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THE OPTICAL IDENTIFICATION OF 2A 0311−227 WITH A NEW AM HERCULIS–TYPE OBJECT

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ABSTRACT

The X-ray source 2A 0311−227 has been precisely positioned by using the *HEAO 1* scanning modulation collimator, resulting in a $B_{\mathrm{mag}} \sim 15$ optical candidate. Medium-resolution optical spectra of this star show remarkable similarity to the spectrum of AM Her, a short-period binary containing a magnetic white dwarf. The Balmer decrement in 2A 0311−227 is also similar to that in AM Her, and may likewise be attributed to collisional excitation in a plasma with $n_e \sim 10^{13}$ cm^{-3}.
Subject headings: stars: binaries — stars: white dwarfs — X-rays: sources

I. INTRODUCTION

AM Her was originally suggested as the optical counterpart of 3U 1809+50 by Berg and Duthie (1977), and was confirmed by Hearn, Richardson, and Clark (1976). Following this identification, spectroscopic, photometric, and polarimetric data on AM Her have revealed that it is a spectroscopic binary with a period of 3.09 hours, probably consisting of a magnetic white dwarf with a red-dwarf companion (Hearn and Richardson 1977; Szkody and Brownlee 1977; Priedhorsky 1977; Tapia 1977*a;* Cowley and Crampton 1977; Crampton and Cowley 1977; Stockman *et al.* 1977; Priedhorsky, Krzeminski, and Tapia 1978). The bulk of the X-ray emission, together with the circularly polarized optical emission and the red continuum, are thought to arise in a single accretion column (Chanmugam and Wagner 1977; Priedhorsky and Krzeminski 1978).

AN Ursae Majoris has recently been established as a second member of the AM Herculis class (Bond and Tifft 1974; Krzeminski and Serkowski 1977; Hearn and Marshall 1978) and VV Pup as the third, by virtue of its optical properties (Tapia 1977*b;* Liebert *et al.* 1978; Liebert and Stockman 1979). It has been suggested that these three objects constitute a new class of magnetic white-dwarf binaries closely related to U Geminorum systems and other cataclysmic binaries (Bond and Wagner 1977; Chanmugam and Wagner 1977; Crampton and Cowley 1977).

We present here our discovery (Griffiths *et al.* 1979) of a fourth member of this class, the high galactic latitude ($b^{\mathrm{II}} \sim -57°$) source 2A 0311−227 (2A flux $\sim 5 \times 10^{-11}$ ergs cm^{-2} s^{-1}; Cooke *et al.* 1978). This is the second source of this type to be observed in the medium energy X-ray range, and the first to be identified with a previously uncataloged variable.

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II. X-RAY OBSERVATIONS

a) Position

Scanning data on 2A 0311−227 were accumulated by the *HEAO 1* modulation collimator (Gursky *et al.* 1978) from 1978 January 25 through 30. In a program of pointed observations of unidentified high galactic latitude sources, 2A 0311−227 was observed on July 19 for four spacecraft orbits (13.40 to 20.10 UT). The source gave a significant signal in both observations, which were made at different spacecraft Z-axis positions (the Z-axis was pointed at the Sun during the scanning observations, and was 8° offset from the Sun for the pointing). The resulting multiple error boxes from these two observations combined to give only two possible intersections in the region of the 2A error box (Cooke *et al.* 1978). The western error box contains no objects brighter than about 19th mag, but the eastern error box (Table 1 and Fig. 1 [Pl. L1]) contains one star brighter than this limit, at $B_{\mathrm{mag}} = 14.8$ on the Palomar Sky Survey prints. A star of similar magnitude lies $\sim 18''$ west of the first, just outside the error box.

b) X-Ray Spectrum

In data from the pointed observation, the source was detected at 9.5 σ in the finer collimator system MC1 and 6.5 σ in the coarser collimator system MC2. Significant fluxes were measured in all three energy channels (0.9–2.6, 2.6–5.4, and 5.4–13.3 keV). From the ratios of counts in these three channels, and on the assumption of a thermal bremsstrahlung spectrum, we estimate a source temperature of at least 6 keV and probably several tens of keV (with a hydrogen column density consistent with zero, $N_{\mathrm{H}} < 3 \times 10^{22}$ H atoms cm^{-2}). On the assumption of a power-law spectrum, we find $\alpha = 0.5 \pm 0.7$, again with $N_{\mathrm{H}} < 4 \times 10^{22}$ H atoms cm^{-2}.

