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AUTHOR(S): J. N. Imamura, M. T. Wolff, R. H. Durisen

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Time Dependent White Dwarf Radiative Shocks

James N. Imamura
Los Alamos National Laboratory
Michael T. Wolff
Naval Research Laboratory
and
Richard H. Durisen
Department of Astronomy, Indiana University

Abstract

We study the oscillatory instability of white dwarf radiative accretion shocks discovered by Langer, Chanmugam, and Shaviv. We extend previous works by examining spherical shocks dominated by (1) bremsstrahlung and Compton cooling, and (2) bremsstrahlung and Compton cooling when the effects of electron thermal conduction are not negligible. The results of our calculations allow us to delineate stability regimes as a function of the dwarf mass, M_*, and the accretion rate, $\dot{M}$. We parameterize $\dot{M}$ in terms of the optical depth to electron scattering through the preshock flow, τ_{es}. In the Compton cooling and bremsstrahlung case, the shocks are unstable to low order oscillation modes if $M_* \lesssim (0.7\pm0.1)\ M_O$ for $\tau_{es} = 14$, and if $M_* \lesssim (0.9\pm0.1)\ M_O$ for $\tau_{es} = 1$. When electron thermal conduction is added, low order oscillation modes are unstable only if $M_* \lesssim (0.3\pm0.1)\ M_O$. The unstable modes have approximate oscillation periods of $1.1\tau_{br}$ and $0.63\tau_{br}$, where τ_{br} is the bremsstrahlung cooling time scale of the postshock plasma. Our results can be scaled to magnetically funneled accretion flows as long as cyclotron emission contributes less than about 10% of the postshock cooling.

I. Introduction

Cataclysmic variables (CVs) are now recognized to form a large and important class of low luminosity ($L_x \lesssim 10^{34}$ ergs s^{-1}) compact, galactic x-ray sources. As a class, they are low mass, short orbital period, mass-transfer binary systems composed of a white dwarf and a late type main sequence star. The late type star is overflowing its Roche lobe, transferring plasma to the white dwarf. The energy gained by the plasma as it falls into the dwarf's gravitational potential well supplies the energy which powers the sources. For white dwarfs with weak magnetic fields, the accreting plasma forms an accretion disk as it settles onto the dwarf's surface. In this case, the x-rays are produced by the interaction of the accretion disk and the dwarf. For dwarfs which are strongly magnetic, the accreting plasma is threaded by the dwarf's magnetic field before it reaches the dwarf forcing the plasma to flow along the field lines to one or both of the dwarf's magnetic poles. The flow is highly supersonic and so, in order to merge onto the dwarf, a stand-off shock forms above the white dwarf heating the plasma to a temperature of (Kylafis and Lamb 1982)

$$kT_s \sim 64 \left(\frac{M_*}{M_O}\right) \left(\frac{5 \times 10^8 \text{ cm}}{R_*}\right) \text{ keV} \tag{1}$$

Here M_* and R_* are the dwarf mass and radius, and the effects of radiation pressure have been ignored. The shock heated plasma cools via optically thin bremsstrahlung (which produces hard x-rays), optically thick cyclotron emission (which produces UV or optical emission), and Compton scatterings with the lower temperature stellar blackbody photons as it settles onto the white dwarf. The blackbody emission is due to the bremsstrahlung and cyclotron photons which strike the dwarf and are thermalized in the dwarf's envelope. Their characteristic temperature lies in the range 10 to 50 eV. The thickness of the cooling region, d_s, is approximately the product of the postshock plasma cooling time scale, τ_{cool}, and the postshock plasma velocity. It is believed that the funneled flow case applies to the more luminous CV x-ray sources and to the pulsing system (e.g., the AM Her objects). As these types of systems are the best observed white dwarf x-ray sources, an understanding of the structures of radiative accretion shocks is clearly needed.

