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THE MASS TRANSFER IN UNSTABLE COMPACT BINARY STARS

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Abstract

The 2001 outburst of WZ Sagittae has shown the most compelling evidence yet for an enhancement of the mass transfer rate from the donor star during a dwarf nova outburst in the form of hot-spot brightening. It has been shown that even in this extreme case, the brightening can be attributed to tidal heating near the interaction point of an accretion stream with the expanding edge of an eccentric accretion disc, with no need at all for an increase in the mass transfer rate. Furthermore, it has been confirmed previous suggestions that an increase in mass transfer rate through the stream damps any eccentricity in an accretion disc and suppresses the appearance of super-humps, in contradiction to observations. Tidal heating is expected to be most significant in systems with small mass ratios. It follows that systems like WZ Sagittae -which has a tiny mass ratio -are those most likely to show a brightening in the hot-spot region.

انتقال الكتلة في النجوم الثنائية المدمجة الغير مستقرة

الخلاصة

اثبت انفجار سنة 2001 في النظام النجمي WZ Sagittae التحسين الذي طرأ على نسبة انتقال الكتلة من النجم المانح خلال انفجار المستعرات الاقزام على شكل لمعان البقعة الحارة. في هذا البحث تم توضيح على انه حتى في هذه الحالة الشديدة فان اللمعان ممكن ان يعزى الى الحرارة المديجزرية او المتذبذبة قرب نقطة التفاعل لتيار الازدياد مع حافة التمدد لقرص الازدياد الشاذ بدون الحاجة ككل للزيادة في نسبة انتقال الكتلة.علاوة على ذلك تم التأكيد على الاقتراحات المنشورة سابقا التي هي الزيادة في نسبة انتقال الكتلة خلال المجرى تخمد اي شذوذ في قرص الازدياد وتوقف ظهور الحدبة العظمى على النقيض من الرصد والملاحظات. الحرارة المدجزرية او المتذبذبة يتوقع لها ان تكون مهمة جدا في الانظمة ذات نسب كتلة صغيرة.وينتج عن ذلك انه في الانظمة مثل WZ Sagittae التي تمتلك نسبة كتلة صغيرة جدا انه من الارجح جدا ان تظهر لمعانا في منطقة البقعة الحمراء.

Introduction

Dwarf novae are cataclysmic variable stars that are observed to undergo bright outbursts lasting a few days. These outbursts are separated by weeks to months of dim quiescence. At the short orbital period end of the dwarf nova distribution (Porb < 2.2 h), it has been found that the SU UMa stars, which also show superoutbursts. These are longer outbursts lasting a couple of weeks or more, with the additional presence of superhumps, a periodic modulation in the V band light curve that repeats on a time-scale very close to the orbital period. Comprehensive review of dwarf novae has been given [1].

The outbursts of dwarf novae have been explained in terms of an instability associated with the gas circulating in the accretion disc.

If the temperature is not higher than this everywhere in the disc, a cyclic behaviour can be established between two thermally stable states: a hot, ionized outburst state and a cool, neutral quiescent state.

The arguments against enhanced mass transfer has been reviewed[2]. They suggested that the eclipses observed for WZ Sagittae could be eclipses of the superhump light source and not the hot spot., as well as the evidence from existing numerical work not discussed by Osaki & Meyer.

A model in which superoutbursts were caused by an enhanced mass-transfer rate from an irradiated secondary star has been originally proposed[3]. However, numerical experiments showed that discs in a Roche potential with $q< 0.3$ could spread to a radius at which the material at the edge of the disc becomes 3:1 resonant with the tidal field of the secondary star[4]. At this point the disc becomes unstable and the gaseous orbits become eccentric. Since superoutbursts are only observed in systems with low mass ratios, it seems likely that such a tidal instability plays a role in their development. Soon after Whitehurst's experiments, Osaki formulated the thermal-tidal instability (TTI) model [5]. The mass transfer rate from the donor remains constant in the TTI model, but with every passing normal outburst the accretion disc expands until it reaches the 3:1 resonant radius. At this point, Osaki suggested that the rate of angular momentum loss becomes more rapid, leading to the accretion of a large amount of mass, and a superoutburst. The TTI picture was broadly supported by the first two-dimensional (2D) hydrodynamic models of superoutbursts [6], which confirmed that while the outburst is initiated by disc instability in the same way as a normal outburst, the tidally-enhanced energy dissipation prolongs the outburst, normal and superoutbursts are explaining the difference in duration between normal and superoutbursts.

