THE ASTROPHYSICAL JOURNAL, 234:L113–L116, 1979 December 1

HIGH-SPEED PHOTOMETRY OF THE NEW AM HERCULIS-TYPE BINARY 2A 0311−227

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Received 1979 May 29; accepted 1979 August 15

ABSTRACT

High-speed optical photometry of the X-ray source 2A 0311−227 shows a light curve modulated with the 81 minute orbital period, with superposed large-amplitude flaring. The light curve, combined with Tapia's polarimetry, suggests that this system is similar to AN UMa in that it contains a white dwarf with an accreting magnetic pole that lies in the hemisphere facing the Earth throughout the orbital cycle.

Subject headings: stars: binaries — stars: white dwarfs — X-rays: binaries

I. INTRODUCTION

AM Her, AN UMa, and VV Pup are the first three known members of a new class of cataclysmic binaries in which a synchronously rotating magnetic white dwarf with a surface field of about 10^8 gauss accretes matter from a lower-main-sequence companion (Chanmugam and Wagner 1977; Stockman *et al.* 1977). The strong magnetic field prevents formation of an accretion disk of the type found in normal cataclysmic binaries; instead the transferred matter falls directly onto the white dwarf through an accretion column at one (or both) of the magnetic poles. These AM Her–type systems can be recognized by the strongly polarized optical cyclotron radiation emitted by the accretion column: once per orbital period, a linearly polarized "pulse" is emitted, and throughout the period continuously varying circularly polarized light is also emitted (Tapia 1977*a*, *b;* Michalsky, Stokes, and Stokes 1977; Krzeminski and Serkowski 1977).

The *Ariel* X-ray source 2A 0311−227 was recently identified with a 15th magnitude blue object by Griffiths *et al.* (1979) and Hiltner *et al.* (1979). Spectroscopic observations by these authors showed the object to have the strong H, He I, and He II emission lines and shallow Balmer decrement characteristic of the AM Her systems, and the line velocities indicated an orbital period of 81 minutes. The object has now been confirmed as the fourth known AM Her system by Tapia (1979), who discovered that it emits strongly linearly and circularly polarized light.

X-ray emission has been detected from three of the four AM Her systems: AM Her itself (Hearn and Richardson 1977; Swank *et al.* 1977; Tuohy *et al.* 1978), AN UMa (Hearn and Marshall 1979), and, of course, 2A 0311−227. Hearn (1979*a*, *b*) has found that the X-ray flux from 2A 0311−227 appears to be modulated with the orbital period, but the period is not yet known with sufficient accuracy to phase Hearn's 1975 measurements with the current observations.

In this *Letter* we present the first high-speed photometric observations of 2A 0311−227. Our data, combined with Tapia's polarimetric observations, will be used to show that 2A 0311−227 is rather similar to AN UMa.

II. OBSERVATIONS

The optical counterpart of 2A 0311−227 can be identified from the information given by Hiltner *et al.* (1979). Two of us (H. E. B. and A. D. G.) obtained high-speed photometry of this object with a single-channel pulse-counting photometer on the No. 2 0.9 m reflector at Kitt Peak National Observatory, on the nights of 1979 February 23 and 26 (UT). Both photometric runs covered slightly more than one complete orbital cycle of 81 minutes. We chose integration times of 5 s the first night, and 3 s the second. The monitoring was continuous, except for interruptions about every 15 minutes to measure either the sky background contribution or a nearby comparison star. The comparison star chosen lies 2'.3 west and 1'.3 south of the variable. One *BV* observation of the comparison star gave $V = 12.68$, $B - V = 0.70$. In order to have a high counting rate, we used only a crystal $CuSO_4$ filter in front of the S-20 photomultiplier during the high-speed monitoring, giving a broad blue bandpass (∼5500 Å down to the atmospheric cutoff).

