesting to note that in this way the strength as well as the shape of the line is modelled, thus using the full spectral information content, but the spectral data has to live up to this expectation of photometric quality, high S/N, and good spectral resolution.

In Roche tomography the stellar surface, which coincides with the critical Roche surface, is modelled by a large number of triangular tiles. Each element is assigned a line intensity value. It is this strength of the line for each surface element which is adjusted when fitting the data. As with eclipse mapping described in Section 3, optimization of the fit is obtained using the maximum-entropy criterion, which arrives at the smoothest possible map which fits the data to within the observational errors.

As an example, the brightness map of the Na I doublet on the surface of the secondary star in IP Peg, computed from the data in Figure 7, is shown Figure 8. This map shows that the Na I line is less strong on the inner hemisphere which faces the white dwarf, presumably due to heating of the star's atmosphere by irradiation from the disk and the compact object. This example shows the viability of Roche tomography, but its real power probably has to come from IR spectroscopy where the secondary star is relatively bright.

6. Looking ahead

In this paper I have tried to give an overview of techniques to reconstruct surface structures in CVs where direct imaging fails to satisfy our needs. Obviously not all indirect mapping techniques and all of their aspects could be covered here, and in particular only sporadically I mentioned limitations and possible future enhancements. This final section will briefly touch on new developments in this field which are currently being explored.

Eclipse analysis. Application of eclipse mapping has largely assumed a flat disk geometry. Exploring the third dimension in a systematic way by incorporating more realistic disk shapes is probably a fruitful extension of the standard eclipse mapping technique. A full three dimensional treatment of the disk would make the situation far more complex and would probably produce results which are even more difficult to interpret, reflecting better the power and the limitations of such light curve fitting techniques.

Another extension of eclipse mapping lies in the kind of parameters that are fitted. To date, eclipse maps have been used to study the disk morphology on the one hand, and to deduce physical parameters of the disk atmosphere on the other hand. An alternative approach to eclipse mapping would be to directly image parameters of interest, such as electron temperatures and densities, rather than just intensities at some wavelength (Horne, private communication). The success of this approach still remains to be proven.

Reprocessed radiation. Some of the radiation received by our instruments is not coming directly from the original source, but may have been (partly) reprocessed. The re-emitted radiation contains characteristics both from its original source and from the reprocessing site. As a light beam from the compact object at the disk center sweeps across the disk the reprocessed light from the disk will exhibit a time delay due to the light travel time. Also the light beam will illuminate material at different radial velocities as is moves across the disk, causing characteristic phase shifts of the observed pulse through spectral lines (Chester 1979). The observed amplitude of the reprocessed pulse and its phase can be used to constrain the geometry of the reprocessing site (Chester 1979, Marsh 1992). The technique of echo mapping (Vio et al. 1994, and references therein) has also been used successfully in extragalactic sources where the light travel times and hence the time delays are much longer.

Magnetic fields on disks. Finally, a technique to trace magnetic structures on accretion disks has been considered (Horne, private communication). It is an adaptation of similar methods successfully employed on cool, magnetically active stars and magnetic A-type stars (Semel et al. 1993).

The spectropolarimetric observations required for this method are very demanding but could lead to important new insights into the generation of magnetic fields in accretion disks.

The field of research of interacting binary systems has greatly profited from the development of the above mentioned techniques, some of which are now considered standard tools for analysing CV data. The information obtained, however, will have an impact on a much wider field of astronomy such as the study of magnetic fields and other surface structures on cool stars, and the physics of accretion disks in star forming regions and active galaxies.

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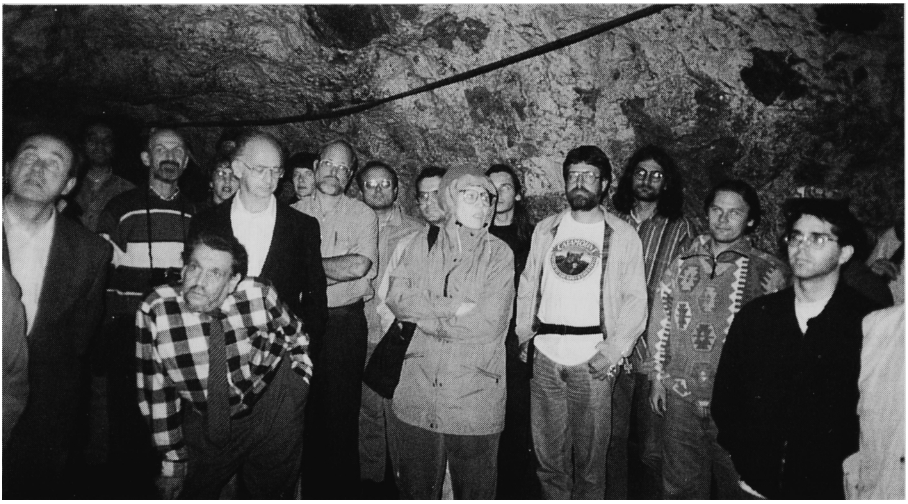
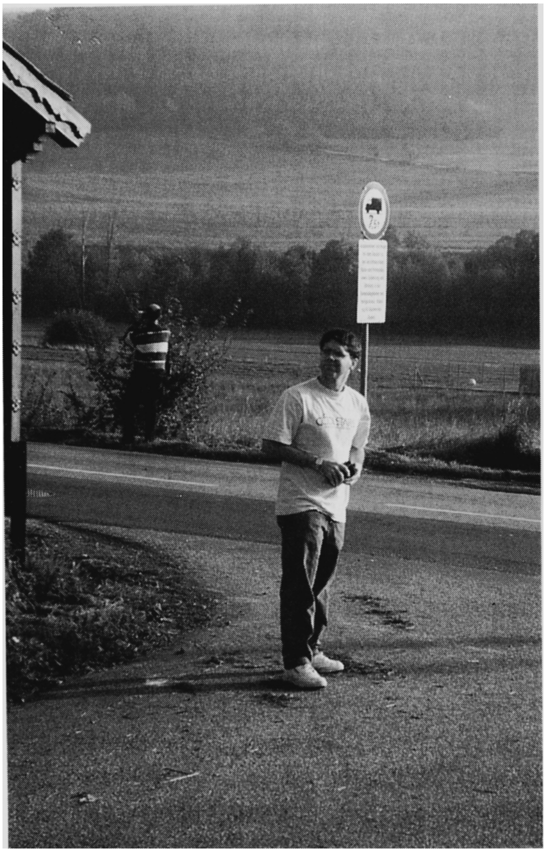


The Linsky's led the "Vienna-Woods" group on their expedition to the largest underground lake in Europe. Thanks to them, they all came back.



...although it was easy to get lost in this wilderness (Bob Dempsey). Notice Frank Fekel in the background. He is a *birdwatcher*!

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