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THE 1979 MINIMUM STATE OF AN URSAE MAJORIS

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ABSTRACT

We report spectrophotometry, photometry, and circular polarimetry of the magnetic binary AN UMa during 1979 February/March when it reached a very low state of $B \sim$ 19–20, 2 mag fainter than ever observed previously. The B light curve was generally similar in shape to that for the high state, though only ~ 0.6 of a period was covered. The energy distribution became markedly redder compared to that in higher states; the I magnitude had dropped only to ~ 17. The low-state I-band circular polarization reached a peak value of -35%, which is considerably stronger than in the high state; thus the presumed cyclotron funnel source remained dominant, at least at red wavelengths. The spectrophotometry at $V \sim 17.5$–18.5 showed a red continuous energy distribution, only weak Hα emission, a probable very broad emission feature (λ4880) near Hβ, but no evidence for strong absorption features from the secondary or magnetic primary.

The increased I polarization and reddened energy distribution may be explained by decreased optical depths in the cyclotron funnel at a much lower rate of mass transfer. It is possible that the strange λ4880 feature could be due to a cyclotron harmonic in emission, in which case $B \gtrsim 3.5 \times 10^7$ gauss. We derive lower limits to the system's distance as a function of the secondary star's type. An updated magnetic ephemeris is also given.

Subject headings: polarization — stars: binaries — stars: individual — stars: magnetic

I. INTRODUCTION

AM Herculis systems are short-period mass-transferring binaries containing magnetic degenerate primaries. Aside from regular variations within the binary period, they show irregular long-term changes in average brightness characterized by occasional drops to much fainter magnitudes than normal. Since these systems are believed to lack an accretion disk around the primary, the average brightness would directly reflect changes in the accretion rate. Careful study of such systems in "low" brightness states offers excellent opportunities to test the basic physical model. First, the reduced gas flow might be simpler than the flow during "high" states and the origins of both line and continuous radiation may be more localized. Second, if the flow were curtailed enough, we might have the opportunity to observed directly the surfaces of the primary and secondary stars, as was shown for AM Her itself in 1980.

Of the four established AM Her systems, AM Her and VV Pup have the best-known long-term histories and have also been studied with modern instrumentation during low states. While AM Her normally shows a striking high-excitation emission-line spectrum, the He II and He I features were lacking on Bond and Tifft's (1974) original spectrum and during the 1980 low-state observations by several groups (Schmidt, Stockman, and Margon 1981; Latham, Liebert and Steiner 1981; Hutchings, Crampton, and Cowley 1981; Young, Schneider, and Schectman 1981; Patterson and Price 1981); a lower-excitation emission-line spectrum was still present. VV Pup is known to take even deeper plunges from maximum brightness, at which time its normal emission-line spectrum is drastically weakened or even absent (Thackeray, Wesselink, and Oosterhoff 1950; Liebert *et al.* 1978). The secondary star was easily measured in AM Her and was probably detected in VV Puppis. More importantly, however, low-state observations permitted the first measurements of magnetic field strengths of the primary stars—13–20 megagauss in AM Her from Zeeman absorption lines by the groups cited above, and about 30 megagauss for VV Pup from cyclotron-harmonic absorption features (Visvanathan and Wickramasinghe 1979; Stockman, Liebert, and Bond 1979).

AN UMa was the second AM Herculis system to be discovered (Bond and Tifft 1974; Krzeminski and Serkowski 1977). The available photographic plate material indicated that the object varied irregularly over an m_{ph} range of 14.5–17.5 (Meinunger and Wenzel 1968; Mein-

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unger 1976), in addition to the ~ 0.6 mag variations within a binary period (Krzeminski and Serkowski 1977). Meinunger's plates and photoelectric photometry by Mumford (1977) show that it reached at least $B \sim 15$ in 1975–1976, around the time of Hearn and Marshall's (1979) X-ray detection. Thus, Szkody and Capps (1980) and Szkody *et al.* (1981) assumed that their 1977 and 1979–1980 observations with $V \sim 16.5$–17 mag pertained to the object's "low" state. However, we are aware of no published or unpublished photoelectric photometry showing the object brighter than 16.0 in U, B, or V since 1977 January. Dr. J. L. Greenstein (1980, private communication) graciously provided us plots of two Palomar 5 m multichannel spectrophotometer observations obtained on 1977 January 14 and March 30 (U.T.) at $m_{5500\,Å} \approx 16.3$. Five nights of observations by Gilmozzi, Messi, and Natali (1981) between 1978 December 8 and 1980 February 8 are interleaved with the times of the Szkody *et al.* (1981) observations and indicate similar *UBV* behavior. Thus photoelectric observations of AN UMa in a truly high state are few and spectroscopic observations may be nonexistent, since most were obtained after 1976. Note that the soft X-ray flux has varied over a factor of 40 (cf. Hearn and Marshall 1979; Szkody *et al.* 1981).

