Mon. Not. R. astr. Soc. (1985) **212**, 353–358

The magnetic field of AM Herculis

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Accepted 1984 August 13. Received 1984 August 9; in original form 1984 May 11

Summary. We show that spectroscopic observations of the magnetic white dwarf in AM Herculis obtained in 1979 when the system was in a low state indicate that the magnetic field geometry is different from that of a centred dipole. A model based on an offset dipole field geometry gives reasonable agreement with observations and suggests that the magnetic field at the accreting pole may be significantly lower ($\sim 1.4 \times 10^7$ G) than has previously been assumed.

1 Introduction

AM Herculis is a binary system of period 3.1 hr consisting of a late-type dwarf and a magnetic white dwarf which is phase locked with the orbital rotation of the system. In its high state, the optical light is dominated by cyclotron radiation from hot plasma located near a shock region at one of its magnetic poles. Studies of the high-state polarization properties of AM Herculis have enabled important parameters such as the orbital inclination and the latitude of the magnetic pole to be determined with reasonable accuracy.

In 1979, AM Herculis was observed to change into an unusual low state in which the cyclotron luminosity of the shock region decreased by ~ 2 mag. The low-state optical spectrum was dominated by Zeeman absorption components of hydrogen arising from the underlying magnetic white dwarf (Latham, Liebert & Steiner 1981). The phase-dependent spectroscopic observations published by Latham *et al.* can in principle be used to investigate the magnetic field structure of the underlying white dwarf since the viewing geometry of the white dwarf is known. In this paper we present such an analysis and argue that the magnetic field at the accreting pole may be significantly lower than has previously been thought possible.

2 Calculations and discussion

2.1 THE VIEWING GEOMETRY OF AM Herculis

AM Herculis-type systems are characterized by the presence of one or sometimes two linear polarization pulses which are believed to occur when the direction of the magnetic field at the accreting pole is perpendicular to the line-of-sight. The rate of change of the polarization

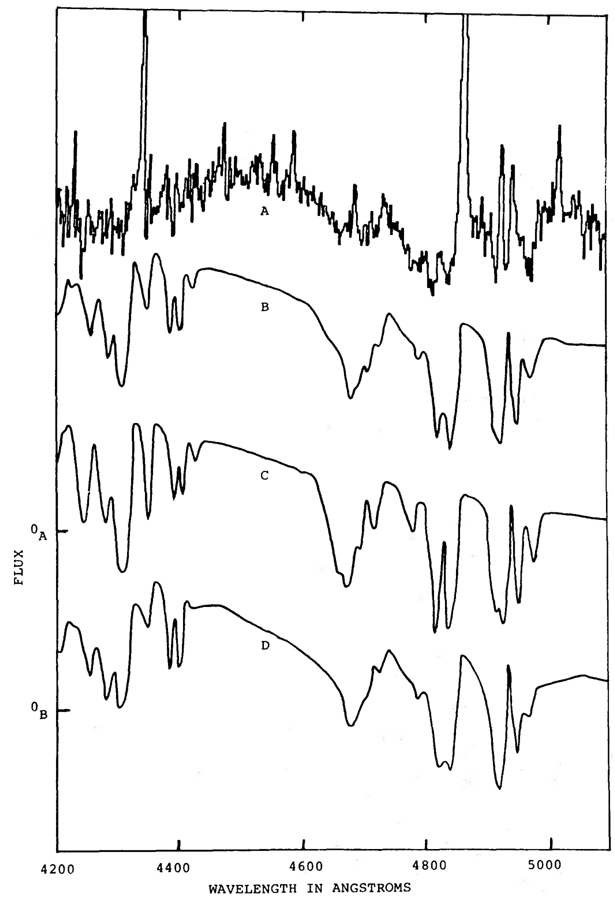

Figure 1. Observed and theoretical flux for AM Herculis. The top curve (A) shows flux measurements for phase $\phi = 0.97$ from Latham *et al.* (1981). The curves below represent flux from a 20 000 K model atmosphere observed at viewing angle $\alpha = 90°$ (equator-on). Curve B is a dipole offset 0.17 radii along the polar axis and opposite the direction of the dipole, with dipole magnetic field strength 2.2×10^7 G. Curve C is a centred quadrupole with quadrupole field strength 2.6×10^7 G. Curve D is a centred dipole with dipole strength 2.2×10^7 G. The flux zeroes of curves A and B are indicated, and the other curves are equally spaced.