A significant eccentricity was generated and superhumps did indeed develop on contact with the 3:1 radius.

In the next section It will be introduced the evidence for enhanced mass transfer in SU UMa stars from observations of hot spot brightness and balance this with a discussion of existing theoretical studies of mass transfer in these systems. In Section 3,It will be presented the results of new, three-dimensional (3D) simulations of tidally unstable accretion discs. These show that tidal heating produces a significant brightening near the stream-impact region, even with no increase in the mass transfer rate through the stream. This means that a simple energetic model for hot-spot luminosity is inadequate for a low-q system in outburst, as the luminosity in this region is dominated by tidal effects. The results therefore lend weight to the arguments that the brightening observed near the stream-impact region in some SU UMa stars is not due to the hot-spot, but is due to the tidal heating of the outer parts of the disc.[2].

Enhanced mass transfer: observation versus simulation

Until the 2001 superoutburst of WZ Sagittae, little evidence for enhanced mass transfer during dwarf nova outbursts had been found. A notable exception is that of VW Hydri; The amplitude of a hump in the light curve increased during normal outbursts occurring within 40 days of a subsequent superoutburst has been found [7]. This was interpreted as brightening of the hot spot in response to an increase in mass transfer rate from the donor star. Similar arguments for an increase in mass transfer rate by a factor of two in outbursts of U Geminorum and Z Chamaeleontis has been used[8], employing the relationship

$$L_{spot} = \frac{1}{2}\dot{M}_2 (v_k - v_b)^2 \qquad (1)$$

Where $\dot{M}_2$ is the mass transfer rate from the donor star, v_K is the Keplerian velocity of the gas circulating in the accretion disc and v_b is the ballistic velocity of the in-falling gas stream.

WZ Sagittae is the brightest known dwarf nova in the V-band, with V □8 at super maximum. It is unusual in only showing superoutbursts, and in its extremely long recurrence time: the 2001 outburst occurred a mere 23 years after a 33 year cycle of previous events in 1913, 1946 and 1978. It has a high-inclination (i□75°) and an orbital period of 81.6 minutes [9]. The secondary star is of unusually low mass, with $M2= 0.045\pm0.003M_{\odot}$ and q □0.06 [10]. The 2001 outburst was observed in great detail, revealing many layers of variability. Superhumps appeared in the light curve 13 days after the onset of the outburst, reaching maximum amplitude 24 hours later. They persisted for 90 days, well into the decline to quiescence, but were preceded by a different modulation on the orbital period for the first 12 days. The depth of eclipses in the light curve increased rapidly 6 days after the appearance of superhumps has been found[11], and then gradually decreased. This change was mirrored by the height of the orbital hump in the light curve. The inclination of WZ Sge is not high enough to make eclipses of the white dwarf itself observable, so the eclipses in the light curve are assumed to be associated with the hot-spot. Patterson et al. concluded that the hot-spot brightened by a factor 60, which is suggestive of a commensurate increase in the mass-transfer rate from the secondary star.

I will discuss briefly the application of analytic methods and hydrodynamic simulations to the problem of stream-disc interactions. The response of an eccentric accretion disc to an increase in the mass transfer rate through a stream has been investigated[12]. It is found that rather than pumping the eccentricity up further, the addition of low specific angular momentum material at a faster rate tended to circularize the gas orbits. Later smoothed particle hydrodynamics simulations of dwarf novae with mass ratios near the border of tidal stability confirmed that super-humps appeared when the mass transfer rate was reduced from a rather high value, but disappeared when the rate was restored [13]. These theoretical results cannot explain the persistence of the superhumps in WZ Sge with an enhanced mass transfer rate. One could circumvent this problem if the superoutburst itself was initiated by a burst of mass transfer and the disc radius expanded from a value well inside the

3:1 radius to a radius beyond it. Unfortunately, this argument fails for WZ Sge. The observed increase in the eclipse depth occurs six days after the appearance of superhumps, so the disc radius has al-ready expanded far beyond the 3:1 radius by the time the hot-spot region is observed to brighten.