On 1979 February 26, AN UMa was found to be much fainter at $B \sim 19$, as communicated by Liebert, Bond, and Grauer (1979). Over the period February 27–March 1, we were able to obtain simultaneous circular polarization measurements. These data allowed us to evaluate whether accretion was still occurring at all in the AN UMa system and to compare its properties with those of VV Pup and AM Her. In § II we present the three types of observations, followed by interpretation in § III. By 1979 April 21, we found AN UMa at $B \sim 16.5$, similar to the Szkody *et al.* results for 1979 May. Our earlier observations are flanked by the Gilmozzi *et al.* results for 1979 Jan. 31. Thus, the *very* low state of AN UMa we describe here lasted less than 3 months, but could represent a deep minimum within a relatively low state lasting several years.

II. OBSERVATIONS

a) *Spectrophotometry*

On 1979 February 26 (all dates herein are UT) AN UMa was found to be unusually faint by J. L. during a 46 min series of spectrophotometric observations with the Steward 2.3 m reflector, Cassegrain spectrograph, and intensified Reticon system. Arrangements were made with H. E. B. and A. D. G. for simultaneous broad-band photometry the following night, and 65 minutes of simultaneous observing were obtained before the onset of thin clouds prevented any continuation. Both spectrophotometric observations were obtained with a 600 lines mm^{-1} grating in first order, affording coverage from 4100 to 7700 Å but at only about 15 Å resolution. The wavelength coverage matches fairly well the response of the four-stage Varo image-tube package. Twin circular apertures with 3".5 diameters were used for simultaneous object and sky observations. This intensified analog Reticon system, and the observational and data reduction techniques, are discussed in Hege, Woolf, and Cromwell (1979).

On February 26, AN UMa remained near $m_{6000\,Å} \sim 17.5$ for four 8 min scans, the sum of which is presented in Figure 1*a*. On February 27 weather conditions were not perfect, though the object appeared to be genuinely fainter at around $m_{6000\,Å} \sim 18.5$. The sum of eight individual scans covering 80 minutes (magnetic phases 0.82 through 0.52) is shown in Figure 1*d*; the wavelength range of the latter is truncated to exclude the hopelessly noisy ends. For contrast, a February 26 observation of AM Her and a 1978 April 29 observation of AN UMa in higher states, both with the same spectrograph parameters, are also displayed.

On both February 26 and 27, AN UMa showed a considerably redder energy distribution over the observed wavelength interval than is the case in its high state (Fig. 1); in fact, the slope matches fairly well the distribution for AM Her. There is no convincing evidence for the absorption pattern of a late M secondary star, or for strong Zeeman absorption features of Hα or Hβ, as recently discovered for AM Her (Schmidt, Stockman, and Margon 1981). The normal emission-line spectrum appears considerably weakened on February 26 and 27 relative to normal (cf. Bond and Tifft 1974; Schneider and Young 1981). A fairly narrow Hα line is seen on both nights, along with some puzzling, broad emission features. The feature near the position of Hβ appears considerably broader and stronger than Hα, especially on 26 February. Likewise, there is a broad emission structure near λ5850 on both of the sums which is not ascribable to He I λ5876 alone.

A number of precautions useful for evaluating such weak features were taken both at the telescope and in the data reduction: spectra of VV Puppis (which was 1 mag brighter) taken just before AN UMa showed no such features in its faint-phase continuum (Stockman, Liebert, and Bond 1979), but did show cyclotron harmonics in absorption during the object's bright phase, as independently discovered by Visvanathan and Wickramasinghe (1979). Likewise, 5 min continuum lamps were measured at the telescope position of AN UMa on February 26, and at the next telescope position on February 27. Flat-field divisions using these lamps instead of an average of those taken at the beginnings and ends of the nights had no appreciable effects on the appearance of the broad structures. Finally, three bright "light bulb" white dwarfs were observed to provide a final check on the lamp division, since the lamp fills the entire entrance aperture and follows a different optical path to the detector from that of the starlight: L745-46A (EG 54) was observed immediately before VV Pup on 26 February, Ross 627 (EG 79) immediately after an AN UMa on 27 February, and the reddish DC star Wolf 489 (EG 100) was scanned after Ross 627. No star showed any hint of corresponding broad features.

No amount of precaution, however, can make up for a lack of photons, and we must worry about the systematic