c) Search for X-Ray Periodicity

Following the independent identification of the X-ray source by Hiltner *et al.* (1979) from the Curtis-Schmidt objective-prism plate collection (using the 2A error box only), the optical counterpart has been studied by

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1979ApJ...232L..27G

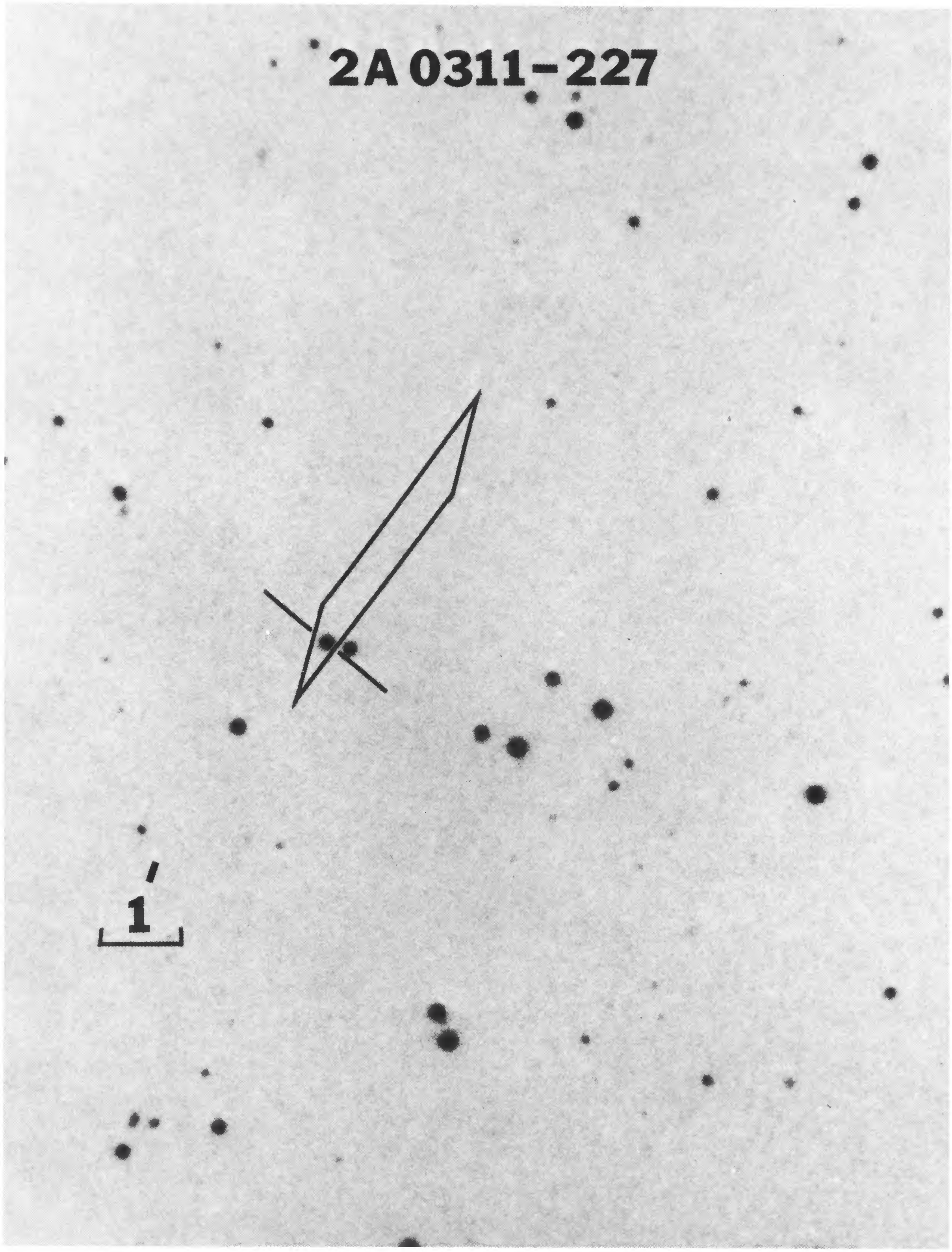

FIG. 1.—The preliminary *HEAO 1* modulation collimator error box from the pointed observation of 2A 0311−227, superposed on the PSS plate, as used for optical identification at Mount Stromlo and the AAT. The candidate star is indicated. The final error box (Table 1) is smaller and displaced slightly to the southeast.

