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SYNTHETIC TIME SERIES EMISSION LINE PROFILES OF NEGATIVELY SUPERHUMPING CATACLYSMIC VARIABLE STARS

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ABSTRACT

Cataclysmic variable (CV) stars are close binary systems with typically a white dwarf primary accreting from a low-mass main-sequence secondary star. One useful technique to study these systems observationally is through time-series spectroscopy. We present in this paper a method by which synthetic line profiles can be produced using our CV modeling program FITDISK, which implements the method of smoothed particle hydrodynamics. Because we compute the velocities and instantaneous energy dissipation ("luminosity") of all the particles in a simulation, it is relatively simple to synthesize line profiles as a function of simulation time. In this work, we simulated the accretion disk of a negatively superhumping CV, where the accretion stream bright spot migrates in turn across the two faces of a tilted, slowly-precessing accretion disk. We are then able to format these data to observe how the emission line profiles change as a function of viewing angle.

Subject headings: accretion, accretion disks — binaries: close — novae, cataclysmic variables

1. INTRODUCTION

Cataclysmic variable (CV) stars are binary star systems typically consisting of a white dwarf primary and a red dwarf or lower main-sequence secondary. These two stars orbit so closely that the material of the secondary overflows its Roche lobe. Outside of this lobe the gravitational pull of the primary becomes dominate over that of the secondary and the material is gravitationaly drawn towards the primary as a result. Conservation of angular momentum, as well as the small size of the primary, prevent the accreted material from landing directly on the white dwarf. As a result an accretion disk forms around the primary. As the disk forms, viscous interactions between material of different radii cause angular momentum to be trasported outward through the disk allowing material to move to smaller radii eventually accreting onto the primary. Tidal forces from the secondary absorb angular momentum transferring it back to the secondary and limit the radial extent of the accretion disk. A more in depth look at CVs can be found in Hellier (2001) and Warner (1995).

Many CVs display modulations in their light curves that differ from their orbital periods by a few percent. These modulations are known as superhumps and can be either positive or negative Wood & Burke (2007). Positive superhumps have light curves with periods slightly longer than their orbital period and are found in systems with mass ratios $M_2/M_1 \lesssim 0.35$. This is due to a prograde precession of an oscillating disk driven by the rotating tidal field of the secondary acting on the inner Lindblad resonance found close to the 3:1 corotation resonance. Negative superhumps have photometric periods slightly less than the orbital periods resulting from the retrograde progression of a disk tilted out of the orbital plane. These are more rare than positive superhumps with only about 17 systems currently known. The physical origin of these light curve modulations comes from the migration of the accretion stream impact point across the face of the tilted disk (Wood & Burke 2007). The cause of the disk tilt in these objects is currently unknown, however magnetic fields between the secondary and primary are believed to play some part.

2. METHODS

Using FITDISK, a program developed to model CVs (Simpson 1995; Simpson & Wood 1998; Wood, Dolence & Simpson 2006; Wood & Burke 2007) using the method of smoothed particle hydrodynamics, it is possible to produce simulation light curves as well as emission line profiles of a simulated CV accretion disk. The SPH method is Lagrangian in nature, where particles are used to approximate the true fluid flow. In the 3D simulations reported here, we used 80,000 particles, each with the same effective size ("smoothing length") but each with a timestep as small as needed to resolve the dynamics, or as large as $P_{\rm orb}/200$, which is the fundamental timestep for the simulation[2]. We use the standard spline kernel which is identically zero beyond 2 smoothing lengths. For each particle, we keep track of the position and velocity, as well as the local density, internal energy, and viscous disipation over the previous timestep, and write out the state of the system each fundamental timestep. Using these data, we can visualize the primary, secondary, and the accretion disk with particles color-mapped to show the luminosity of each particle at each step through the systems rotation. These images can then be combined to produce animated models of CVs. The velocity data can then be used to calculate an emission line profile of the disk, as described below. The intensity plot of each frame was added to these images allowing us a more convenient way of comparing the profile with the appearance of the disk.

