

DISCOVERY OF A MAGNETIC COMPACT STAR IN THE AM HERCULIS/3U 1809+50 SYSTEM

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ABSTRACT

Linear and circular polarization observed in the V and I spectral bands reveal the presence of a compact star with a magnetic field $B \sim 2 \times 10^8$ gauss. Large variations of both polarization states, with a period of 0.128918 days, appear to be caused by a rotation of the compact star. Unpolarized radiation observed in the U band suggest that a hot source, companion to the compact star, is unaffected by the magnetic field.

Subject headings: polarization — stars: U Geminorum — X-rays: sources

I. INTRODUCTION

Discovered by Wolf in 1924, AM Her has been under intense observation during the last year. The renewed interest stems, in general, from the work by Berg and Duthie (1977) that place the star in the category of the Z Cam-type dwarf novae and from the suggestion, by the same authors, that AM Her may be the optical counterpart of 3U 1809+50. Independently, and observing with the SAS-3 satellite, Hearn, Richardson, and Clark (1976) have discovered a variable soft X-ray source with an error box that contains the position of AM Her within the 95% confidence region. More recently, Priedhorsky (1977) and Cowley *et al.* (1976) have observed radial velocity variations in the optical emission lines pertaining to H, He, He II, and the broad feature formed by C III, N III, and O II at 4630–4655 Å. The radial velocity curve exhibits a semi-amplitude of ~ 300 km s $^{-1}$ and a period of about 3.1 hours. It now appears that the new soft X-ray variable (=3U 1809+50) and AM Her constitute the same system.

The purpose of this *Letter* is to report optical observations of AM Her that comprise broad-band photometry and measurements of linear and circular polarization. The results suggest some unique characteristics of this system.

II. OBSERVATIONS

The observations were obtained with the *Minipol* photopolarimeter described by Frecker and Serkowski (1976) attached to either the 2.29 or 1.53 meter reflector of the University of Arizona. An on-line minicomputer was used to provide simultaneous photometry and polarimetry, real-time reductions, and sampling times of 30 or 60 s. For the linear polarization measurements the instrument was used in its original design. Most of the linear polarization observations were made in broad spectral bands that approximate the U , V , and I standard bands. On four nights, measurements were made in a broad spectral band (centered at 4600 Å and half-peak bandwidth of 3000 Å) defined by a cooled S-11 spectral response. For circular polarization mea-

surements the polarimeter was modified following the precepts described by Serkowski (1974). A quarter wave plate, with 90° retardance at 5890 Å, was inserted in the beam as the first element of the analyzer. To avoid instrumental polarization produced by circular dichroism a Corning 3-70 filter was placed as the last element. This combination permitted measurements of circular polarization in the V band only. An observational test performed with the white dwarf Grw +70°8247 indicates that the linear-to-circular conversion of this modified polarimeter is less than 10^{-2} .

Differential photometry of AM Her was derived with respect to the $UBVR$ magnitudes of the star sequence defined by Meinunger (1960).

a) Linear Polarization

During the first attempt to measure the linear polarization of AM Her, on 1976 June 4, it was noted that the uncertainty of the results was larger than the value corresponding to the photon statistics of the incoming signal. On that occasion, after a few minutes of integration the average linear polarization of AM Her was less than 0.4% in the U and V bands. Variations of linear polarization were discovered on 1976 June 27 (JD 2,442,956.5), when AM Her was observed for a second time. The U band, sampled first, did not reveal differences from the former observations. However, during the measurements with the V band the linear polarization suddenly started increasing its value by about 1% per minute. It reached 5.3% and then decreased, at approximately the same rate. Similar variations of the linear polarization observed on four subsequent nights were sufficient to determine that such variation reappears with a period of 3.094 hour. Afterward the observations were scheduled according to this period. Table 1 lists 13 maxima of linear polarization observed during the two month term ending on 1976 August 27. Column (1) presents the time of the recorded maximum polarization to an accuracy of ± 45 s. Column (2) states the spectral band used. The registered maximum polarization and its position angle are

