Accretion Phenomena and Related Outflows, IAU Colloquium 163
ASP Conference Series, Vol. 121, 1997
D.T. Wickramasinghe, L. Ferrario, and G.V. Bicknell, eds.

On Modelling the Lightcurves of Binary X-ray Sources

F.V. Hessman, A. van Teeseling, K. Beuermann

Universitäts-Sternwarte, Geismarlandstr. 11, D–37083 Göttingen, Germany

Abstract.
The lightcurves of non-magnetic X-ray binaries are usually modelled using standard techniques developed for ordinary double stars plus some assumptions about the geometry and temperature distribution of the accretion disk. The analyses of the observed optical lightcurves of systems suggest that the disks must have extremely large rims ($H/R \sim 0.3$) in order to produce the variable obscuration needed to reproduce the often asymmetric lightcurves. However, even models with large rims have problems explaining the X-ray absorption seen in systems with smaller inclinations. We discuss two phenomena which show that non-standard effects in X-ray binaries can play major roles in the determination of the lightcurves: the "spray" caused by the passage of the accretion stream through the "bow-shock" at the outer rim of the disk; and the effects of soft X-ray illumination of the secondary star.

1. Introduction

Much of our information about the structure of X-ray binaries (XRB) like cataclysmic variables (CV), low-mass X-ray binaries (LMXB), and super-soft X-ray sources (SSS) comes from analyses of the lightcurves – if possible at X-ray, UV, optical, and IR wavelengths. Many types of XRB show very asymmetric X-ray and optical lightcurves, which cannot be simply due to an accreting primary star, a surrounding flat and axisymmetric accretion disk, a "bright spot" formed by the collision of the accretion stream and the disk, and a partially illuminated secondary star.

Given this difficult situation, the most straight-forward means of explaining the lightcurve data has been to allow the disk to have some vertical structure. The consideration of the phase visibility of the X-ray absorption effects in LXMB and SSS has lead to the conclusion that this structure must be due to highly vertically extended and azimuthally variable accretion disk rims (Hellier & Mason 1989). If present, these rims cannot be maintained hydrostatically and so must be produced by some more dynamic process. The term "spray" has been used in this context (Schandl, Meyer-Hofmeister & Meyer 1996) but no detailed "rim-spray" model has appeared, so it is not clear what the concept really means.

In the following, we describe two effects which hitherto have been neglected and which are each capable of substantially modifying the observed lightcurves and spectral behavior.

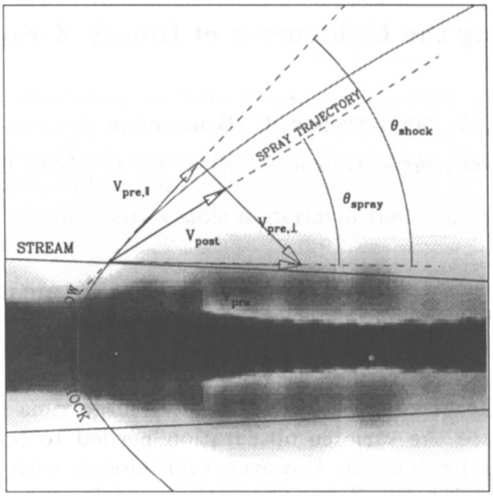

Figure 1. A cartoon showing the geometry of the stream-disk interaction. The underlying image is taken from Armitage & Livio (1996) and represents the structure of the bright spot and the dense stream overflow. The schematic stream and bow shock are for the more diffuse parts of the stream. The arrows indicate the kinematic effects of the passage of the diffuse stream through the bright spot's bow shock.

2. The "Spray" from the accretion stream bow-shock

The possibility, that the accretion stream could flow under and over the disk was first mentioned by Lubow & Shu (1976): given a sufficiently geometrically thick stream, only a fraction of the total mass transfered will be stopped at the bright spot. Armitage & Livio (1996) have presented elaborate numerical simulations of the accretion stream - disk interaction using a "Smoothed Particle Hydrodynamics" (SPH) code (the image in Fig. 1). However, SPH codes are inefficient in providing information about the diffuse vertical structure of the disk and stream. Also, in order to increase the vertical resolution, unrealistically high sound speeds in the stream and in the disk have to be used. Thus, the derived vertical extents of structures have to be scaled down by large factors (2-4).

Livio, Dgani & Soker (1986) presented a simple analytical model for the stream - disk interaction region. If the disk is substantially geometrically thinner and denser than the stream, the resulting "bow-shock" can be modelled as the result of the hypersonic flow of a (uniform) medium past a blunt object. The effect of an inclined shock front can be seen in Fig. 1: the component of the stream velocity perpendicular to the bow shock is diminished whereas that parallel is left unchanged. For a polytropic equation of state, the strong-shock Rankine-Hugenout equations determine the post-shock perpendicular velocity to be a fraction $(\Gamma - 1)/(\Gamma + 1)$ of the pre-shock velocity. For a given shock angle θ_{shock}, the angle between the post-shock spray trajectory and the pre-shock stream trajectory can be large enough to send the spray material on essentially free particle trajectories high above the disk. The vertical boost is roughly in-

https://doi.org/10.1017/S0252921100042883 Published online by Cambridge University Press