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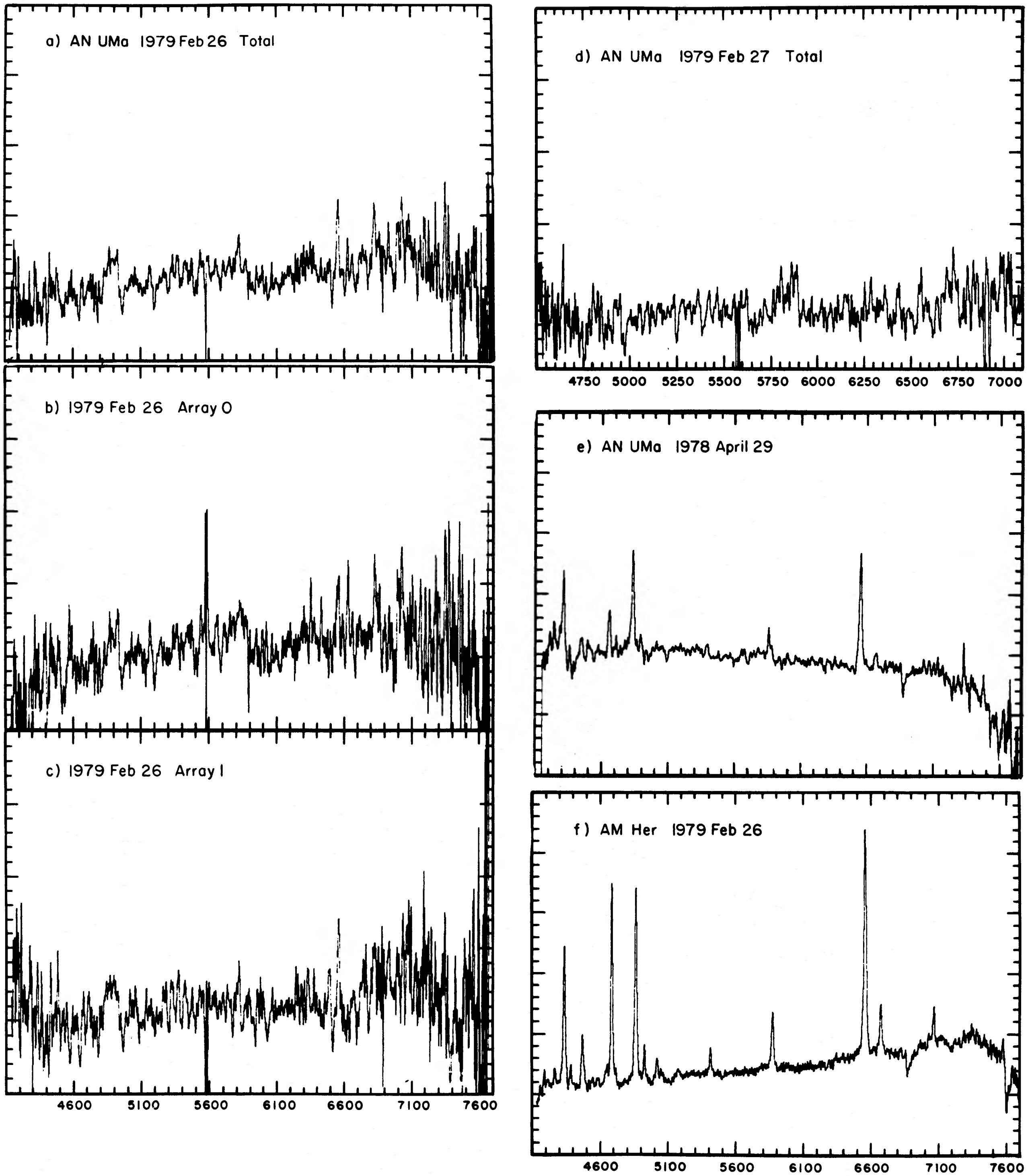


FIG. 1.—Steward 2.3 m Reticon spectrophotometry of AN UMa and AM Her. Relative fluxes per unit frequency interval, with zero at the bottom, are plotted against wavelength in angstroms. (*a*) AN UMa on 1979 Feb. 26, sum of both arrays; (*b*) 1979 Feb. 26, array 0 only; (*c*) 1979 Feb. 26, array 1 only; (*d*) 1979 Feb. 27, with AN UMa at mag. 18.5, the very noisy end wavelengths are omitted; (*e*) AN UMa on 1978 Apr. 29 in its high state; (*f*) AM Her on 1979 Feb. 26, in its high state.

noise properties of the intensified Reticon detector at low light levels. Pulses similar in width to our emission lines may be produced sporadically by cosmic rays and ion events, though the data acquisition algorithm can identify and reduce these to a level similar to photon events, if the threshold is properly set (Hege, Wolfe, and Cromwell 1979). Thus it is of considerable importance to note (Fig. 1) that the broad 4880 Å feature clearly appears in both independent array sums on February 26; it is present with reduced width and strength on February 27, though at 50 Å width it is still much broader than the corresponding weakened Hα feature. Also, we did not find spurious emission "bursts" at this wavelength on any of the three individual noisy scans making up the February 26 sum, or the eight comprising the February 27 sum. As far as we can judge, the feature was present throughout the time-resolved sequences. The chances thus seem good that the feature is real, but we simply cannot rule out a chance superposition of strong ion events tending to reinforce a narrow Hβ line from the star. The case for the 5850 Å feature is not so strong: It is weak at best in the February 26 "1" array sum, and appears shifted in part to longer wavelengths on February 27. Narrower features appear near the red and blue ends of the arrays where the system sensitivity is low, but do not appear on both of the February 26 and 27 sums.

