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Multicolour polarimetry of AM Herculis

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Summary. We present multicolour photometry and polarimetry of the binary system AM Herculis, obtained in 1979 September. From the wavelength dependence of the circular polarization curve we derive a geometrical model for the system. By comparison with earlier observations we find that changes in the orientation of the system must have occurred. We propose that the rotation axis of the white dwarf is inclined to the orbital axis of the binary and precesses about it.

1 Introduction

The binary system AM Herculis shows a large circular polarization varying with its 186-min period (Tapia 1977). This circular polarization is generally interpreted as being due to cyclotron radiation from accretion columns above the magnetic poles of a highly magnetized ($B \sim 10^8$ G) white dwarf which accretes material from a cooler companion star.

The wavelength dependence of the polarization curve is of importance in understanding the structure of the system and the physics of the accretion column. Observations by Michalsky, Stokes & Stokes (1977) and Priedhorsky, Krzeminski & Tapia (1978a) showed considerable wavelength variation in the form of the polarization curve. However, in both these cases the different colours were not observed simultaneously, so the possibility that some of the difference is due to variations with time cannot be excluded. Long term variations in the polarization curve, particularly in the linear polarization are known to occur (Bailey *et al.* 1978), and short time-scale flickering in the polarization is also observed (Stockman & Sargent 1979).

We present four-colour polarimetry of AM Her obtained with an instrument which permits two colours to be observed simultaneously and so avoids these difficulties.

2 Observations

The observations were obtained on the 1.5-m telescope of the Cabezon Observatory, Tenerife using the RGO People's photometer in its polarimetric mode (Bailey 1978). This two channel instrument permits simultaneous determination of all four Stokes parameters in two colours. Observations were made on the nights of 1979 September 16, 17 and 26. On all three nights one channel was used to observe in the V band (0.55 μm) while the second channel was used for observations in the B band (0.44 μm) on September 16 and the R (0.68 μm) and I_K (0.83 μm) bands on September 17 and 26 respectively. Integrations of 200 s were used, and data covering at least one complete cycle of the 186-min period were obtained on each night.

Observations of the comparison star AM Her W (Priedhorsky & Krzeminski 1978) were made at intervals during the runs and used to calibrate the photometry. Photometric data from the September 16 and 17 observations are plotted in Fig. 1. The V curve combines data from both nights, the scatter in these data being due to the flickering of AM Her (Bailey, Mason & Parkes 1977). The effect of flickering is largely removed in the $B-V$ and $V-R$ colour curves, each of which is obtained from simultaneous two colour observations using the two channels of the instrument. The night of September 26 was of poor photometric quality as shown by variations in the comparison star, and therefore this night's photometric data were not used.

The linear polarization data on the three nights do not show a strong pulse similar to that observed by Tapia (1977). There is, however, evidence for a weak double peaked pulse similar to that observed in 1977 May (Bailey *et al.* 1978).

The circular polarization data in all four colours are plotted in Fig. 2. The 0.55 μm data show good agreement between the three nights which have been combined on to a single curve. The phase in Figs 1 and 2 is calculated from the ephemeris (Priedhorsky *et al.* 1978b) $T = \mathrm{JD}_{\odot}\, 2443014.765 + 0.128927E$.

3 Polarized flux distribution

The simultaneous photometry and polarimetry can be used to derive absolute polarized fluxes as well as the percentage polarizations. A comparison of the wavelength distribution

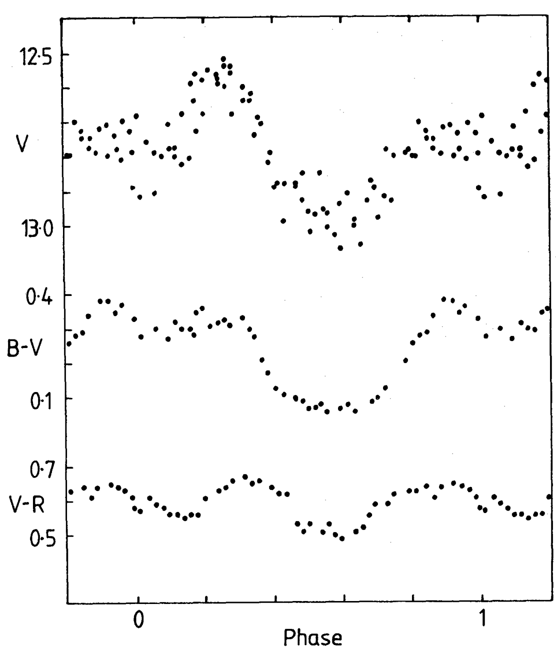

Figure 1. V light curve of AM Her observed in 1979 September 16 and 17, and $B-V$ and $V-R$ colour curves from simultaneous two-colour photometry.

