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SPECTROSCOPY OF 2A 0526−328: A TRIPLE PERIODIC CATACLYSMIC VARIABLE

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ABSTRACT

The cataclysmic variable X-ray binary 2A 0526−328 has a spectroscopic (orbital) period of 0.228600 days, a photometric (rotation) period of 0.21631 days, and a beat (photometric) period of 4.024 days. Radial velocity behavior is complex, suggesting orbital motions, a disk hot spot, and a spiraling gas stream. Emission line variations are large and not generally periodic. The system is discussed in terms of a nonsynchronously rotating white dwarf of the DQ Her type. The system presents several unique phenomena for this type of binary.

Subject headings: stars: dwarf novae — stars: individual — X-rays: binaries

I. INTRODUCTION

The weak, high galactic latitude X-ray source 2A 0526−328 was identified with a blue emission line object by Charles, Thorstensen, and Bowyer (1978) and Charles *et al.* (1979), and further discussed by Schwartz *et al.* (1979). The spectrum is that of a cataclysmic variable, which shows highly variable line strengths from night to night. While the spectrum is similar to the highly magnetic AM Her stars, the lack of strong polarization seems to rule out fields of more than a few $\times 10^6$ g.

Extensive optical photometry has been reported by Motch (1981), who initially reported the discovery (Motch 1979) of a ~5.2 hour periodicity in the star. His full report confirms this period but includes complications, such as a phase range in the light curve maximum, and a 4 day modulation of the entire light curve, with an amplitude similar to that of the 5.2 hour one.

The radial velocities were found to vary on time scales of a few hours by Watts, Greenhill, and Thomas (1980). Various attempts to find a spectroscopic period and orbit have been reported (van Paradijs, van den Heuvel, and Verbunt 1980; Hill 1980) which have not agreed with the photometric values. Our own initial data met with similar drawbacks. As a result, we have had to accumulate a formidable amount of spectroscopic material before fully disentangling the three periodic clocks in the system. Even so, it is clear that more needs to be done before we can fully interpret the behavior of this remarkable object.

II. OBSERVATIONS AND MEASUREMENTS

The spectrographic data are listed in Table 1. All exposures were made on baked IIIa-J emulsion at 47 Å mm^{-1} with at least a 1 mm wide trail. The time resolution is ~10 minutes or ~0.03 of the orbit. The data were obtained on three observing runs with the Ritchey-Chrétien spectrograph on the Cerro Tololo Inter-American Observatory (CTIO) 4 m telescope in 1979 December (J. R. T.) and 1980 February and November (A. P. C. and J. B. H.). Many of the 1980 November spectrograms were 2 mm wide single-trailed to look for rapid spectrum changes. These were measured in two strips for radial velocity. The results are recorded in Table 1 as two separate observations.

Radial velocities were measured for the main (base) part of all emission profiles as well as for the line peaks. In general, the peak and base velocities were not the same, and, at some phases, two peaks are seen with a separation of some 600 km s^{-1}. Table 1 gives mean values from the Balmer lines Hβ–H8, He I λλ4471, 4026, 4387, 4920, 5015 lines, and the peak of He II λ4686. Measures of the weaker or more blended features are too scattered to be of interest in this paper. Occa-