If the 4880 Å feature *were* real, it would seem necessary to look for an explanation other than the Hβ transition. If the Hβ transition were broadened due to kinematics or Zeeman splitting, the effect at Hα should be seen at least as easily. Furthermore, for magnetic broadening the centroid of Hβ should be shifted blueward, not redward, of the rest wavelength. Yet we cannot invoke any set of high- or low-excitation lines at 4830–4930 Å likely to produce such a distinct blend. This feature and the λ5850 feature cannot be ascribed to TiO band edges from a late-type secondary star, since the much stronger bands at λ6200 and λ6800 simply do not appear—see, for example, the spectrum of the AM Her secondary star obtained with the same spectrophotometer in Latham, Liebert, and Steiner (1981). The peculiar appearance of the Hα emission line in the AM Her low state spectrum was attributable to Zeeman absorption for which there is no evidence here. We discuss an alternative explanation for the possible emission features in § III.

b) Photometry

The broad-band photometry was obtained by H. E. B. and A. D. G. with the No. 2, 0.9 m reflector at Kitt Peak National Observatory on 1979 February 27. A crystal $CuSO_4$ filter was used, giving a broad blue bandpass (5500 Å down to the atmospheric cutoff). Each point in Figure 2*a* represents the sum of five 10 s integrations. The total counts per 50 s integration are plotted against Heliocentric Julian Date (HJD) and magnetic phase, and the counts have been corrected for sky background and extinction (which was determined by occasionally measuring a comparison star which lies 1.′8 east and 0.′2 south of the variable). Two *UBV* measurements of the comparison star give $V = 12.07$, $B - V = 0.66$, $U - B = 0.23$.

The conversion from counts to blue magnitude is shown on the right-hand side of Figure 2*a*; it was assumed that the comparison star has $m_{\rm blue} = 12.73$. AN UMa was below 18.5 mag throughout our observations, which were terminated by the onset of clouds. The variable was rather fainter than one normally attempts with an 0.9 m telescope; however, although invisible to the eye, the star was readily located by a blind offset.

It is instructive to compare this light curve with the smoothed light curve of Krzeminski and Serkowski (1977), obtained for AN UMa at $B \sim 16.0$–16.5. Both light curves show a maximum at, or slightly after, phase zero, followed by a decline to minimum near phase 0.35. Remarkably, even though AN UMa was more than 2 mag fainter at the time of our observations, both light curves show nearly the same amplitudes, about 0.5–0.6 mag. Our light curve also may show at least one prominent flare above the noise level, at phase 0.1. Another AM Her object, 2A 0311−227, also shows a maximum just after phase zero, a decline to a minimum around phase 0.4, and active flickering at maximum light (Bond, Grauer, and Chanmugam 1979).

A more direct comparison with a higher state light curve is provided by similar 3300–5500 Å blue photometry of AN UMa obtained by H. E. B. on 1980 April 11, shown in Figure 2*b*. The Louisiana State University 0.9 m and two-star photometer (Grauer and Bond 1981) with an unfiltered EMI 9840 PMT was used. Counts in 15 s integrations are plotted, showing better time resolution than that published by Gilmozzi, Messi, and Natali (1981) and Szkody *et al.* (1981). A second photomultiplier tube was used to monitor a nearby comparison star simultaneously; these comparison counts were used to divide out extinction and small variations in atmospheric transparency. Again the general shape and amplitude of the brighter light curve is similar to that in the low state, but there may be greater flickering activity in the high state. If so, this would be a behavior opposite to that seen in normal dwarf novae, which show the most conspicuous flickering when they are at minimum light.

c) Circular Polarimetry

AN UMa was observed by S. T. for one complete cycle each on 1979 February 28 and 1 March (UT) with the Minipol polarimeter (Frecker and Serkowski 1976) on the Catalina Station 1.53 m reflector of the University of Arizona Observatories. At magnetic phase 0.9 on February 28, approximate broad-band magnitudes (fluxes) for the object were obtained as follows: $B = 20.2 \pm 0.3$ (3.7×10^{-28} ergs cm^{-2} Hz^{-1} Hz), $V = 19.8 \pm 0.3$ (4.6×10^{-28}), $R_{\rm J} = 18.3 \pm 0.4$ (1.44×10^{-27}), $I_{\rm J} = 17.0 \pm 0.5$ (3.85×10^{-27}). The magnitudes on the Johnson system are estimated using standard stars and mean extinction coefficients. The results indicate that the object had faded still another magnitude in *B* from February 27, yet was still relatively bright at *I* (λ8500 ± 500 Å). Palomar multichannel scans of AN UMa in a higher state by Greenstein (1980, private communication) and Lick image-dissector scanner observations by Kwitter and Margon (1978) show monochromatic fluxes at *I* compar-