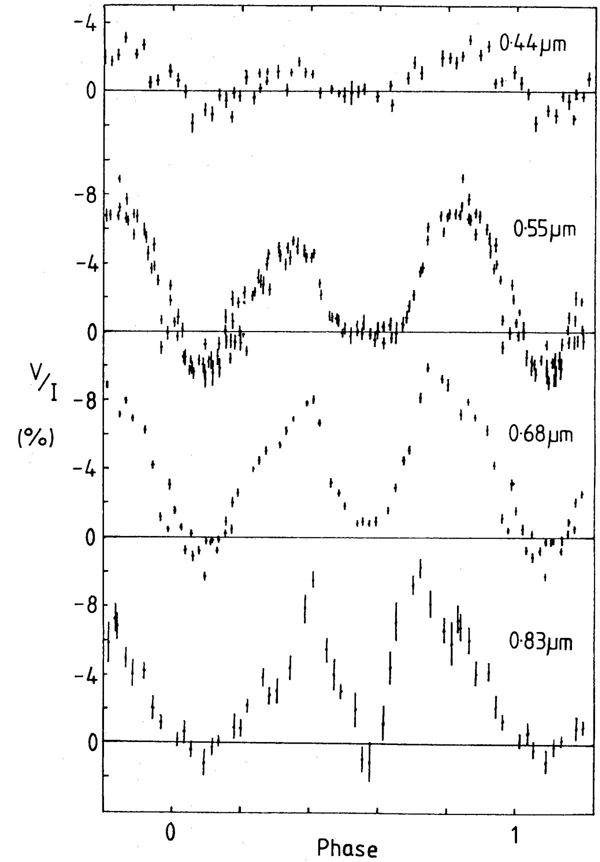

Figure 2. Four-colour circular polarization curves of AM Her. As the polarization is normally negative we have plotted the data with negative polarization increasing upwards.

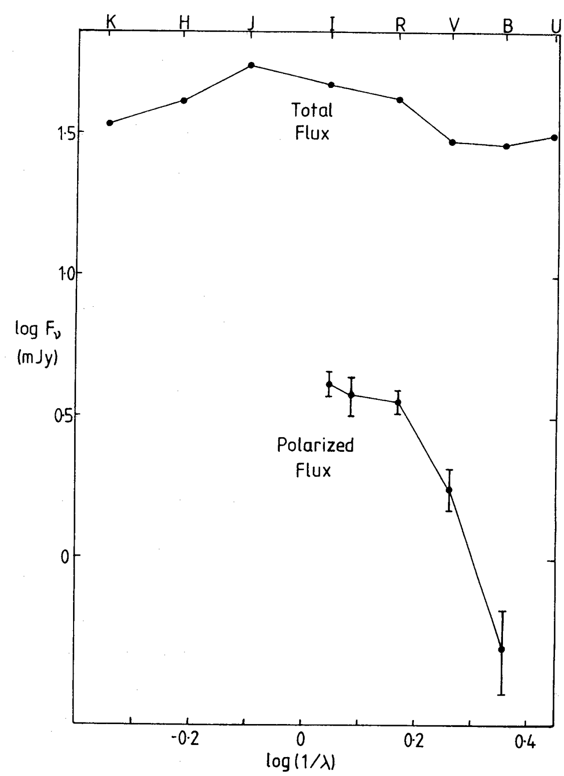

Figure 3. Wavelength distributions of the total and circularly polarized flux for AM Her, averaged from measurements at phases 0.4 and 0.8.

of the total flux and the circularly polarized flux is given in Fig. 3. The data is the average of measurements at phases 0.4 and 0.8 where the circular polarization is near maximum at all colours. The total flux points at *B, V* and *R* are from the data presented here. Points at other colours have been taken from light curves given by Priedhorsky *et al.* (1978a, b) and Jameson *et al.* (1978). There seems to have been little change in the system brightness over the 2-yr interval from these observations.