It has recently been suggested that coherent, short time scale (0.1 to several seconds) x-ray luminosity variations may be a common feature of the AM Her objects because of an instability of radiative shock waves discovered by Langer, Chanmugam, and Shaviv (1981, 1982, hereafter collectively referred to as LCS). LCS showed that radiative shocks are unstable under certain circumstances in the sense that if the shock front is perturbed away from its steady state equilibrium position, the subsequent motion does not damp. Rather, the shock front oscillates about an equilibrium position. For a power law cooling function of the form $\Lambda \propto \rho^2 T^\alpha$, LCS reported that if $\alpha < 1.6$ radiative shocks were unstable. However, after re-analyzing their results they revised the limit to $\alpha = 0.6$ (Langer 1985). Further studies of the oscillatory instability in the linear regime (Chevalier and Imamura 1982, hereafter CI), and in the nonlinear regime (Imamura, Wolff, and Durisen 1984, hereafter IWD) also found instability for small values of α. The CI and IWD results are in excellent quantitative agreement with each other and in reasonable agreement with LCS. CI and IWD found that there are several possible oscillation modes which they called, in order of increasing oscillation frequency, the Fundamental (F), the First Overtone (1O), the Second Overtone (2O), and so on. The lowest order modes were found to be unstable for $\alpha \lesssim 0.4$, 0.8, and 0.8 respectively. LCS isolated what appeared to be the F mode. They did not find evidence of overtone modes. This disagreement between the calculations is probably numerical in origin (see IWD). Both groups do agree, however, that when the dominant cooling mechanism is bremsstrahlung ($\alpha = 0.5$), oscillatory instabilities may be excited. In this work, we use the IWD hydrodynamics code and thus are assuming that the F mode is stable for bremsstrahlung dominated shocks.

Bremsstrahlung dominates the cooling in shocks produced by accretion onto weakly magnetic white dwarfs of mass $\lesssim 1.2\ M_\odot$. However, for dwarfs of mass $\gtrsim 1\ M_\odot$, other processes such as Compton cooling and electron thermal conduction can play nonnegligible roles in the formation of the shock structures (Kylafis and Lamb 1982, Imamura *et al.* 1985). Further, for strongly magnetic white dwarfs, cyclotron emission can dominate the cooling. Thus, an assessment of the importance of oscillatory instabilities to white dwarf radiative shocks requires the consideration of these physical processes.

Improving our understanding of this instability is important because of the value an unambiguous observation of an oscillatory instability carries. Oscillatory instabilities have periods which are functions only of the dwarf mass, the luminosity of the source, and the accretion geometry (in particular, the surface area of the emitting region). Thus, for a particular source, the observation of an oscillatory instability constrains these parameters (see also

LCS and CI). It further constrains other system parameters in that it requires upper limits on the importance of stabilizing mechanisms, like electron conduction, Compton cooling, and cyclotron emission.

In this work, the stability properties of radiative shocks produced by spherical accretion onto nonmagnetic white dwarfs, as a function of the dwarf mass, M_*, and the accretion rate, $\dot{M}$, are studied, particularly, the effects of electron thermal conduction (ETC), relativistically correct bremsstrahlung, and Compton cooling on the structure of white dwarf accretion shocks. We note that spherically symmetric, nonmagnetic white dwarf calculations are relevant to the strongly magnetic AM Her systems because (1) accretion shock structures with parameters appropriate to the AM Her objects have shock thicknesses which are no more than 10-30% of R_*, and so geometric effects are usually negligible, and (2) from observations and theoretical inferences, it is believed that the shocks in the AM Her systems are dominated by bremsstrahlung, not by cyclotron emission.

The rest of this paper is organized as follows. In Section II, the results of our linear and nonlinear analyses of shocks with power law cooling functions are presented. In Section III, the results of our nonlinear calculations of white dwarf radiative shocks are presented and the implications of all of our results for the AM Her objects are discussed. In Section IV, our principal conclusions are summarized.

II. White Dwarf Radiative Shocks

a) Numerical Techniques

We calculated time-dependent shock structures produced by spherical accretion of plasma onto nonmagnetic white dwarfs of masses ranging from 0.2 to 1.0 $M_\odot$ and accretion rates such that the optical depth of the preshock flow to electron scattering, τ_{es}, ranges from 1 to 14. Here the optical depth to electron scattering is taken to be

$$\tau_{es} = 82 \left(\frac{M_\odot}{M_*}\right)^{0.5} \left(\frac{L_{acc}}{L_E}\right)\left(1-\frac{L_{acc}}{L_E}\right)^{-0.5} \left(\frac{R_*}{5\times10^{8}\ \mathrm{cm}}\right)^{0.5} \quad (2)$$

where we have taken the plasma to have a composition of $X = 0.7$ and $Y = 0.3$, L_{acc} is the accretion luminosity, L_E ($= 1.48 \times 10^{38}$ $[M_*/M_\odot]$ ergs s^{-1}) is the Eddington luminosity, and the term $(1-L_{acc}/L_E)$ is included to take account of the effects of radiation pressure on the preshock flow (Kylafis and Lamb 1982). We used one-temperature hydrodynamics equations which included ETC, Compton cooling, and relativistic corrections to the bremsstrahlung rate. The equations and the manner in which they were solved, and the various rate coefficients we used are given in IWD and Imamura (1985).