Recently, a 2D hydrodynamic scheme to model the evolution of spectral line profiles generated by an eccentric accretion disc in a binary with q= 0.1 has been used[14]. They found significant changes in the profile over the precession cycle of the disc and were able to distinguish between the individual components from the stream-impact region and the spiral arms. Both components contribute to the superhumps seen in the light curve.

Results

In this section It has been presented the results from new, three-dimensional smoothed particle hydrodynamics (SPH) simulations of the accretion disc and stream in WZ Sge.

1- Numerical Method

The calculation in present work carried by using a parallelized version of a 3D SPH code optimized for the simulation of accretion discs in compact binary stars. It is an evolution of the original developed code [15]. In the SPH method, the fluid equations are solved for each of a set of moving points which called particles. Local physical quantities are calculated by means of a weighted sum over all the nearby particles within a set distance. This distance, called the smoothing length, h, is tuned to the local density, making the method extremely adaptable in resolving large density contrasts. A review of the SPH method can be found in [16]. In this work, h is calculated for each particle such that a minimum of 50 neighbour particles is maintained regardless of the local density. Here, a total particle number of order 400,000 allows a resolved length-scale h< 0.01Rdisc over most of the accretion disc.

The simulation proceeds by the continuous injection of particles from the inner Lagrangian (L1) point. The gas dynamics of the particles is calculated in the full 3D Roche potential of a binary system, with particles being rejected from the simulation if they pass through an inner boundary of the disc at a radius R< 0.05a where a is the separation of the two stars in L.Y., if they intersect the Roche lobe of the secondary star or if they achieve the escape velocity at a radius larger than a. The viscosity used in the SPH calculation is a refinement of that described to mimic an α-viscosity:[15]

$$\nu = \alpha cs H = \alpha cs^{2}/\Omega. \qquad (2)$$

The length scale is chosen to be the scale height H rather than the smoothing length, giving closer compatibility with the prescription.[17]

No viscous calculation is performed for the particles in the stream, which move on a purely ballistic orbit. The equation of state of all the particles is isothermal, so the rate of energy generation in the disc is purely from the viscous dissipation induced by the interaction of the particle orbits. Therefore, the effects of radiative processes are neglected, making this a simple calculation of the total bolometric luminosity due to viscous dissipation at each point in the disc.

2- Simulations

It has been used parameters representative of WZ Sge: q =0.07, Porb =0.056 days, $-\dot{M}_2$=3 $\times 10^{-11}$ M⊙ yr^{-1} [18]. The thermal parameters of the particles in the disc are chosen as a conservative estimate for a CV disc in outburst that is at the lower end of their probable range: α =0.1, cs=0.04 aΩorb, which assuming a mean molecular mass μ =0.6M⊙ corresponds to a mid-plane temperature Tc=42,500K^0. The initial conditions for the 3D simulation are generated in the same way as in [19], where a 3D disc is replicated from a particle distribution derived from an initial 2D simulation. The conditions are then relaxed to a steady-state before the 3D simulation proper. The disc is built up using a constant mass transfer rate of 3 $\times 10^{-11}$ M⊙ yr^{-1}.

The 3D runs start at a point after the outer edge of the disc has crossed the 3:1 radius and superhumps have developed. Three runs are then performed with initial conditions that are identical except for the rate of mass injection. Run A continues with the same mass transfer rate. Run B proceeds with a rate five times lower, run C with a rate five times higher. The number of particles at the start of each run was N =428685.

Fig.1 shows the evolution of the viscous energy dissipation rate and the (k,l) =(1,0) eccentric mode. The superhumps are clearly visible in the run with the unchanged mass transfer rate (A) and in the run with the reduced rate (B). However, they disappear when the rate is increased in run C, with the eccentricity falling throughout the simulation as the disc edge is driven away from the 3:1 radius. The difference in length of the simulations is due to the finite supercomputer time.

