THE ENERGY DISTRIBUTIONS OF MAGNETIC VARIABLES: THE EFFECTS OF INHOMOGENEOUS ACCRETION COLUMNS

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ABSTRACT. Previous shock models for the AM Herculis-type magnetic variables have assumed homogeneous accretion columns, with constant infall densities out to a characteristic column radius. The resulting energy distributions are strongly peaked in the visible to ultraviolet and are in disagreement with observations. We report the preliminary results of calculations with more general radial functions of the infall density. Exponential and gaussian profiles yield continua similar to those of the standard model. More tapered, power-law profiles produce continua which are flatter and in better agreement with observations. Comparisons are made to data for AM Her and E2003+225.

1. INTRODUCTION

For the AM Her-like systems, which show strong, circularly polarised optical light and Zeeman-shifted hydrogen absorption features appropriate for field strengths of 20-30 megagauss(MG), the Lamb and Masters (1979) shock model (hereafter LM) succeeds in qualitatively explaining the observed soft and hard X-ray continua (Lamb 1985.) However, the model disagrees with observation in predicting a blue optical continuum peaking between 2000-4000Å and falling rapidly into the ultraviolet. Instead, the sources typically peak in the mid-visible to near-infrared and, in AM Her and other sources, have equally strong components in the 1200-2000Å band. This disagreement, which has never been successfully explained, led us to explore the consequences of tapered, inhomogeneous accretion profiles. Basically, we expect that the use of more realistic flow models would lead to large regions of near-IR emitting shocks and cooler UV-emitting photosheres surrounding a small hard and soft-X-ray emitting core (Liebert and Stockman 1985; Schmidt, Stockman, and Grandi 1986.)

2. MODEL CALCULATIONS

The model we have developed is similar to the LM model. No detailed hydrodynamic calculations are performed and the local shock

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characteristics are assumed constant along a given streamline. Continuity equations in mass, energy, and pressure provide the essential ingredients to define the shock. Like LM, we permit the electron temperature (TE) and the ion temperature (TI) to be determined by the standard collision theory. The radiation rates are given by the usual bremsstrahlung formulae, and the cyclotron opacities are those of Dulk and Marsh (1982). Numerical experiments show that cyclotron fluxes calculated for 45° rays produce reasonable agreement with fully angle-averaged fluxes.

One significant departure from the LM model was our treatment of the shocks at low accretion rates where LM found non-hydrodynamic solutions which were not self-supporting. In our model, the incoming ions can interpenetrate the shock and heat both ions and electrons. For this low accretion rate regime, the results are higher compression ratios, lower shock heights, and lower ion temperatures than previously obtained. Electron temperatures and the actual cyclotron fluxes are set by the shock luminosity balancing the accretion luminosity and are essentially unaffected.

For a given accretion profile, the shock for each streamline is calculated separately. The only coupling between streamlines is in the radiation equation where we adopt a characteristic length defined by the shock height and the axial rate of change of the accretion luminosity (dr = l * dr/dl). Here r is the radial distance from the central accretion axis and l is the local accretion luminosity per unit area. This simulates more efficient cyclotron radiation through the sides of a tall column. In practice, this constrains the shock height to values near or below the characteristic radial length scale. Full 3-D ray tracing of typical shocks has shown that this treatment is qualitatively correct.

3. MODEL RESULTS

We have run models for axially symmetric flows with gaussian, exponential, and power-law profiles where the local area accretion luminosity is given by l(r) = f(r). These functions are normalized to produce the correct luminosity, L, and the overall <L/f> value is given by the luminosity-averaged local L/f. In Figure 1, we show the resulting total spectra for a rough fit to the active state of AM Her (Liebert and Stockman 1985): L = 10^{33} ergs/s ; <L/f> = 10^{38} ergs/s ; M = 0.8 $M_{\odot}$; B = 20 MG. The gaussian and exponential profiles produce spectra essentially identical to those from the homogeneous LM model: three well defined spectral shapes in the optical, soft X-ray and hard X-ray regions. The power-law profile, l(r) α $1/(1+r^2)$, produces a somewhat lower, flatter hard X-ray spectrum, a much flatter UV-soft X-ray spectrum, and a red optical continuum.

Figure 2 shows the shock characteristics versus radial distance for the power-law profile. The upper panel shows the decoupling of the ion and electron temperatures and the dropping of the ion temperature in the interpenetrating regime, which is also reflected in the post-shock velocity in the second panel. The third panel down indicates a growing shock height as the accretion rate falls, while the fourth

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panel displays the cumulative X-ray and cyclotron luminosity (half of which is absorbed by the stellar photosphere). The next to last panel indicates the local peak cyclotron wavelength increasing as the local accretion luminosity (sixth panel) falls. We arbitrarily truncated the power-law profile at one/half the stellar radius.

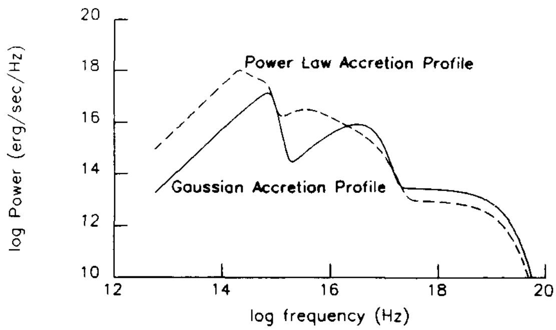

Figure 1: AM Her predicted energy distributions

4. COMPARISONS WITH OBSERVATIONS

We find much better agreement between the spectrum predicted by the quadratic power-law accretion profile and the observed AM Her spectrum than with the standard LM model. In particular, the optical spectrum has the correct slope and approximate amplitude. Below 4500Å the cyclotron spectrum falls sharply, perhaps corresponding to the observed decrease in circular polarization. The predicted ultraviolet/optical flux ratio is an order of magnitude lower than observed but this is partially due to the truncated profile, the angle-averaging, and the lack of any Balmer continuum. Certainly, the slope of the UV spectrum below 1000Å which is due to the r^{-2} power-law, is encouraging. We note that the predicted optical/X-ray flux ratio is too high for AM Her but that this can be adjusted by slightly decreasing either the white dwarf mass or the magnetic field strength.