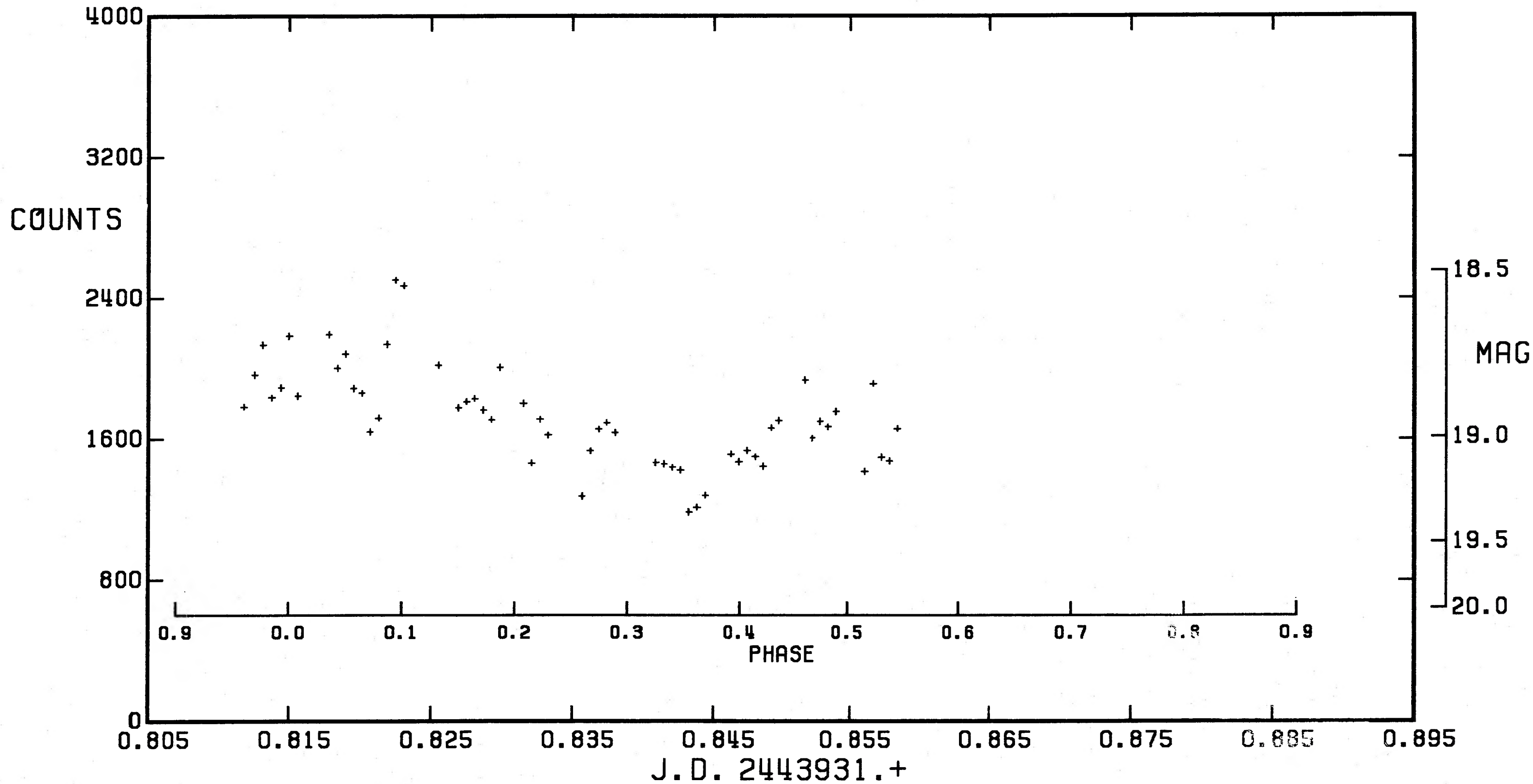
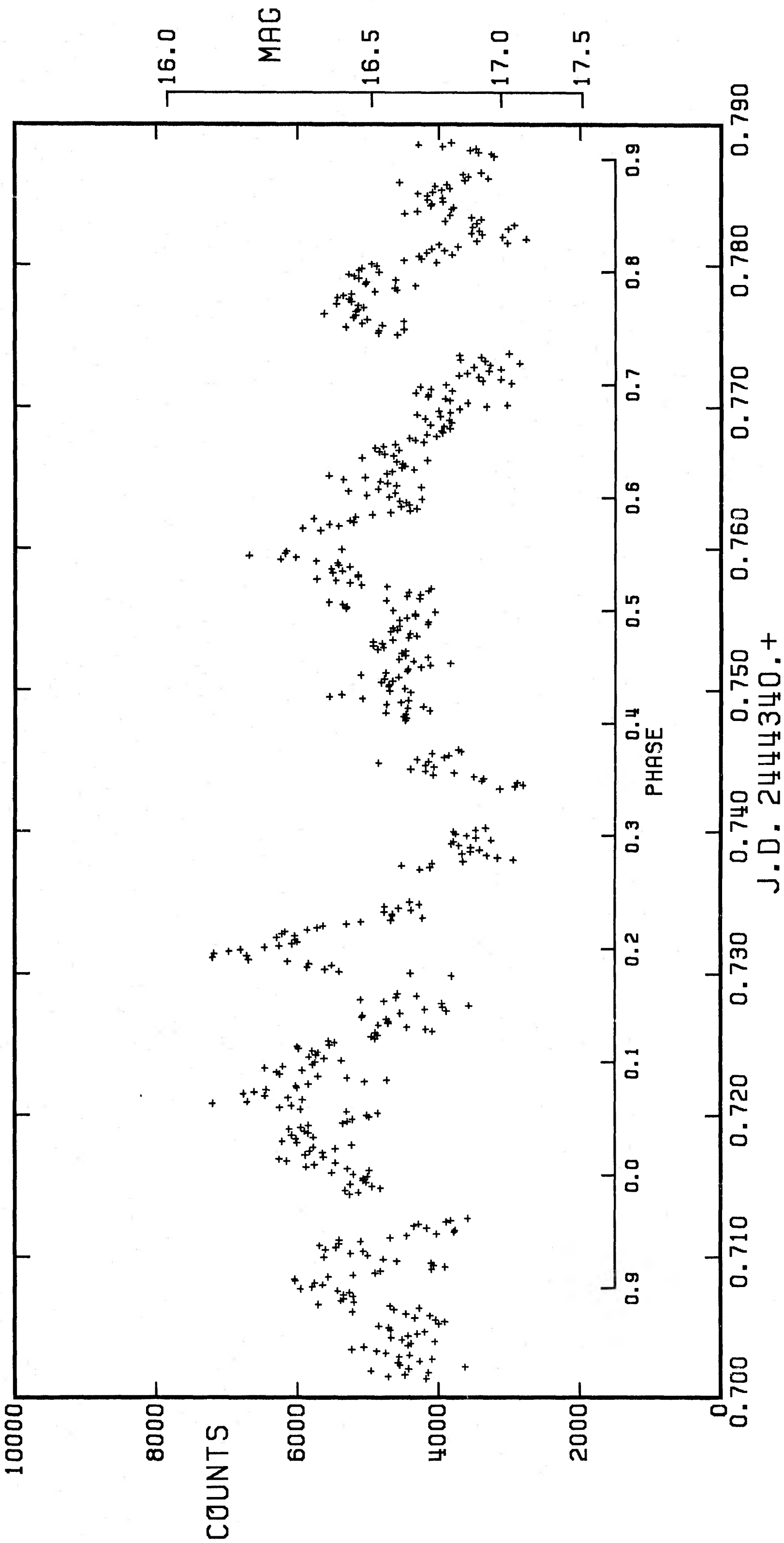