GRIFFITHS *et al.* (*see* page L27)

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1979ApJ...232L..27G

TABLE 1

POSITIONS FOR 2A 0311−227

	Center	90% Confidence Error Region[a]
X-ray......	$03^h12^m00\overset{s}{.}9$, −22°46′46″	42 E 21 W 42 W 21 E 75 S 08 N 75 N 08 S
Optical.....	$03^h12^m00\overset{s}{.}0$, −22°46′49″	±5″ AAT

[a] The corners of the X-ray error box are given as offsets in arcseconds from the most probable position.

Boley, Johns, and Maker (in Hiltner *et al.* 1979) revealing a spectroscopic binary with a period of 81.05 ± 0.16 minutes (Boley 1979, private communication).

From the *HEAO 1* pointed data obtained on 1978 July 19, we have folded our MC1 data with the above trial period. Because of the poor statistics, the data were divided into only four phase bins, which were also slipped in phase by half a bin. At the 95% confidence level, the X-ray source is not fully eclipsed for more than 25% of the binary cycle. We cannot, however, rule out large ($\lesssim$50%) modulation in the X-ray flux at the binary period.

III. OPTICAL SPECTRA

Medium-dispersion optical spectroscopy of the candidate optical counterpart (Fig. 1) was performed between λλ3650 and 7100, using the Cassegrain spectrograph and photon counting array (Stapinski, Rodgers, and Ellis 1978) on the Mount Stromlo 1.9 m telescope on 1978 November 27.67 UT, revealing a rich emission-line spectrum. The star 18″ W of the candidate was observed for a short integration time, showing no emission features, but an absorption near λ5190 which is probably the late-type stellar blend of Mg I lines. Further spectra of the emission-line star were taken at the 3.9 m Anglo-Australian Telescope with the RGO spectrograph and image photon counting system (Boksenberg 1972) on 1978 December 2 (the 250 lines mm^{-1} grating gave a dispersion of 140 Å mm^{-1} over the spectral range λλ3400–7300). The object was observed with both "narrow" and "wide" circular apertures (2″.0 and 7″.5, respectively), the "narrow" aperture being used to optimize the resolution (~6 Å), at the expense of photometric accuracy because of wavelength-dependent atmospheric dispersion, while the "broad"-aperture observation was made for precise spectrophotometry (resolution ~22 Å). For the broad-aperture observations, the star was exposed for 200 s in each of the two apertures (commencing at 14^h25^mUT on December 2); while for the narrow-aperture observations (commencing at 14^h40^m) the integration time was 500 s in each, The "star plus sky" and "sky" apertures were separated by 27″ and 22″ (center to center) for the "wide"- and "narrow"-aperture observations, respectively.

The reduced "narrow"-slit spectrum is shown in Figure 2, corrected photometrically by observation of the standard star LB 227 (Oke 1974). The main features include the Balmer series of hydrogen in emission, from Hα through H10, with a strong Balmer continuum, together with emission from He I (λλ4026, 4388, 4472, 4291, 5016, 5876, and 7056), He II (λ4686), Ca II (λ3934), C II (λ4267) and C III/N III (λλ4640–4650). A full list of detected lines and corresponding equivalent widths from the narrow-slit spectrum is given in Table 2, where the relative line intensities (col. [4]) have been measured by combining the quoted equivalent widths with continuum measurements from the broad-slit spectrum.

