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OPTICAL PULSATIONS IN AM HER SYSTEMS

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I. Introduction

The AM Her systems are widely believed to be mass transfer binaries containing a white dwarf primary accreting from a red dwarf secondary (see Chiappetti, Tanzi, and Treves, 1980 for a review of these systems). The magnetic field of the white dwarf is so strong that it prevents the formation of an accretion disk and funnels the accretion flow onto the polar caps of the white dwarf. The accreting matter is decelerated from free fall by passage through a standoff shock located somewhat above the surface of the white dwarf. The hot postshock gas radiates hard X-rays and electron cyclotron emission and cools until it settles onto the photosphere.

Langer, Chanmugam and Shaviv (1981) carried out theoretical studies of the AM Her systems through the use of a numerical hydrodynamics code. They reported the discovery of a thermal instability in the hot postshock gas that led to oscillations with a period of order a second in the height of the standoff shock and in the hard X-ray luminosity. More detailed results were presented by Langer, Chanmugam and Shaviv (1982, hereafter LCS), including the relationship between the pulse period and the system parameters. These papers did not discuss what pulsations, if any, would be expected in the optical.

Middleditch (1982) reported the discovery of a broad feature between 0.4 and 0.8 Hz in the power spectrum of AN UMa and E1405-451. Observations of AM Her and of AN UMa in its faint state did not show similar features. This feature was tentatively identified with the instability discovered by LCS, but it was clear that improved observations and models were both required to confirm the identification. Recent observations by Larsson (1985) confirm the presence of the feature in the power spectrum of E1405-451 and show clearly visible pulsations in the light curve as well as demonstrating that the pulsation is predominantly in red light. As a result it seems worthwhile to present theoretical predictions for optical pulsations. The next section describes the model of the system, emphasizing the general physics of the problem at the expense of details about the numerical aspects. The next section presents some of the expected properties of the optical emission, and the final section suggests the observations and model improvements that are of the most immediate interest.

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II. The Model

There are several sources of emission in these systems, all of which contribute to some extent to the optical light. The first two components are the normal emission from the white dwarf and the red dwarf secondary, and would be present even if mass transfer ceased. Both of these sources have been seen in the low state of AM Her (Szkody, Raymond, and Capps 1982), and the white dwarf has been seen in the low state of AN UMa (Liebert et al 1982). The accretion stream between the two stars is a source of emission lines, but can be ignored for the purposes of the continuum under consideration here. The results of Kallman and McCray (1982) show that the matter just above the shock will be almost completely ionized by the hard X-rays, but its temperature will be only about 10^6 K which will not lead to significant continuum emission in the optical or near infrared. The postshock gas will have a temperature of roughly 10^8 K and will emit hard X-rays. If the white dwarf has a magnetic field at the generally accepted level of 10^7 gauss, there will be strong cyclotron emission in the infrared, optical, and perhaps the ultraviolet. This light will be both circularly and linearly polarized (see Lamb and Masters 1979, Chanmugam and Wagner 1979). The final component is the emission from the portion of the white dwarf photosphere that lies just below the accretion shock. This region is strongly heated by the hard X-rays and cyclotron radiation hitting it from above, and will radiate at soft X-ray temperatures. This component will not make a significant contribution in the optical.

The situation is complicated by the possibility that accretion occurs onto both polar caps, leading to two independent sources of cyclotron emission. If the mass flux is not uniform across a polar cap, there is a strong possibility that the flow will break up into accretion along several independent flux tubes. Effects of this type can considerably reduce the predicted pulsation amplitude. In the spirit of considering a simple model, we include only one flux tube. Our results are thus upper limits on the pulsation amplitude.