The circularly polarized flux at *B, V* and *R* is taken from the data of this paper. That at 0.83 μm has been obtained by combining the percentage polarization with an interpolated flux at this wavelength from the total flux curve. The point at 0.9 μm is taken from Priedhorsky *et al.* (1978a).

The polarized flux shows a very sharp fall off blueward of the *R* band. The total flux (see also Priedhorsky *et al.* 1978b) also falls from *R* to *V* but then flattens out and increases slightly towards the ultraviolet, indicating the presence of a blue component in the radiation which is unrelated to the polarized flux. Szkody & Margon (1980) find that flickering occurs earlier in *U* than in *V* and suggest that the ultraviolet radiation originates in a different region from that at longer wavelengths.

4 Interpretation of the circular polarization curve

It is generally accepted that the polarized flux from AM Her is due to cyclotron radiation from an accretion column above the magnetic pole of a white dwarf rotating with the 186-min period. The magnetic axis of the white dwarf is inclined to the rotation axis. Changes in sign of the circular polarization will then occur when the magnetic axis passes through the plane perpendicular to the line-of-sight.

The deep minimum in the polarization curve at about phase 0.6 has been explained in two different ways. Priedhorsky & Krzeminski (1978) propose that this minimum, and the photometric minimum at the same phase are due to an eclipse of the cyclotron emitting region by the body of the white dwarf. Chanmugam & Wagner (1978) propose the geometrically opposite model in which the pole is presented towards us at primary minimum, the minimum being due to cyclotron self absorption in the accretion column. We consider that the sharply defined total eclipses shown by our polarization curves at all colours provide strong support for the white dwarf eclipse model.

This model requires activity of both magnetic poles in order to explain the X-ray eclipse and possibly other features such as the secondary optical minimum and the single minimum observed in the 2.2 μm light curve (King & Lasota 1979; Kruzewski 1978). However, the zero circular polarization at mid-eclipse indicates that only one pole is contributing to the optical circular polarization, so that the polarization curve can be discussed in terms of a single pole model.

The width of the polarization eclipse shows a decrease with increasing wavelength. Measured full widths at half eclipse are 0.31*P* at 0.55 μm, 0.23*P* at 0.68 μm and 0.17*P* at 0.83 μm. This behaviour is to be expected as cyclotron radiation at longer wavelengths arises from regions of weaker magnetic field further from the white dwarf. In the next section we will use the wavelength variation of the eclipse width, combined with the duration of the reversal in sign of the polarization, to determine the geometry of the system.

Changes in the polarization curve have clearly occurred since the 1976 and 1977 observations. When first observed in 1976 (Tapia 1977) the reversal of sign of the polarization in the *V* band lasted for 0.27*P* whereas our 1979 September observations show a duration of only 0.14*P*. Changes have also occurred in the polarization eclipse and its wavelength dependence. The implications of these changes will be discussed in Section 6.

5 A geometrical model

We assume that the white dwarf rotation axis has inclination i to the line-of-sight, and the magnetic axis is inclined at an angle θ to the rotation axis (see Fig. 5). We assume the cyclotron emitting region lies on the magnetic axis. The phase duration $\Delta\phi_R$ of the reversal of sign of the circular polarization is then given by

$$\cos(\tfrac{1}{2}\Delta\phi_R) = \frac{1}{\tan\theta\,\tan i}\,.$$

For the observed duration of $0.14P = 50.4$ degrees this gives the relation

$$\cot i = 0.9048\tan\theta\,. \qquad (1)$$

If the emitting region were on the surface of the white dwarf it would go into eclipse at the same phase as the polarization changes sign. This appears to be the case in VV Puppis where cyclotron radiation appears to be confined to a very small region around the magnetic pole (Liebert *et al.* 1978). In AM Her this would imply an eclipse duration of $0.86P$. As the observed eclipse duration is much shorter than this at all wavelengths, the emitting regions must lie at some distance from the surface of the white dwarf. For an emitting region on the magnetic axis at a distance R (in units of the white dwarf radius) from the centre of the white dwarf, the phase duration $\Delta\phi_E$ of the eclipse is given by

$$\cos(\tfrac{1}{2}\Delta\phi_E) = \frac{(1-1/R^2)^{1/2} - \cos\theta\cos i}{\sin\theta\,\sin i}\,. \qquad (2)$$

Since we do not know the heights of the emitting regions we cannot use this relation directly to obtain a second relation between θ and i and so determine the geometry. However, for