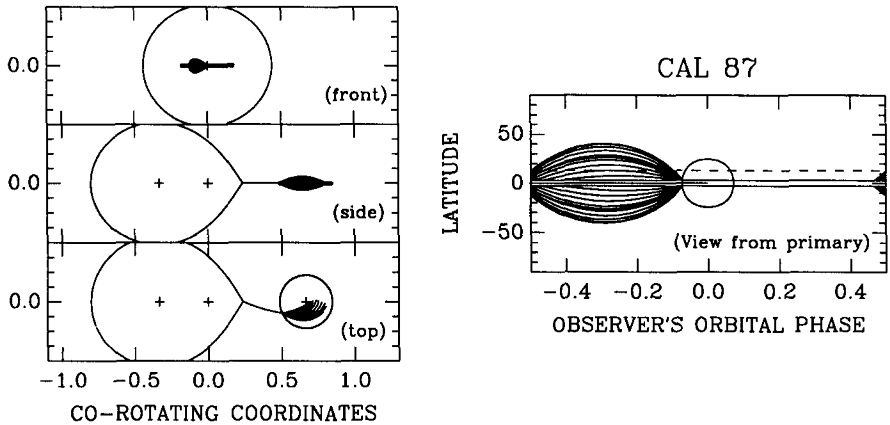

Figure 2. Result of the spray calculation for orbital parameters appropriate for the Super-Soft X-ray Source CAL 87. Left: the appearance of the spray. Right: the appearance of the spray in the frame of the primary star, indicating the near-obscuration of the secondary star and the possibility to produce EUV and X-ray absorption at orbital phases around 0.6-0.9.

dependent of θ_{shock} for any reasonable value of the latter between about 25 and 65°. Thus, for a wide range of shock inclinations, a vertically (and presumeably also laterally) extended diffuse structure should be created by the bright spot's bow shock.

We have computed such trajectories using standard techniques. In order to give the spray a 3-dimensional structure, the bow shock is considered to be a cone with an opening angle equal to θ_{shock}. Thus, the final spray structure consists of the paths of many test spray particles which are followed until they hit the disk. The result of such a calculation for the SSS Cal 87 is shown in Fig. 2. One can easily see that the spray could have several important effects on the observed lightcurves:

- The spray can create EUV and soft X-ray absorption features around orbital phase 0.7 even at moderate inclinations.

- The spray hides some of the secondary and some of the accretion disk from the inner disk's illuminating radiation, changing the amount of heating in both.

- Given a slightly different lateral spread of the spray (the assumption of a cone-geometry is admittedly crude), it may even be possible to cover the primary.

As simple as this model is, such a spray is easily capable of reproducing the observed X-ray and EUV absorption in CV like U Gem with a minimum of (relatively physical) parameters (Hessman, in preparation).

https://doi.org/10.1017/S0252921100042883 Published online by Cambridge University Press

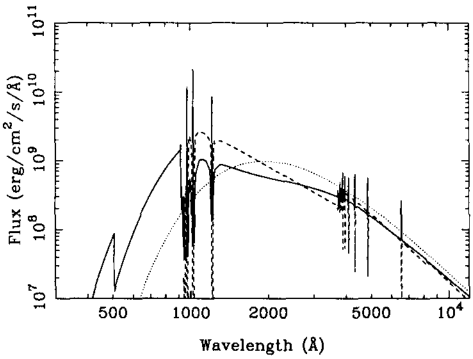

Figure 3. The spectrum of a blackbody (dotted), an unilluminated star (dashed), and an illuminated star (solid), all with $T_{eff} = 15\,000K$.

3. Soft X-ray illumination of the donor star

When modelling XRB light curves, it is important to understand how the incident radiation is reprocessed by the secondary star. Most modellers simply assume that some fraction of the incident bolometric flux is thermalized and re-emitted by a blackbody. However, the spectrum of the irradiation, the surface gravity, and the chemical abundances play important roles in the determination of the final atmospheric structure of the star. The irradiation effects are particularly important in SSS, where the optically thick radiation from the accreting compact star is completely absorbed, mainly by helium in an optically-thin surface layer, and may exceed the intrinsic flux by factors > 100.

In a pilot study, we have calculated LTE model atmospheres for late main-sequence stars, including irradiation of the surface with 4×10^5 K blackbody radiation. The calculated temperature structure shows several temperature inversions with different degrees of ionization of the absorbing elements (cf. Van Teeseling et al. 1994).

The spectrum of a significantly irradiated atmosphere deviates strongly from a blackbody and from an unirradiated atmosphere (Fig. 3), showing much more EUV emission. However, an unirradiated atmosphere with a higher effective temperature is often a good approximation for the optical continuum: a blackbody gives the correct colour but is too bright by $\Delta V \sim 0.3 - 0.4$.

For strong irradiation – i.e. for realistic conditions in SSS – no hydrostatic equilibrium could be achieved at the base of the hot corona-like layer, suggesting that strong mass-loss is present (see Basko & Sunyaev 1973).

References

Armitage, P.J., Livio, M. 1996: ApJ, in press

Basko, M.M., Sunyaev, R.A. 1973: ApSpSc 23, 117

Hellier, C., Mason, K.O. 1989: MNRAS 239, 715

Livio, M., Soker, N., Dgani, R. 1986: ApJ 305, 267

Lubow, S.H., Shu, F.H. 1976: ApJ 207, L53

Schandl, S., Meyer-Hofmeister, E., Meyer, F. 1996: A&A, in press

van Teeseling, A., Heise, J., Paerels, F. 1994: A&A 281, 119