The Compton cooling rate used in the calculations was taken to be proportional to $U_\gamma \rho T$, where U_γ, the radiation energy density, is given by

$$U_\gamma = \chi \left(\frac{f_{bb} L_{acc}}{4\pi r^2 c}\right) . \tag{3}$$

Here χ is determined by the geometry of the radiation field, $f_{bb} = L_{bb}/L_{acc}$, and L_{bb} is the blackbody luminosity. The values of f_{bb} and χ we used were taken from Tables 2 and 4 of Kylafis and Lamb (1982).

b) Instability Regimes and X-ray Light Curves

For the Compton cooling and bremsstrahlung case, white dwarf accretion shocks are unstable to 10 and 20 mode oscillations if $M_* \lesssim (0.7\pm0.1)\ M_\odot$ for $\tau_{es} = 14$ and if $M_* \lesssim (0.9\pm0.1)\ M_\odot$ for $\tau_{es} = 1$. For the stable model of $0.8\ M_\odot$, $\tau_{es} = 14$, and the unstable model of $0.6\ M_\odot$, $\tau_{es} = 14$, the ratios of the average Compton cooling losses to the average bremsstrahlung losses are 0.40 and 0.19, respectively. These ratios increase as M_* and/or τ_{es} increase.

For the case where ETC, Compton cooling, and bremsstrahlung are all included, white dwarf accretion shocks are unstable to 10 mode oscillations for $M_* < (0.3\pm0.1)\ M_\odot$ for all of the τ_{es} we consider. We note that, for $M_* < 0.3\ M_\odot$, $kT_s < 8$ keV, and thus such objects are not likely to be strong hard x-ray sources. For the stable model $M_* = 0.4\ M_\odot$, $\tau_{es} = 1$, and the unstable model $M_* = 0.2\ M_\odot$, $\tau_{es} = 1$, the ratios of the average Compton cooling losses to the average bremsstrahlung losses are 0.0088 and 0.0012, and the ratios of the characteristic bremsstrahlung cooling time scale,

$$\tau_{br} = \frac{\rho_s I_s}{\Lambda_{br}} = 0.012 \left(\frac{M_*}{M_\odot}\right)\left(\frac{L_E}{L_{acc}}\right)\left(1-\frac{L_{acc}}{L_E}\right) \text{ seconds} , \tag{4}$$

to the characteristic ETC time scale,

$$\tau_c = \frac{\rho_s I_s}{|\nabla\cdot q|} = 0.032\left(\frac{L_E}{L_{acc}}\right)\left(\frac{R_*}{5\times10^8\,\text{cm}}\right) \text{ seconds} , \tag{5}$$

are 0.026 and 0.069. Here ρ_s and I_s are the postshock density and specific internal energy, and Λ_{br} is the nonrelativistic bremsstrahlung cooling rate evaluated at the shock. The assumptions implicit in these definitions of τ_{br} and τ_c are presented in Kylafis and Lamb (1982). The ratio τ_{br}/τ_c increases as M_* increases.

The 10 and 20 modes are stabilized primarily by the effects of ETC. Because of the dissipative nature of ETC flux ($\propto T^{2.5}\nabla T$), it tends to smear out temperature variations and thus is particularly effective at damping out high-order modes. The effects of ETC increase as the dwarf mass increases.

The x-ray light curve of the $M_* = 0.6\ M_\odot$, $\tau_{es} = 14$ Compton cooling and bremsstrahlung model is presented in Figure 1a. The light curve luminosities are in units of 10^{36} ergs s^{-1} and the times are in units of seconds. The quantity $(L_{max}-L_{min})/0.5(L_{max}+L_{min})$ for this model is 0.28. This is typical of the fractional luminosity variations that we find. The power spectrum of the x-ray light curve shown in Figure 1a is given in Figure 1b. The Fourier powers are normalized such that the average power is 1 and the frequencies are in units of Hz. The large peak at 6.6 Hz is due to the damping F mode. If the power spectrum of only the second half of the light curve is taken, this feature does not appear.

