CORRUGATION INSTABILITIES IN STRONG, SLOW MHD SHOCKS

SYNOPSIS

• We will carry out theoretical research on Polar and Intermediate Polar (IP) accretion shocks. Polars and IPs are important plasma physics laboratories because of the wealth of detailed x-ray spectral information available and a foundation of well-understood hydrodynamics. This provides a testbed for the study of strong, slow MHD shocks, furthering our understanding of the interplay between known hydrodynamic phenomena and magnetic fields. We will utilize data to guide and constrain development of theoretical MHD Polar and IP shock models and use that to extend our knowledge of strong, slow MHD shocks, pertinent to accretion systems in general.

• We will perform steady-state calculations and linear stability analyses of the corrugation instability for strong, slow, parallel MHD shocks under conditions appropriate for Polars and IPs.

• Steady-state and time-dependent x-ray spectra of Polars and IPs will then be calculated. Polar and IP observations will provide stringent tests for our theoretical models enabling us to sharpen diagnostic tools used to interpret temporal and spectral features of Polars and IPs, such as quasi-periodic oscillations (QPOs), x-ray light curves, and x-ray line and continuum spectra.

• We will study the stability of adiabatic MHD shocks under general conditions. We consider fully three-dimensional perturbations and oblique shocks. Such calculations are needed to follow-up the work of Stone & Edelman (1995). Stone & Edelman suggested that all strong, slow MHD shocks are either aperiodically unstable and degenerate into turbulence or are overstable and produce quasi-periodic variability, even in the limit of strong magnetic field. This has implications for a wide range of astrophysical sources; magnetically channeled flows which produce parallel or nearly parallel MHD shocks arise not only in the Polar and IP systems mentioned above, but also in neutron star x-ray pulsar systems and possibly in classical T Tauri systems.

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1 Introduction

Magnetically channeled accretion onto the polar cap of a magnetic star is one of the central theoretical problems of high energy astrophysics. Strongly magnetic plasma flows are found and play important roles in a wide range of high energy astrophysical systems, *e.g.,* T Tauri stars, the cataclysmic variables known as the Polars and Intermediate Polars (IPs), and the neutron star x-ray pulsars. Although the accreting stars in these systems are radically different in nature, there are similarities in all of their accretion flows. In each case, a magnetic field guides accretion onto one or both of the star's magnetic poles and the flows are transonic, so that the accreting plasma must pass through a shock in order to merge onto the star's surface. The detailed nature of the shocks differs because gas pressure generally dominates over radiation pressure in the Polar, IP, and T Tauri accretion flows while the reverse condition holds in accretion flows in neutron star systems (*e.g.,* Frank *et al.* 2002). The systems form a set of mutually-complementary laboratories for the study of magnetically channeled accretion flows and the effects of strong magnetic fields on high-energy emission mechanisms.

We propose a research program designed to refine our understanding of radiating and adiabatic strong slow MHD shock waves. We will use the well-observed Polar and IP systems as testbeds for our modeling of MHD shocks. The coupling of theory and observation will allow quicker and more reliable advances to be made in our understanding of the MHD shocks in Polars and IPs and will lead to a sounder understanding of MHD shocks, in general.

2 Scientific Background

Polars are characterized by strongly polarized optical and/or IR emission and intense soft and hard x-ray emission modulated on the binary orbital period with a strongly magnetic white dwarf primary, $B_* \sim$ 7-230 MG (*e.g.,* Cropper 1990). IPs show neither strongly polarized optical nor IR emission, but do show hard x-ray emission modulated on the rotational period of the white dwarf. The white dwarfs in IPs are thought to have $B_* \sim$ 1-30 MG (Pirola *et al.* 2008). In both Polars and IPs, matter accretes onto the white dwarf from a low mass companion star which is overflowing its Roche lobe.

