TIME DEPENDENCE IN ACCRETION ONTO MAGNETIC WHITE DWARFS

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I. INTRODUCTION

In this talk we consider cataclysmic variable systems containing a white dwarf with a strong magnetic field. These include systems like AM Her (see, e.g., Chiappetti, Tanzi, and Treves 1981) in which the white dwarf rotates at the orbital period and systems such as AE Aquari in which the white dwarf rotates much faster than synchronously (see Patterson et al. 1980). The magnetic field in all of these systems is strong enough to disrupt the accretion disk at a point far above the surface of the white dwarf and may prevent the formation of a disk altogether. We will present theoretical models for the temperature, density, and velocity structure of the accretion flow in the region near the surface of the white dwarf where the kinetic energy of the flow is thermalized and radiated in the form of X-rays and ultraviolet radiation. This information is required to calculate accurate model spectra, and the results also have immediate consequences for the interpretation of observations.

The flow is characterized by a strong standoff shock that forms in the accretion column and thermalizes the kinetic energy of the infalling material. Below the shock, the hot gas cools by radiating and then settles onto the white dwarf. In an earlier paper (Langer, Chanmugam, and Shaviv 1981), we showed that the postshock flow is thermally unstable. This instability leads to periodic oscillations in the height of the standoff shock, and in the luminosity and the spectral temperature of the X-rays. We have recently studied the effects of varying the system parameters on the properties of the oscillation (Langer, Chanmugam, and Shaviv 1982).

Our model includes the effects of the gravitational field, heat

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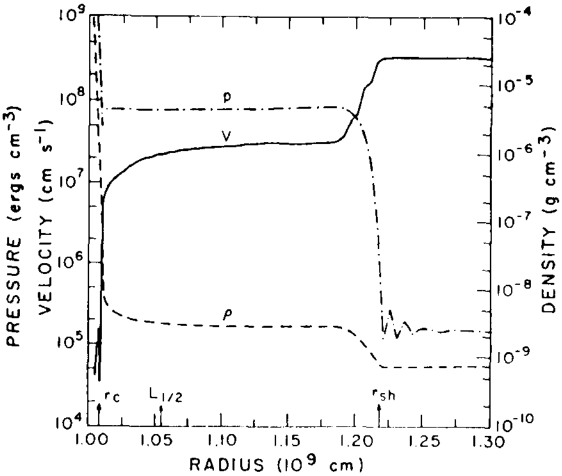
conduction, and radiative cooling by bremsstrahlung radiation. We ignore, for now, the effects of electron cyclotron line radiation (see, e.g., Chanmugam and Wagner 1979), Compton scattering, nuclear burning of the accreted matter, non-hydrodynamic flow (see King 1983), and possible differences between the electron and ion temperatures. We solve the three time-dependent, non-linear differential equations for the transport of mass, momentum, and energy numerically, using an implicit, finite-difference method. We obtain the solution on a discrete grid of radius points and follow its evolution with time. At the upper boundary of our grid, the matter is cool and in free fall. At the lower boundary, which is placed well inside the photosphere of the white dwarf, the mass flux is zero. The models start with a smooth, but arbitrary, initial density, temperature and velocity profile.

II. RESULTS

The models have as free parameters the mass, M, and radius, R, of the white dwarf, the accretion rate, $\dot{M}$, and the area on the surface of the white dwarf over which accretion occurs, A. In figure 1 we plot the pressure, velocity, and density as functions of the height above the surface of the white dwarf for a model in which $M = M_\odot$, $R = 10^9$ cm, $\dot{M} = 2.5 \times 10^{15}$ g s^{-1}, and $A = 10^{16}$ cm^2. The shock is located at r = 1.22R; it has been spread across several mesh points by the artificial viscosity in the numerical model. The sharp jump in the density and pressure at r = 1.01R marks the point where the accreting matter rapidly cools to the photospheric temperature and the hydrostatic, isothermal atmosphere of the white dwarf begins. The radiative cooling is cutoff at the photospheric temperature to simulate the approach to LTE. Figure 2 shows the shock height for the same model as a function of time. The first cycle is affected by the initial conditions, but after that the shock height undergoes a periodic limit cycle with repetitive properties and no indication of damping. The shock height ranges from just above the photosphere to a value somewhat less than twice the shock height found by solving the static flow equations. The results may be understood by noting that on dimensional grounds the shock height is roughly the product of the radiative cooling time of the postshock gas and the postshock velocity, while the period is a few times the radiative cooling time.

