Final Report

NAG 5-10709: Accretion Flows in Magnetic White Dwarf Systems

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We received Type A and B funding under the NASA Astrophysics Data Program for the analysis and interpretation of hard x-ray data obtained by the Rossi X-ray Timing Explorer and other NASA sponsored missions for Intermediate Polars (IPs) and Polars. For some targets, optical data was available. We reduced and analyzed the x-ray spectra and the x-ray and optical (obtained at the Cerro Tololo Inter-American Observatory) timing data using detailed shock models (which we constructed) to place constraints on the properties of the accreting white dwarfs, the high energy emission mechanisms of white dwarfs, and the large-scale accretion flows of Polars and IPs.

IPs and Polars are white dwarf mass-transfer binaries, members of the larger class of cataclysmic variables. They differ from the bulk of the cataclysmic variables in that they contain strongly magnetic white dwarfs; the white dwarfs in Polars have $B_* = 7$ to 230 MG and those in IPs have $B_* < 10$ MG. The IPs and Polars are both examples of funneled accretion flows in strong magnetic field systems. The IPs are similar to x-ray pulsars in that accretion disks form in the systems which are disrupted by the strong stellar magnetic fields of the white dwarfs near the stellar surface from where the plasma is funneled to the surface of the white dwarf. The localized hot spots formed at the footpoints of the funnels coupled with the rotation of the white dwarf leads to coherent pulsed x-ray emission. The Polars offer an example of a different accretion topology; the magnetic field of the white dwarf controls the accretion flow from near the inner Lagrangian point of the system directly to the stellar surface. Accretion disks do not form. The strong magnetic coupling generally leads to synchronous orbital/rotational motion in the Polars. The physical system in this sense resembles the Io/Jupiter system. In both IPs and Polars, pulsed emission from the infrared to x-rays is produced as the funneled flows merge onto the white dwarfs through the formation of strong radiating shock waves.

A comparative study of the IPs and Polars can elucidate the primary effects of the magnetic fields on the dynamics and thermodynamics in accreting white dwarf systems. In this vein, V2301 Oph is particularly interesting because it is an eclipsing source, it is bright in the hard x-rays for a Polar, and it has the weakest field ($B_* \sim 7$ MG) of the Polars. V2301 Oph may encroach into IP territory on occasion. V2301 Oph offers the rare opportunity among Polars for detailed studies of white dwarf radiative shocks (because the effects of cyclotron emission are minimized) and may be an unique laboratory for gaining insight into the processes which differentiate between the different accretion geometries found in the Polars and IPs.

We critically examined the veracity of the shock model by comparing its predictions to the hard x-ray observations and, when available, to optical data for several Polars and IPs. The characteristics of white dwarf shocks are determined using the computer code FASTAR (Wolff, Gardner, & Wood 1989, Steiman-Cameron & Imamura 1997, Wolff et al. 2000) and a steady-state radiation/hydrodynamics computer code that includes an explicit treatment of cyclotron cooling (Imamura & Bryson 2005,2006). FASTAR uses adaptive gridding and the Flux Corrected Transport algorithm to model discontinuities. It includes *e-i* energy cooling, electron thermal conduction, and the electron cooling processes *e-i* and *e-e* bremsstrahlung, cyclotron cooling, and Compton cooling. The cyclotron emission model follows the work of Chanmugam, Langer, & Shaviv (1985, from heron CLS). CLS suggested that their cooling function was accurate to within a factor of two.

The primary difficulty of the theoretical modeling has been the proper inclusion of cyclotron cooling. The major issue was the available computing power. The Institute of Theoretical Science's Dec Alpha micro-computer was used for the bulk of the simulations for this proposal and has proven fully capable of performing the calculations made using the computer code FASTAR. The approximation of CLS effectively reduced cyclotron to a local cooling problem where the cooling was handled using an isotropic optically thin loss function. The FASTAR code was adequate for very weak field systems where the effects of cyclotron cooling are weak. For the strong field systems (and, in fact, even for the weak-field systems) the persistent uncertainty was a nagging problem. We wrote, in collaboration with University of Oregon undergraduate Mr. William Bryson, newer software to calculate the structure of radiative shock waves with a proper treatment of cyclotron emission. The computation of a grid of models for use in comparisons to data required more computing power than was available in the Institute of Theoretical Science.