The cyclotron emission process is complicated due to the strong dependence of the opacity on frequency, polarization and angle (see e.g. Chanmugam and Dulk 1981). In the case of the simple models considered here an approach outlined by LCS will retain all the essential features. The opacity drops very rapidly as the frequency moves past successive harmonics of the cylcotron line. As a result the accretion column is optically thick and follows a Rayleigh-Jeans curve up to some harmonic number m^* and then rapidly cuts off. The temperature in the postshock gas is high enough that for harmonic numbers greater than roughly 3 the different lines will overlap and the cyclotron spectrum will be relatively smooth. For the purposes of this model it is sufficiently accurate to characterize the cyclotron spectrum as a Rayleigh-Jeans flux up to a frequency of m^* times the cyclotron frequency with the flux dropping off with the thermal line width above that point.

$$m^* = 9.87\,(\Lambda/10^7)^{0.05}\,(T/10^8\ \mathrm{K})^{0.5} \qquad (1)$$

In this expression $\Lambda = 4\pi enh/B$ where n is the electron density, h is the shock height, and B is the white dwarf magnetic field. The principal errors made by this approach are to ignore polarization effects which make one polarization mode become optically thin before the other at the same frequency, and to ignore the angular dependence of the opacity which causes the column to be optically thick in some directions and not in others.

LCS provide a fit to the pulsation period in terms of the system parameters

$$p = 3.8\ \varphi/\Psi\ \mathrm{sec} \qquad (2)$$

where

$$\Psi = (\dot{M}/10^{16}\ \mathrm{g\ s^{-1}})/(A/10^{16}\ \mathrm{cm^2}) \qquad (3)$$

and

$$\varphi = (M/M_\odot)/(R/10^9\ \mathrm{cm}). \qquad (4)$$

In these expressions M is the white dwarf mass, R the white dwarf radius, A is the area of the polar cap over which accretion occurs, and $\dot{M}$ is the accretion rate. A fit to the maximum shock height is also given by LCS

$$h = 2 \times 10^8\ \varphi^{1.5}/\Psi\ \mathrm{cm}. \qquad (5)$$

The models of LCS indicate that the postshock temperature oscillates with an amplitude of roughly 50 % and the shock height oscillates 180° out of phase with an amplitude of roughly 60%. More recent results (Langer, Chanmugam, Shaviv 1983 and Chanmugam, Langer, and Shaviv 1985) indicate that if the cyclotron emission is strong enough to carry off a significant fraction of the luminosity, the oscillations in the shock height will damp out. Thus if B is much larger than 10^7 gauss there should be no pulsations.

The stability of the flow is fairly sensitive to the details of the radiative cooling. Imamura, Wolff, and Durisen (1983) have also presented numerical models of accretion flows. They find that for bremsstrahlung dominated cooling the shock height is unstable to oscillations at an overtone of the pulsation frequency found by LCS. The amplitude of the postshock temperature oscillation is comparable to that found by LCS, so the amplitude of optical pulsations will be about the same as that derived here. The reason for this discrepancy must be discovered before measured pulsation frequencies can be used to infer system parameters (see also Langer 1985).

The model for the optical spectrum thus consists of blackbody radiation from the surfaces of the red and white dwarfs, blackbody radiation from the polar cap, and the Rayleigh-Jeans cyclotron emission from the hot postshock gas. The first two sources are constant, but the emission from the final two sources varies during the course of the shock oscillation. This model does not account for the possibility that there are several independent flux tubes oscillating at different frequencies.

III. Results

In Fig. 1 the angle averaged intensity at several wavelengths is shown as a function of pulse phase. The white dwarf has a temperature of 20,000 K, a mass of 0.5 $M_\odot$, a radius of 10^9 cm and a magnetic field of 10^7 gauss. The red dwarf secondary has a temperature of 2500 K and a radius of 2.2 x 10^{10} cm. In the infrared, the pulsation amplitude is $\sim$8% which reflects the linear dependence of the flux on the postshock temperature (diluted by other sources of light in the system). All pulsation amplitudes given here are equal to the difference between the maximum and minimum values divided by the sum of the maximum and minimum. At 6000 to 9000 Å the amplitude is higher, $\sim$12%, because the cutoff frequency for the cyclotron emission passes from below to above the wavelength during a pulsation, leading to 100% modulation of the cyclotron flux. At wavelengths shorter than 5000 Å the cyclotron emission is always negligible and the emission is essentially unmodulated. The pulsations are clearly quite red, as they are observed to be in E1405-451. Increasing the polar cap area or reducing the red and white dwarf temperature will increase the pulsation amplitude.