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TABLE 1

2A 0526−328 SPECTROSCOPIC DATA*

JD 244....	ϕ_{spec}	ϕ_{phot}	Radial Velocities[a] (km s^{-1}) Balmer Pk	Balmer Base	HeII Pk	HeI Base[b]	Remarks[c]
4225.732	0.693	0.900		4			$\phi_4 = .51$
.736	.710	.916	-34	62			
.742	.737	.943	-47	160			
.751	.776	.987	-42	112			
4226.578	.394	.809	50	-100	185	53	$\phi_4 = .72$
.587	.433	.852	14	-70	178		
.597	.472	.896	-85	-115	-207		
.627	.608	.039	70	-56	-226		
.637	.652	.084	39	8	-222	30	
.646	.691	.126	38	-62	-164	110	
.655	.730	.167	-137	30	-114	109:	
4227.635	.017	.697	295,-245	144	-99		$\phi_4 = .98$
.652	.092	.774	316	58			
.663	.136	.824	362	224	358	190	
.674	.188	.875		174	88		
4289.620	.168	.253	334,-256	94	119	144	$\phi_4 = .38$
.682	.435	.540	104	-6:	198		
.697	.505	.609	64:	-182	81	-74	
.712	.570	.678	44:	-66	-44	8	
4290.529	.144	.455	354,-256	144			$\phi_4 = .61$
.546	.219	.534	294,-266	44			
.581	.372	.696	64	-36	198	24	~ phot. max
.591	.415	.742	19	-56	301	4	
.602	.464	.793	44	-81	138	4	
.611	.503	.834	24	-96	17	-51	
.622	.551	.885	-26	-106	-96		
.633	.599	.936	-76	-56	-108		
.647	.660	.001	-116	-16	-223	-12	
.659	.713	.056	-46	24	-308	139	
.671	.765	.112	-66	-6:	-358		
.689	.844	.195	-102	64	-165		
.703	.905	.260	-116	114	-158	194	
4291.577	0.729	0.300	-54	-11	-65	144	$\phi_4 = .87$
.586	.768	.342	-86	134	-190		
.596	.812	.388	-52	94	-148	107	

JD 244....	ϕ_{spec}	ϕ_{phot}	Radial Velocities (km s^{-1}) Balmer Pk	Balmer Base	HeII Pk	HeI Base	Remarks
4556.785	.869	.356	-190	70	-153		$\phi_4 = .77$
.794	.906	.395	-95	105:	-154	195:	
4557.594	.408	.096	130	-5	208	10:	$\phi_4 = .97$
.603	.445	.135	60	-60	173	-70	
.612	.487	.179	120	-75	233	-5:	
.621	.524	.217	80	-60:	136	-60:	
.630	.564	.260	55	-50	12	-30	
.638	.601	.299		-20	31	-15	
.651	.656	.357	-70	3	-55	100	
.659	.692	.396	-125	10	-146	200:	
.669	.734	.440	-70	55	-162	160:	
.677	.771	.479	-80	80	-185	80:	
.687	.813	.523	-110	125	-164	105:	
.695	.850	.562	-110	95	-191	140:	ϕphot. min.
.705	.891	.606	-75	135	-119	190:	
.713	.928	.644	-100	140	-68	190	
.724	.975	.694	515,-105:	180:	-81	140: A292	
.732	.011	.733	-85: 440:	220:	19	180:	
.741	.052	.776	310	100	29	110	
.750	.089	.815	310	140	78		
.759	.131	.859	245	140:	205	150	
.768	.168	.898		150:			
.778	.212	.944	-230:	183:		141:	$(M_B \sim 13.7)$
.786	.248	.983		100:	463		phot. max.
.796	.289	.026	180	57:	341		
.804	.326	.065	120	-33:	241	36	
4558.581	.726	.659	-5	80	-397	150:	$\phi_4 = .22$
.590	.763	.698	500,-370:	150:	-339	190:	
.601	.812	.750	-70, 580:	160	-213		
.647	.015	.965	520,-180:	60	-70	A 210	phot. max.
.686	.185	.144	-305, 400	120	545	A-3	
.695	.222	.183	340,-335	32	464	A-90	
4559.660	.446	.647	105	-30:	116	-10:	$\phi_4 = .48$
.737	.783	.004	10	134:	-334	100:	$(M_B \sim 14.1)$

*47 Å mm^{-1} spectrograms λλ3850–5050. Time resolution: ~10 minutes per datum.

[a]Velocity values are ±15 km s^{-1} or less; values with colon, ±30 km s^{-1} or less.

[b]Absorption components denoted A.

[c]4 day phases (ϕ_4) from ephemeris. Other remarks are from observations.