Fig.2 shows a map of the energy dissipation rate in the disc and a corresponding Doppler velocity map at time t =8 days for run A. The hot-spot region and tidally-induced spiral structure are clearly evident, as are velocity components consistent with gas on ballistic and Keplerian trajectories. There is also a non-Keplerian component in the velocity map, similar to that noticed by [14]. The radial luminosity profile of the disc is presented in Fig.3 for the two sectors shown in the dissipation map. This has been calculated by dividing the disc up into annular bins of width 0.01a and averaging the luminosity (dissipation rate per unit area multiplied by the area of each bin) in the azimuthal direction. Also plotted is the expected total bolometric hot-spot luminosity calculated from equation (1) for three different mass transfer rates. Even with this small emitting area per radial bin, the luminosity in the hot spot region is well above that expected for

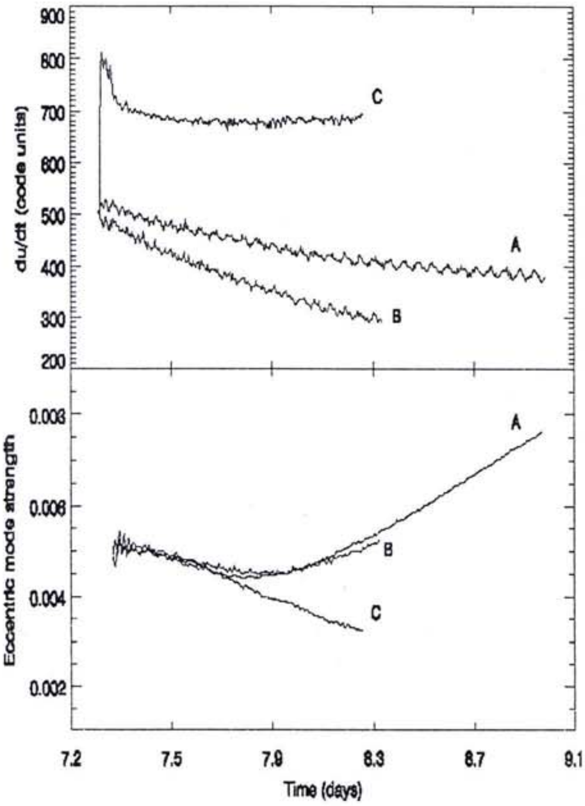

Figure (1): Viscous energy dissipation rate per unit mass and eccentric mode strength during the three simulations. A: $-\dot{M}_2$ =3×10^{-11}M⊙ yr^{-1} , B: $-\dot{M}_2$ =6×10^{-12}M⊙ yr^{-1}, C: $-\dot{M}_2$ =1.5×10^{-10}M⊙ yr^{-1}

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$-\dot{M}_2$ =3×10^{-11}M⊙ yr^{-1}.

If one assumes that the radial extent of the hot-spot covers the region of tidally-enhanced dissipation between R =0.5a and R =0.6a, the total 'hot-spot' luminosity is nearly an order of magnitude higher still.

A feature that becomes apparent from the 3D simulations is the magnitude of the eccentricity, which is far smaller than has been found in previous 2D work. The mode strength in Fig.1 is of the order a few times 10^{-3} , in comparison with □0.5 for 2D superoutburst simulations of Z Cha (TMW). As a result, the pattern of dissipation shown in Fig. 2 does not change appreciably over the course of the simulation, and the dissipation remains enhanced in the region of the hotspot throughout. However, the Fig.1 shows that the eccentricity of the 3D discs in runs A and B are increasing at the end of the simulations. It remains unclear whether this trend would continue if the simulations were allowed to run indefinitely, although the growth rate of the eccentric mode in 3D does not suggest that the eccentricity will reach the levels achieved in the 2D case over a sensible time-scale for a dwarf nova outburst.