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[2] A demonstration version of FITDISK for machines running the Windows operating system is available for free download at `www.astro.fit.edu/cv/fitdisk.html`

2.1. *The Simulation Run*

For the simulation we used the same parameters as Wood & Burke (2007). The parameters for the simulation are: primary mass $M_1 = 0.8M_{\odot}$, secondary mass $M_2 = 0.32M_{\odot}$. The mass ratio $q = M_2/M_1 = 0.4$ outside the range that will undergo positive superhumps. The scaled orbital separation is about 1.15 $R_{\odot}$, and orbital period is $\sim$3.2 h. Because the simulation results are independent of the actual masses and only sensitive to the mass ratio, these results will be valid for any $q = 0.4$ system.

We injected 1,000 particles per orbit for 80 orbits, and in addition anytime a particle is accreted or lost from the system a new particle is injected at the L1 point. At the end of orbit 80, we have 80,000 particles in the disk, and we maintain that number of particles by prompt replacement when they are accreted by either star or ejected from the system. The system reaches a dynamical equilibrium state by orbit 200 (see Figure 1 from Wood & Burke (2007)). At this point the simulation is stopped, and the disk is rotated 5°, and the simulation is restarted with the tilted disk. As discussed in Wood & Burke (2007) the disk then precesses slowly in the retrograde direction. The accretion stream impact point ("bright spot"), which is in the orbital plane, sweeps across first one face and then the other of the tilted disk over one orbital period, hitting the edge of the disk only twice per orbit. The bright spot is thus the source of the negative superhump light curves, which are at a maximum brightness when the bright spot is at the smallest radial distance from the primary and the stream velocity is at a maximum. In order to bring out the effect in the simulation, we injected a burst of particles at a rate of 2,000 per orbit for 10 orbits.

2.2. *Calculations*

In this preliminary study we estimate the line profile only very crudely, and assume an inclination of $i = 45°$ throughout. We assume that each particle emits radiation who's intensity is proportional to the net work done on the particle over the previous timestep, and that each particle contributes over a range of wavelengths centered on zero radial velocity in the particle's frame. In fact we use the same SPH smoothing function and a velocity smoothing width of 0.25 in system units or 105 km/s in physical units. We finally assume that we can estimate a spectral line as the sum of the velocity-smoothed contributions of all particles, the set having been rotated to a given inclination angle and each contribution Doppler shifted to the observer's frame.

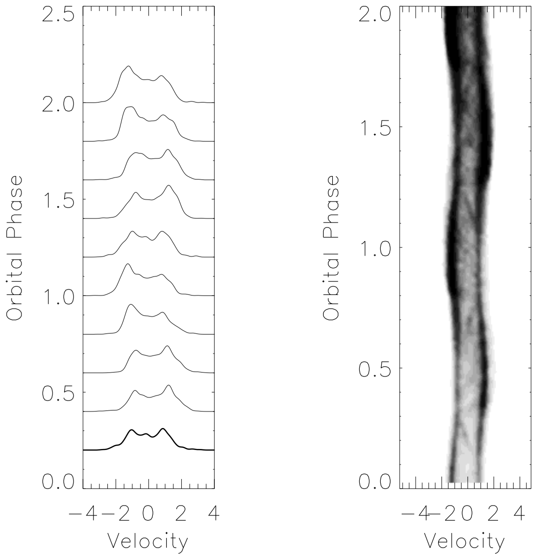

FIG. 1.—Comparison between two different ways of presenting intensity data. The left plot allows for a basic understanding of how the intensities evolve over time, however,the s-curve plot on the right allows for a much more detailed representation and a better understanding. Units of velocity are in data units produced by FITDISK, where 1 in simulation units is $(420/\sin i)$ km/s.

The calculated intensity values are then stored into an array `w(200,part)` where each column corresponds to one of our sampling points and each row corresponds to one of the particles. Each column is then totaled to produce the intensity value of the velocity corresponding to that column. This value is then stored into an array `grayscale(200,nf)` where each row corresponds to the intensity values of one file. This array is the basis for our eventual s-curve image.

