Simulations of spiral structure in the accretion disc of IP Pegasi during outburst

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ABSTRACT

We consider the implications of the detection of spiral structure in the accretion disc of the binary IP Pegasi. We use numerical simulations of the development of a disc outburst to construct predicted Doppler tomograms, which are found to be in close agreement with the observations if the spiral pattern arises as a transient feature when the disc expands viscously at the start of the outburst. The good agreement of such viscous disc simulations with the data is consistent with models in which most of the angular momentum transport in the disc originates in internal stresses rather than globally excited waves or shocks. Future detailed observations of the development of transient spiral features offer the potential to measure the dependence of the disc viscosity on the local physical conditions in the disc.

Key words: accretion, accretion discs — instabilities — hydrodynamics — binaries: close — novae, cataclysmic variables — stars: individual (IP Pegasi).

1 INTRODUCTION

Recent observations of the dwarf nova IP Pegasi provide convincing evidence for spiral structure in the emission from an accretion disc in a binary system (Steeghs, Harlaftis & Horne 1997). During an outburst, changes in the profile of spectral lines with binary phase were inverted using the technique of Doppler tomography (Marsh & Horne 1988) to reveal a loosely wrapped, two-armed spiral pattern in the disc emission. No such structure is observed in the quiescent disc (Marsh & Horne 1990).

These observations provide a potential new constraint on the angular momentum transport processes operating in accretion discs. Two mechanisms are known that can provide a source of viscosity in ionized, non-self-gravitating accretion discs in binary systems; turbulence driven by the non-linear development of the Balbus-Hawley instability (Balbus & Hawley 1991; Tout & Pringle 1992; Stone et al. 1996; Brandenburg et al. 1996); and spiral waves or shocks driven by the gravitational perturbation of the secondary (Sawada, Matsuda & Hachisu 1986; Spruit 1987; Rozyczka & Spruit 1989; Savonije, Papaloizou & Lin 1994). It is obvious that the second scenario leads to a spiral pattern of disc emission, but even if tidally induced shocks are unimportant for the angular momentum transport budget in the steady-state they might still be observable in outburst, when the enhanced viscosity forces the disc to expand into a region where the strength of the tidal forces is greater (Papaloizou & Pringle 1977; Lin & Pringle 1976). We note that although it is generally believed that the spiral shock mechanism is inefficient in the relatively cool discs found in cataclysmic variables (Livio 1994; Savonije, Papaloizou & Lin 1994), there are considerable theoretical uncertainties in both mechanisms, and additional observational input is highly desirable.

In this Letter, we compare simulations of accretion disc evolution with the observations of IP Peg. Our goal is to test whether viscous disc simulations, which are predicated on the existence of an internal origin for the disc viscosity, are consistent with the strong spiral structure observed in the data. We describe our calculations in Section 2, and present in Section 3 model Doppler tomograms for comparison with the observations. Section 4 summarises our conclusions, and outlines the theoretical expectations for spiral structure in other disc systems.

2 SIMULATION OF AN OUTBURST IN IP PEGASI

The parameters of the dwarf nova IP Peg are given, for example, by Warner (1995). The masses of the white dwarf and secondary are \(1.02 \, M_\odot\) and \(0.5 \, M_\odot\) respectively, and the orbital period is 3.8 hr. The outburst magnitude is \(\sim 2\) magnitudes, and the rise to maximum lasts for 1-1.5 days. Thermal disc instability models for such outbursts have been studied in great detail (e.g. Cannizzo 1993; Lasota...
1998; and references therein), here we construct a simplified three-dimensional simulation that nevertheless reproduces the main dynamical effects of the outburst.

### 2.1 Numerical method

We calculate the evolution of the disc using the smooth particle hydrodynamics (SPH) code described in detail by Murray (1996, 1998; for general descriptions of SPH see Benz 1990; Monaghan 1992), with minor modifications to extend the code to three dimensions. As compared to other hydrodynamics methods, SPH codes have a relatively large but well-characterized shear viscosity (Murray 1996), they are thus suitable choices for modelling discs if there is a local source of viscous stresses.

The quiescent disc is set up by commencing the simulation with an annulus of particles near the predicted tidal truncation radius (Papaloizou & Pringle 1977), and allowing this to relax while injecting gas at a steady rate through the inner Lagrange point \( L_1 \). Particles are accreted onto the primary when they stray inside an accretion radius \( R_{\text{acc}} = 0.02a \), where \( a \) is the binary separation. As we are primarily interested in the dynamics of the outer disc we impose a fixed sound speed \( c_s \), and a constant SPH smoothing length \( h = 0.02a \). Under these conditions the kinematic viscosity \( \nu \) of the code is given by,

\[
\nu = \frac{1}{10} \alpha_{\text{SPH}} c_s h
\]

where \( \alpha_{\text{SPH}} = 1 \) is the usual SPH linear viscosity co-efficient (Monaghan 1992). We take \( \beta_{\text{SPH}} = 0 \), and set \( c_s \) such that the Mach number in the outer regions of the quiescent disc is \( M \sim 30 \). The resultant Shakura-Sunyaev viscosity parameter \( \alpha_{\text{SS}} \) (Shakura & Sunyaev 1973), defined by,

\[
\nu = \alpha_{\text{SS}} \frac{c_s^2}{\Omega}
\]

with \( \Omega \) the angular velocity, is then around \( \alpha_{\text{SS}} \approx 0.15 \) in the outer disc (note that it is not constant with radius). Around 30 binary orbital periods of evolution are required to reach an approximate steady-state, at which point there are close to \( 2 \times 10^6 \) particles in the disc. This is sufficient for good resolution in the disc plane, though in the cool quiescent state the simulation has only limited resolution in the vertical direction.