Figure 2 shows the pulsation amplitude as a function of frequency for several magnetic fields. Each curve is flat in the infrared, has a broad peak, then becomes unmodulated at high frequency. The region of highest modulation lies between the cyclotron cutoff harmonic, m^*, for the minimum and maximum postshock temperature. If the postshock temperature can be determined from the hard x-ray spectrum, the value for m^* can be used to infer the magnetic field.

IV. Conclusions

If the connection between the instability discovered by LCS and the pulsations observed by Larsson (1985) can be firmly established, it will be possible to constrain such basic parameters as B and the white dwarf mass and radius. Further progress clearly requires additional observations. The detection of the pulsations in additional AM Her systems would clearly help to clarify their dependence on the properties of the system. In this context it is important to note that the DQ Her systems in which the magnetic field is not strong enough to lock the white dwarf's rotation to the orbital period, but is strong enough to channel the accretion flow, might also show pulsations. If the magnetic fields in these systems are weaker, the pulsations might well occur only in the infrared.

Current theoretical models indicate that if the magnetic field is strong enough to produce cyclotron emission in the ultraviolet, it is probably also strong enough to damp out the thermal instability. Consequently, observations of pulsations in the ultraviolet would either force modifications of the LCS theory or require an alternate explanation for the pulsations. The models predict that an increase in the accretion rate should lead to a shorter oscillation period. Tracking an individual pulsation in the power spectrum would permit an observational check on this prediction. A final point to note is that the flickering on time scales of around a minute that is seen in AM Her systems (Panek 1980) probably represents changes in the accretion rate. Such changes will re-excite the oscillations in the accretion column and lead to a change in the oscillation period. For this reason any power spectrum taken on time scales long compared to 100 seconds would be expected to show a broad feature around the typical pulsation frequency, independent of the stability of the underlying clock.

There are several points at which the theoretical models need to be improved. Perhaps the most obvious is the need for models that include the dependence of the cyclotron opacity on angle and polarization so as to permit predictions for the polarization and orbital phase dependence of the pulsations. It will also be necessary to improve the calculations of how strong the magnetic field must be to damp out the oscillations. This would permit accurate predictions of the shortest wavelength at which strong optical pulsations should be observed. Accurate predictions of the pulsation amplitude should consider the possibility that accretion occurs onto both magnetic poles and that the mass accretion flux may not be uniform across the polar cap.