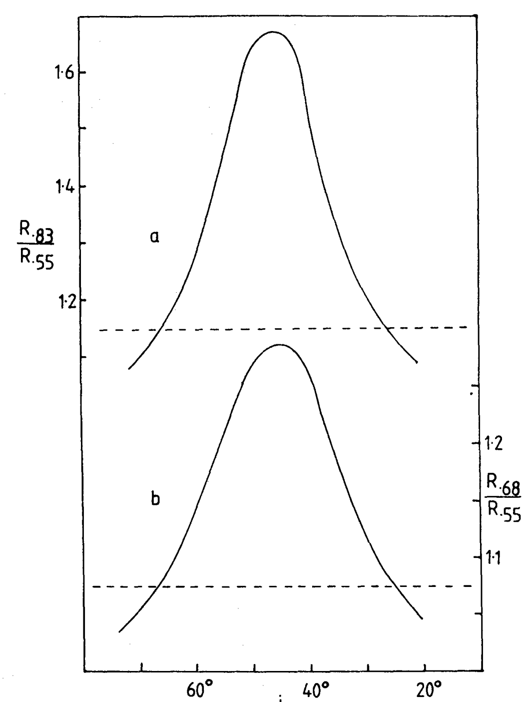

Figure 4. (a) Ratio of the heights of the emitting regions which give the observed eclipse widths at 0.83 and 0.55 μm as a function of inclination of the white dwarf rotation axis. The dashed line shows the ratio of heights expected for cyclotron radiation in a dipole field. (b) As (a) but using eclipse widths at 0.68 and 0.55 μm.

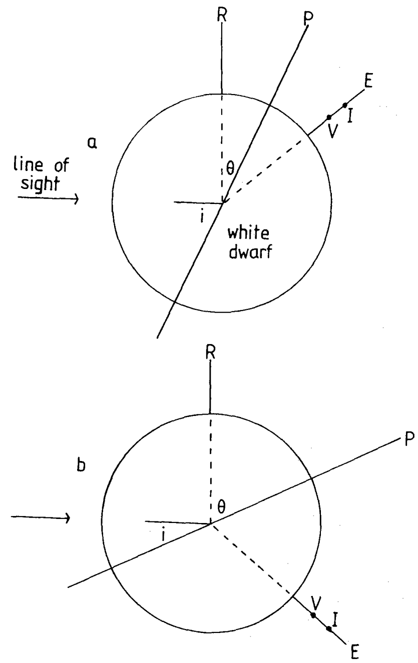

Figure 5. Two possible geometries for AM Her. P indicates the position of the white dwarf rotation axis, R the magnetic axis at polarization reversal (phase ~0.1), E the magnetic axis at polarization eclipse (phase ~0.6), V and I the locations of the cyclotron emitting regions at wavelengths of 0.55 and 0.83 μm respectively.

cyclotron radiation in a dipole field for which the flux $\propto R^{-3}$ we know that the ratio of the heights of the emitting regions at 0.83 and 0.55 μm must be $(0.83/0.55)^{1/3} = 1.147$.

Using equations (1) and (2) we have calculated the values of R which give the observed eclipse widths at 0.83 and 0.55 μm. The ratio of these values is plotted as a function of i in Fig. 4(a). Fig. 4(b) shows the results of the same calculation using the eclipse widths at 0.68 and 0.55 μm. It will be seen that there are two possible values of i for which the observed wavelength dependence of the eclipse width can be obtained. The resulting geometries for the system are shown in Fig. 5. Geometry a has $i = 66°$, $\theta = 26.2°$, geometry b has $i = 26°$, $\theta = 66.2°$. The emitting region at 0.55 μm lies at a radius of close to 1.24 in both geometries. This requires the surface field of the white dwarf to be $3.5/n \times 10^8$ G, where n is the number of the cyclotron harmonic observed. n is unlikely to be greater than 3 as we observe only one harmonic over the wavelength range studied.

6 Long term changes

Observations in 1976 (Tapia 1977) showed a polarization sign reversal lasting $0.27P$. This requires that relation (1) becomes

$$\cot i = 0.661 \tan \theta$$

implying a change in either i or θ. The polarization eclipse has also become deeper at a given wavelength from 1976 to 1979 (compare the data presented here with that of Michalsky *et al.* 1977). In the case of geometry a it is clear that a change in i is required to explain the observed changes. Keeping θ at 26.2° and putting $i = 72°$ instead of 66° will give the observed duration of the reversal in 1976. Such a change in i is physically plausible if we assume that the rotation axis of the white dwarf is inclined to the orbital axis of the binary system. Precession of the rotation axis about the orbital axis could then cause the changes required.