The results for this particular model are quite interesting, and have led us to examine the behavior of the limit cycle as a function of the system parameters. For the models we have considered, the cooling is dominated by bremsstrahlung and heat conduction is unimportant. Under these conditions the solutions of the dimensionless hydrodynamic equations depend on a single parameter, which is a combination of M, R, $\dot{M}$, and A. In figure 3 the maximum shock height during the cycle and the period of the limit cycle are shown as functions of this parameter. The points are taken from models with a variety of white dwarf masses and radii, and with a range of mass accretion rates. The points all lie on a single curve, as the equations predict.



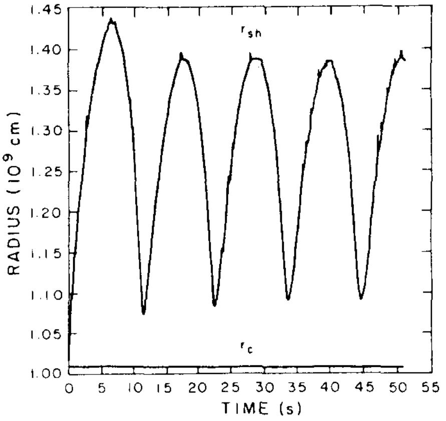


Fig. 1: The density, pressure and velocity as functions of radius for $M = 0.5\ M_\odot$, $R = 10^9$ cm, $\dot{M} = 2.5 \times 10^{15}$ g s^{-1} and $A = 10^{16}$ cm^2. Half of the accretion luminosity is radiated above the point marked $L_{1/2}$.

Fig. 2: The shock height, r_{sh}, and the photospheric radius, r_c, as functions of time for the model of Figure 1.

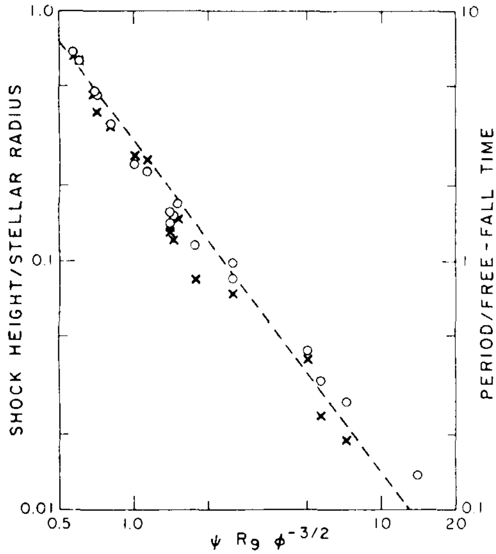


Fig. 3: The shock height in units of R and the period in units of the free-fall time are shown as functions of $(\dot{M}/A)\ R\ (M/R)^{-3/2}$ in dimensionless units. The scatter in the points is due to numerical uncertainty. [Figures taken from the Astrophysical Journal 258, 289 (1982).]

III. DISCUSSION

The accretion flow is characterized by a stand-off shock with a region dominated by radiative cooling below it. The shock height tries to adjust itself so that the flow time from the shock to the surface is equal to the time required to cool from the postshock temperature to the photospheric temperature. The cooling gas exhibits a thermal instability which instead forces the shock to move in a periodic limit cycle. The varying amount of hot material between the shock and the photosphere leads to a periodically varying X-ray luminosity. Because there is a range of gas temperatures behind the shock at any one time, the X-ray spectrum is not a pure thermal bremsstrahlung spectrum. There are thus several potentially observable effects in the X-rays from the system. In a real system the behavior is apt to be more complicated than indicated for several reasons. The matter probably becomes attached to the magnetic field lines in a non-uniform manner so that the mass flux varies across the accretion column. The flow is only weakly coupled across magnetic field lines, so the accretion column should consist of several independent flux tubes, each with its own mass flux. The resulting X-ray flux will not be strictly periodic, but there should be a bump in its power spectrum at the frequency corresponding to the average mass flux.

The hard X-ray flux from these systems is so weak that it is difficult to detect variability at periods on the order of one second. However, the same variations will also occur in any other radiation emitted in the accretion column and in any radiation resulting from the reprocessing of radiation emitted in the column. This suggests that it might be interesting to examine not only X-ray data, but also optical radiation for evidence of this oscillation. This has been done for AN UMa, E1405-451, and AM Her (Middleditch 1982). Both E1405-451 and AN UMa show a bump in their power spectrum at a period of about 1.7 seconds. The data for AM Her failed to reveal any evidence for periodicity near this period. Our model predicts periods that are of the order of one second for reasonable accretion rates and polar cap areas, in agreement with these observations.