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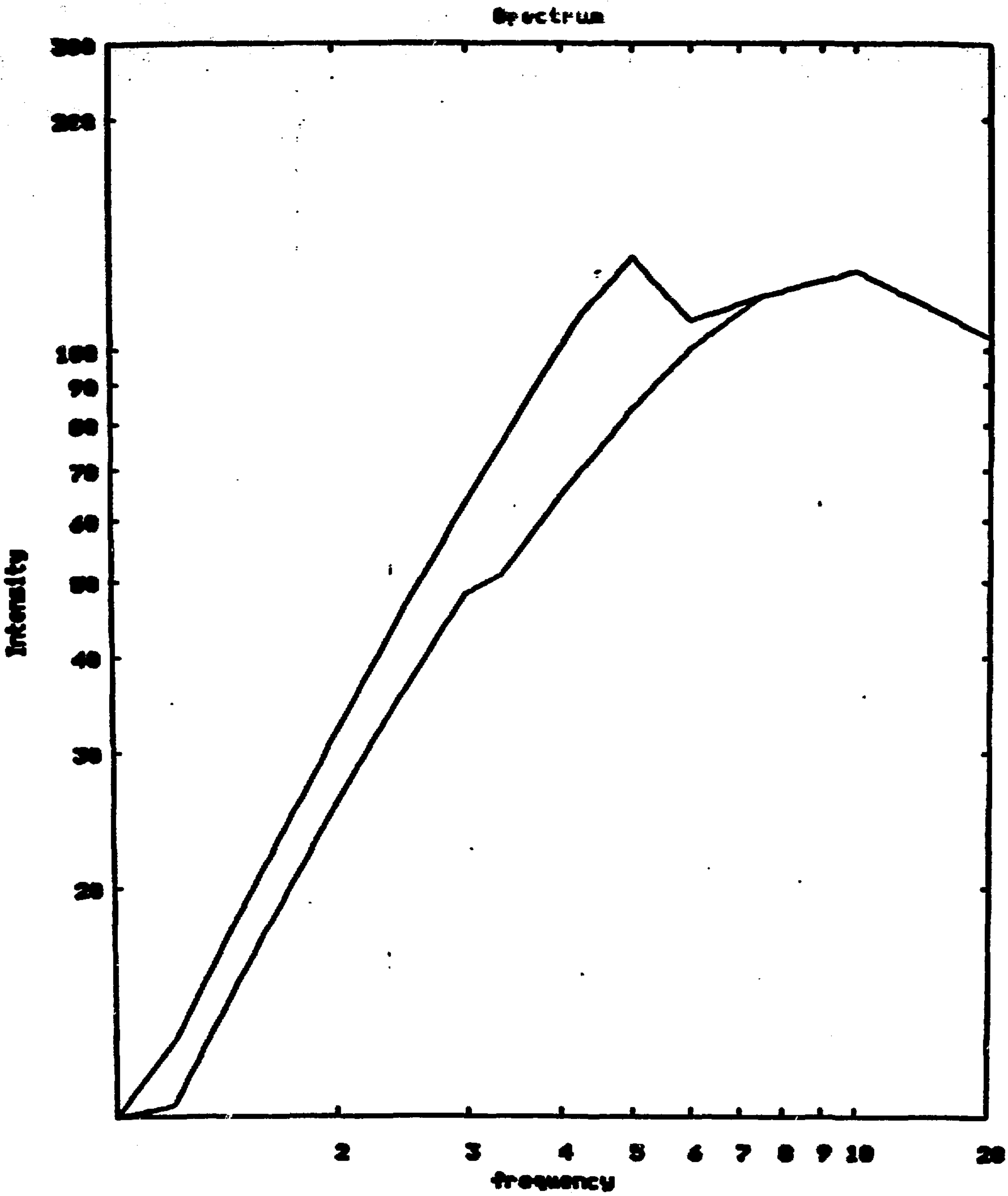

Fig. 1 The intensity (in arbitrary units) is plotted as a function of the frequency in units of 10^{14} Hz at the times of minimum (lower curve) and maximum (upper curve) postshock temperature. The break in the spectrum at $\nu = 3 \times 10^{14}$ Hz and $\nu = 5 \times 10^{14}$ Hz (respectively) occurs at the cutoff of the cyclotron emission. The red dwarf has a temperature of 2500 K and a radius of 2.2×10^{10} cm. The white dwarf has a temperature of 20000 K, a radius of 10^{9} cm, a mass of 0.5 $M_{\odot}$ and a magnetic field of 10^{7} gauss. The polar cap area is 10^{16} cm^{2} and the accretion rate is 2.5×10^{15} g s^{-1}.