The light curves resulting from our observations are shown in Figures 1*a* and 1*b*. We have plotted the count rates (per 5 s and 3 s integration times) against heliocentric Julian date. The counts have been corrected for sky background, and the comparison-star observations were used to remove effects of atmospheric extinction. The figures also show the orbital phases, calculated from the ephemeris $JD_{\odot} = 2{,}443{,}894.6803 +$

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[1] Visiting Astronomers, Kitt Peak National Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

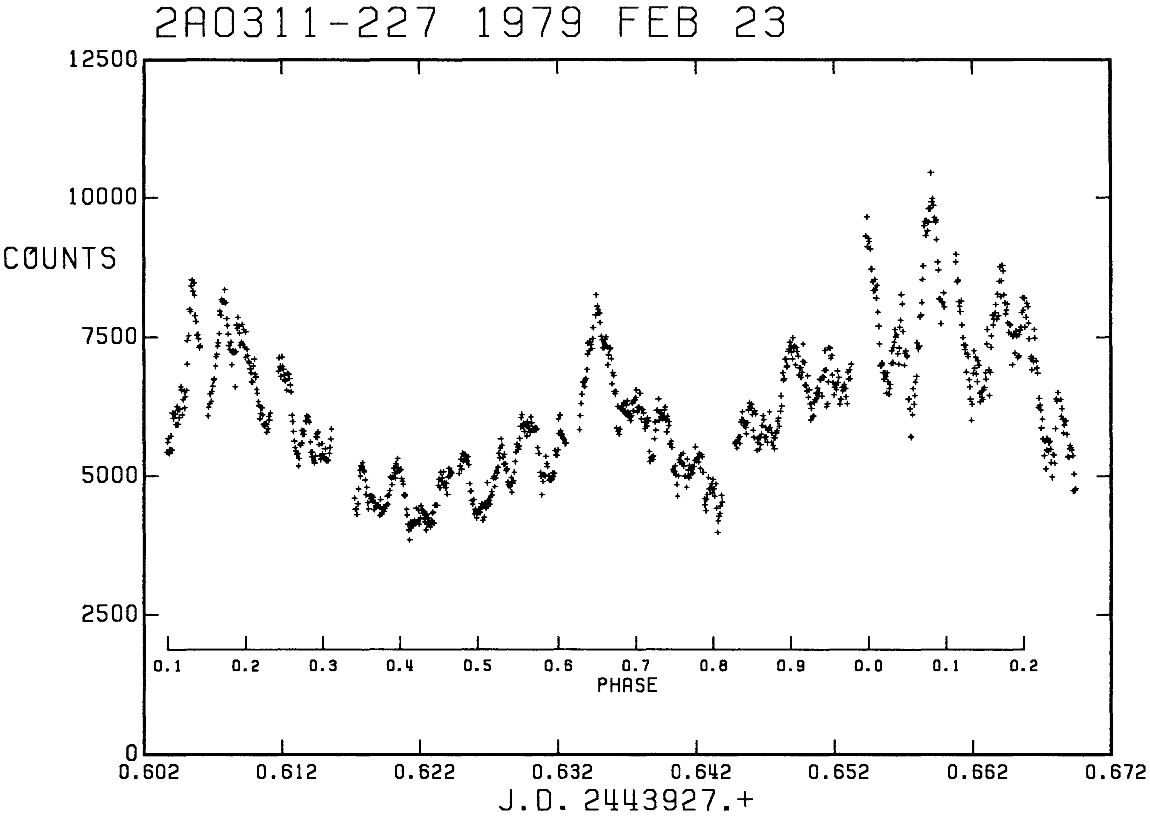

FIG. 1*a*

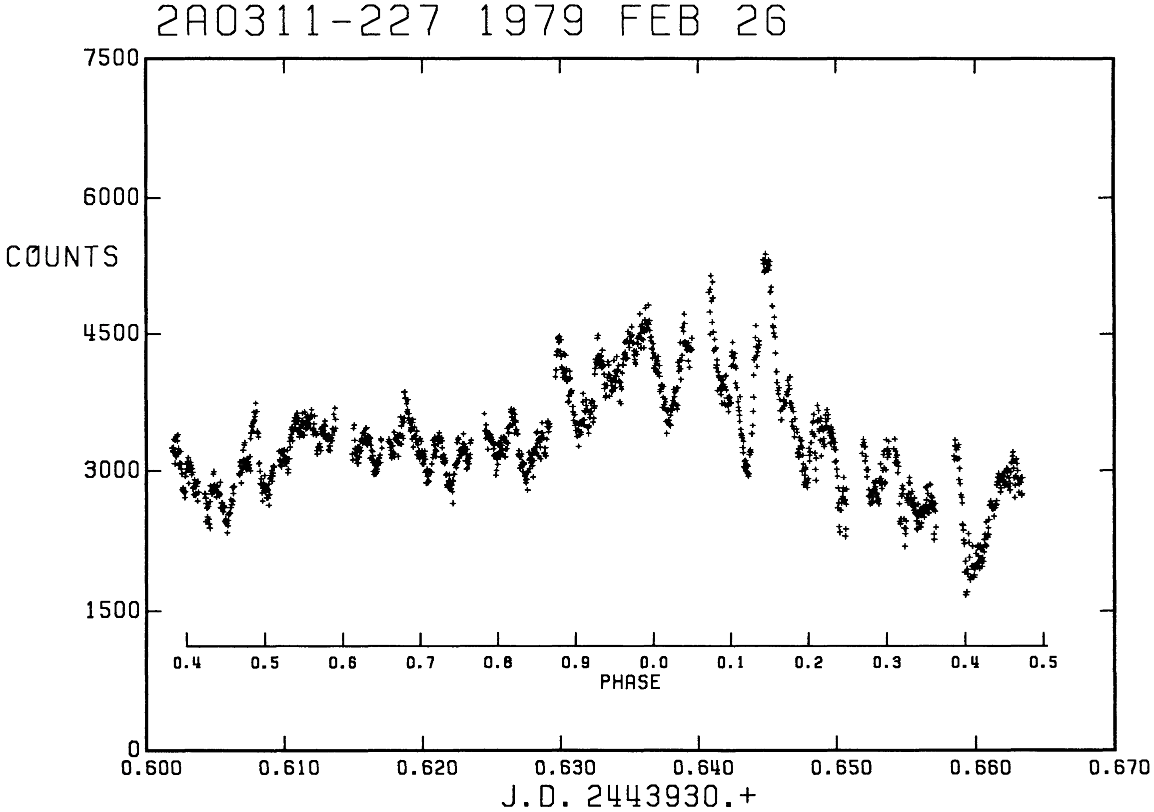

FIG. 1*b*

FIG. 1.—(*a*) Light curve of 2A 0311−227 on 1979 February 23 with 5 s time resolution. (*b*) Light curve on 1979 February 26 with 3 s resolution. Counts per integration time are plotted against heliocentric Julian date. Orbital phases computed from Tapia's ephemeris for the linear-polarization pulses are also indicated.

0.05627*E*, which gives the times of the linear-polarization pulses (S. Tapia, private communication). Tapia states that the period is accurate to $\pm 0^{\mathrm{d}}00002$; his observations were made from 1979 January 28 to February 18, so phasing with our observations should be accurate to ±0.05 of the orbital period. Tapia has also informed us that the circular polarization, measured on 1979 Feburary 18 with nearly the same blue bandpass that we used, varies as follows: q is near 0 at phase 0, rises to about 15% at phase 0.25, declines to near 0 at phase 0.4, rises again to 15% at phase 0.6, then declines to 0 at phase 1.0. There is a shallow dip in q during the steep decline to phase 1.0, near phase 0.8.

