SPECTRAL MODELS OF AM HER STARS

S.H. LANGER
Lawrence Livermore National Laboratory, University of California, Livermore, California, U.S.A.

Abstract
Most of the optical light from AM Her systems is cyclotron radiation. Simple models for the spectrum and polarization are successful for some systems, but in others the spectrum rolls over more gently at high frequencies and is polarized over a wider range of frequencies than the models predict. This paper considers the emission from both the sides and top of the accretion column and the effects of oscillations in the shock height. These features lead to a slower roll over at high frequencies than is found in the simple models, but it is still not as flat as in some of the AM Her systems.

I. Introduction

The cataclysmic variables are close binary systems in which mass is transferred from a red dwarf secondary to a white dwarf primary. The AM Her systems are CV's in which the magnetic field of the white dwarf is so strong that it prevents the formation of an accretion disk and forces the accreting matter to follow magnetic field lines to the polar cap of the white dwarf (see Chiappetti, Tanzi, and Treves 1980 for a review of these systems). The accreting matter is nearly in free fall until it passes through a standoff shock located somewhat above the surface of the white dwarf. The shock heats the gas to temperatures of order 10^8 K. The gas then cools by emitting hard X-rays and electron cyclotron radiation and settles onto the photosphere.

The AM Her systems are relatively easy to observe optically, and quite a bit is known about the spectrum, polarization, and time dependence of the optical emission. The hard X-rays, which provide the most direct signature of 10^8 K gas, are harder to observe because they are relatively faint. This problem is made even worse by the current lack of X-ray satellites. Thus, in the next few years, most advances in understanding these systems will come from comparisons of the data and models of the optical emission. This paper presents a calculation of the optical spectrum, compares it to observations, and discusses some of the effects that have been ignored in the model.

Paper presented at the IAU Colloquium No. 93 on 'Cataclysmic Variables. Recent Multi-Frequency Observations and Theoretical Developments', held at Dr. Remeis-Sternwarte Bamberg, F.R.G., 16–19 June, 1986.

Astrophysics and Space Science **131** (1987) 577–581.

II. The Model

The cyclotron emission dominates the optical light from the AM Her systems, but a serious model should include all sources of light in the system. The red dwarf and the white dwarf both radiate optical light, and both components have been seen when the systems are in a low state (Szkody, Raymond, and Capps 1982 and Liebert et al. 1982). The portion of the white dwarf photosphere at the polar caps is heated to soft X-ray temperatures by absorbing radiation from the hot postshock gas above. The optical light from this region will be significant only if the white dwarf is cool and the cyclotron emission is weak. The accretion stream between the two stars is a source of emission lines, but not of continuum light (Schneider and Young 1980). The models for X-ray heated gas presented by Kallman and McCray (1982) can be used to show that the gas just above the shock is highly ionized and has a temperature of roughly 10^6 K. This gas will not emit a significant amount of optical continuum radiation. These sources of light are easy to model (e.g. as blackbodies), but they introduce additional system parameters.

The most important task is modelling the cyclotron emission. The simplest model for the accretion flow assumes that the mass flux is uniform across the polar cap, that the electrons and ions have the same temperature, and that the radiative cooling is dominated by hard X-rays. If these assumptions are met, the emitting region will be a 'pillbox' of hot gas whose properties depend only on the distance from the shock (the top of the pillbox).

The cyclotron emission can be calculated by using the full energy, angle, and polarization dependent opacity (see, e.g., Dulk 1985) and directly solving the equation of radiative transfer. The first models of this type calculated the flux from the top of a uniform slab of hot gas that is perpendicular to the magnetic field (see Chanmugam and Wagner 1979 and Lamb and Masters 1979). In this paper the emission from both the sides and the top will be calculated. This calculation can be greatly simplified by treating the top and sides separately and ignoring the effects of the edges. This means that the flux from the top is set to the flux from a slab with a thickness equal to the shock height and the flux from the sides is set to the flux from an infinite cylinder parallel to the B-field that has a radius equal to the polar cap radius. The emitted spectrum in any direction is then calculated by multiplying the two fluxes by the projected area of the top and sides of the column and summing. This approximation will introduce errors only near the frequency where the column starts to be optically thin, and should not be a serious problem. The entire pillbox is assumed to be at the shock temperature. Tests have shown that this gives results similar to those obtained with a temperature distribution taken from a full flow solution, because most of the emission comes from the hottest gas.

