Journal of the Southeastern Association for Research in Astronomy, **4**, 42-44, 2010 July 1
© 2010. Southeastern Association for Research in Astronomy. All rights reserved.

PRELIMINARY RESULTS FROM A HYDRODYNAMIC SIMULATION OF THE DIRECT IMPACT ACCRETION MODEL WITH PLUTO

William D. Baez
Department of Chemistry and Physics, Augusta State University, Augusta, Georgia, 30901

Matt A. Wood, Isaac Silver
Physics and Space Sciences Department, Florida Institute of Technology, Melbourne, FL 32901

ABSTRACT

Recent observations and simulations suggest that the double degenerate, ultracompact binary systems V407 Vul (RX J1914.4+2457) and HM Cnc (RX J0806.3+1527) represent the only two binary white-dwarf systems that exhibit Algol-like direct impact behavior. In this paper, we provide preliminary results from a simulation of the direct impact accretion model using PLUTO, a numerical hydrodynamics code. Our results consist of a qualitative, two-dimensional representation depicting a ballistic accretion stream directly striking the atmosphere of a close primary white dwarf.

Subject headings: accretion, accretion discs — binaries: close — hydrodynamics — novae, cataclysmic variables — stars: individual(HM Cnc; V407 Vul) — X-rays: binaries

1. INTRODUCTION

The physical properties of the ultracompact, double degenerate systems V407 Vul and HM Cnc have been the subject of intense study over the past decade. Originally discovered in 1996 and 1999, respectively, both feature the following observations (Marsh & Steeghs 2002; Cropper et al. 2004; Dolence et al. 2008; Wood 2009):

1. X-ray and optical pulsations of 9.5 minutes (V407 Vul) and 5.4 minutes (HM Cnc); no observed periodic signals within either spectrum.
2. Optical light curve phase leads X-ray by ∼0.2 in both systems.
3. Presence of soft X-rays ($<$ 1 keV) with a noticeable absence of hard X-rays ($>$ 1 keV).
4. Absence of strong line emissions or polarization within the optical spectrum.
5. Sawtooth "on/off" X-ray profile. Light curve shows a sudden rise before more slowly reaching a maximum, accompanied by a slower decline toward the minimum.
6. Long-term variability in mean luminosities.
7. Decreasing orbital period consistent with gravitational radiation.

Several theoretical models have been proposed to determine the cause of these observed characteristics. Three such models have received substantial attention: (1) the unipolar inductor, or electric star, model (Wu et al. 2002; Dall'Osso et al. 2007), (2) the double-degenerate polar model (Motch et al. 1996; Norton, Haswell, & Wynn 2004), and (3) the direct impact (DI) accretion model (Marsh & Steeghs 2002). While all three have been able to provide some explanation, no one model provides a complete picture. However, models (1) and (2) have several drawbacks. As noted by Dolence et al. (2008) and Wood (2009), the unipolar inductor model, where an electric current develops between the primary and the secondary, has yet to be tested and/or proved within a stellar system. Additionally, the model predicts the phase offset between the optical and X-ray light curves as being ∼0.5, in conflict with the properly calibrated observations. The polar model, similarly, is unable to account for the lack of emission lines and polarization commonly observed with strongly magnetized white dwarfs. Further information on models (1) and (2) can be found in Wu et al. (2002) and Cropper et al. (1998), respectively. For the remainder of this paper, we focus only on the DI accretion model.

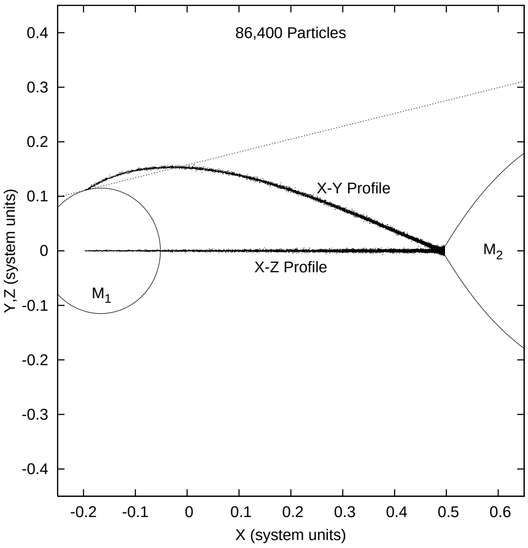

Fig. 1.— The trajectory of SPH particles as viewed perdendicular and parallel to the orbital plane. The horizon of the impact spot is shown as the dotted line. Note that the altitude of the incoming accretion stream at the white dwarf surface is $\lesssim 20°$ above the local horizon. Adapted from Dolence et al. (2008).