TABLE 1
OBSERVED MAXIMA OF LINEAR POLARIZATION

HJD 2,442,000+ (1)	Spectral Band (2)	$P_{\max}$ (%) (3)	θ (degrees) (4)	Sequence Number (5)	Sample Time (s) (6)
956.879.....	V	5.3 ± 0.5	152	-449	60
963.841.....	V	5.0 ± 0.4	150	-395	60
978.925.....	S-11	4.3 ± 0.2	156	-278	30
1004.836.....	S-11	3.9 ± 0.2	152	-77	60
1005.740.....	S-11	3.1 ± 0.2	150	-70	30
1005.870.....	S-11	4.2 ± 0.2	157	-69	30
1006.642*....	U,V	6.0 ± 0.7	150	-63	30
1006.772*....	U,V	6.8 ± 0.5	155	-62	30
1009.734.....	I	5.8 ± 1.3	154	-39	60
1014.765*....	U,V	5.1 ± 0.7	148	0	30
1016.698*....	U,V	4.6 ± 0.3	153	+15	30
1016.823.....	I	4.7 ± 0.7	168	+16	60
1017.730.....	V	5.6 ± 0.4	156	+23	60

* U and V bands alternated. Polarization in the U band is less than 0.5%.

reproduced in columns (3) and (4). The sequence numbers of the 13 maxima, relative to the maximum observed on 1976 August 24.265 (J.D. 2443014.765), are presented in column (5). The last column gives the sampling times used to monitor the variations.

On three different nights the U and V bands were alternated, over 30 s sample time, in order to examine the wavelength dependence of the polarization. The results indicate that the linear polarization measured in the ultraviolet remains below the 3σ level throughout the periodic variation registered in the V band. Figure 1 displays the U (circles) and V (dots) results secured on 1976 August 16 (JD 2,443,006.5). Error bars of 1σ have been added to the polarization values in the V band. Uncertainties of the same magnitude affect the polarization measured in the U band. The weakness of the ultraviolet polarization indicates that a very steep wavelength dependence is present at the time of maximum linear polarization in the V band. Null ultraviolet polarization also causes the lower maxima observed with the S-11 band.

Two linear polarization maxima were observed with the I band. Data from this band contain about twice