The relative line intensities from the AAT spectra show remarkable similarity to those in AM Her at a phase of 0.4 (Stockman *et al.* 1977). The unusual Balmer decrement Hα:Hβ:Hγ of 0.40:1.00:1.18 is fairly similar to the average seen in AM Her, viz., 0.75:1:1.09 (Stockman *et al.* 1977; Crampton and Cowley 1977). It has been shown (Crampton and Cowley 1977), that the Hβ/Hγ decrement increases sharply in AM Her around photometric phase of $\phi_{\rm phot} \sim 0.9$, and that the decrement is about 1 for the remainder of the orbital phase. Stockman *et al.* (1977) have suggested that the low decrement is the result of collisional ionization in a dense (~10^{13} cm^{-3}) plasma (Adams and Petrosian 1974), and that this dense region is eclipsed by the cool companion near conjunction (Crampton and Cowley 1977).

The He I λ5876/λ4472 ratio from the AAT spectrum is measured as 0.3, which is also an inversion of the optically thin recombination value (Baker and Menzel's case B; Brocklehurst 1971). It is, however, again similar to the value found in AM Her, viz., 0.6 (Stockman *et al.* 1977).

In a search for variability in the emission-line strengths in the two AAT spectra, we have found that for six of the 10 strongest lines, the AAT narrow-aperture intensities relative to Hβ (Table 2, col. [4]) agree to within 15% with the intensities derived directly from the broad-aperture spectrum (for the remainder, the agreement is to within 50%). There is thus no evidence for variability between the two spectra, for which the mean time difference is ~20 minutes (i.e., a quarter of the 81 minute binary period). The AAT narrow-aperture and Mount Stromlo observations were separated by 4.934 days. Although we cannot determine the absolute phase of either observation by extrapolation from the ephemeris of Tapia (1979), this time difference between the observations corresponds to 87.68 ± 0.04 binary cycles. The Mount Stromlo observations were made with a narrow slit only, so that relative line intensities could not be determined with any certainty, especially at wavelengths shorter than ~4500 Å because of wavelength-dependent atmospheric dispersion and the consequent loss of the blue versus red image. There is, however, significant evidence for a change in the equivalent widths of the Balmer lines between these observations (Table 2, cols. [3] and [4]). Thomas, Greenhill, and Watts (1979, private communication) have obtained a further spectrum of the object at the AAT on 1979 February 16 which shows an increase in the strength of He I λλ5876 and 4471 relative to the December 2 observation, together with a significant change in the Balmer decrement, thus confirming