The importance of the magnetic field for the the accretion flow dynamics is measured by

$$\beta = \left(\frac{U_B}{0.5\rho_{in} v_{in}^2}\right) = \left(\frac{v_A}{v_{in}}\right)^2 \qquad (1)$$

where U_B is the magnetic energy density, v_A is the Alfvén speed and ρ_{in} and v_{in} are the preshock flow density and velocity. For typical Polar and IP parameters $\beta \sim 5$ - 230. In Polars, $\beta \gtrsim 25$ and the magnetic field enforces synchronous rotation of the binary system with the white dwarf with field-aligned accretion forced from the inner Lagrangian point, while in IPs, β is somewhat smaller and an accretion disk forms. The magnetic field is strong enough, however, to disrupt the disk before it reaches the white dwarf. In both cases, after the magnetic field threads the plasma, the plasma flows toward the white dwarf along the magnetic field lines. As the flow approaches the white dwarf's surface, a shock wave forms. Behind the shock transition, the heated plasma cools via bremsstrahlung, Compton cooling, and cyclotron emission as it settles onto and merges with the white dwarf. The structure composed of the shock transition and the cooling region is referred to as a radiative shock. The *standard* radiative shock model predicts a three-component spectrum with the bremsstrahlung producing a hard x-ray component, cyclotron radiation producing an optical/infrared component, and a black-body component resulting from reprocessing of bremsstrahlung and cyclotron photons in the white dwarf's surface (Lamb & Masters 1979). This general picture is roughly supported by observation.

The shock-heated plasma reaches temperatures, kT_*, of roughly

$$kT_* \sim 64 \left(\frac{M_*}{M_\odot}\right) \left(\frac{R_*}{5 \times 10^8\,\mathrm{cm}}\right)^{-1} \quad \mathrm{keV} \qquad (2)$$

where M_* and R_* are the white dwarf mass and radius, respectively. The high post-shock temperature of the gas coupled with the strong magnetic field makes Polars and IPs important plasma physics laboratories because of two important observational consequences: the shock-heated plasma i) is a strong source of hard x-rays with a rich line spectrum, and ii) it emits cyclotron radiation as the hot electrons spiral in the magnetic field. These features allow the development of sensitive diagnostics which can be used as probes of the thermal properties of radiating MHD shock waves.

The stability of hydrodynamic radiative shock waves has been studied since the early 1980s after Langer *et al.* (1981) discovered an oscillatory thermal instability of white dwarf radiative shock waves. Chevalier & Imamura (1982) elucidated the instability through a one-dimensional linear stability analysis, the results of which were verified in the nonlinear simulations of Imamura *et al.* (1984). Bertschinger (1986) extended the work to include the corrugation instability of radiative shock waves. In corrugation instabilities, a two-dimensional (2-D) perturbation (*rippling*) is applied to the shape of the shock front. Strickland & Blondin (1995) studied the corrugation instability of hydrodynamic shocks with power law cooling functions in 2-D using numerical hydrodynamics verifying the results of Bertschinger (1986). Corrugation instabilities have also been studied in adiabatic (Lessen & Deshpande 1967, Edelman 1989b, Stone & Edelman 1995) and radiating strong, slow MHD shock waves (Edelman 1989a), although a much smaller part of the parameter space has been investigated than for the hydrodynamic shock case. An interesting result was found by Stone & Edelman (1995) who suggested that all strong, slow MHD shocks are unstable to corrugation instabilities if three-dimensional (3-D) perturbations are considered. They hypothesized that either aperiodic instabilities would cause MHD shocks to degenerate into turbulence or that overstable modes would lead to short timescale quasi-periodic variability and simple timing studies of Polars and IPs could then shed light on and enhance our understanding of the dynamic properties of MHD shock waves. Because of the ubiquitous nature of strong, slow MHD shocks this suggestion, if confirmed, would have far-reaching consequences and warrants further consideration.

3 Proposed Research

Polar and IP shock theory has advanced from exploratory exercises and time-independent calculations of spectra to full hydrodynamical modeling of the structure of accretion columns that are roughly able to reproduce the main features of the observed spectra (Woelk & Beuermann 1996) and the observed temporal variability (Langer *et al.* 1981). However, most shock spectral models do not properly include the effects of the strong magnetic field on the thermodynamics or dynamics (however, see Woelk & Beuermann 1996). The thrust of our proposed theoretical/archival research focuses on the careful modeling of thermal and dynamic effects which arise because of the strong magnetic fields in Polar and IP systems and their consequences for the observable high-energy emission from Polars and IPs.