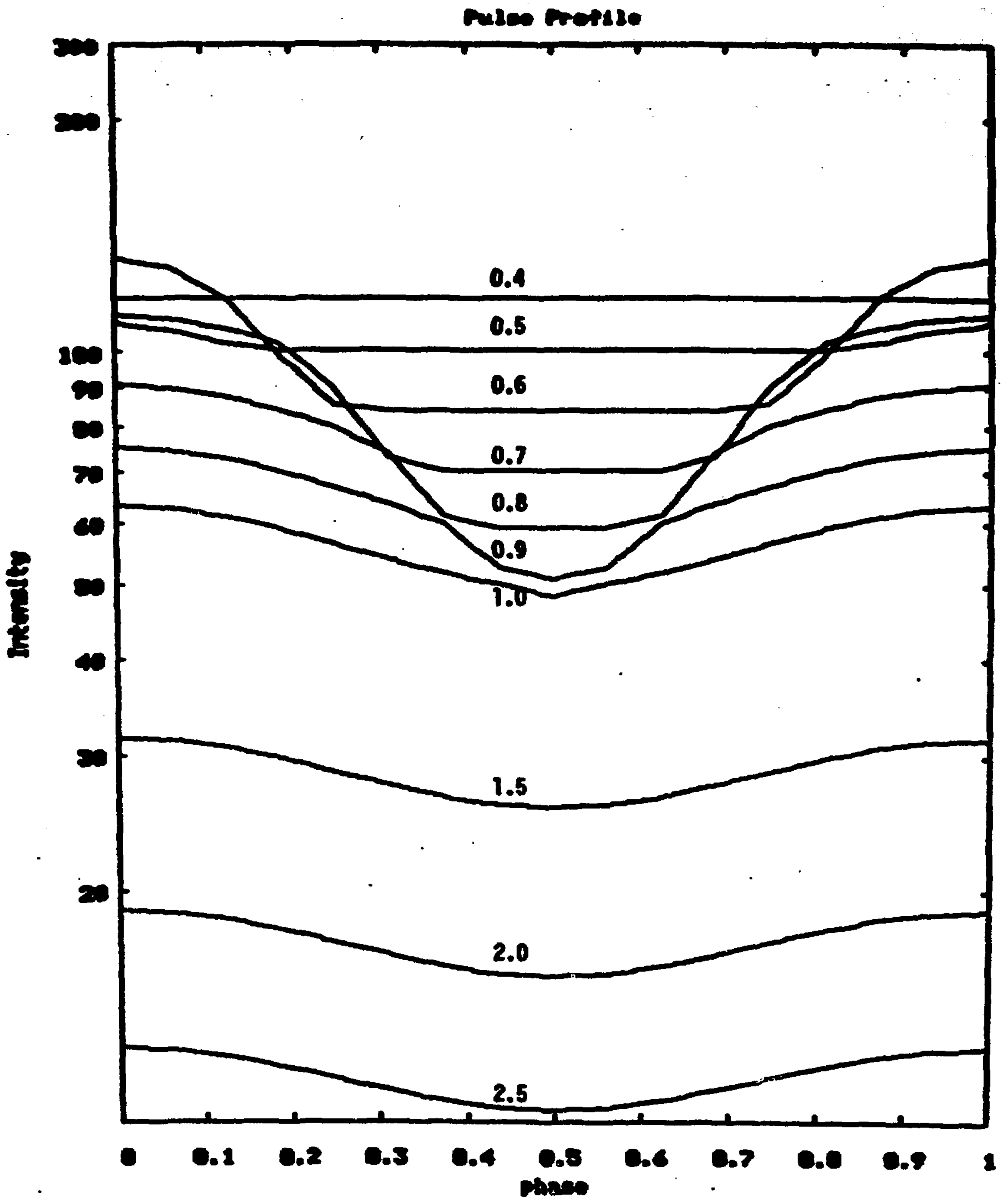

Fig. 2 The pulse shape is shown for several wavelengths (curves labeled by λ in microns) for the model of Fig. 1.