In the DI accretion model, the two white dwarfs are close enough that the accretion stream from the Roche-lobe filling secondary impacts the surface of the primary white dwarf directly and at a location that is fixed in the binary co-rotating frame. V407 Vul and HM Cnc are the only two double-white-dwarf systems known where this appears to occur. The spectrum of the system ES Cet (Warner & Woudt 2002; Espaillat et al. 2005) with a slightly longer orbital period of 10.3 min shows features that likely result from a truncated accretion disc, possibly resulting from a grazing impact of the accretion stream with the white dwarf atmosphere as the system makes the transition from a direct impact system to a normal AM CVn accretion disk (Wood 2009). The geometry of the DI system is thought to be such that the angle of impact, as seen from the primary's surface, to be $\lesssim 20°$ from the horizon, and the impact point on the "back" side of the primary – opposite the secondary. Dolence et al. (2008) used a smoothed particle hydrodynamics code to demonstrate that a supersonic accretion stream would strike the primary's surface at the near-horizontal trajectory, as seen in Figure 1. The area of this impact region would measure 107,000 km^2, which is approximately the area of Iceland on a white dwarf of $\sim$1.5R$_\oplus$. This impact footprint was consistent with the initial analytical estimate. Because the impact angle is nearly horizontal, an equitorial flow should be established in the prograde direction.

Marsh & Steeghs (2002) also argue that the stream's ram pressure would be greater than the primary's upper atmospheric pressure. This would cause the stream to plunge below the photosphere and thermalize, upwelling downstream to give rise to the observed soft X-ray spectrum. In the DI model, Marsh & Steeghs propose that the phase offset between the optical and X-ray light curves is the result of a cooling equitorial flow. A distant observer would see the increasingly hot material at the equator brought into view before the X-ray hot spot. Using IDL, Wood (2009) modeled the temperature distribution along a cylindrical wall representing the equatorial band of an accreting white dwarf. This work reproduced the optical/X-ray phase offset as well as the general shape of the light curves for both V407 Vul and HM Cnc (see Figure 2).

The remainder of this paper is organized as follows: In §II, we discuss the specific model parameters used to model a direct impact scenario using the hydrodynamics code PLUTO. In §III, we present our results, and in §IV we discuss those results our conclusions.

2. MODEL AND METHOD

In order to model the flow of accreted material onto a white dwarf, we used the numerical, hydrodynamics code PLUTO (Mignone et al. 2007). This code is suited for modeling highly supersonic flows in 1, 2, or 3 dimensions under several different physical conditions (i.e., classical, nonrelativistic non-magnetized, magnetized, and relativistic magnetized). The program is modularized for increased flexibility allowing users to modify existing modules or add new modules as needed. PLUTO also provides multiple numerical integrators for users who may require a particular algorithm. The code, written entirely in C, also has parallel computational abilities provided via the message passing interface (MPI) library.

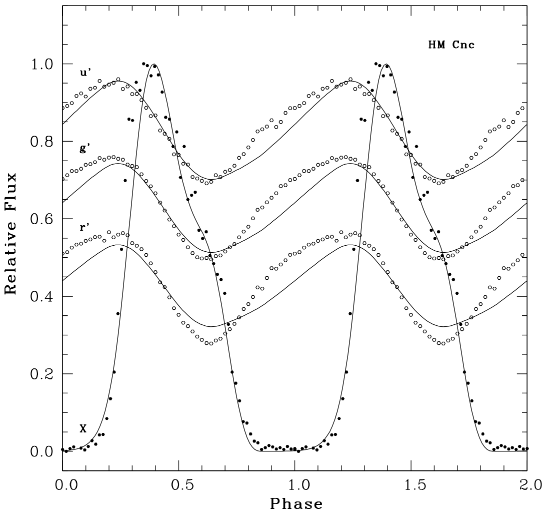

FIG. 2.— HM Cnc optical (Barros et al. 2007) and X-ray (Strohmayer 2005; Barros et al. 2007) light curve data with Wood (2009) model results overplotted. The reasonable match supports the plausibility of the DI model as applied to these systems. Figure adapted from Wood (2009).