3.1 Physical Picture

We model strong slow radiative shocks in the ideal MHD approximation where, by strong, we mean shocks where the flow velocity is large compared to the sound speed in the preshock flow, that is, $|v|/c_s \gg 1$ where the isothermal sound speed is given by $c_s = \sqrt{\gamma P/\rho}$, γ is the adiabatic index, P is gas pressure and ρ is mass density and by slow, we mean shocks where the flow speed is less than the Alfvén speed in the preshock flow.

We expect several types of shocks to form corresponding to the different wave modes supported by adiabatic, magnetic plasmas. One type corresponds to Alfvén modes, two to the slow and fast magnetosonic modes, and a final one to an entropy wave. Alfvén waves are characterized by disturbances perpendicular to the plane defined by the wave propagation vector and the equilibrium magnetic field. Entropy waves are zero frequency modes whose disturbances are advected with the flow. Magneotsonic modes are characterized by disturbances in the plane defined by the wave propagation vector and the equilibrium magnetic field. The slow magnetosonic modes may propagate with speeds up to c_s or v_A, whichever is larger while fast magnetosonic modes propagate with speeds between v_A and $\sqrt{v_A^2 + c_s^2}$. Alfvén waves propagate with speed v_A. Thus, both magnetosonic waves and Alfvén waves may propagate upstream as well as downstream of slow MHD shock waves, *i.e.,* in flows where $v_A > |v_{in}|$.

The stability of radiative MHD shocks is determined by the interaction between MHD waves excited at the shock front and cooling in the postshock plasma.

3.2 Radiative MHD Shocks

We will first determine the steady-state hydrodynamic structures and spectra of strong slow parallel MHD shock waves under conditions appropriate to those of Polar and IP systems to develop a set of diagnostics for MHD shocks. Our calculations will be two-temperature in nature and include the effects of bremsstrahlung, Compton cooling, and a self-consistent treatment of cyclotron emission (Imamura, Bryson, & Steiman-Cameron 2008). Using our shock structures we will determine the x-ray line spectrum and the continuous emission from the optical to the hard x-ray. We are currently extending our spectral code to produce x-ray line spectra suitable for comparison to Chandra spectra. We calculate x-ray line spectra using our calculated shock emission region structures and tables of isothermal plasma line spectra calculated from collisional line models produced by XSPEC based on the MEKAL line spectral model. Our shock/spectral model is a significant improvement over earlier works which did not include detailed solutions of the radiation transfer equation to determine self-consistent cyclotron intensities when the shock structures utilized to determine x-ray spectra were calculated. Our techniques are sufficiently general that all relevant Polar and IP parameters such as accretion rate, M_*, and B_* can be explored. **The x-ray spectra will be directly comparable to Polar and IP data acquired by Chandra and thus strin-**

gent tests of the viability of Polar and IP MHD shock models may be made.

We will next investigate corrugation instabilities in strong, slow parallel MHD radiative shocks with power law cooling functions in the linear regime. Edelman (1989a) attacked this problem but only considered bremsstrahlung, the cooling function appropriate for nonmagnetic white dwarf shocks, and plasmas where the electrons and ions were strongly coupled and shared a common temperature, a one-temperature approach. We will extend this work to include a wider range of cooling functions, in particular, cyclotron emission, and to include two-temperature effects necessary to model shocks accurately when cyclotron cooling is important. Edelman made the interesting discovery that shocks with β over the range 4 to 100 were either aperiodically unstable or unstable to overstable oscillations. **We will first refine these theoretical predictions, and then produce x-ray spectra suitable for comparison to Chandra data. We will develop diagnostics for time-dependent x-ray spectra of unstable Polar and IP radiative shocks**.