FIG. 2*a*

FIG. 2.—(*a*) Kitt Peak No. 2 0.9 m photometry on 1979 Feb. 27. The use of a $CuSO_4$ filter allowed broad bandpass measurement from 3300–5500Å. Data are plotted in 50 s integrations, and are corrected for sky background and extinction. (*b*) A comparison light curve of AN UMa in its high state, 1980 Apr. 11, obtained at the Louisiana State University 0.9 m. The bandpass is similar but the data are plotted in 15 s integrations.


COUNTS
10000
8000
6000
4000
2000
0
MAG
16.0
16.5
17.0
17.5
PHASE
0.9
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0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
0.700
0.710
0.720
0.730
0.740
0.750
0.760
0.770
0.780
0.790
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FIG. 2b

able to those at V and B. Thus, AN UMa is normally bluer than AM Her over 4000–10,000 Å. It became decidedly redder in its low state, with $(V - I)_J$ resembling an M3 V star (Johnson 1964). However, the absence of an M-dwarf spectrum contribution out to 7500 Å demonstrates that the bulk of this color change is not due to the emergence of a late-type stellar spectrum.

The object was observed polarimetrically at the I band for one binary period on each of two consecutive nights, as shown in Figure 3. We did not attempt with the 1.53 m telescope to monitor the polarization in the fainter colors. For comparison, two complete I-band cycles were obtained in 1979 April, at more normal brightness levels ($B \sim 16.5$, $I \sim 15.5$); these data are also presented in Figure 3. Comparison with the earlier data of Krzeminski and Serkowski (1977) indicates that AN UMa in a higher state has a larger polarization amplitude in U, B, and V than it does at I. While the I polarization curve shows a single broad maximum, like the U, B, and V curves, the maximum I-band polarization (at magnetic phase ~ 0.5) reached $\sim -19\%$ on 1977 April 23 and 25. Our low-state I observations again show polarization and photometric light curves similar in shape to the 1979 April data, but the amplitude was larger at $\sim 35\%$: It should also be noted that the circular polarization reached essentially zero near phase 0, the time of the linear polarization pulse, in both sets of I-band data, though the peak polarization occurred ~ 0.1 phase later in the low state data.

The results leave no doubt that the cyclotron source remained on and accretion was presumably still happening in AN UMa during these low-state observations, but we are unable to say much about the origin of the B and V radiation. If the cyclotron source reached $\sim 100\%$ polarization due to reduced optical depth (§ III), it must have contributed a minimum of 30% of the I radiation.

All magnetic phases in this paper are based on an updated ephemeris, derived from 18 linear polarization pulses observed over the span of 1977 February 16 to 1981 February 6 (18,193 cycles):

$$\mathrm{HJD} = \underset{\pm 0.0002}{2443190.9921} + \underset{\pm 0.00000003}{0.07975320}E.$$

III. DISCUSSION

a) The Funnel Source at Minimum

The large infrared polarization and shift to redder color exhibited by AN UMa in its low state can be explained qualitatively by recent theoretical work: It is believed that the polarized optical radiation in AM Her objects is due to discrete, optically thick, high-harmonic cyclotron transitions broadened greatly in the extreme temperatures of the accretion column shock region (cf. Masters 1978; Lamb and Masters 1979; Chanmugam and Wagner 1979; Chanmugam and Dulk 1981). As one reduces the optical depths in the models, the net circular polarization at any given harmonic (frequency) is expected to increase, and the slope of the polarized continuum may shift from "blue" to "red" at wavelengths approaching the cyclotron fundamental (Pavlov, Mitrofanov, and Shibanov 1980, Figs. 3 and 5). Discrete emission peaks corresponding to individual harmonics might also appear above the continuum. In addition to AN UMa, we note that AM Her exhibited broad-band circular polarization in its low state comparable with that for its high state (Latham, Liebert, and Steiner 1981), despite the substantial dilution by the M secondary star. Finally, VV Puppis was measured to have an I-band circular polarization of 15% on 1977 December 5 and 7, near the time of Liebert *et al.'s* (1978) spectroscopic observations in the low state. This value is again larger than typical high-state values (Tapia 1982).