2.3. *Displaying the Data*

The intensities that we have produced can be displayed in several different ways. The first is by stacking each intensity plot as a function of orbital period. This display allows for a basic understanding of what the overall intensity profile looks like, however, it is restricted in how many plots can be placed on the chart before it becomes cluttered and difficult to read. As a result it does not go very in depth and lacks many of the features that are present in the s-curve diagram. The s-curve diagram allows us to see how the intensity changes over time with a more detailed look by displaying each frame. However, the s-curve plot only lets the observer see velocities in along the line of view. These first two methods can be compared in Figure 1, where the velocity units are such that ±1 in simulation units is $\pm(420/\sin i)$ km/s .

3. ANALYSIS AND DISCUSSION

Emission line profiles have been produced for a simulated negatively superhumping CV from disk rotation angles of 0°, 90°, 180°, and 270° (Figure 2). This has allowed for a greater understanding of what causes certain features in these profiles as it has given us a look at the same disk from different views. For a comparison to a non tilted disk please consult Figure 3. We visualized these results using IDL to create an animation of a negatively-superhumping system, available at `www.astro.fit.edu/cv/viz/negsh-spect.wmv`. A single frame from this animation is shown in Figure 4.

3.1. *Particle Stream and Disk Tilt*

The disk is tilted at an angle of 5° once it has reached orbit 200 and dynamical equilibrium. Because of this the particle stream is able to travel both over and under the disk. As the stream is drawn over the top of the disk it will eventually settle near the center of the disk where the disk rises above the orbital plane of the secondary. The impact causes a high density of particles and shock heating at its location which disipates as the particles merge with the disk accretion flow around the primary. This higher density area of particles leads to a higher luminosity at its corresponding velocity in our plot. In disk rotations of 0° and 180° this gives rise to the greater intensity of one peak in the profile over that of the other peak usually on the side of the disk opposite the secondary. In disk rotations of 90° and 270° this high-luminosity area shows up as a diagonal line accross the profile.

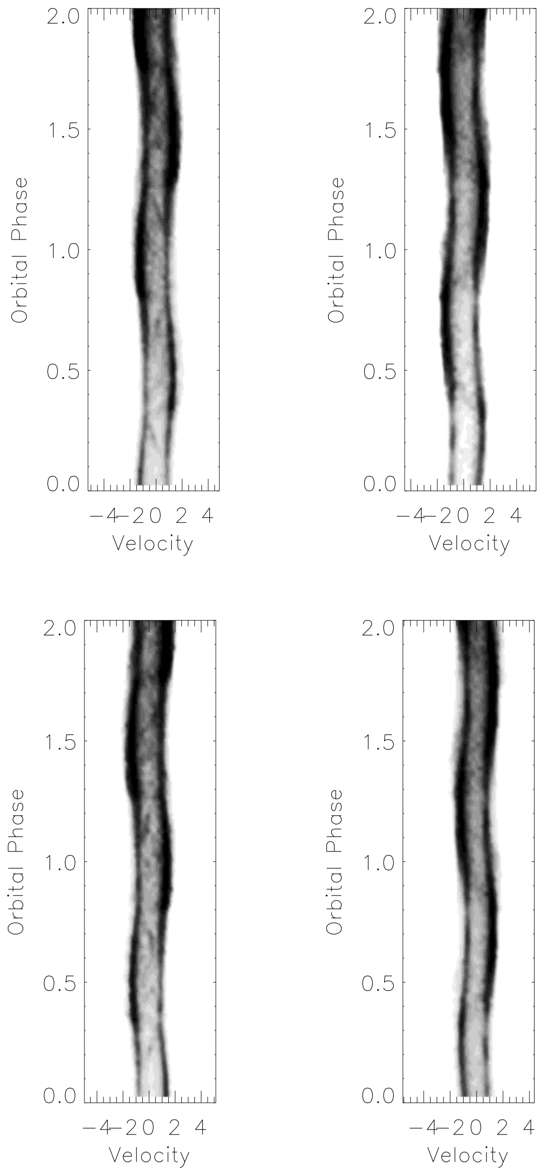

FIG. 2.—Profiles of the disk when rotated 0° (top left), 90° (top right), 180° (bottom left), and 270° (bottom right). Units of velocity are in data units produced by FITDisk.