Despite the low eccentricity, a clear superhump signal is still seen and the tidal interaction still has a significant influence on the luminosity generated in the hot-spot region. Of course, if the eccentricity were higher the interaction would be even stronger. It would be also expected to see more modulation in the dissipation map over a precession cycle, as discussed by [14].

secondary star is required to produce this brightening. Therefore, even for a disc with low eccentricity the simple model for the luminosity of the hot-spot given in equation 1 is inadequate to estimate the mass transfer rate from the

As a final check, a short simulation was performed for a disc not subject to the tidal instability, with an outer radius well in-side the 3:1 resonance. The results are shown in Figs. 4 and 5. In this case, the structure of the hot spot is exactly as expected. There are clearly defined components of emission at the ballistic and Keplerian velocities and very little else, only a very weak spiral structure. The integrated luminosity of the hot-spot is now consistent with equation 1 for the mass transfer rate that has been measured in quiescence, and that is used in the simulation: $-\dot{M}_2 = 3\times10^{-11}\,M_\odot\,yr^{-1}$.

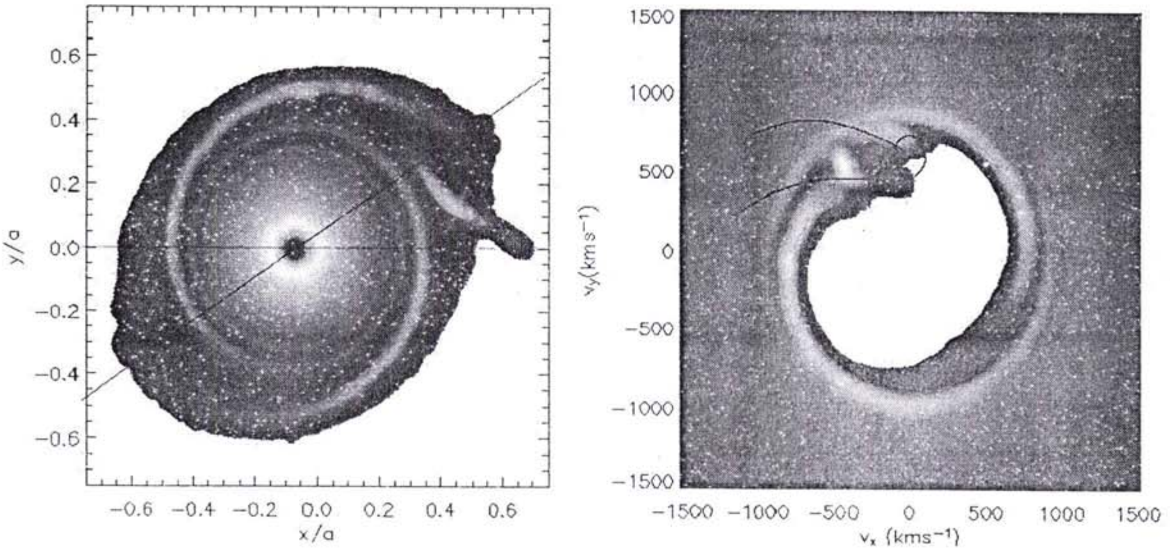

Figure (2): Map of energy dissipation rate in the simulation with $-\dot{M}_2=3\times10^{-11}M_\odot\ yr^{-1}$ and corresponding Doppler velocity map. The straight lines on the left define the sectors. The Roche lobe of the secondary star and velocities of the ballistic stream and its Keplerian equivalent are plotted on the right for q=0.07.

The luminosity and the eclipse of the hot spot

It has been shown that tidal heating accounts for a significant fraction of a significant fraction of the energy dissipated near the stream-impact region in an eccentric accretion disc. The tidal heating component dominates that due to the impact of the ballistic stream, producing an apparent brightening near the hot-spot. No increase in the mass transfer rate from the donor. Of course, this equation is not incorrect: but for a small correction due to the slightly non-Keplerian velocity of the orbiting gas in the disc, the luminosity of the impact alone will be given correctly. It is just that this luminosity is swamped by the tidal heating component. It has been suggested that the eclipse of the superhump light source (dominated by the tides) and not the hot-spot that has been observed in WZ Sge. This work supports this view, with the caveat that it could well be that the eclipse is that of the hot-spot, the luminosity in this region is simply being dominated by the tides. For a disc with zero eccentricity, such as a quiescent disc with an outer radius much smaller than the 3:1 radius, the expression in equation 1 remains a good diagnostic of the mass transfer rate. This brightening of the hot spot region will be observed in systems with mass ratio $q = M2/M1 < 0.3$, where tidal instability becomes important. It may seem intuitive to take this assertion a step further; that the lower the mass ratio, the stronger the tidal heating and the brighter the hot-spot. In terms of the sequence of events during an outburst of WZ Sge, the picture that has emerged from this work would be as follows. It has been assumed that the outburst is initiated in the normal way by the disc instability, with the disc spreading past the 3:1 radius some time later. The growth rate of the eccentricity must be very fast as the superhumps were observed to reach maximum amplitude within 24 hours of appearing in the light curve.