The basic properties of the cyclotron radiation follow directly from the behavior of the opacity. The cyclotron opacity drops rapidly as frequency increases, is smallest along the magnetic field, and depends on the polarization. As a result of the steep frequency dependence, the cyclotron spectrum follows a Rayleigh-Jeans law up to some frequency ν^* and then rapidly drops to zero. The value of ν^* is a function of the viewing angle relative to the magnetic field, which means that the cyclotron radiation will be a function of orbital phase. The cyclotron emission also shows strong circular and linear polarization at some frequencies and angles.

The observed optical spectrum in some systems is steeply decreasing, while in others it may be as flat as ν^{-1}. (Schmidt, Stockman, and Grandi 1986). In most systems the strong circular polarization extends over most of the optical band. The simple model described above always predicts a steep rollover and strong polarization over only a narrow range of frequencies. It is easy to show that any model in which the peak temperature is the same over the whole accretion column will have the above properties, so it is necessary to consider some additional effect that introduces a range of temperatures.

One such effect is the radiative instability first discovered by Langer, Chanmugam, and Shaviv (1981,1982, hereafter LCS) in theoretical models of the accretion flow. The instability leads to oscillations in the shock height and variations in the cyclotron emission. Observations by Middleditch (1982) of AN UMa and E1405-451 showed a feature in the power spectrum near 0.5 Hz. Recent observations by Larsson (1985) confirm the feature in the power spectrum of E1405-451 and show clear pulsations in the light curve. This feature has been tentatively identified with the radiative instability discovered by LCS. The model spectra presented below average over the shock height and temperature oscillations found by LCS because observed spectra are obtained on time scales long compared to the oscillation period. This averaging will result in a range of values for ν^* which will broaden the rollover in the spectrum.

III. Results

Figure 1 shows the spectrum at several angles relative to the magnetic field. The calculation is made using a white dwarf mass of 0.5 $M_{\odot}$, a radius of 10^9 cm, a surface temperature of 2×10^4 K, a polar cap temperature of 5×10^5 K, and a magnetic field of 1.5×10^7 Gauss. The accretion rate is 2×10^{16} gm/s over a polar cap area of 10^{16} cm^2. The equilibrium shock height is 5×10^7 cm and the equilibrium temperature is 1.5×10^8 K. The shock height is assumed to oscillate with an amplitude of 60% and the temperature oscillates with an amplitude of 50% and leads the shock height in phase by 90°. A red dwarf with a radius of 3×10^{10} cm and a temperature of 2400 K is also included.

https://doi.org/10.1017/S0252921100105354 Published online by Cambridge University Press