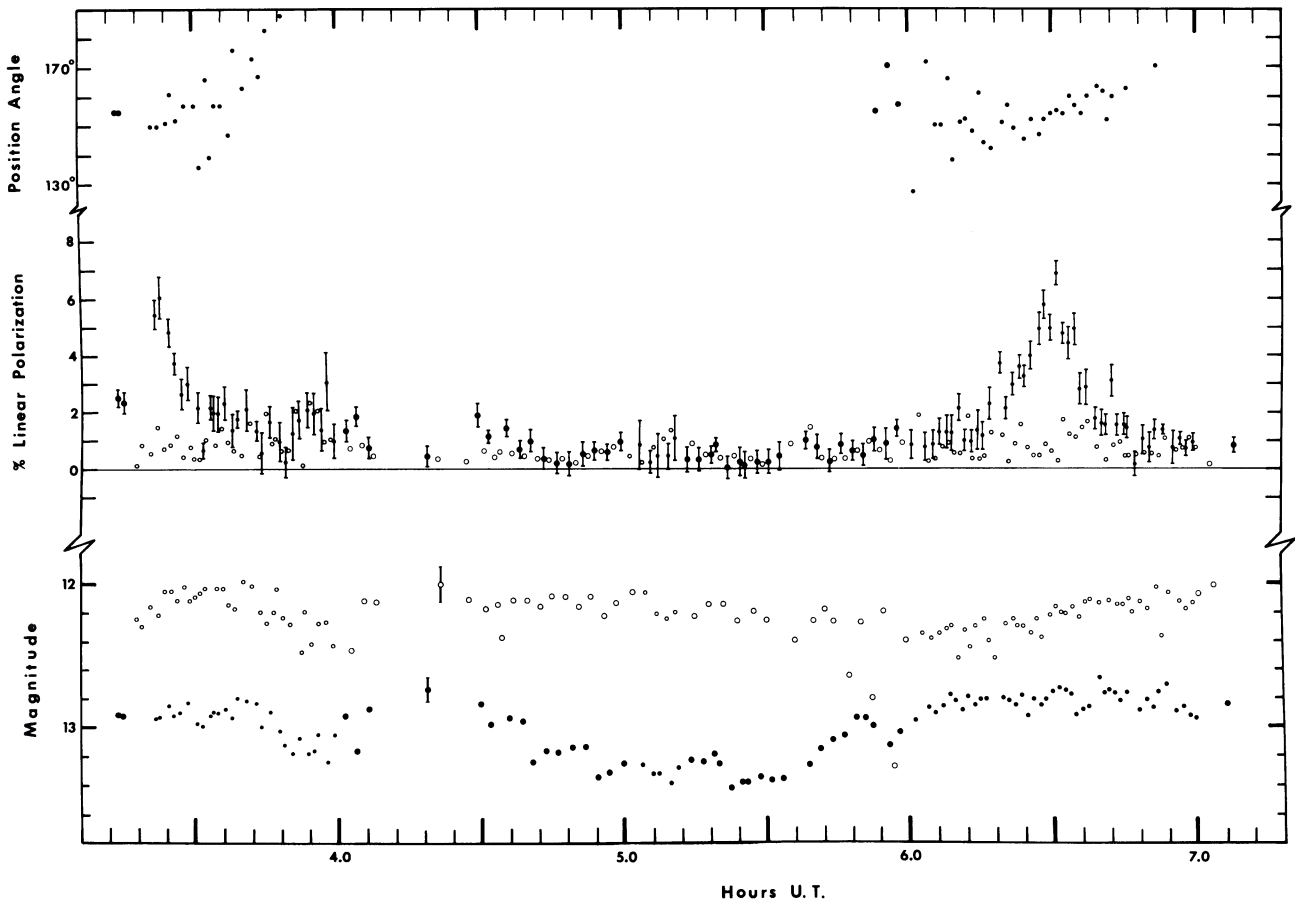


FIG. 1.—Upper, linear polarization observations and (lower) photometry of AM Her obtained on 1976 August 16 (JD 2,443,006.5). Small and larger symbols indicate sample times of 30 and 60 s, respectively. Dots are used for data from the V band. Circles represent data from the U band. One standard deviation error bars have been added to the polarization observed in the V band. The accuracy of the other data is explained in the text.

the uncertainty that is present in the V band. Nevertheless, the results indicate that (i) the variation of polarization in the near-infrared displays the same pattern as observed in the V band and (ii) the period and the phase of the maximum polarization are the same in both spectral regions.

The behavior of the position angle of linear polarization, θ , is presented in the upper part of Figure 1. The uncertainty of θ is given by the relation $\sigma(\theta) = 28.6^\circ \times \sigma(P)/P$, where P is the amount of polarization. Values of θ for which $|\sigma(\theta)| < 20^\circ$ have been plotted in Figure 1. In general, at the time of maximum polarization $\theta = 155^\circ \pm 5^\circ$. However, it appears that θ changes from $\theta \approx 150^\circ$ at the peak to $\theta \approx 170^\circ$ after the peak of linear polarization. With similar uncertainty the same effect is observed in the 13 events listed in Table 1.

The sharp maxima of linear polarization provide an accurate ephemeris. Linear regression between the heliocentric times presented in Table 1 and their sequence numbers renders

$$\text{HJD} = 2443014^d 7647 + 0^d 128918 \text{ E} \\ \pm 5 \quad \quad \quad \pm 9$$

to 99% confidence level. This ephemeris improves and supersedes the early elements communicated by Tapia (1976).

b) Circular Polarization

These observations were obtained on 1976 September 17 and 18 with the polarimeter attached to the 2.29 m reflector. The results are presented in Figure 2 in terms of the phase computed with the ephemeris given above. Phase 0.0, corresponding to the time of *maximum linear polarization*, was covered three times. The sign of the circular polarization has been determined according to the *angular-momentum convention*. In other words, the circular polarization is positive when the optical E -

vector carries positive angular momentum to the observer.