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1979ApJ...232L..27G

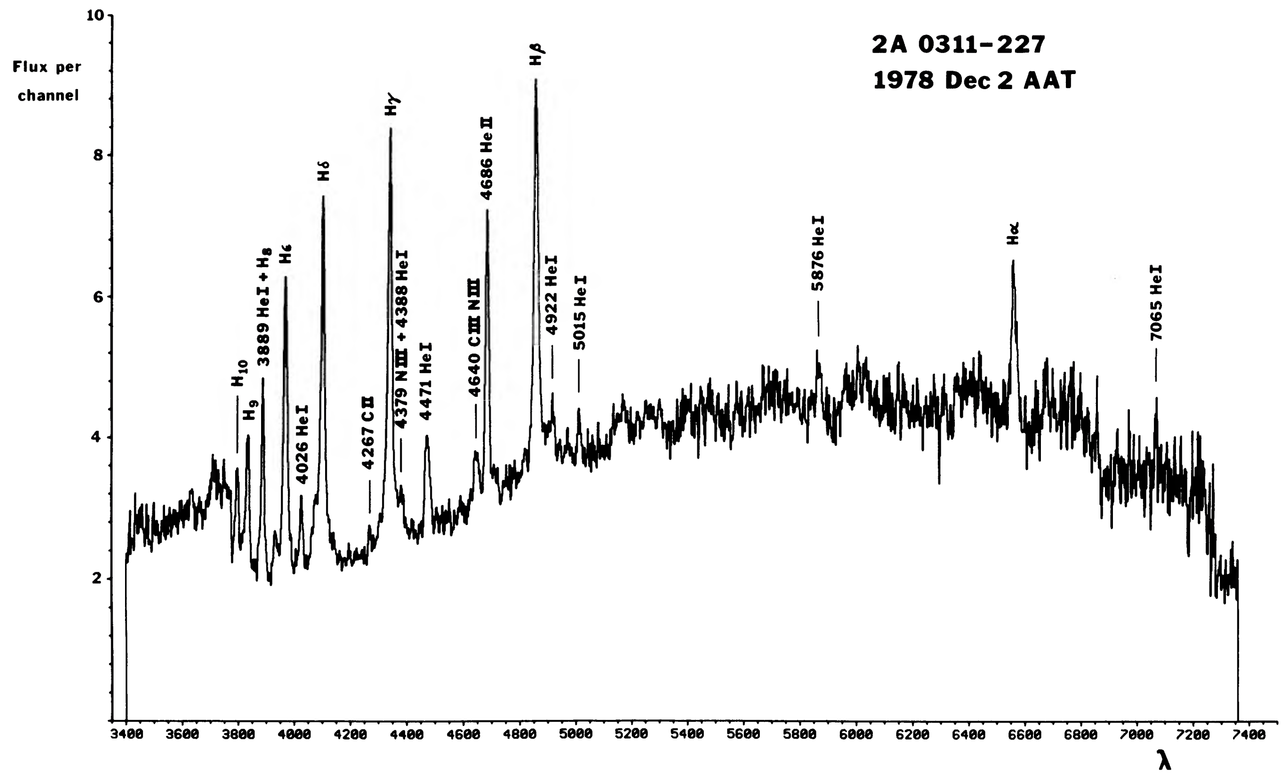

FIG. 2.—Optical spectrum of counterpart to 2A 0311−227, taken at the AAT on 1978 December 2, using the RGO spectrograph and the IPCS. Resolution is ~6 Å, and the ordinate scale is arbitrary.

TABLE 2

EQUIVALENT WIDTHS AND RELATIVE LINE INTENSITIES FOR OPTICAL COUNTERPART TO 2A 0311−227

Identification	Wavelength (Å)	Mount Stromlo, 1978 Nov 27.67 Equivalent Width (Å)	AAT, 1978 Dec 2.60 Equivalent Width (Å)	AAT, 1978 Dec 2.60 Relative Intensity	Relative Intensity for AM Herculis at Phase 0.4(0.7) (Stockman *et al.* 1977)
He I	3634.3	...	1.3[a]	7[a]	...
H15	3712.0	...	1.6[a]	9[a]	...
H12	3750.2	...	1.4	8	...
H10	3797.9	...	7.7	29	...
Hη (H9)	3835.4	11	12.5	42	...
Hζ (H8)	3889.1	10	18.1	53	66
Ca II	3933.7	...	3.1	9	16
Hε (+Ca II)	3968.5 +3970.1	21	30.0	82	86 (44)
He I	4026.3	...	8.1	21	20
Hδ	4101.7	32	42.8	108	128 (74)
C II	4267	...	1.8	4	...
Hγ	4340.5	28	46.8	118	103 (101)
He I (+N III?)	4387.9 +4379.1	...	1.8	4	12
He I	4471.6	9	10.5	28	25
He II	4541.6	...	0.7[a]	2[a]	4
C III/N III	4640	4.8	5.4	16	12
He II	4685.7	14.3	18.7	55	82 (82)
He I	4713	...	0.6[a]	2[a]	...
Hβ	4861.3	24	31.7	100	100 (100)
He I	4921.9	3.1	1.8	6	16
He I	5015.7	...	2.6	9	15
He II	5411.5	...	1.0[a]	4	12
He I	5875.8	...	2.3	8	...
Hα	6562.8	20	11.2	40	(107)
He I	7065.2	...	3.0	8	...

NOTE.—Errors in equivalent widths and intensities are estimated as ± 15% for the strong lines, but are larger for the weak lines where errors due to noise are dominant.

[a] The detection of the line is not certain.

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1979ApJ...232L..27G

variability. The present observations were limited to the one Mount Stromlo and the two AAT spectra discussed here, and did not cover the latterly discovered 81 minute period.

Intercomparing the wavelengths of the lines H10, H9, H8, Hϵ, Hδ, Hγ, He I λ4686, and Hβ, we find agreement between the two AAT spectra (taken ~20 minutes apart) to within 2 Å. The corresponding upper limit on radial-velocity changes ranges from 158 km s^{-1} (H10) to 123 km s^{-1} (Hβ).