angle with phase across a linear pulse gives a direct measure of the orbital inclination i (Meggitt & Wickramasinghe 1982). In AM Herculis itself, only a single linear polarization pulse is usually observed and the time of the pulse is defined as phase $\phi = 0$. Circular polarization observations obtained during the low state of AM Herculis show that the active pole is eclipsed during $\phi = 0$–0.1 (Latham *et al.* 1981). Evidence for such an eclipse is also present in soft X-ray observations of AM Herculis (Tuohy *et al.* 1978, 1981). Once i is known, the eclipse duration enables the colatitude δ of the active magnetic pole to be determined directly. Brainerd & Lamb (1984) have given an analysis of observations of AM Herculis along the above lines and deduced $i = 35° \pm 5°$, $\delta = 58° \pm 5°$. For the sake of definiteness, we adopt values $i = 30°$, $\delta = 60°$ in our analysis. Our conclusions are not significantly altered provided i and δ are within the quoted ranges.

2.2 THE OBSERVATIONAL BASIS FOR THE ANALYSIS

We use as an observational basis for our analysis the phase-dependent spectroscopic data of Latham *et al.* (1981). We concentrate in particular on the high S/N ratio spectra near phases

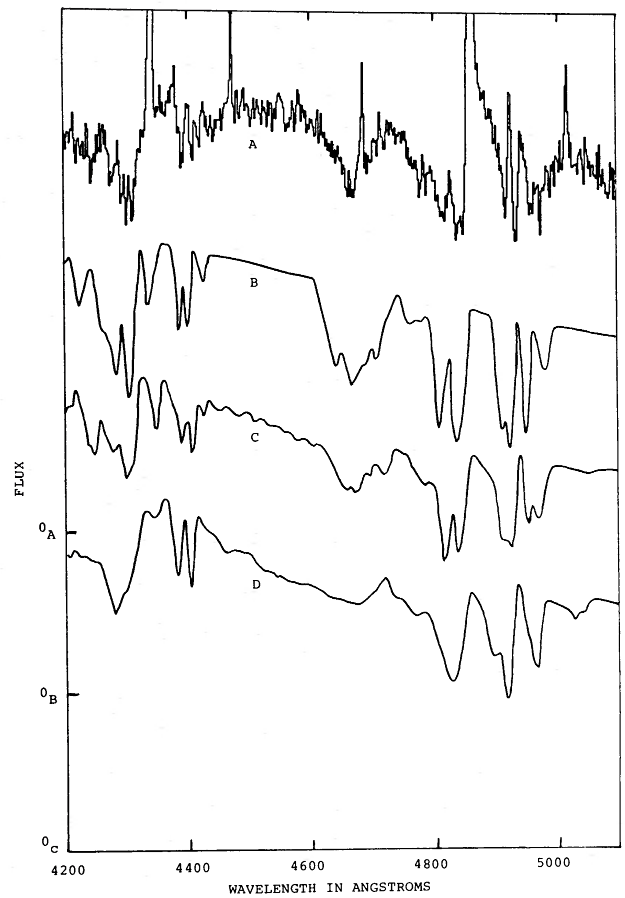

Figure 2. As Fig. 1, except that the observations from Latham *et al.* (1981) are for phase $\phi = 0.55$, and the theoretical curves are for viewing angle $\alpha = 30°$.