Some of the features present in the light curves are the following:

1. The mean count rates (~5500 on the first night, ~3400 the second) correspond in both cases to about blue magnitude 15.0, if the comparison star is assumed to have $m_b = 13.4$.

2. A broad minimum in the light curve occurs around phase 0.4 (the time of the second minimum in the circular polarization). There is possibly a shallower minimum around phase 0.8, followed by a rise to a maximum near phase 0.1. The smoothed light curve of AN UMa (Krzeminski and Serkowski 1977, Fig. 4) is remarkably similar.

3. Superposed on this 81 minute light curve is conspicuous flaring, presumably produced by inhomogeneities in the infalling gas stream. The flaring is present at all phases, but is must active between about phases 0 and 0.2 (the time of the light-curve maximum), and least active around the light-curve minimum at phase 0.4. On several occasions the system brightened by more than 0.5 mag in less than 100 s. However, the flaring is not extremely rapid, the shortest time scales present being ~30 s.

4. Both photometric runs were tested for short-period coherent oscillations, using the discrete Fourier-transform technique of Deeming (1975). No oscillations were found, but the relatively short data runs permit detection only for amplitudes greater than about 0.015 mag.

III. INTERPRETATION OF THE OBSERVATIONS

We will now discuss 2A 0311−227 in terms of a simple model in which the white dwarf has a centered pure dipole magnetic field and the optical emission comes from an accretion column above one of the two poles. Let θ be the angle between the dipole axis and the axis of rotation (assumed perpendicular to the orbital plane), and let the orbital inclination be i (see Chanmugam and Wagner 1978, Fig. 1). Let ϕ be the orbital phase of the pole nearer the observer, defined such that $\phi = 0$ corresponds to the line of sight, rotation axis, and dipole axis all lying in the same plane (with the rotation axis between the line of sight and the dipole axis). Then the angle ψ between the line of sight and the dipole axis is given by

$$\cos\psi = \cos i \cos\theta\,(1 - \tan i \tan\theta \cos 2\pi\phi)\ .$$

The linear-polarization pulses occur when $\cos\psi \approx 0$, while values of $\cos\psi$ near 1 favor circular polarization for optically thin emission. There are two possible types of behavior of ψ during the orbital period:

Case 1.—If $i + \theta > 90°$, the magnetic pole alternately lies in the hemispheres of the white dwarf facing, and hidden from, the observer, so that the circular polarization shows both signs during the orbital period. This change of sign is observed in AM Her (Tapia 1977*a*, *b*) and VV Pup (Liebert *et al.* 1978). Linear-polarization pulses occur when the pole crosses the limb of the white dwarf, but the pulse from one of these crossings is usually obscured, possibly by material leaving the outer Lagrangian point. Most of the light emission from VV Pup originates very close to the surface of the white dwarf, and this light suffers a deep "self-eclipse" when the magnetic pole passes into the back hemisphere (Chanmugam and Wagner 1978; Liebert *et al.* 1978; Liebert and Stockman 1979). In AM Her, however, the emitting region above the accreting pole apparently does not pass very far behind the limb, since its light-curve minimum is less deep than that of VV Pup.

Case 2.—If $i + \theta < 90°$, $\tan i \tan\theta$ is always less than 1, so that $\cos\psi$ never reaches zero. One magnetic pole therefore remains in the facing hemisphere of the white dwarf throughout the orbital period, and the circular polarization does not change sign. The linear-polarization pulse corresponds to the minimum value of $\cos\psi$, which occurs at phase $\phi = 0$. This case seems to apply to both AN UMa and 2A 0311−227, neither of which shows either a change of sign in the circular polarization (Krzeminski and Serkowski 1978; Tapia 1979, and private communication) or a deep photometric minimum.