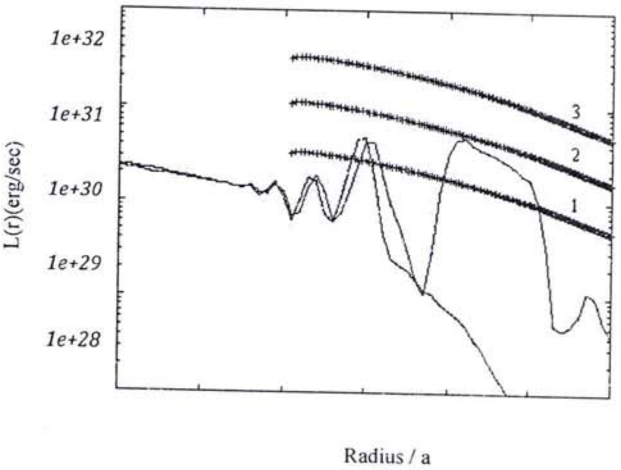

Figure (3): Radial profile of luminosity per radial bin of width 0.01a for the two sectors. The solid line has been smoothed over the sector that includes the hot-spot, the dashed line is the equivalent for the diametrically opposite sector. The numbered curves are the expected total bolometric hot-spot luminosity calculated from equation 1 for $-\dot{M}_2=3\times10^{-11}$ (1), 10^{-10} (2) and $3\times10^{-10} M_\odot\ yr^{-1}$ (3).

The brightening effect

The brightening effect due to the tides will be first observed up to one precession cycle later when the apastron of the disc passes L1. This is consistent with the delay of a few days that was observed between the appearance of the superhumps and the brightening event. As the disc empties and the outer radius finally shrinks inside the 3:1 radius, the effect will diminish over the course of the outburst until the brightness of the hot-spot becomes consistent with the value given by equation 1 for the mass transfer rate measured in quiescence.

It has been confirmed that an increase in mass transfer rate from the donor drives the disc away from the 3:1 resonance and suppresses the appearance of superhumps. This is in contradiction to what has been observed in WZ Sge. There are interesting differences between the 3D results presented here and Previous 2D work. In particular, while eccentricity and superhumps develop in the same way in 2D and 3D, it is much more difficult to generate high eccentricities in 3D for reasonable values of sound speed and viscosity parameter. Indeed, the eccentricity of $e \geqq 0.3$ estimated for WZ Sge is not found in these 3D simulations. However, the tidal heating effect is still significant even with a small eccentricity.

The eccentricity

If future observations can reveal with accuracy the exact shape of the disc and e is found to be as high as 0.3, we will need to consider how this can be achieved. A possible solution may lie in a magnetic field anchored on the rotating white dwarf, which could have a propelloring effect on the gas that keeps the outer edge of the disc past the 3:1 radius and allows a large eccentricity to develop.

As an aside to these issues, it is interesting to note that an eccentric disc has no well-defined single outer radius. Indeed, if we assume the disc is an ellipse with an eccentricity e, the ratio of the semi-major to semi-minor axes is

$$\frac{r_+}{r_-} = \frac{1 + e}{1 - e} \qquad (3)$$

So, for e □0.3, there is nearly a factor of 2 variation in apparent radius over a single precession cycle. This should always be borne in mind when inferring accretion disc radii from observations in tidally unstable systems, especially given that the precession period can be several days in comparison to the orbital or superhump periods, which are usually shorter than a couple of hours.