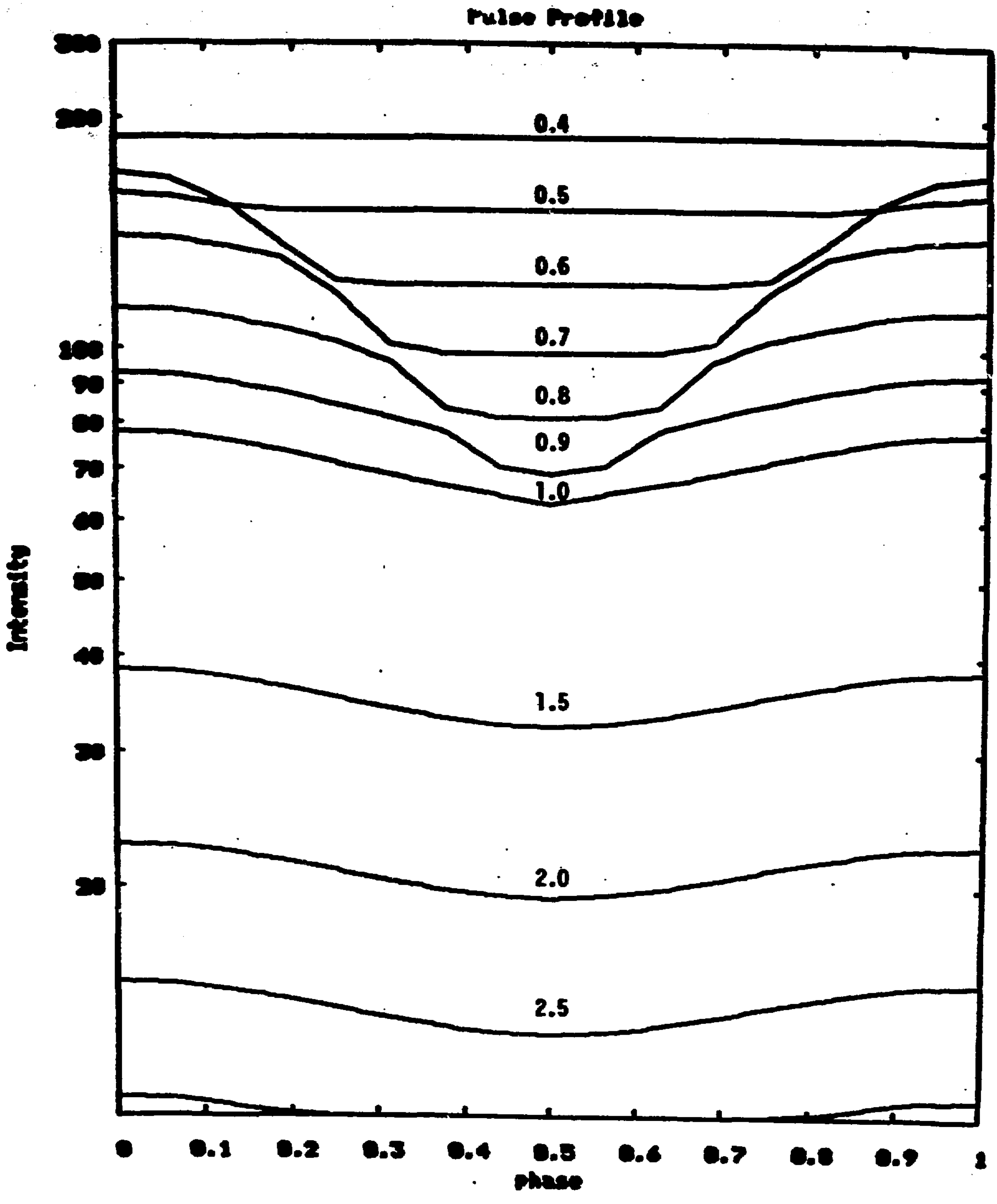

Fig. 3. Same as Fig. 2 except the red dwarf has a temperature of 3000 K and the white dwarf has a temperature of 50000 K.