In addition to the increased polarization and redder energy distribution, the Pavlov, Mitrofanov, and Shibanov (1980) calculations suggest the identification of the $\lambda 4880$ feature (and possibly other emission lines) with cyclotron harmonic frequencies. Given the narrow width ($\Delta\lambda/\lambda < 0.02$) and weakness of the $\lambda 4880$ feature, the implied cyclotron emitting region is surprisingly cold at $kT \sim 4 \times 10^{-4}\ mc^2 \sim 200$ eV. Perhaps we can identify only the peak of a broader emission profile buried in the noise and coming from higher temperatures. The energy distribution of the object also suggests that the fundamental frequency lies in the infrared. If the possible $\lambda 5850$ feature were the next lower harmonic, the derived $\Delta\nu \simeq 1 \times 10^{14}$ Hz implies $B \sim 3.5 \times 10^7$ gauss. But a lower harmonic (generally expected to be *stronger*!) should appear at $\lambda 7300$. Furthermore, we emphasize that the reality of neither the $\lambda 4880$ nor $\lambda 5850$ features could be conclusively demonstrated (§ II). Mitrofanov (1980) has previously identified a possible $\lambda 3400$ emission feature in the low state VV Puppis observations (Liebert *et al.* 1978) with the cyclotron fundamental frequency: this interpretation, however, fails to explain the four absorption features, equally spaced in frequency, which fit a much lower field value in that star (Visvanathan and Wickramasinghe 1979; Stockman, Liebert, and Bond 1979). Thus, while circumstantial evidence suggests that $\lambda 4880$ could be a cyclotron harmonic emission line, better observations in another AN UMa low state will be required to demonstrate this. If it *were* real, given the absence of other strong features, we regard 3.5×10^7 gauss as a reasonable lower limit to the field strength. Infrared spectroscopic observations might uncover stronger harmonic emission lines in a future AN UMa low state.

b) Limits on the Distance, Secondary Type, and Primary Temperature

We can derive a lower limit to the distance of AN UMa as a function of the secondary's assumed spectral type from the brightnesses observed at various wavelengths. In fact, we have done this in three ways:

1. The nondetection of dM absorption features with AN UMa at $m_{7000} \sim 18.5$, or $R_J \sim 18.3$ using Johnson's (1966) flux calibration, probably permits a limit on the secondary's red light contribution of $R_J(\mathrm{dM}) \gtrsim 19.0$, if the star is later than $\sim$ dM2 with normal TiO and MgH features.