The time-scale of the changes observed would then require the precession period to be $\gtrsim 10$ yr.

For the value of i required in 1976 we can recalculate the expected eclipse width as a function of wavelength. At 0.55 μm the width should be $0.24P$ in reasonable agreement with observations. For 1976 geometry the model predicts no eclipse at wavelengths longer than 0.79 μm. The calculations refer to a point source, so a source of finite size might show a partial eclipse at slightly longer wavelengths but the eclipse depth should be less than 50 per cent. The polarization curves of Michalsky *et al.* (1977) show an eclipse of greater than 50 per cent at 0.69 μm (the model predicts an eclipse of width $0.12P$ at this wavelength). An eclipse of depth less than 50 per cent is present at 0.84 μm, while Priedhorsky *et al.* (1978a) observe no eclipse at 0.9 μm. These results are in excellent agreement with the predictions of the model

For geometry b the same changes would have to be caused by a 6° change in θ with i remaining constant. Such a movement of the magnetic axis does not seem plausible and so we regard geometry b as unlikely. It does, however, give equally good agreement with the 1976 observations. Possibly if the emitting region was positioned slightly off the magnetic axis, movement of the emitting region could give rise to the same effect as a change in θ. There is some evidence for such an off axis emitting region in our data. The polarization curves are not exactly symmetrical as the model would predict. Also the duration of the polarization reversal appears to be slightly shorter at longer wavelengths. Interpreted in terms of our model this would require θ to be ~ 1° different if determined from the long wavelength data. This might indicate that the accretion column curves slightly away from the magnetic axis. However, the effect seems too small to account for the 6° change required since 1976.

7 Discussion

We have described a model which can account for the wavelength and time dependence of the circular polarization curve. We now discuss its relation to other observed properties of AM Her. One problem with any model of AM Her is the observed linear polarization behaviour. Cyclotron radiation should show linear as well as circular polarization. When first observed (Tapia 1977), AM Her showed a sharp linear polarization pulse once per cycle. Similar behaviour is observed in other AM Herculis binaries, and mechanisms to explain such a pulse have been discussed by Stockman (1977). But we would expect to see two pulses rather than one per cycle since a pulse should be observed whenever the line-of-sight is perpendicular to the magnetic axis. (This corresponds to the two changes of sign of the circular polarization.) However, the linear polarization pulse in AM Her was observed to disappear during 1977 (Bailey *et al.* 1978), and recently the linear polarization has been low at all phases. We are unable to offer a convincing explanation for this behaviour, an understanding of which is clearly important for any detailed model of AM Her.

If all the radiation from the accretion column were due to cyclotron radiation then we would expect the photometric primary minimum at a given wavelength to have the same width as the polarization eclipse. In fact, although the photometric data show the same trend of decreasing width with increasing wavelength (Olson 1977; Priedhorsky *et al.* 1978b), the photometric minimum is always wider than the polarization eclipse at the same wavelength. Also the I band data of Priedhorsky *et al.* (1978a) show a photometric minimum but no polarization eclipse. This would suggest that a substantial proportion of the radiation from the accretion column is not due to cyclotron radiation and therefore does not follow the same wavelength–height relation as the polarized radiation.

An interesting test of our model would be to increase the wavelength range of the circular polarization data. For 1979 September geometry our model predicts a point source eclipse out to a wavelength of 1.1 μm. Thus we might expect to see a small partial eclipse in the J (1.25 μm) band but no eclipse at H (1.65 μm). This assumes that cyclotron radiation is still present at the corresponding heights in the column. To our knowledge no infrared circular polarimetry of AM Her has been obtained, although Szkody & Capps (1980) report an attempt to detect linear polarization at K (2.2 μm).

Another test of our model would be to remeasure the duration of the X-ray eclipse. If the X-rays are produced close to the surface of the white dwarf and at the opposite pole to the optical cyclotron radiation, the X-ray eclipse should have the same duration as the polarization reversal. Observations in 1976 showed an X-ray eclipse duration ~ $0.3P$ (Hearn & Richardson 1977) in good agreement with a polarization reversal of $0.27P$ (Tapia 1977). We would now therefore, expect the X-ray eclipse width to have dropped to around $0.14P$ due to the changes in orientation required by our model.

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