$\phi = 0.97$ and $\phi = 0.55$ which represent phase averages over phase bands of width $\Delta\phi \sim 0.08$. These data are presented in Fig. 1 ($\phi = 0.97$) and Fig. 2 ($\phi = 0.55$). Several points should be noted regarding these observations. First, the presence of emission lines indicates ongoing accretion even during the low state, indicating that there may be a contribution to the continuum optical radiation from the accretion stream. Secondly, the optical radiation is observed to be strongly circularly polarized (maximum ~ 20 per cent) during the low state, which indicates that cyclotron radiation from the shock region continues to make a significant contribution to the optical radiation from the system. Latham *et al.* (1981) estimate that this component would contribute *at least* 10 per cent of the radiation in the wavelength region of the spectroscopic observations. The actual contribution could be considerably higher since the Latham *et al.* estimate is based on the assumption that the cyclotron component is 100 per cent polarized at the phase of maximum polarization. This value could not be achieved in the present system since the emission region is never viewed along the direction of the field. We estimate that the Zeeman features from the underlying white dwarf may be 20–30 per cent deeper than indicated by the observations as a result of the presence of this background component of radiation. Finally, we note that the M star is not expected to contribute significantly to the radiation at blue wavelengths ($\lambda \lesssim 5000$ Å).

2.3 CALCULATIONS OF MODEL SPECTRA

Theoretical Zeeman spectra for magnetic white dwarf atmospheres with a pure hydrogen composition have been discussed in a series of our papers (Martin & Wickramasinghe 1978, 1981, 1982, 1984; Wickramasinghe & Martin 1979; see also O'Donoghue 1980). Our earlier work, which presented results for different field strengths and field structures (Wickramasinghe & Martin 1979), did not include magneto-optical effects which have since been found to be important for computing absorption lines (Martin & Wickramasinghe 1981, 1982). Furthermore, it is likely that the importance of Stark (pressure) broadening had been overestimated in these calculations. In our present analysis we use a computer code which includes magneto-optical effects and allows for the use of different Stark widths for individual components. For the present calculation we adopt a Stark width corresponding to 0.01 times the zero-field value, so that the dominant broadening mechanism is in fact magnetic broadening.

The effective temperature of the magnetic white dwarf in AM Herculis cannot be determined with any accuracy from the optical observations. We adopt an effective temperature $T_e = 20\,000\,K$, consistent with the presence of strong Balmer lines, and assume a typical white dwarf gravity $\log g = 8.0$. Since our main aim is to determine the field strength of the magnetic white dwarf, uncertainties in these quantities are not critical to our investigation.

We start by assuming that the magnetic field structure corresponds to that of a centred dipole. Let α be the angle between the magnetic axis and the line-of-sight. Then, according to the standard interpretation of the linear pulse, the viewing geometry of AM Herculis is such that phase $\phi = 0$ corresponds to equator-on viewing ($\alpha = 90^\circ$) of the surface while phase $\phi = 0.5$ corresponds to viewing at an angle $\alpha = 30^\circ$. We have constructed a series of models for different values of the dipole field strength B_d and the best fit to the data in Fig. 1 (equator-on viewing) was achieved for $B_d = 2.2 \times 10^7\,G$. The theory and observations are compared in Fig. 1. We note that there is good agreement in the wavelengths of all the major components. The calculations predict features that are somewhat deeper than observed, but this is probably a result of the presence of the background component of radiation discussed earlier.

Although the simplest dipole model gives good agreement with the equator-on ($\phi = 0$) observations, serious problems are encountered in attempting to match the data at the opposite phase ($\phi = 0.5$) using the same model. This is illustrated in Fig. 2 where we present results for the same dipole field strength but viewed at $\alpha = 30^\circ$ to the dipole axis. We immediately see that the $H\beta(\sigma^-)$ blend at $\lambda 4650$ Å which consists of strongly field-dependent components has a width that exceeds the observed width by a large amount. Since the broadening of this blend is almost entirely due to magnetic field broadening, the conclusion is that the effective spread in field strength in this star is lower than is indicated by a centred dipole field geometry (see also Latham *et al.* 1981).

Ironically, the centred dipole models would give an excellent representation of the data if the inferred phases were reversed. That is, the centred dipole model viewed equator-on ($\alpha = 90^\circ$) gives an excellent fit to the data in Fig. 2 where the inferred viewing angle is $\alpha \sim 30^\circ$, and vice versa the centred dipole model with $\alpha = 30^\circ$ fits the data in Fig. 1 with $\alpha \sim 90^\circ$. But since the inferences about viewing angles made on the basis of the linear polarization pulse appear to be secure, such a reversal of angles cannot be entertained.