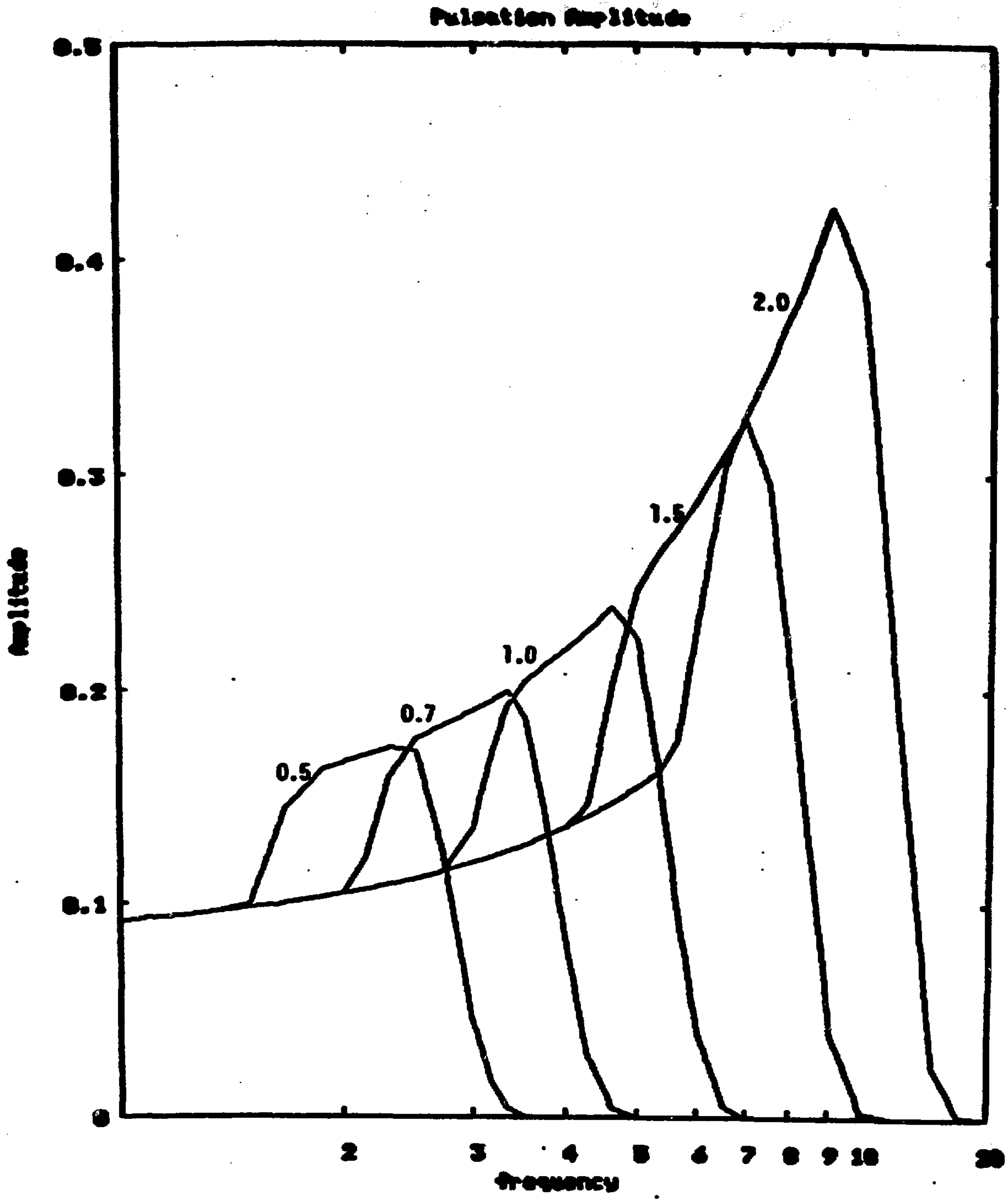

Fig. 4 The spectrum is shown for a series of models which differ from that of Fig. 1 only in the magnetic field. The curves are labeled by B in units of 10^7 gauss.