Boley *et al.* (in Hiltner *et al.* 1979) have reported that the equivalent widths of Hβ and He II in 2A 0311−227 vary with the 81 minute orbital period, with greatest intensities at negative velocities, as found in AM Her. They also observe radial-velocity motion of peak-to-peak amplitude nearly 800 km s^{-1}, again similar to that found in AM Her, for which it has been established that the amplitude varies from ~750 km s^{-1} for H and He II through 650 km s^{-1} for H I to ~560 km s^{-1} for Ca II K (Crampton and Cowley 1977).

We have searched for stellar absorption lines from a red-dwarf companion, viz., Ca I *g* λ4226, Mg I *b* λ5175, Fe I λ5270, Na I D λ5893, and Ca I λ6165, but we find no compelling evidence for the presence of any of these lines in our spectra (see Stockman *et al.* 1977).

The shape of the continuum has been determined from the broad-aperture AAT observation, and is represented quite well by $F(\nu) \propto \nu^{-3.3}$ between 4000 and 5700 Å, although the extrapolation of this fit toward the red lies above the data points out to 6800 Å. This spectral slope corresponds to $B - V \approx 0.9$ mag (neglecting the contribution from emission lines) and is greater than the phase-averaged slope found for AM Her, viz., $F(\nu) \propto \nu^{-1}$ from spectrophotometry by Stockman *et al.* (1977). We note, however, that photometry of AM Her (Priedhorsky and Krzeminski 1978) shows that $B - V$ varies from 0.5 mag to a maximum of 1.0 mag around photometric phase 0.5 (primary V band minimum), and can be 0.9 mag or greater for as much as a third of the orbital period.

IV. LONG-TERM OPTICAL VARIABILITY

We have searched the Harvard photographic collection for long-term optical variability of our candidate, with the results shown in Figure 3. Useful plate coverage is rather sparse, as the measurements were hampered by the presence of the $B_{\rm mag} = 15.8$ star which lies only 18″ W of our candidate. Some of the magnitudes are therefore derived from unresolved images. Generally, the object was fainter than $B_{\rm mag} = 16.7$ from 1926 to 1928, and was around $B_{\rm mag} = 15$ in 1929, with subsequent fading. At the epoch of the Palomar Observatory Sky Survey (1953 November 13) the star was relatively bright ($B_{\rm mag} = 14.8$).

V. DISCUSSION AND CONCLUSION

On the basis of the precise X-ray position, the optical spectrum and the hard X-ray spectrum from 1 to 13 keV, we identify 2A 0311−227 as a new member of the AM Herculis class. Since the preliminary version of these results was first presented (Griffiths *et al.* 1978), the star has been discovered to be a spectroscopic binary (Boley *et al.*, cited in Hiltner *et al.*) and to have optical linear and circular polarization at the binary period of 81.03 ± 0.03 minutes (Tapia 1979), confirming the similarity to AM Her.

We measure an average X-ray intensity in the 2–10 keV band of $4.3 \pm 1.0 \times 10^{-11}$ ergs cm^{-2} s^{-1}. This agrees well with a previously cataloged value of 1.1 ± 0.1 *Ariel* counts s^{-1} ($=5.3 \pm 0.5 \times 10^{-11}$ ergs cm^{-2} s^{-1}) (Cooke *et al.* 1978), and is consistent with the upper limit of 2 *Uhuru* counts s^{-1} (5×10^{-11} ergs cm^{-2} s^{-1}, 2–10 keV) from the absence of the source in the 4U catalog (Forman *et al.* 1978). The 2–10 keV X-ray intensity of 2A 0311−227 is a factor of 2 weaker than that of AM Her (Cooke *et al.* 1978; Forman *et al.* 1978), and the $B_{\rm mag}$ is typically two magnitudes fainter, so that the ratio of $L_x(2\text{–}10\ \text{keV})/L_{\rm opt}$ is similar in the two objects.