The oscillation periods of the low order modes for various M_* and τ_{es} as functions of τ_{br}, are generally well approximated by the relations $\tau_F = 3.1\tau_{br}$, $\tau_{1O} = 1.1\tau_{br}$, and $\tau_{2O} = 0.63\tau_{br}$ found by the linear analysis of CI for a cooling function $\Lambda \propto \rho^2 T^{0.5}$, i.e., bremsstrahlung. At large τ_{es} the oscillation periods are systematically smaller than the values predicted by the linear analysis, however. This is due to the effects of Compton cooling. Compton cooling shortens the postshock plasma cooling time scale and thus shortens τ_{osc}. This effect lowers τ_{osc} by $\lesssim 20\%$.

c) Observational Implications

When considering funneled accretion onto magnetic white dwarfs several points need to be kept in mind. (1) The quantity (L_{acc}/L_E) in the τ_{br} expression (Eq. [4]) should be replaced by (L_{acc}/fL_E), where f is the fraction of the dwarf's surface area covered by the accretion funnel. This modification is necessary because τ_{br} is primarily determined by the density in the postshock region which is determined by the accretion rate per square centimeter, not simply by the magnitude of the accretion rate. (2) The radiation pressure term $(1-L_{acc}/L_E)$ in the τ_{br} expression may usually be ignored, because in funneled accretion flows the effects of radiation pressure are small except under extreme conditions (Imamura and Durisen 1983). (3) For funneled accretion, the stability limit for the bremsstrahlung/Compton cooling case, in terms of the white dwarf mass, is probably close to the limit found by the $\tau_{es} = 1$ calculations independent of the τ_{es} considered, because the relative importance of Compton cooling to bremsstrahlung is determined by the mass of the accreting white dwarf and the quantity $(f_{bb}\chi)$. For optically thin flows, $(f_{bb}\chi) \sim 1$ regardless of the geometry, while for optically thick flows, the value of $(f_{bb}\chi)$ depends on the geometry of the flow. In funneled accretion flows, $(f_{bb}\chi)$ increases more slowly with τ_{es} than it does in spherical accretion flows. This lessens the effects of Compton cooling on the shock structures as τ_{es} increases (Imamura and Durisen 1983). (4) The stability limit for the ETC and bremsstrahlung/Compton cooling case is not affected by the difference in geometry.

The best energy band in which to search for shock oscillations is the x ray. Unfortunately, only the x-ray emission from AM Her has been searched on the appropriate time scales. The analysis of the HEAO-A1 soft x-ray (0.15-0.5 keV) data (Tuohy et al. 1981) and HEAO-A2 hard x-ray (0.5-20 keV) data (Imamura et al. 1985) has shown that there are no large amplitude coherent periodicities lasting over the duration of the observations. Other AM Her sources need to be analyzed. In the optical, two out of the ten AM Her objects (AN UMa and E1405-451) show short time scale (0.4 to 1 Hz) features (Middleditch 1982, Mason *et al.* 1983, Larsson 1985, Imamura and Steiman-Cameron 1985). AN UMa and E1405-451 are variable at levels of about 2.4% and 1.2% r.m.s., respectively. An unambiguous interpretation of the optical results is difficult, however, because the optical emission may not be due to cyclotron emission produced in the shocked plasma. It may be cyclotron emission produced higher up in the accretion flow. Temporal studies of the x-ray emission from these sources should help to decide whether the optical variations are physically related to shock instabilities.

IV. Summary

We have determined the stability regimes for white dwarf radiative shock waves when cyclotron cooling is relatively unimportant ($\lesssim$10%). Such shocks are thought to apply to the AM Her systems. We find that spherical white dwarf radiative shocks (1) are unstable to 10 and 20 mode oscillations if $M_* < (0.7 \pm 0.1)\, M_\odot$, for $\tau_{es} = 14$, and if $M_* \lesssim (0.9 \pm 0.1)\, M_\odot$ for $\tau_{es} = 1$ when Compton cooling and bremsstrahlung are considered, and (2) are unstable to 10 mode oscillations if $M_* < (0.3 \pm 0.1)\, M_\odot$, for all τ_{es} considered when electron thermal conduction is included.