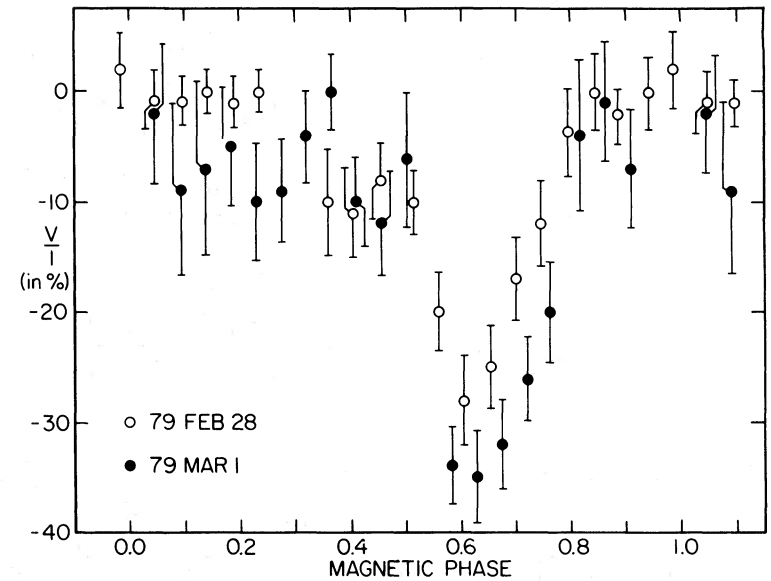

FIG. 3a

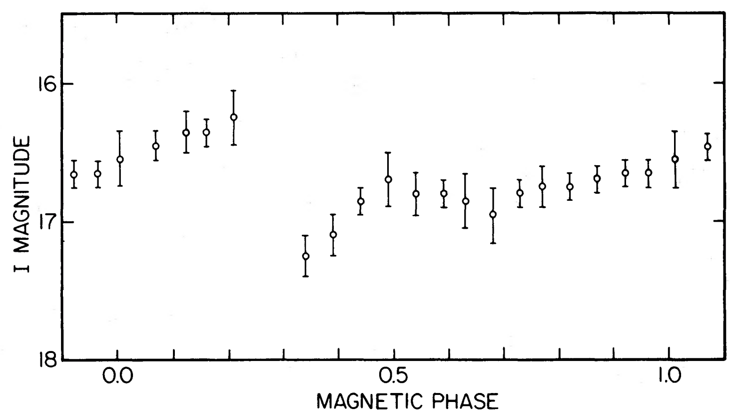

FIG. 3b

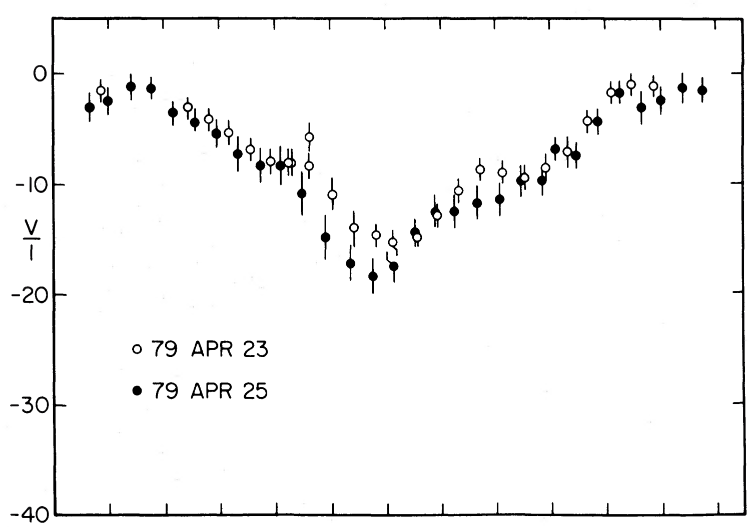

FIG. 3c

FIG. 3.—(*a*, *b*) Johnson *I* polarimetry and photometry for one magnetic period each on 1979 Feb. 28 and Mar. 1, obtained with the Catalina 1.53 m reflector. Standard deviation error bars are given for points after averaging in 5 min intervals; (*c*, *d*) Similar *I*-band polarimetry and photometry for 1979 Apr. 23–25 after return to a higher state.

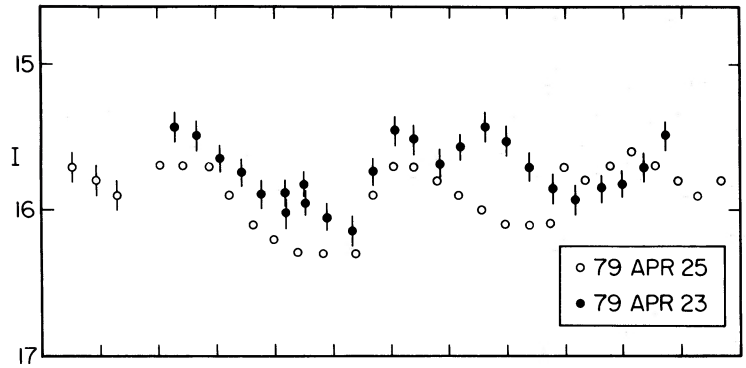

FIG. 3*d*

2. Since up to 70% of the I flux measured on February 28 could have originated with the secondary star, we have $I_J(\mathrm{dM}) \gtrsim 17.4$.

3. Finally, we can assume that all of the Szkody and Capps's (1980) 2.2 μm flux ($K = 15.3$) was due to the secondary.

The K flux limit is best only if $(I - K) \gtrsim 2.1$ in the companion, true only for the very coolest (dM6 and later) stars with $M_v > 15.5$. If the companion had the colors and absolute magnitude of VB 10, the faintest known main-sequence star at $M_v \sim 18.9$ and $M_K \sim 9.85$ (Greenstein, Neugebauer, and Becklin 1970), we would require the system to be more than 120 pc away. The I-band limit is strongest for possible companions in the range $11 \lesssim M_v \lesssim 15.5$. If the companion has $M_v \sim 13.5$, not unlike the secondary in AM Her (Young, Schneider, and Shectman 1981; Schmidt, Stockman, and Margon 1981), the minimum distance is 330 pc. For $M_v < 11$ the R limit is best, but its application is limited by the weakening of M star absorption features to perhaps $M_v > 10$. At $M_v = +10$ the minimum distance is 1000 pc. Note that all of these limits are increased if the secondary is overluminous for its color, as Wade (1979) argued for U Gem. Luyten (1977, private communication) measured a proper motion of $0''.07 \pm 0.02$ yr^{-1} from Luyten Palomar Schmidt plates. However, this affords only a weak upper limit of perhaps 3 kpc.

The meager optical radiation at AN UMa's minimum could be dominated by the primary's photosphere, which must be at least 4 mag fainter than AM Her's photosphere ($V \sim 15$). If the two magnetic white dwarfs had similar temperatures, AN UMa should be at least 300 pc distant. However, AN UMa could lie closer than this if both the primary and secondary have cooler photospheres than AM Her.

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