We have also investigated the possibility of a centred quadrupole field distribution. The quadrupole presents a more uniform equatorial region in comparison to a centred dipole field distribution. The best fit quadrupole models are also shown in Figs 1 and 2. Contrary to the dipole model, the quadrupole model for $\alpha = 30^\circ$ gives an excellent fit for the data for $\phi = 0.5$, whereas the quadrupole model for $\alpha = 90^\circ$ predicts the $\lambda 4650\, H\beta(\sigma^-)$ to be much deeper than observation for $\phi = 0$. The reason for the difficulty is the same as for the dipole: the most uniform field is in the equatorial region, whereas the observations suggest the most uniform field should be toward the observer more when $\alpha = 30^\circ$ than when $\alpha = 90^\circ$.

Analyses of isolated magnetic white dwarfs and magnetic Ap and Bp stars have shown that better agreement can often be achieved with observations if it is assumed that the dipole is off-centred (Borra & Landstreet 1981; Wickramasinghe & Martin 1979). In the context of magnetic white dwarfs, the consequences of adopting more complicated field structures have been investigated by Martin & Wickramasinghe (1984). The simplest way to obtain a field distribution that is more uniform at $\alpha \sim 30°$ is to offset the dipole away from the centre of the star along the magnetic axis so that the weaker pole is in the visible hemisphere most of the time. We have constructed a series of models in which the dipole is offset along the dipole axis by various fractions d/R, where d is the offset distance and R is the stellar radius. Good agreement can be achieved with both sets of observations for a model with $B_d = 2.2 \times 10^7$ G and $d/R = -0.17$: the results are shown in Figs 1 and 2. The field strength at the weaker pole is $B_d/(1-d/R)^3 = 1.4 \times 10^7$ G. We note that the offset dipole model is clearly an improvement on the centred dipole model in that (1) the width of the λ 4650 Hβ (σ^-) blend is now in good agreement with observations, and (2) the Hβ(π) components are better resolved, as also appears to be indicated by observations.

The offset dipole is also an improvement on the centred quadrupole, and this difference is of some significance in this case. As we have argued elsewhere (Martin & Wickramasinghe 1984), it is possible to obtain almost whatever field distribution one likes by suitable off-setting (including offsetting perpendicular as well as parallel to the magnetic axis) or by choosing a suitable combination of multipoles. But multipoles (dipole, quadrupole, octupole, etc.) all have their regions of greatest field variation near the poles, and this is precisely the case ruled out by observations of AM Herculis. To summarize the possible field geometries for AM Herculis:

(1) Centred dipole field. The appropriate polar field strength for the best-fit centred dipole model is about 2.2×10^7 G. This gives a poor fit for the viewing angles normally inferred. But *if* the viewing angles assumed in Figs 1 and 2 were reversed, the centred dipole would give a good fit. However, the data on linear polarization angle and pulse appear to rule this out.

(2) Centred quadrupole field. The appropriate polar field strength for the best-fit centred quadrupole field is about 2.6×10^7 G. But as in the case of the centred dipole, a good fit cannot be obtained for the viewing angles normally inferred, for similar reasons.

(3) Offset dipole field. The appropriate polar field strength (for the accreting pole) for the best-fit dipole field off-centred along the dipole axis is about 1.4×10^7 G. This model with $B_d = 2.2 \times 10^7$ G and $d/R = -0.17$ gives a good fit to the observations for the viewing angles normally inferred. The offset dipole model has at least two consequences which need to be investigated further. First, what are the theoretical reasons for expecting the dipole to be offset by such a degree? Secondly, are there dynamical reasons why accretion should occur preferentially at the weak rather than the strong pole?

3 Conclusions

We have presented an analysis of the Zeeman absorption features seen in the low state spectrum of AM Herculis and shown that the field distribution of the magnetic white dwarf must be significantly different from that of a centred dipole. An offset dipole model in which the dipole is displaced opposite to the direction of the dipole axis by 0.17 radii gives reasonable agreement with observations. With this magnetic field geometry, the field strength at the active pole is $\sim 1.4 \times 10^7$ G, considerably lower than has previously been assumed. The consequences of such a low field strength for cyclotron emission models of AM Herculis will be investigated in a subsequent communication.

Acknowledgment

Vital financial support was provided by the Australian Research Grants Scheme.

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