Although q does not change sign in either AN UMa or 2A 0311−227, the behavior of $|q|$ in the two stars is different: in AN UMa, the observations of Krzeminski and Serkowski (1978) show that $|q|$ rises from a minimum at phase 0 to a maximum near phase 0.5, and then declines again to minimum at phase 1.0; Tapia's data on 2A 0311−227 show fairly similar behavior with the exception of a deep minimum in $|q|$ near phase 0.4. We suggest that for 2A 0311−227, ψ becomes so low near $\phi = 0.4$ that cyclotron self-absorption (Masters *et al.* 1977) in the accretion column reduces the polarization, as in the case of AM Her (Chanmugam and Wagner 1978, 1979).

There is also a broad light minimum in 2A 0311−227 near $\phi = 0.4$ (see Figs. 1*a* and 1*b*). This indicates that, as in AM Her and VV Pup, a sizable fraction of the optical radiation is polarized, probably because it is cyclotron emission (Priedhorsky, Krzeminski, and Tapia 1978; Chanmugam and Wagner 1978). The dip or flattening of the light curve around phase 0.8 also coincides with a dip in q. However, at phase 0, q has a minimum, but the light curve is approaching a maximum. This may be understood qualitatively by assuming that the total optical luminosity of the accretion column is $I(\psi) = I_u(\psi) + I_c(\psi)$, where I_u is an unpolarized blackbody-like component arising from near the magnetic pole and I_c is the polarized cyclotron emission from further up the accretion column (Chanmugam and Wagner 1979; cf. Masters 1978). Now if the unpolarized flux originates at the polar cap and is preferentially emitted along the field lines, while the cyclotron radiation is emitted mainly perpendicular to the field (Stockman 1977; Chanmugam 1979), the maximum in I will not occur at $\phi = 0$ or 0.5 but at some intermediate point. Since the observed maximum occurs at phase $\phi \approx 0.1$, I_u(max) should be somewhat less than I_c(max). If the X-rays are beamed along the field lines as in AM Her, we can predict that the X-ray maximum should occur near phase 0.5. No X-ray eclipse is expected.

It is also noteworthy that the flaring activity is least at the time of the broad light minimum ($\phi \approx 0.4$) when the circular polarization $q \approx 0$. This implies that flaring arises in the same region that emits the polarized light, and that the flares may be highly circularly polarized as is sometimes the case in AM Her (Stockman and Sargent 1979, Fig. 3).

In conclusion, we suggest that 2A 0311−227 and AN UMa are similar in that their accretion columns are visible throughout their orbital cycles; they differ in that the column in 2A 0311−227 points so nearly toward the Earth (near phase 0.4) that self-absorption significantly reduces the circular polarization at that time, whereas in AN UMa, ψ is never small enough for there to be self-absorption. The other two known AM Her-type systems, VV Pup and AM Her itself, have accretion columns that are on the side of the white dwarf facing the Earth for only part of their orbital periods. One can imagine other types of behavior that might be exhibited by still undiscovered AM Her binaries; two possibilities are (1) systems like 2A 0031−227 or AN UMa, but where the pole never approaches sufficiently close to the limb to produce a linear-polarization pulse, so that only slightly variable circular polarization is exhibited; and (2) systems where the active (i.e., accreting) pole is always on the back hemisphere, so that only extremely weak polarization from the inactive hemisphere of the white dwarf is present. A possible example of the second type of system is V Sge: although spectroscopically somewhat similar to the AM Her systems (Herbig *et al.* 1965; unpublished observations by H. E. B.), it does not emit detectable polarized light (Tapia, private communication).

We thank S. Tapia for providing results of his observations in advance of publication, and J. Barnes for assistance with data handling. This research was supported partly by NSF grant AST 76-06807 A01 and is Contribution No. 152 of Louisiana State University Observatory.

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Note added in proof.—Another candidate for an AM Her-type system with the active pole always on the back hemisphere is 2A 0526−328. Its spectrum is very similar to that of AM Her (P. Charles *et al.*, *Ap. J.* [*Letters*], **231**, L131 [1979]), but it does not have measurable polarization.

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