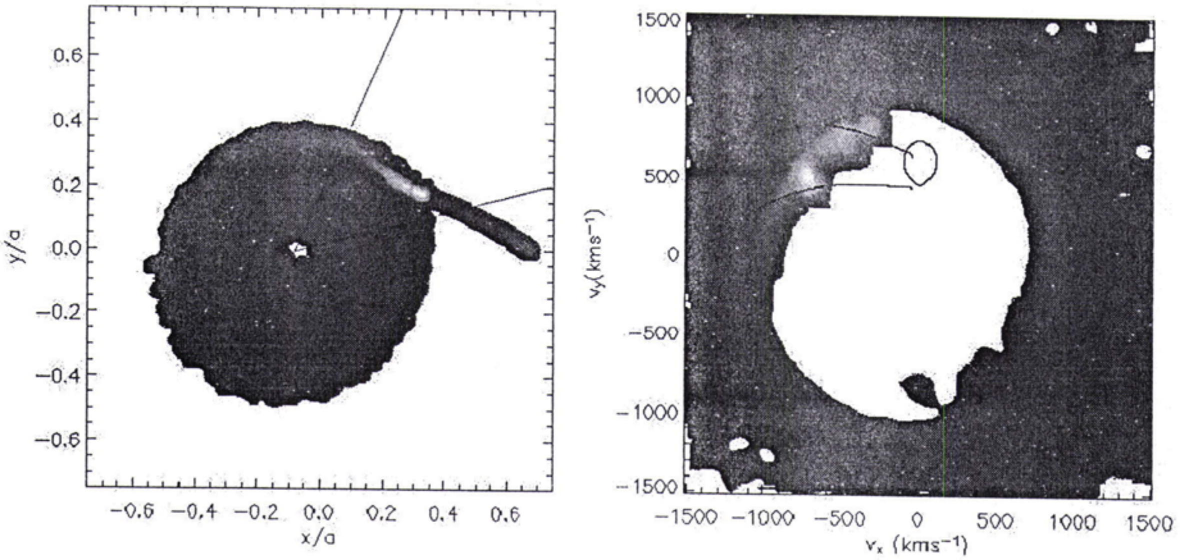

Figure (4): A smaller disc with R_{disc}<R3:1. The ballistic and Keplerian components are much more clearly defined in the Doppler map and there are only very weak spiral features. The straight lines on the left hand side define the sector of the disc

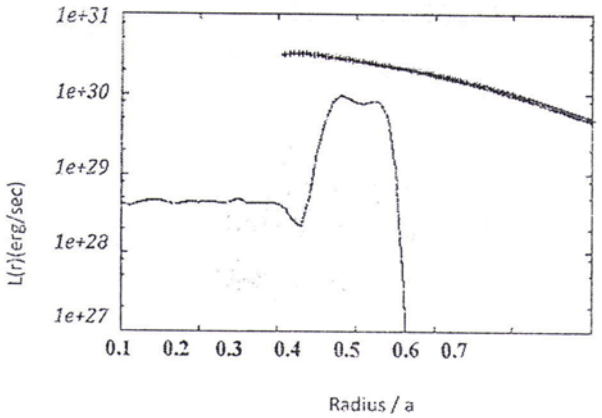

Figure (5): The integrated hot spot luminosity is consistent with the curve calculated from equation 1 with $-\dot{M}_2= 3\times10^{-11}$ M⊙ yr^{-1}.

Conclusions

1) It is apparent from this work that the observations of hot spot brightnesses during dwarf nova outbursts can be attributed to the interaction of a constant-$\dot{M}$ accretion stream with the edge of an eccentric accretion disc.

2) Future work on the theoretical side should take into account the effects of radiative transfer in the spot region. This will be a challenge, and has not been considered in this work, however it is expected to have an impact on the predicted brightnesses. In particular.

The amount of stream overflow above and below the rim of the disc is sensitive to the radiative cooling rate in the hot-spot region. This will have observable consequences on the shape of the measured eclipses and the appearance of the orbital hump in the light curve.

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