For this study, we assumed the primary was a 0.6 M$_\odot$ white dwarf. We used the ballistic stream parameters obtained from Marsh & Steeghs (2002) who proposed that the jet's density and velocity were $\rho = 3 \times 10^{-5}$ g cm^{-3} and $v = 4 \times 10^{8}$ cm s^{-1} $\sim$ 0.01c, respectively. We also used an accretion stream width of $\sim 10^{-4}\ R_\odot$ to stay consistant with Marsh & Steeghs (2002) and Dolence et al. (2008).

To model the primary's atmosphere, numerical data for the radius, density, and temperature were obtained from Wood (1995). We limited atmospheric modeling to only a fraction of the primary's atmosphere with the assumption that the ballistic stream would not penetrate further than 2% beneath the photosphere. Initial density and temperature profiles were modeled through a polynomial and linear fit, respectively. The inital pressure profile was then obtained using the ideal gas law,

$$P = \frac{\rho k_B T}{\mu m_H} \tag{1}$$

where ρ is the density, k_B is Boltzmann's constant, T is temperature, μ is mean molecular weight, and m$_H$ is the unit of atomic mass. It should be noted that the systems V407 Vul and HM Cnc have hydrogen depleted, or helium rich, photospheres.

The simulated atmospheric density ranged between $3{\times}10^{-7} \leq \rho \leq 1.2 \times 10^{-5}$ g cm^{-3} and the photospheric temperature $7.8 \times 10^4 \leq T \leq 1.7 \times 10^5$ K. Using Eq. (1), the initial pressure profile used in our simulation was $4.3 \times 10^6 \leq P \leq 3.4 \times 10^8$ dyne cm^{-2}.

3. RESULTS

Figure 3 shows a time-lapse series of DI simulation snapshots within the orbital co-rotating frame of reference. These snapshots depict the atmospheric and accretion stream density before and after the impact. Note that in the first frame there is a shock front at the tip of the accretion stream. The second frame shows that the