The problem of cyclotron cooling is numerically taxing. The photon emission is not isotropic, it is strongly frequency dependent, and it is optically thick at many wavelengths. To show how these properties affected the computational problem, we considered numerical shock models calculated through solution of the equations of conservation of mass, conservation of momentum, and the conservation of matter energy on a planar grid composed of 250-1,000 computational cells. Fully including the cyclotron emission required that, in addition, multiple photon *energy* conservation equations also be solved. Photon energy conservation equations were solved for each photon energy and each path followed by the photons. This meant that had to be $N_\nu \times N_\mu$ photon conservation equations for each photon polarization mode, where N_ν and N_μ are the number of photon frequencies sampled and the number of photon paths followed. Typically, we used 100 photon frequencies and 10 photon paths. Minimally, this increased the computing demands by a factor of 1,000. Calculating individual models was feasible using the current Institute of Theoretical Science computer, our Dec Alpha, however, generating a grid of models necessary for data analysis was beyond its capability. We purchased a personal computer based on one of the new available 64-bit chips with 4.096 Gigabytes of memory. This configuration led to a 5 times increase in speed, with a 16-fold increase in memory.

0.1 RXTE DATA ANALYZED IN THIS PROJECT

"Quasi-Periodic Oscillations and the Temporal Characteristics of the AM Herculis VV Pup (12.2 ks), and V834 Cen (12.2 ks). The sources are extremely faint and no clear detections were made. We have re-analyzed the data using improved background models. The results were reported at the winter 1997 American Astronomical Society meeting and published in Publications of the Astronomical Society of the Pacific.

"Accretion Flows in AM Herculis Objects," P20013, V2301 Oph (50 ks) and BL Hyi (25 ks). The BL Hyi data are published in The Astrophysical Journal and the V2301 Oph data have been reported in the Annapolis CV workshop. A paper on V2301 Oph using earlier RXTE data has previously been published (Steiman-Cameron & Imamura 1999). The data has has been reanalyzed using updated background models for the RXTE satellite and improved theoretical models and has been submitted for publication in The Astrophysical Journal (Wolff et al. 2005).

"Accretion Flows in Magnetic Cataclysmic Variables," P20023, AO Psc (13 ks) and V1223 Sge (12.6 ks). The data are currently begin re-analyzed using the new background model and interpreted using theoretical models based on FASTAR calculations. The work is currently in preparation (Johnson, Imamura, & Steiman-Cameron 2005).

"The Eclipsing AM Herculis Objects as Probes of the Accretion Geometry," P20016, V2301 Oph (13.6 ks), RE2107-05 (15 ks), and UZ For (15.4 ks). Only V2301 Oph was a positive detection. The x-ray data were compared to optical data by us and detailed light curve and eclipse modeling performed. The work on V2301 Oph was published in The The Astrophysical Journal. The UZ For and RE2107-05 data were re-analyzed using improved RXTE background models. The data were not suitable for publication.

"The Eclipsing AM Herculis Objects as Probes of the Accretion Geometry," P30011, EP Dra (13.8 ks) and WW Hor (12.6 ks). The data were analyzed but did not yield suitable results for publication.

Grant-Related Publications

1. "Optical and X-ray Observations of Bl Hydri," Wolff, M.T., Wood, K.S., Imamura, J. N., Middleditch, J., & Steiman-Cameron, T.Y. 1999, *The Astrophysical Journal*, 526, 435
2. "Coordinated Optical and X-ray Observations of BL Hydri," Wolff, M.T., Imamura. J.N., Middleditch, J., Wood, K.S., & Steiman-Cameron, T.Y. 1999, in ASP Conference Series Vol. 157, eds. C. Hellier & K. Mukai, p. 149

3. "Coordinated Optical and X-ray Observations of VV Puppis, V834 Centauri, and EF Eridani", Imamura, J. N., Steiman-Cameron, Middledtich, J, & Scargle, J. 2000 *Publications of the Astronomical Society of the Pacific*, Vol. 112 Issue 767, 18
4. "All Season Rapid Photometry of SN1987A: A 2.14 Msec Pulsar?" Middleditch et al. 2000, *New Astronomy*, Vol. 5 #5
5. "RXTE Observations of V2301 Ophiucus & BL Hydri," Wolff, M.T., Wood, K.S., Imamura, J.N., & Steiman-Cameron, T.Y. 2000, eds. P. Charles, A. King, & D. O'Donoghue, *New Astronomy Reviews* Vol. 44 No 1-2
6. "RXTE Observations of V2301 Ophiucus," Wolff, M.T., Imamura, J.N., Wood, K.S., & Steiman-Cameron, T.Y. 2000, in "Rossi 2000: Astrophysics with the X-ray Timing Explorer," conference held at Goddard Space Flight Center, E86
7. "RXTE Observations of V2301 Ophiucus," Wolff, M.T., Imamura, J.N., & Steiman-Cameron, T.Y. 2005, *The Astrophysical Journal*, submitted
8. "A Timing Study of AO Piscium," Johnson, E. & Imamura, J.N., 2005, *The Astrophysical Journal*, in preparation
9. "The X-ray Spectra of BL Hyi and V2301 Oph," Imamura, J.N., & Bryson, W. 2006, *The Astrophysical Journal*, in preparation
10. "The X-ray Spectrum of Magnetic Accretion Shocks," Imamura, J.N., & Bryson, W. 2006, *The Astrophysical Journal*, in preparation