The circular polarization of AM Her, as observed in the V band, is remarkable in terms of its strength and the elaborate periodic variation. The near coincidence of the maximum linear polarization with the change of sign of the circular polarization, at phase 0.0, provides conclusive evidence for a common origin of both polarization states.

Angel and Stockman (1976) have confirmed that the circular polarization displays the same wavelength dependence observed for the linear polarization.

c) Photometry

Flickering, of the type discovered by Berg and Duthie (1976), seems to provide the main source of error for the magnitudes reported here. Variations with time scale of a few minutes are evident in the U and V photometry secured on 1976 August 16 (JD 2,443,006.5) and plotted in the lower part of Figure 1. In addition to these variations, the V and R magnitudes show a modulation with the period of 3.094 hours. The brighter phase of the modulation coincides with the maximum of linear polarization, and the amplitude reaches about 0.5 mag. The same periodic variations have been observed by Cowley *et al.* (1976). These authors refer their observations to the minimum of the light curve; the maximum of linear polarization is observed four tenths of the period after the photometric minimum.

A 3.094 hour modulation in the U magnitude is very small, or nonexistent, in the data available. Absence of modulation in the ultraviolet is also consistent with small increases of brightness registered in the S-11 band during four maxima of linear polarization.

The long-term photometric variations that led to the early classification of AM Her as an irregular variable

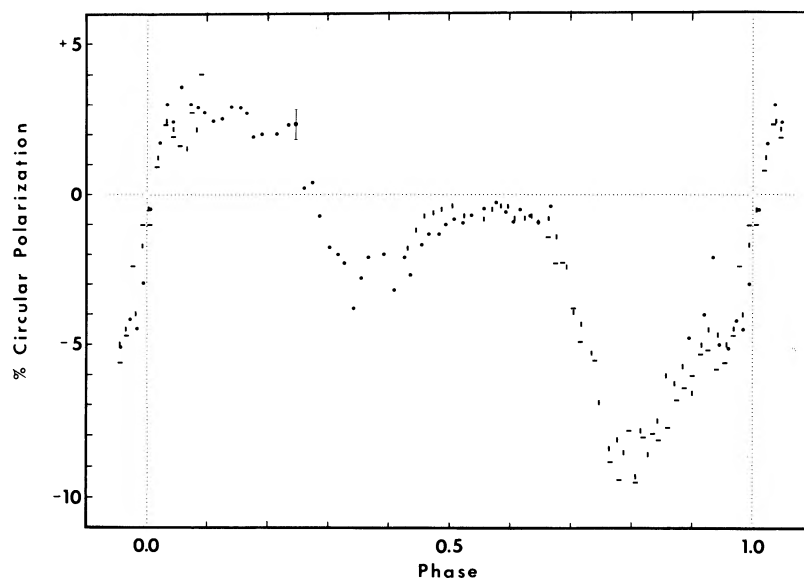


FIG. 2.—Circular polarization of AM Her observed in the V band. The data, obtained on 1976 September 17 (presented with dots) and 18 (presented with bars), have been plotted in terms of the phase derived with the ephemeris given in the text. Vertical and horizontal bars represent measurements made with the polarimeter at two perpendicular orientations. Error bars typical of two standard deviations are also indicated.

(Beyer 1950) were also present during the time covered by these observations. *UBVR* photoelectric magnitudes obtained at different dates, since the polarization observations were started, are collected in Table 2. The different spectral bands were observed in sequence and, in general, near the minimum of the light curve ($0.2 < \text{phase} < 0.8$) observed in the *V* and *R* bands. Allowing for the permanent flickering of the observed flux, the uncertainty of the individual magnitudes is estimated at ± 0.15 mag.

Color indices derived with these data trace two components of the energy distribution. A blue component is indicated by the ultraviolet flux and its lack of modulation over the 3.094 hour period. This component, which can be roughly characterized by $(U - B) \approx -1.1$ mag, was present throughout the 2.5 mag increase in brightness observed during 84 days. In addition, the redder bands reveal a component with $(V - R) \approx +0.9$ mag on the average. The independence of this component from the ultraviolet flux is outlined by the 3.094 hour modulation observed in both the *V* and *R* magnitudes. Fewer in number, however, and obtained only during the brighter level of AM Her, the *R* magnitudes are insufficient to describe the long-term evolution of the red component.