The tentative suggestion from the X-ray data for the absence of X-ray eclipses (eclipse duration <25% of cycle, at 95% confidence) contrasts with the behavior

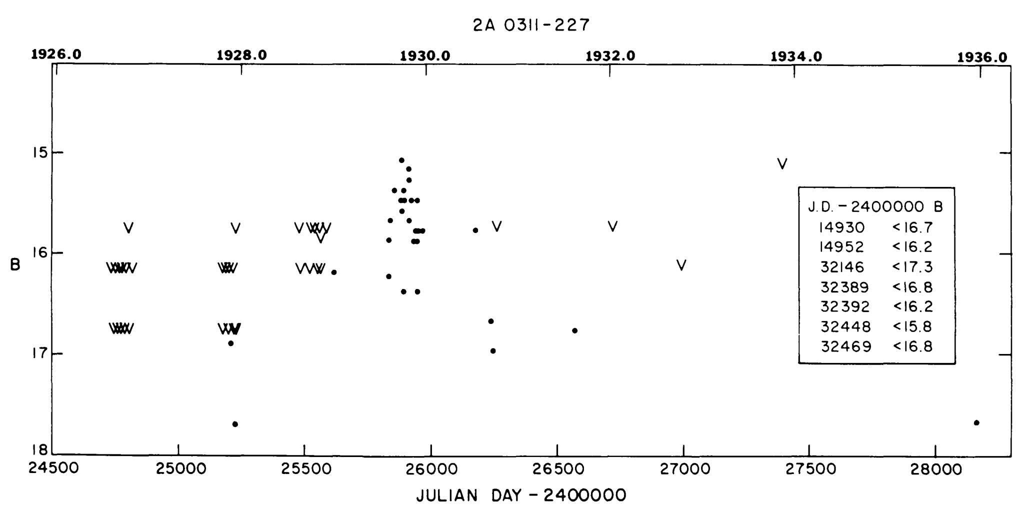

FIG. 3.—Long-term optical light curve of candidate star, assembled from the Harvard plate stacks. The inset shows upper limits outside the time range plotted. Upper limits are indicated by the symbol **V**. Standard errors are typically ±0.2 mag.

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1979ApJ...232L..27G

of AM Her (Hearn and Richardson 1977; Swank *et al.* 1977; Tuohy *et al.* 1978) in which the X-ray flux is almost totally eclipsed for $\sim 20\%$ of the cycle and is strongly modulated at other phases, i.e., with a gradual ingress and egress. In the accretion disk (fast rotator) model for AM Her (Fabian *et al.* 1977), variability of the *soft* X-ray flux at the binary period is supposed to be caused by excess absorbing material in the line of sight to the emitting accretion column or scattering wall. This model was already in difficulties with the observation of hard X-ray eclipses at the binary period of 3 hours (Swank *et al.* 1977) and was effectively eliminated by the absence of fast periodic changes in the circular polarization on the predicted time scale of a few seconds (Stockman and Sargent 1979). We are thus left with synchronous rotation of the magnetic dwarf as the only plausible model, with X-ray occultation of the emitting accretion column and shock region by the white dwarf itself (Swank *et al.* 1977). Whereas a single accretion column model may be applicable to AM Her (Chanmugam and Wagner 1977; Priedhorsky and Krzeminski 1978), our tentative evidence for the absence of X-ray eclipses suggests that in 2A 0311−227 both of the white-dwarf magnetic poles may be active, as suggested for VV Pup from observations of both positive and negative circular polarization (Liebert and Stockman 1979). Our data are consistent with the possibility that one pole is significantly stronger than the other, however. Alternatively, we cannot rule out source geometries in which one or both polar accretion columns are never fully occulted.

A soft X-ray flux has also been reported from 2A 0311−227, in the energy band around $\frac{1}{4}$ keV, both from *HEAO* A-2 low energy detector scans (Charles and Mason 1979) simultaneous with the scanning data discussed here, and also from *SAS 3* data 2 years previously (Hearn 1979). It is well established that AM Her also has a complex X-ray spectrum with both soft and hard components (Tuohy *et al.* 1978; Bunner 1978; Swank *et al.* 1977), for which it has been suggested that the hard component arises from thermal bremsstrahlung in the shock region near the white-dwarf surface, whereas the soft component comes from the heated surface of the white dwarf and to a lesser extent from cyclotron emission in the postshock region (Tuohy *et al.* 1978). The presence of this soft X-ray flux is a further indication of a degenerate dwarf (Kylafis *et al.* 1979).

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