3.3 Adiabatic MHD Shocks

We will investigate the properties of general MHD shock fronts by a study of the corrugation instability in strong slow *adiabatic* MHD shocks. We will consider fully 3-D perturbations and oblique shocks relaxing the assumptions of 2-D perturbations and parallel shocks used for the Polar and IP studies. Because of the complexity of the physical and numerical problem, we will perform both linear and nonlinear calculations. Earlier linear work by Lessen & Deshpande (1967) used 2-D perturbations for the case where the sonic Mach number = 2 and Stone & Edelman (1995) performed a 3-D analysis, but restricted themselves to nearly parallel MHD shocks. The linear work is particularly useful because it is considerably more computationally inexpensive to obtain so that we may more thoroughly explore parameter space and more easily isolate the important physics of MHD shocks than the fully nonlinear calculation will be able to do. The linear results will allow checks of the early phases of our nonlinear simulations.

In the nonlinear regime, we are constructing a fully 3-D code to study the long-term evolution of the corrugation instability. Previous nonlinear studies have focused on a fairly sparse distribution of parameter space and utilized methods developed for hydrodynamic modeling for managing the necessary transparent, artificial boundary conditions (Stone & Edelman 1995). These methods, while successful in hydrodynamics, are ineffectual in strongly magnetic cases, and early tests with our code have shown that even small magnetic boundary reflections produce a detrimental feedback mechanism to the instability. As such, we have developed our code to incorporate a new boundary handling approach that will improve upon existing results and allow for careful and explicit evaluation of boundary condition performance during tests.

4 Budget

We request funds to cover three journal publications (3 papers x 10 pages x $110/page = $3,300), and funds to cover attendance at three domestic meetings to report results (3 x $1,500/meeting = $4,500) for a total of $7,800. Indirect costs at 51% = $3,978 are also requested. The grand total is $11,778.

5 References

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6 Previous Chandra Programs

NONE

7 Biographical Sketch

Imamura, Ph.D., Indiana University, 1981.
Imamura joined the University of Oregon in 1985 where he is a member of the Physics Department faculty and the Institute of Theoretical Science. His principal research interests are accretion and radiation processes in compact X-ray binaries, binary star formation, instabilities in massive disks in star/disk systems, and gravitational wave emission during core collapse. Imamura performed pioneering work on the structure and spectra of white dwarf accretion shocks, QPO mechanisms in cataclysmic variables, and the stability properties of rapidly rotating stars.

7.1 Selected Shock Theory/Modeling Publications:

1. ”Linear Analysis of an Oscillatory Instability of Radiative Shock Waves,” Chevalier, R. A. & Imamura, J. N. 1982, *The Astrophysical Journal*, 261, 543
2. ”A Numerical Study of the Stability of Radiative Shocks,” Imamura, J. N., Wolff, M. T., & Durisen, R. H. 1984, *The Astrophysical Journal*, 276, 667
3. ”On the Stability Properties of White Dwarf Accretion Shocks,” Imamura, J. N. 1985, *The Astrophysical Journal*, 296, 128
4. ”The UV and X-ray Spectra of Accreting White Dwarfs. IV: Effects of a Two-temperature Treatment with Electron Thermal Conduction,” Imamura, J. N., Durisen, R. H., Lamb, D. Q., & Weast, G. J. 1987, *The Astrophysical Journal*, 313, 298
5. ”On the Stability Properties of White Dwarf Accretion Shocks: Settling Solutions,” Imamura, J. N., & Wolff, M. 1990, *The Astrophysical Journal*, 355, 216
6. ”Noise-Driven Radiative Shocks: A New Model for the Optical Quasi-Periodic Oscillations of the AM Herculis Objects,” Wolff, M. T., Wood, M. T., & Imamura, J. N. 1991, *The Astrophysical Journal*, 375, L53
7. ”The Optical Emission From Oscillating White Dwarf Radiative Shock Waves,” Imamura, J. N., Rashed, H., & Wolff, M. T. 1991, *The Astrophysical Journal*, 378, 665
8. ”Noise-Driven Radiative Shocks II. Further Implications for the Quasi-Periodic Oscillations of the AM Herculis Objects,” Wood, K. S., Imamura, J. N., & Wolff, M. T. 1992, *The Astrophysical Journal*, 398, 593
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11. ”The Hard X-ray Spectra of the Polars V2301 Oph, BL Hyi, and WW Hor,” Imamura, J.N., Bryson, W.C., & Steiman-Cameron 2008, *Publications of the Astronomical Society of the Pacific*, 120, in press