MAPPING THE LINE EMISSION DISTRIBUTION OF CATACLISMIC VARIABLE STARS

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ABSTRACT. We describe a method for imaging the accretion disc of a Cataclysmic Variable star. We use the two-dimensional information contained in the line profiles as they vary with phase to invert the line formation process. Asymmetries in the disc, as are caused by the bright-spot, for example, are accounted for naturally.

1. INTRODUCTION

The broad emission lines of Cataclysmic Variable stars come from the accretion disc. For binary inclinations greater than ≈ 15° Doppler shifting is the dominant broadening mechanism in the disc (Horne & Marsh 1986). Thus, the shape of the lines reflects the distribution of emission over the disc (Smak 1969). This opens the possibility of inverting the profile formation to deduce the pattern of emissivity over the disc. The pattern of emission can reveal structure in the disc as might be caused by the impact of the gas-stream; it also provides strong constraints upon the formation mechanism of the emission lines.

We now discuss the principles behind the inversion, and then illustrate these with reconstructions of simulated data.

2. THEORY OF THE INVERSION

We consider the inversion in velocity space - that is we regard the emission pattern (henceforth the 'image') as a function of velocity (Vx,Vy) rather than of position (x,y). The two forms of image are related by a simple transformation of coordinates. The flux at a specific velocity in the line profile is the sum of the emission from all the parts of the disc with that radial velocity. In velocity space the lines of equal radial velocity are straight lines with direction dependent upon the binary phase. Thus, the formation of a line profile

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from a velocity space image is particularly simple: it is the result of integration along one dimension of the image, otherwise known as the 'projection' of the image. This point is illustrated in figure 1 in

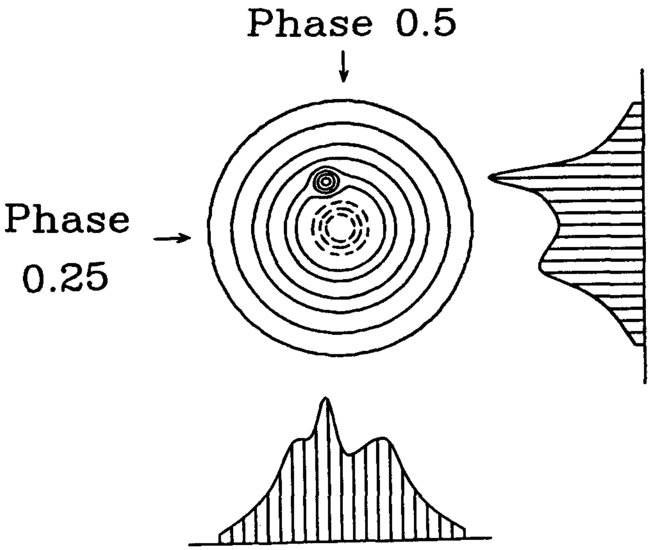

Figure 1. The contour map of a velocity space image and the line profiles seen at phases 0.5 and 0.25. The profiles are the result of integrating along the direction shown by the arrows. The intensity of the image rises to a peak at the radius of the bright-spot and then falls in the centre (dashed countours).

which the line profiles at two phases are plotted next to a contour plot of the image that produced them. The outer parts of the velocity space image correspond to the inner regions of the accretion disc; the bright-spot is positioned to match the location in the accretion disc (with the x axis pointing from the white dwarf to the secondary star and the y axis pointing in the direction of motion of the secondary star, $V_y > 0$, $V_x < 0$ for the bright-spot).

The problem of finding the image from a set of line profiles has been reduced to finding a two-dimensional image from a set of projections. Problems of this type have been solved before; in medicine, images of sections of the human head have been reconstructed from a set of X-ray photographs taken at different angles around the head. The reconstruction method, called 'computed tomography', has been applied with considerable success (Rowland 1979).

3. THE INVERSION IN PRACTICE

The discussion above shows that the inversion can be achieved; however, in practice, there are a number of effects such as eclipses by the red

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star, high optical depths in the lines and large intrinsic line widths in the disc that cannot be included by the linear inversion described by Rowland (1979).

We choose instead to apply the maximum entropy method (Gull & Skilling 1984) to the inversion problem. The image is represented by a grid of points over the disc; the intensities, positions and velocities are stored for every point. From this image we can compute the line profile at any phase, including high optical depths (Horne & Marsh 1986) and eclipses. We used the FORTRAN code of Skilling & Bryan (1984). During the computation, the image is compared to the data by computing the χ^2 of the fit, and is then adjusted to improve the fit; the user sets the required χ^2 at the start of the process. Since in general there are many images that can match or better the pre-set χ^2, another criterion is needed to pick just one of these images. We select the image of maximum entropy, S, where $S = -\Sigma p_i \log(p_i)$. The values p_i are defined by the iamge values, I_i, to be $p_i = I_i/\Sigma I_j$.