In outburst, the sound speed and Shakura-Sunyaev \( \alpha_{\text{SS}} \) parameter increase. For IP Peg, whose outbursts are of rather modest amplitude as compared to other dwarf novae, it is straightforward to mimic this behaviour numerically. Starting with the steady quiescent disc, we instantaneously increase \( \alpha_{\text{SPH}} \) by a factor of 4, and simultaneously raise \( c_s \) by a factor of \( \sqrt{5} \). This leads to a rise in the bolometric luminosity of the disc by a factor of \( \approx 6 \), and is consistent with a \( \sim 2 \) magnitude increase in luminosity caused by a suddenly enhanced mass accretion rate through a Shakura-Sunyaev disc.

### 2.2 Disc structure in quiescence and in outburst

Figure 1 shows the structure of the disc in quiescence and in outburst. The disc in quiescence is mildly tidally distorted, with an outer radius that varies from about 0.32\( a \) to 0.4\( a \). This is consistent with the expected size of a disc truncated at the outer edge by tidal torques from the companion (Papaloizou & Pringle 1997; Paczynski 1977). Clearly there is some non-axisymmetry in the outer part of the disc, but the corresponding map of the disc luminosity (Figure 2) shows that the main non-axisymmetric contribution to the disc luminosity in quiescence arises from the hotspot or stream overflow region where the accretion stream from \( L_1 \) meets the disc.

The right panels of Fig. 1 and Fig. 2 show the disc in the outburst state. These snapshots were taken after the outburst had been in progress for 8 binary orbits, or around 30 hours for the parameters of IP Peg. This approximately matches the timing of the observations of Steeghs et al. (1997), which were taken a day into outburst. By this stage in the simulation the disc mass had declined by almost a factor of two – comparable but probably somewhat greater than would be expected in a detailed disc thermal instability model.

In outburst, the disc is somewhat expanded relative to the quiescent state and some material has escaped the Roche lobe of the primary – large changes in the outer radius are not expected because of the rapidly increasing strength of the tidal torques with increasing radius. A two-armed spiral pattern in clearly seen in the outer regions of the disc, extending in phase from \( \phi = 0.9 - 0.25 \), and from \( \phi = 0.4 - 0.75 \). Fourier decomposition of the modes present in the disc shows that this two-armed pattern is indeed dominant, the resonant \( m = 1 \) modes seen in simulations of low mass ratio systems (Murray 1996) are relatively weak. The same pattern is seen in the dissipation from the disc (Fig. 2), not only is the overall disc luminosity greatly increased in outburst, but the integrated contribution from the spiral arms is now comparable or greater than that from the hotspot in the outer regions of the disc.

### 3 MODEL DOPPLER TOMOGRAMS

The best observational probe of non-axisymmetry in interacting binary accretion discs is provided by the technique of Doppler tomography (Marsh & Horne 1988). If the emission from the disc is assumed stationary in the rotating frame of the binary, then the observed spectral line profiles as a function of phase \( \phi \), \( f(v, \phi) \), can be inverted to yield the best-fitting Doppler map, \( I(v_x, v_y) \), of line flux as a function of the velocity \( \vec{v} = (v_x, v_y) \) in the binary frame. The detection of spiral structure in IP Peg by Steeghs et al. (1997) is based on such a Doppler mapping method.

For a disc simulation, of course, both \( \rho(v_x, v_y) \) and \( I(v_x, v_y) \) (with some assumption about the disc emission) are directly available without the need for further assumptions. In principle we can also construct the distorted maps that arise if the emission is not stationary in the binary frame, although that is not required here as the two-armed spiral pattern seen in the simulations evolved only slowly compared to the orbital timescale.

Figure 3 shows the density disc in quiescence and in outburst projected into velocity space. The disc in quiescence is not axisymmetric in the outer regions, and this is reflected in the distorted elliptical pattern seen at low velocities in the quiescent disc. We note that during a lengthy
Figure 1. Simulations of the accretion disc of IP Peg in quiescence (left panel) and outburst (right panel). The disc rotates counterclockwise, with mass being added in an unresolved stream from the L1 point to the left of each panel. The dashed curve shows the Roche lobe of the primary. The disc in outburst is lower mass, somewhat more extended radially, and displays a clear two-armed trailing spiral structure in the outer regions.