III. DISCUSSION

The polarization observed in the optical flux of AM Her provides strong evidence for cyclotron emission of hot electrons in a magnetic field of the order of 10^8 gauss (Ingham, Brecher, and Wasserman 1976). Radiation from this process exhibits both states of polarization in about the same percentage. Up to now, similar polarization has been observed only in nine white dwarf stars—a fact that favors a white dwarf for the seat of the magnetic field in AM Her also. Admittedly, a white dwarf and a short period are consistent with previous

observational results that appear to characterize AM Her as a dwarf nova. However, the wavelength dependence of the polarization observed in AM Her demands a different scenario.

On the one hand, there is the polarized radiation that appears in the photometry as the red component of the observed energy distribution. To the extent that the source is cyclotron emission, its location is in the magnetosphere or at the Alfvén surface that surround the magnetic star. The shortest wavelength of this radiation determines, via the definition of the Larmor frequency, the strength of the magnetic field. In AM Her the shortest wavelength is about 5000 Å, which corresponds to $\sim 2 \times 10^8$ gauss. Because magnetic fields in excess of 10^7 gauss are not possible in main-sequence stars, the magnetic object in AM Her should be a compact star. On the other hand, there is the unpolarized ultraviolet radiation of the blue component detected by broad-band photometry. Lack of circular polarization is sufficient to indicate that the source of this radiation is located outside the Alfvén surface of the magnetic star. Consequently, the observations presented here suggest a system formed by a magnetic star, from which only cyclotron emission is observed, and a blue source unaffected by the magnetic field.

The location of the X-ray source in this system is not evident, however. According to Hearn, Richardson, and Clark. (1976) the soft X-ray source 3U 1809+50 is relatively nearby, the total flux observed above 100 eV is $F_x \sim 1.1 \times 10^{-10}$ ergs cm $^{-2}$ s $^{-1}$, and contains no clear indications of interstellar X-ray extinction. Assuming that the distance to the source lies in the range between 50 and 400 pc, the value of F_x translates into a range of luminosity $0.01 L_\odot \leq L \leq 0.5 L_\odot$. Since the soft X-ray spectrum corresponds to a rather cool source, its equivalent blackbody temperature is in the vicinity of 10^5 K. Therefore, the region where the X-ray luminosity is produced has a radius between 2×10^7 and 2×10^8 cm, namely, the size of a degenerate dwarf. The relatively large dimensions of the emitting region eliminate the magnetic poles of the compact star as the X-ray source.

These inferences are based mainly on observations obtained during the brighter level of the long-term variation. However, dramatic changes at minimum light are unlikely, as indicated by the near constant color index of the blue component in the energy distribution. In conclusion, it seems that the AM Her/3U 1809+50 system departs significantly from the canonical models available for close X-ray binaries.

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TABLE 2
LONG-TERM PHOTOMETRIC VARIATIONS

JD 2,442,000+	MAGNITUDE				PHASE*
	<i>U</i>	<i>B</i>	<i>V</i>	<i>R</i>	
933.86.....	14.5	15.2	15.1	...	0.43
956.88.....	13.1	14.3	14.0	...	0.99
957.86.....	13.4	14.3	14.1	...	0.60
963.94.....	...	...	14.0	...	0.76
964.96.....	...	14.4	...	...	0.67
978.96.....	...	13.4	...	...	0.26
1002.70.....	...	...	...	12.0	0.41
1004.80.....	...	13.3	13.0	11.9	0.70
1006.79.....	12.1	13.2	12.8	...	0.14
1009.69.....	12.4	13.6	13.4	12.1	0.63
1014.75.....	...	...	12.7	...	0.88
1016.73.....	11.8	13.0	12.6	11.9	0.24
1017.77.....	11.9	13.1	12.9	12.3	0.31
1038.83.....	...	...	12.9	...	0.66
1039.79.....	...	...	12.6	...	0.12

* In terms of the 3.094 hour period.

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