The image of maximum entropy is as close to uniformity as allowed by the data. Normally this is too restrictive, as it can bias the image towards a single intensity, and so we apply a generalised definition of the entropy which measures the departure from an azimuthally symmetric version of the image. This reduces the bias but still permits a single image to be chosen. We illustrate the method with a reconstruction of simulated data. We started with an image made up of an azimuthally symmetric component with a brightness proportional to $R^{-1.3}$ (R, the radius in the disc) and a bright-spot on the edge of the disc. Profiles were computed at twenty phases and gaussian noise was added. Finally, starting from a uniform image as the first guess, we reconstructed this image for three differing amounts of added noise. The results are displayed in figure 2. Image (A) is the model image, images (B), (C) and (D) are the three reconstructions with increasing amounts of noise. The reconstruction technique is very effective at recovering the original structure of the image. The main effect of noise is to degrade the reconstruction of the bright-spot. This occurs because as more noise is added, it is possible for the image to be almost symmetric and yet still be consistent with the data.

In practice, the signal-to-noise ratio of the data for image (C) could be achieved in about one night for a sixteenth magnitude star, however this ignores flickering noise and so in general several orbits of the binary should be observed.

We have studied the dwarf nova Z Cha; the Hγ line shows structure which indicates penetration of the disc by the gas-stream. We also detected a very weak bright-spot which contributes at most a few percent of the flux which is remarkable since the orbital hump in Z Cha is very bright ($\approx$ 0.5 mag).

4. DISCUSSION

The maximum entropy method does not depend on specific properties of the line profile formation. This has the disadvantage of making it heavy on computer time, but, far more importantly, any physical model can be

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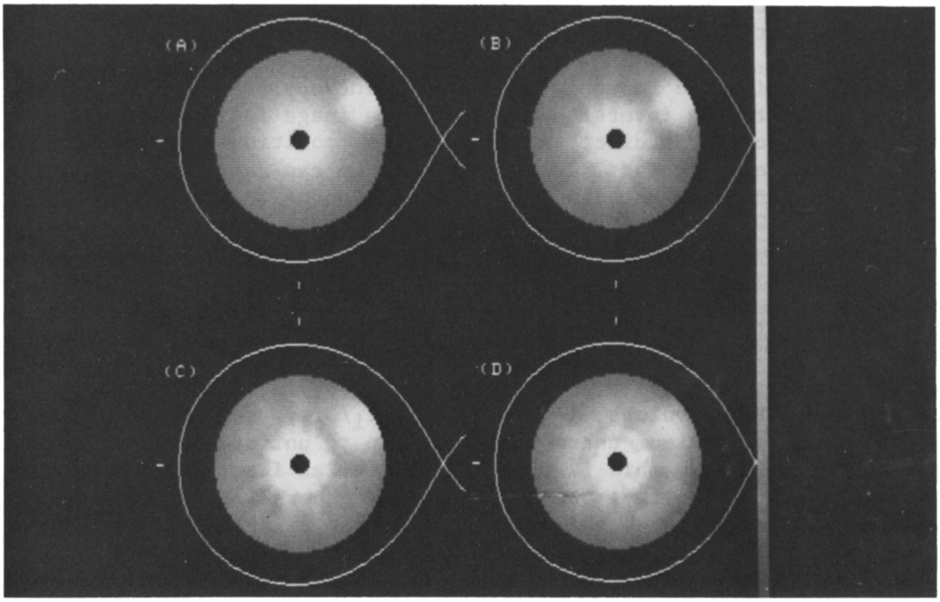

Figure 2. Image (A) is the model image; images (B), (C) and (D) are reconstructions from data with increasing amounts of added noise. The red star lies to the right of each image and the binary rotates anti-clockwise.

used. It is, for example, possible to reconstruct the images of blended lines by the trivial extension of having more than one image stored and accounting for the wavelength difference between the lines.

Reconstruction by maximum entropy was first applied to Cataclysmic Variable stars by Horne (1985) who reconstructed the continuum image from the light curves of eclipsing systems. The two applications differ in the number of coordinates involved: eclipse mapping reconstructs a two-dimensional image from the one-dimensional light curve, while the emission line mapping uses two-dimensional information. For this reason and because of the different physics involved in each case, the two techniques are suited to different problems: eclipse mapping is suited to the study of the temperature distribution in the disc (e.g. Horne & Steining 1985), while emission line mapping reveals two-dimensional structure in the disc.

5. CONCLUSIONS

We have presented a method for retrieving the information contained in the trailed spectra of Cataclysmic Variable stars. It is a very flexible and powerful technique for the study of the structure of accretion discs.

REFERENCES

Gull, S.F. & Skilling, J., 1984. in Indirect Imaging p267, ed. Roberts J.A., Cambridge University Press
Horne, K.D., 1985. Mon. Not. R. astr. Soc. **213**, 129
Horne, K.D. & Marsh, T.R., 1986. Mon. Not. R. astr. Soc. **218**, 761
Horne, K.D. & Steining, R.F., 1985. Mon. Not. R. astr. Soc. **216**, 933
Rowland, S.W., 1979. in Image reconstruction from projections p9, ed. Herman, G.T., Springer-Verlag
Skilling, J. & Bryan, R.K., 1984. Mon. Not. R. astr. Soc. **211**, 111
Smak, J., 1969. Acta Astron. **19**, 155

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