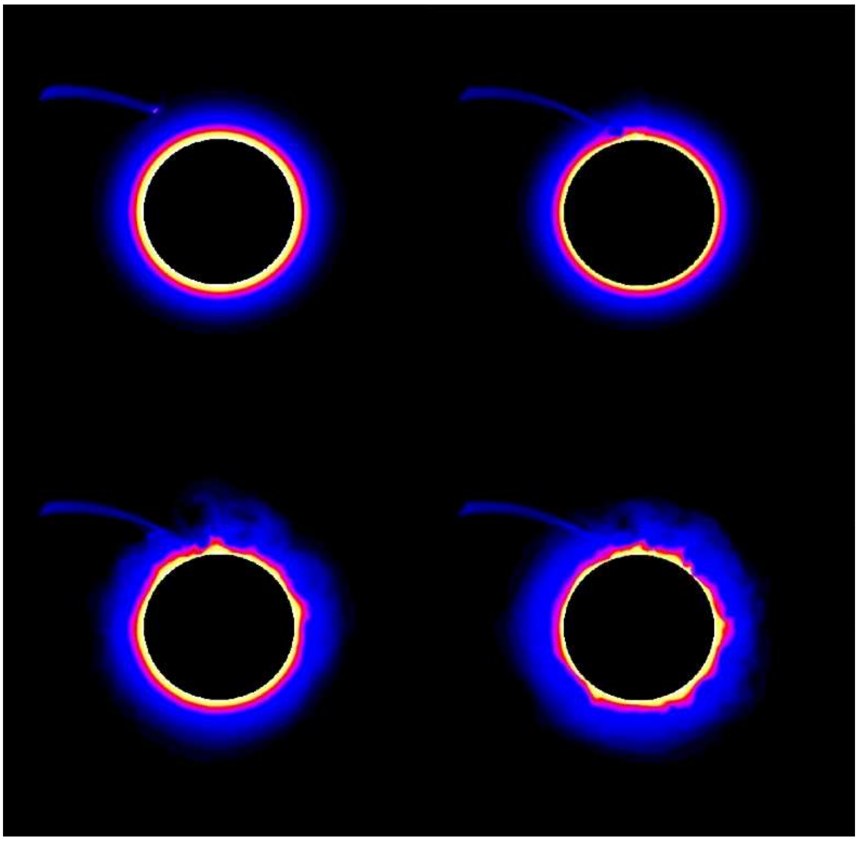

FIG. 3.— Four snapshots in time from a preliminary direct impact accretion model. In the first frame the accretion stream is starting to penetrate the outer atmosphere. In the second frame the stream has disturbed the atmosphere, and given rise to an upwelling downstream. The thrid frame shows the simulation at a time of $t = 5$ s, and the fourth frame shows the simulation at a time of $t = 10$ s. Clearly the stream impact causes significant turbulence in the stellar envelope.

impact leads to an upwelling downstream of the impact point. The third and fourth frames show the significant turbulence generated in the atmosphere of the accreting object. Note that the stream collides nearly horizontally to the primary's surface, which is also seen in Figure 1.

4. DISCUSSION AND CONCLUSION

The time-lapse series above serves as a "proof of principle" that PLUTO is capable of simulating the geometry and DI accretion within cylindrical coordinates. However, refinements to the initial parameters, such as accounting for hydrogen depletion of both stars, will be necessary to model more accurately the atmospheric conditions after impact. Additionally, the DI model proposes that neither V406 Vul or HM Cnc are in a synchronous orbit and are, thus, rotating under the impact site. These preliminary tests did not take this into account. Rotating the primary will be critical simulating the offset phase seen in the optical/X-ray spectrum. To obtain the simulated light curves, a complete profile of the accretor's photospheric temperature distribution will also be necessary.

As mentioned in Dolence et al. (2008) and Wood (2009), to completely investigate the DI model, a direct hydrodynamic simulation in spherical coordinates is needed to corroborate the observed characteristics of V407 Vul and HM Cnc. The two dimensional work presented here, though, not only demonstrates that a three dimensional simulation is entirely possible, but also that PLUTO is well suited to carry out such an investigation.

REFERENCES

Barros, S. C. C., et al. 2007, MNRAS, 374, 1334

Cropper, M., Harrop-Allin, M. K., Mason, K. O., Mittaz, J. P. D., Potter, S. B., & Ramsay, G. 1998, MNRAS, 293, L57

Cropper, M., Ramsay, G., Wu, K., & Hakala, P. 2004, IAU Colloq. 190: Magnetic Cataclysmic Variables, 315, 324

Dall'Osso S., Israel G. L., & Stella L., 2007, A&A, 464, 417

Dolence, J., Wood, M. A., & Silver, I. 2008, ApJ, 683, 375

Espaillat C., Patterson J., Warner B., & Woudt P., 2005, PASP, 117, 189

Marsh, T. R., & Steeghs, D. 2002, MNRAS, 331, L7

Mignone, A., Bodo, G., Massaglia, S., Matsakos, T., Tesileanu, O., Zanni, C., & Ferrari, A. 2007, ApJS, 170, 228

Motch C., Haberl F., Guillout P., Pakull M., Reinsch K., Krautter J., 1996, A&A, 307, 459

Norton A. J., Haswell C. A., Wynn G. A., 2004, A&A, 419, 1025

Strohmayer T. E., 2005, ApJ, 627, 920

Warner B., Woudt P. A., 2002, PASP, 114, 129

Wood, M. A., 1995, in White Dwarfs, Proceedings of the 9th European Workshop on White Dwarfs Held at Kiel, Germany, 29 August - 1 September 1994. Lecture Notes in Physics, Vol. 443, eds. Detlev Koester and Klaus Werner. Springer-Verlag, Berlin Heidelberg New York, p.4

Wood, M. A., 2009, MNRAS, 395, 378

Wu, K., Cropper, M., Ramsay, G., & Sekiguchi, K. 2002, MNRAS, 331, 221