The oscillation periods of the unstable modes are $\tau_{10} \simeq 1.1 \tau_{br}$ and $\tau_{20} \simeq 0.63 \tau_{br}$. For small τ_{osc}, the effects of Compton cooling shorten τ_{osc} when compared to these relations. The dependence of the periods on τ_{br} (Eq. [4]) is important because it shows that if the area of the emitting region and L_{acc} can be deduced and an oscillatory instability observed, the mass of the accreting white dwarf can be inferred.

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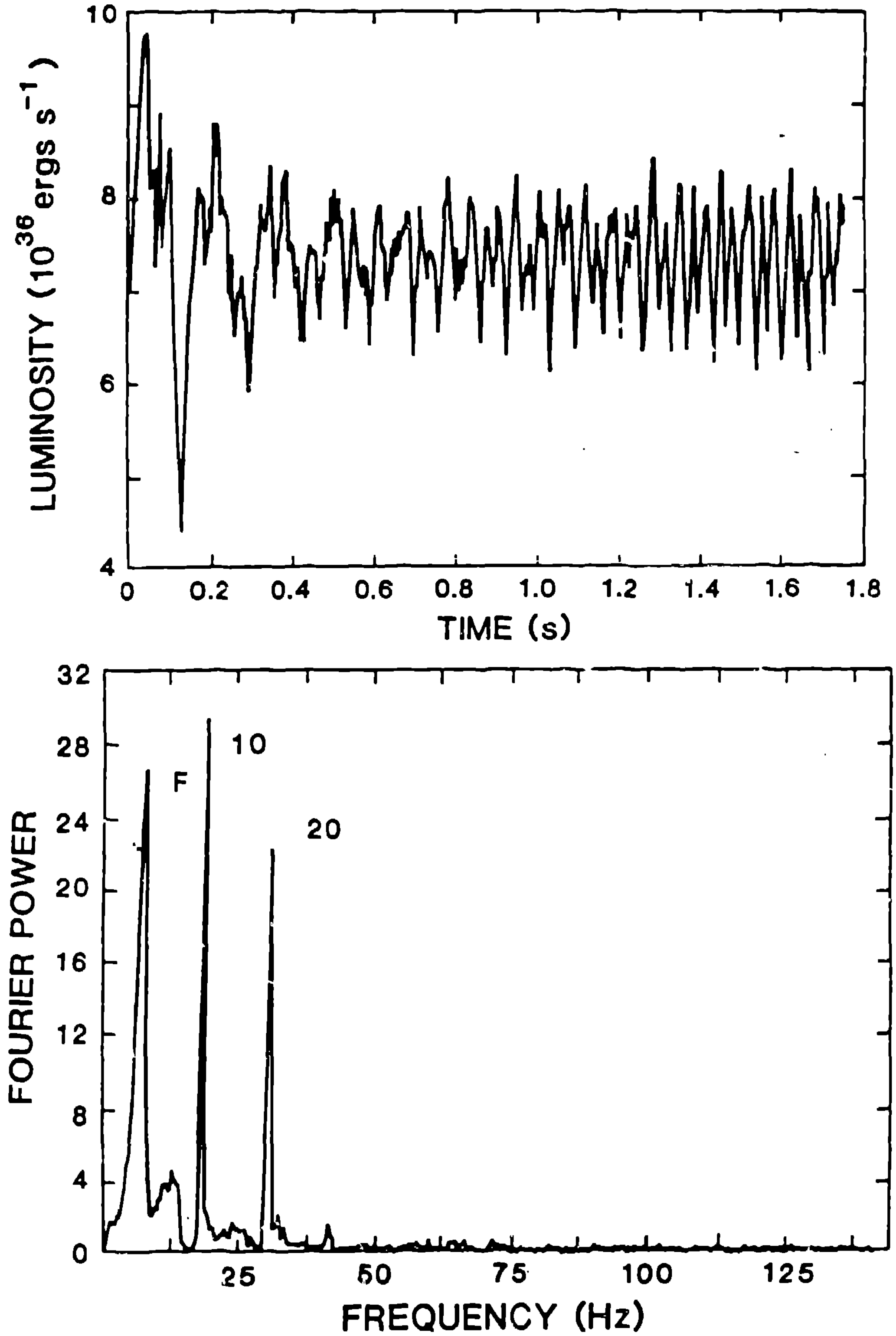

Figure 1: (a) The x-ray light curve of the $M_* = 0.6\ M_\odot$, $\tau_{es} = 14$ model. (b) The power spectrum of the light curve in Figure 1a. The F marks the fundamental mode, the 10 marks the first overtone, and the 20 marks the second overtone.