We have also fit the integrated spectrum of E2003+225 presented in Osborne et al. (1986). Like AM Her, E2003+225 requires a r^{-2} accretion profile to fit the optical continuum. Unlike AM Her, E2003+225 has more cyclotron flux than hard X-ray flux. This affects the choice of white dwarf mass and <L/f>. In Figure 3, we show fits to the E2003+225 energy distribution with the following models: a) $M = 0.4\ M_\odot$ $\langle L/f\rangle = 10^{36}$ ergs/s; b) $M = 0.6\ M_\odot$ $\langle L/f\rangle = 10^{37}$ ergs/s; and c) $M = 0.6\ M_\odot$ $\langle L/f\rangle = 10^{37}$ ergs/s. All models assumed a field of 30 MG, a distance of 150 pc, and a total luminosity of $2.5\ \times 10^{32}$ ergs/s. Once again, the optical continuum is approximately correct and the UV is lower than observed. Slight adjustments to the major parameters could improve the fit but the qualitative agreement is consistent with the simplicity of our approach.

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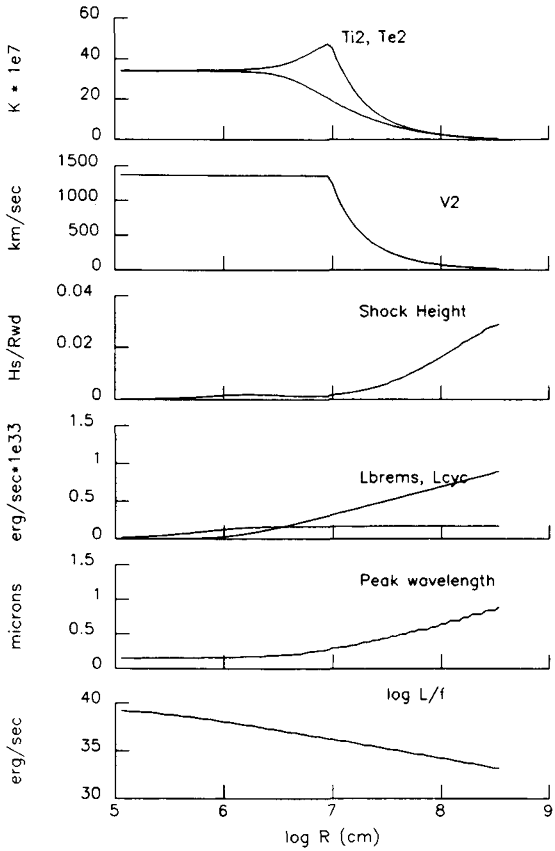

Figure 2: Shock parameters for AM Her power-law model

5. CONCLUSIONS AND FUTURE WORK

The preliminary results of our more generalized shock model and the power-law accretion profiles in particular can best explain the observed optical continua in most AM Her-like magnetic variables. The shape of the predicted UV continua shortward of 1000Å strongly suggests that the observed UV flux seen in the IUE bandpasses is due to photospheric radiation from most of the surface of the white dwarf. If this is the case, this UV flux should show only weak variations with the rotation period and no sharp eclipses. The predicted peaks in the near-IR flux are strongly dependent on the actual edge of the accretion column and the physics of low-density accretion shocks. A separate study of this regime indicates that a transition to low-temperature photospheric cooling is possible and that the observed peak will depend sensitively on the nature of this transition. Both the power-law accretion profiles and the likely UV radiation from the whole white dwarf strongly suggest that the upstream threading process is more complicated than the current "splash" picture. In particular, much of the infalling material must become fully threaded close to the white dwarf. Whether this is due to the accretion stream penetrating deep into the magnetosphere or perhaps a cascade of falling "rain" from the splash region is unclear. Whichever is the case, our understanding of the lower-field, "Intermediate Polars" will be profoundly affected.

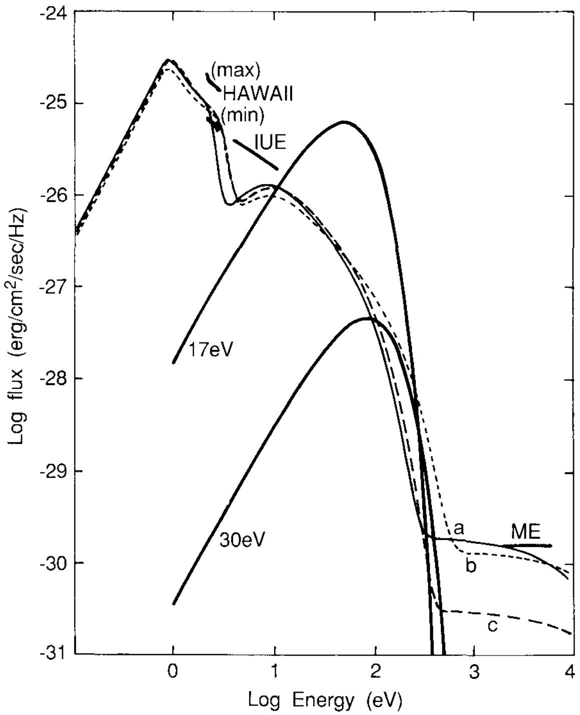

Figure 3: Predicted versus observed spectra for E2003+225

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