We have recently run a few models which include electron cyclotron line emission. If the magnetic field is strong enough, or the accretion rate is low enough, the cyclotron lines dominate the radiative cooling, and the flow becomes stable. The characteristic magnetic field at which the flow stabilizes is roughly 2×10^7 Gauss. This is comparable to the values measured for AM Her (Schmidt, Stockman, and Margon 1981) and VV Pup (Visvanathan and Wickramasinghe, 1979). This suggests that some of the AM Her systems will exhibit oscillations and others will not, depending on the magnetic field. In addition, it is possible that the oscillations will appear and disappear in a single system as the accretion rate varies. It should be emphasized that the results on the cyclotron cooling are preliminary, and that the identification of the feature in the power spectrum with the limit cycle must still be confirmed. However, the study of these features can provide new information about the AM Her system and seems worthy of further effort, both observationally and theoretically.

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DISCUSSION FOLLOWING S. LANGER'S TALK

KING: I have a question about your lower boundary condition, you have a sort of box there, that the matter falls into, it is not allowed to go into the star, does that not mean that your whole structure gradually rises out of the star as matter piles up?

LANGER: Yes, it is true that it would rise upward, but if you look at the specific volume of material at the temperature where we cut it off, at a few 10^5°K, it is pretty small and it goes nowhere. As a matter of fact, you can see that the photospheric radius in the curve is not doing anything discernible on the timescale of this calculation.

KING: Have you tried playing around with that boundary condition to see if it effects your results?

LANGER: We have not played with the boundary condition, but I can't possibly see how it could, the boundary is buried deep inside by far more matter than the accreting mass can in anyway influence, we can see that we are not getting any response to those oscillations down at the point where we cut it off.

KING: But the point I am driving at is that you have not really matched that flow to the atmosphere of the white dwarf.

LANGER: We have not matched that flow to the white dwarf only because we have taken a rather faky means of handling optical thickness effects at the cut off. That was a computational decision.

KING: This instabilities you are talking about are global in nature, so it is very important that your boundary condition is really the physical one.

LANGER: There is one thing I can say on that, it is a comparison between two numerical solutions, neither of which is entirely physical. In the first paper which we had in Ap. J. Letters over a year ago, we had a different treatment for what happened when the matter got too cool to cope with the cooling time. In that case, the periods and the shock heights that we got, are consistent within the numerical noise with what we get now with this entirely different treatment.

KING: You get the same period because that is the cooling time, I don't think that is telling you anything, I think you are going to get that regardless of what you did at the bottom.

LANGER: There is no requirement that I know of that requires the thing to oscillate and that is what we are interested in, is there some physical process that would damp the oscillations. It is hard to see how you can do that at the photosphere, where you don't have the energy to do anything to what is up at the shock.

LAMB: John Middleditch's data is optical data whereas what you are talking about here are X-ray oscillations. Reprocessing of the hard and/or soft X-rays would therefore be necessary. Tuohy, Lamb, Garmire and Mason (1978) do discuss quasi-periodicities in the soft X-ray flux, but at a few tenths of a second, but to my knowledge those oscillations were not detected in the hard X-ray component. The number of counts in the hard X-rays is much smaller than in the soft X-rays and therefore it may be that if the amplitude is small, it would be below detector threshold. Also, it seems premature to be sure that these kinds of oscillations can take place for two reasons, besides the possible stabilizing effect of cyclotron emission in a strong field. One is that the region right below the shock, whether you have nuclear burning or not, is going to be predominantly cooled by Compton cooling from the photospheric black body flux. Such cooling depends only on the electron density in the column and is greater if the electron temperature is higher. I would be surprised if this does not have a stabilizing influence on the structure. The second point is that conduction transfers energy from just below the shock to further down, and again I would intuitively expect that this would have a stabilizing influence on the shock.

LANGER: We have included the standard $K\frac{dT}{dr}$ type heat flux in our equations in the latest runs, when we revised cooling law, we did not have it in the earlier ones. We did not see any difference, we did not see it damping out, the heat flux never got to be a large fraction of the accretion luminosity for the models that we considered. If you had a shock that was very close to the surface, perhaps that would break down.

LAMB: But these calculations are only one fluid calculations and the effect of the conductivity within the emission region is completely different if you actually allow the conductivity to be treated in a two fluid situation.

LANGER: Which requires that you have, say, Compton cooling to cause a difference between the electron and ion temperatures. In some situations where Compton cooling was very important, the electron and ion temperatures were different, I cannot claim that this works, I do not know what happens then.

LAMB: What about just the Compton cooling from the black body flux itself?

LANGER: If we had put in the observed black body flux in AM Her, I think that would have been enough to do something. Depending upon the shock height and the geometry we would have had different optical depths and it would depend upon the optical depth to Compton scattering. We have not included that strong black body component, we want to put it in.

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