Twice per orbit we notice that the accretion stream impacts the edge of the disk when the stream is transfering from under the disk to over the disk or visa versa at the line of nodes. At disk rotations of 0° and 180° the stream first impacts particles travelling at positive or negative velocities and lastly impacts particles of negative or positive velocities respectively as it passes over/under the disk. In profiles relating to disk rotations of 90° and 270° this impact can be seen as a brief increase in intensity in the peak of less intensity.

3.2. *Discussion*

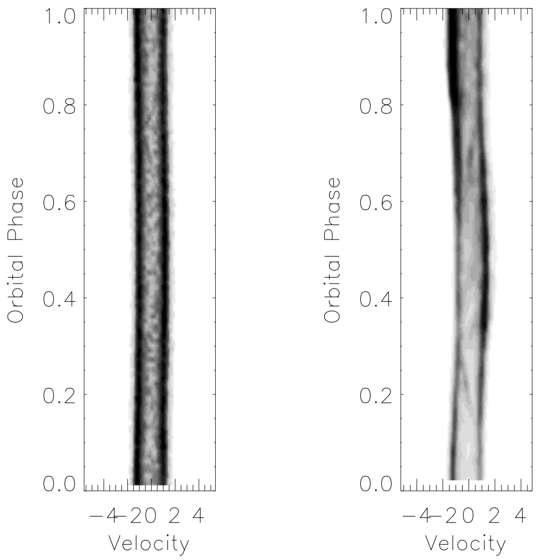

FIG. 3.—(left) Plot of a non-superhumping cataclysmic variable star which only slightly bends as a result of an acretion stream which only impacts the edge of the disk. (right) Plot of a negatively superhumping CV which has a much more prominant bend resulting from the stream impacting near the center of the disk. Units of velocity are in data units produced by FITDisk.

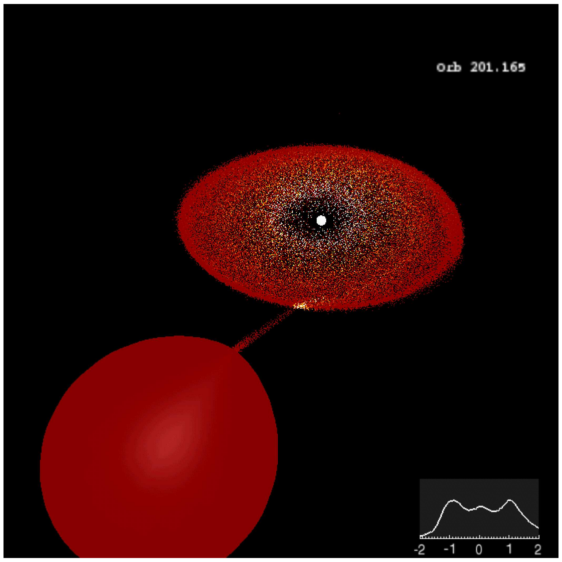

FIG. 4.—A single frame from the visualization animation of the disk with the estimated spectral line shown as an inset. For the full animation, download `www.astro.fit.edu/cv/viz/negsh-spect.wmv`

We have taken a first step in estimating the possible line profile variations using the method of smoothed particle hydrodynamics. Currently the profiles that we can produce take into account every particle in the disk. However an actual observer sees only the photosphere of the disk. In future work we will use our ray-trace code (Wood & Burke 2007) to construct time-series spectra of only the "photosphere" of our simulated disks. In addition, obvious next steps include expanding this study to common superhumps, and including the effects of eclipses by the secondary. This work is in progress.

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