Figure 2. Luminosity of the disc in quiescence (left panel) and outburst (right panel), at times corresponding to the snapshots in Fig. 1. The contours and greyscale levels are the same in both plots, and are plotted at intervals of $\Delta \log(\sigma T^4_e) = 0.25$. The disc in outburst is hotter, and has a larger non-axisymmetric component to the emission in the outer regions.
Figure 3. Particle positions from the simulation projected into \((v_x, v_y)\) space in quiescence (left panel) and in outburst (right panel). The units are km/s. The small circle shows the velocity of the white dwarf, the larger circle that of the secondary. The dashed circles in the outburst panel delineate the velocity extent of the spiral structure, and are plotted at 500 km/s and 700 km/s relative to the velocity of the white dwarf.

period of quiescence the disc radius will decrease due to the addition of low angular momentum material from the accretion stream, and that this will reduce the strength of tidal distortions when compared to the (relatively short duration) simulations reported here.

In outburst, the spiral arms seen in Fig. 1 are seen as clear density enhancements in the upper right and lower left quadrants of the map. These match the observed azimuthal extent of the spiral arms seen in IP Peg. Also plotted are circles delineating the velocity range of the spiral features seen in the data, which were between approximately 500 km/s and 700 km/s relative to the white dwarf (Steeghs et al. 1997). Again this is in good agreement with the velocity extent of the spiral arms seen in the simulation.

Figure 4 shows the simulated Doppler map for the quiescent and outburst states. This is obtained by weighting the density map of Fig. 3 with the viscous dissipation rate at the location of each particle, and then adaptively smoothing the resulting map with a gaussian window function. Emission from the hot inner disc (which is noisy, and not seen in the H\(\alpha\) and HeI line maps) has been removed by not plotting particles with velocities relative to the white dwarf of greater than 1000 km/s. In general the outburst map matches the observations well, especially for the HeI line Doppler map. The same asymmetry between the strengths of the spiral arms is seen, and as the dominant emission is found to arise from the high density regions in Fig. 3 the velocity and azimuthal extent of the arms also agree well. The hotspot emission is seen more clearly in the synthetic map than in the observations, suggesting that the luminosity from the hotspot is probably weak in the H\(\alpha\) and HeI lines.

As a check against possible systematic errors arising from the Doppler mapping procedure, we have also generated maps indirectly by first creating synthetic trailed spectra from the simulation, and then projecting the spectra into the Doppler map using the same techniques as are used observationally. The map seen in Fig. 4 is again recovered, though at the cost of considerably enhanced noise.

4 DISCUSSION

In this Letter we have presented a simulation of the evolution of the accretion disc for the parameters of the binary IP Pegasi in outburst. We find as our main result that a spiral pattern is formed in the outer disc during outburst as the enhanced viscous stresses push the disc edge into a region of strong gravitational perturbations from the secondary. The spiral structure obtained in the simulation is two-armed, non-resonant, and much more prominent in outburst as compared to quiescence. Comparing the results with the observations of Steeghs, Harlaftis & Horne (1997), we find that there is excellent agreement with the azimuthal extent, velocity range, and asymmetry of the observed pattern.

The observations of IP Pegasi and other cataclysmic variables find no clear evidence for spiral patterns in quiescent discs. This is consistent with theoretical expectations...
Figure 4. Map of dissipation projected into \((v_x, v_y)\) space for the disc during quiescence (left panel) and in outburst (right panel). The units are km/s. In each case the greyscale is linear, but the lowest intensity in the quiescent map is a factor of 6 reduced from that in outburst. Note that in outburst the spiral arm in the upper right quadrant is markedly stronger than that in the lower left quadrant of the map.

The current observations can be modelled adequately using a highly simplified three-dimensional model of an outburst caused by a thermal disc instability, in which the only inputs are the change in \(\alpha_{SS}\) and \(c_s\) between quiescence and outburst. Future observations, extending over the rise to outburst and during the decline, may be able to provide stronger constraints on the assumed disc model. In particular, since the spiral pattern arises as a result of the imbalance between internal viscous stresses and well-understood gravitational torques, such observations can probe the variation of the disc viscosity with the local physical conditions in the disc. Eclipsing systems such as IP Peg are particularly promising in this regard as the radial run of quantities such as the effective temperature can readily be derived simultaneously from eclipse mapping.

The detection of spiral structure in the accretion disc of IP Peg, which has relatively feeble outbursts, implies that similar or stronger features may be expected in most dwarf novae. Theoretically, we note that qualitative differences are expected in systems with low mass ratio (roughly, \(q < 1/4\)). In these binaries both the observations of superhumps in the light curve, and numerical simulations (Murray 1996, 1998), suggest that a strong \(m = 1\) mode is excited in outburst. These features are not stationary in the corotating binary frame, making detailed investigation via Doppler mapping harder. It would also be worthwhile investigating whether spiral structure is observable in magnetic systems such as intermediate polars, where non-axisymmetry might be induced at the inner edge of the disc as a result of magnetic torques from the white dwarf.

Note added: Godon, Livio & Lubow (1998) have recently presented calculations showing that a steady tidally induced spiral pattern does not match the observations of IP Peg. This is consistent with our finding that consideration of the transient behaviour of the disc during outburst is required.

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