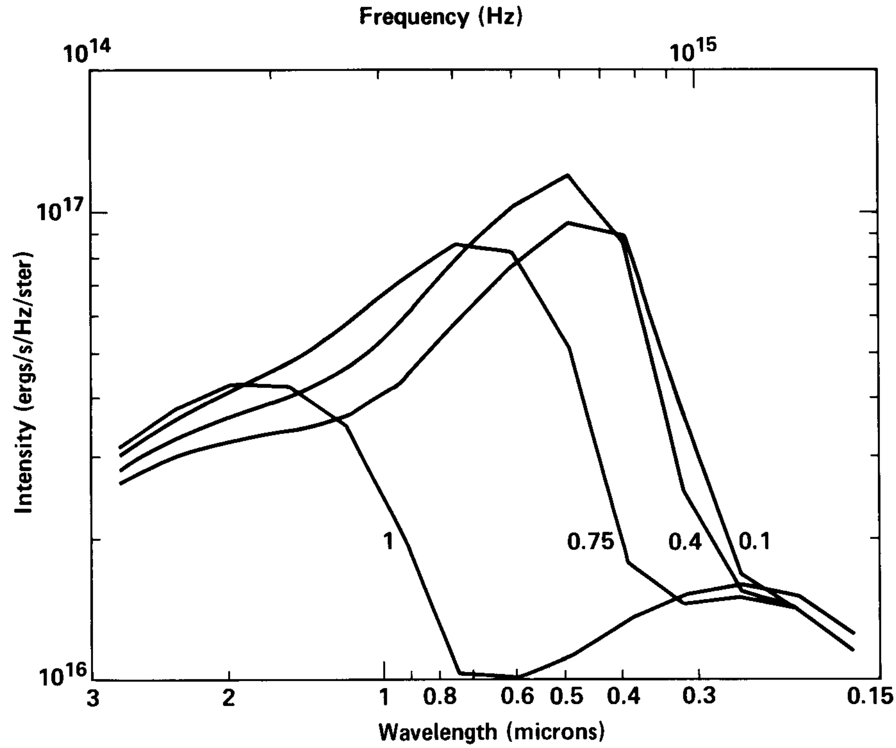

Fig. 1. The cyclotron spectrum is shown at four viewing angles away from the magnetic field (curves are marked by the cosine of the viewing angle). The spectra include the emission from both the sides and top of the accretion column and have been summed over polarization. At wavelengths longer than 1 μm, there is a contribution from a 2400 K red dwarf. At wavelengths shorter than 0.3 μm, the spectrum is dominated by the 20,000 K white dwarf.

The first point to note is the way in which the cyclotron spectrum rolls over at high frequencies. The spectrum peaks in the optical for most viewing angles, but when viewed directly along the magnetic field it cuts off in the IR. The radiation from the surface of the hot white dwarf can be seen in the ultraviolet, and the infrared flux includes a contribution from the red dwarf. Models of this type can explain steeply decreasing optical spectra but, even with the shock oscillations, the rollover is steeper than that found in some systems. The shock oscillation goes away at large magnetic fields (see Chanmugam, Langer, and Shaviv 1985) and the cyclotron luminosity is negligible for low fields, so the the field chosen here is the most interesting value for a model with oscillations. AM Her and some other systems have fields of roughly $3x10^7$ Gauss, so this model does not apply to them. The most obvious way to avoid a steep rollover is to have a distribution of temperatures across the polar cap. This will occur only if the electrons do not reach the shock temperature, which will happen when cyclotron losses dominate the cooling and cause the electron and ion temperatures to differ. Even if cyclotron losses dominate, temperature variations will occur only if there is a variation in the mass flux across the column or if radiation transport effects lead to much stronger cooling in some parts of the flow (e.g. the cooling might be higher near the sides of the column).

IV. Conclusions

This paper has presented a relatively simple model for the optical spectrum of the AM Her stars. Including the shock oscillation produces a gentler rollover at high frequency than is found in the simplest models, but it is still not possible to get a spectrum as flat as ν^{-1}. A full explanation of the optical spectra will probably need to include the effects of a mass flux that varies across the polar cap and should allow the electron temperature to differ from the ion temperature. These same effects will be needed to explain the presence of strong polarization across the whole optical band. Observations that show how the optical continuum varies as a function of orbital phase will be important in determining the conditions in the accretion column. Simultaneous observations in the infrared, optical, UV, soft X-ray, and hard X-ray bands (or as many bands as possible) are helpful because they make it possible to study the energy budget of the system and help in separating the various sources of emission.

REFERENCES

Chanmugam, G., Langer, S.H., and Shaviv, G. 1985, Ap. J. (Letters), 299, pp. L87.
Chanmugam, G., and Wagner, R.L. 1979, Ap. J., 232, pp. 895.
Chiappetti, L., Tanzi, E.G., and Treves, A. 1980, Space Sci. Rev., 27, pp. 3.
Dulk, G.A. 1985, Ann. Rev. Astr. Ap., 23, pp. 169.
Kallman, T.R., and McCray, R. 1982, Ap. J. (Supplement), 50, pp. 263.
Lamb, D.Q., and Masters, A.R. 1979, Ap. J. (Letters), 234, pp. L117.
Langer, S.H., Chanmugam, G., and Shaviv, G. 1981, Ap. J. (Letters), 245, pp. L23.
Langer, S.H., Chanmugam, G., and Shaviv, G. 1982, Ap. J., 258, pp. 289 (LCS).
Larsson, S. 1985, Astr. Ap., 145, pp. L1.
Liebert, J., Tapia, S., Bond, H.E., and Grauer, A.D. 1982, Ap. J., 254, pp. 232.
Middleditch, J. 1982, Ap. J. (Letters), 257, pp. L71.
Schmidt, G.D., Stockman, H.S., and Grandi, S.A. 1986, Ap. J., 300, pp. 804.
Schneider, D.P., and Young, P. 1980, Ap. J., 240, pp. 871.
Szkody, P., Raymond, J.C., and Capps, R.W. 1982, Ap. J., 257, pp. 686.