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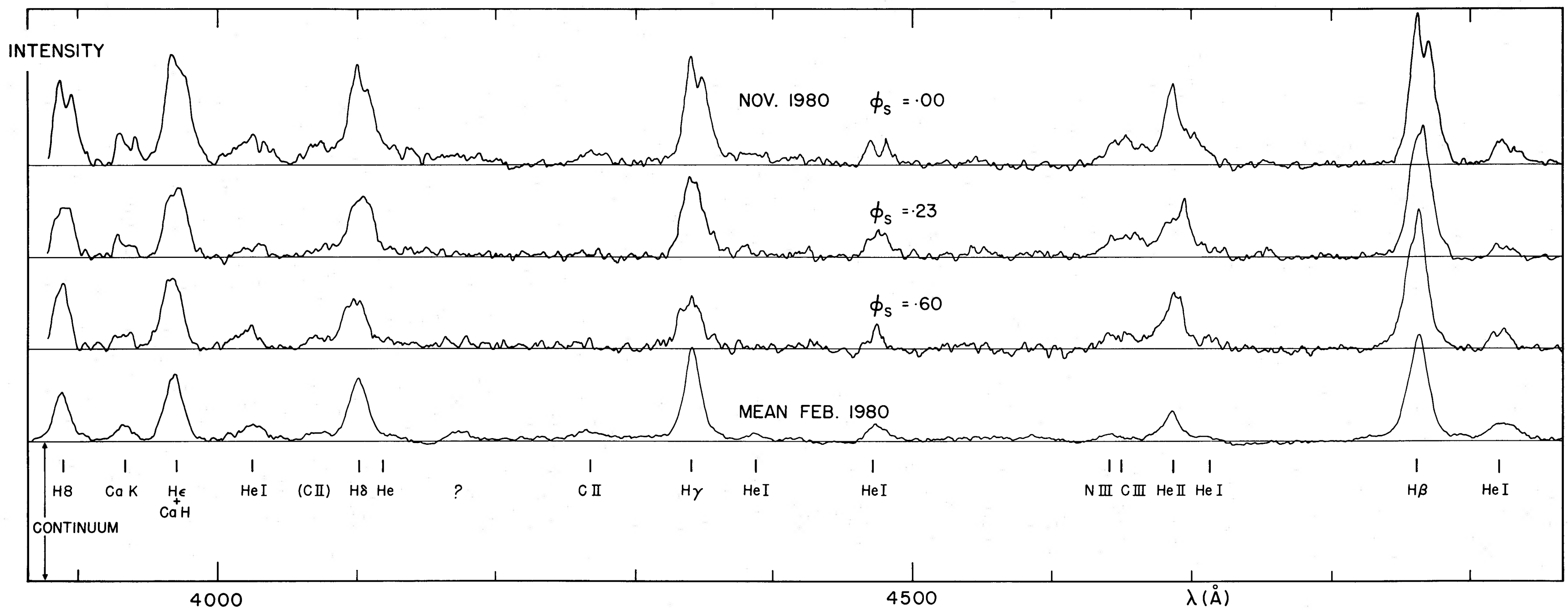

FIG. 1.—Representative spectra of 2A 0526−328. Upper three show orbital phase-related changes in 1980 November. Lower spectrum is mean of 12 spectra over all phases in 1980 February. Positions and identifications of major line features are given.

sional absorption features were seen near the He I λλ4026, 4471 lines. These are given in Table 1 also.

During observations a record was kept of the exposure meter count rate. On any one night it was often possible to trace the general shape of the 5.18 hour light curve in this way. Night-to-night changes were less certain because of possible seeing and transparency variations, but it was also possible to estimate the 4 day photometric modulation as well. On two of the nights in 1980 November, B photometry was done by M. Liller on the CTIO 1.5 m telescope which was valuable in verifying our exposure meter photometry and establishing the 4 day phasing.

All the 1979 December and 1980 February spectra and a sample of the 1980 November spectra were converted to rectified intensity tracings. Line profiles were measured on all of these, and subsets of them were added to look for spectroscopic changes related to the three periods in the system.

Figure 1 shows some representative tracings. The spectrum resembles that of DQ Her in the lines present (Hutchings, Cowley, and Crampton 1979), although the C II and C III in 0526−33 are relatively weaker. We note the presence of emission at λλ4070, 4175 also seen in DQ Her, AM Her, and 0311−22, but not in SS Cyg or EX Hya. Large changes occur in line equivalent widths, but relative intensity changes are more subtle. We discuss these later, after establishing the periodicities present in the system.

III. THE THREE PERIODS

Motch (1981) reported finding a basic photometric period of 0.21627±0.00007 days and a longer modulation of the entire light curve with a period of 3.95±0.15 days. These variations are clearly present in all our data, principally from the exposure meter counts recorded for each exposure. The spectroscopic (radial velocity) period is different from the photometric; different lines have different velocity amplitudes, means, and phasing; and sharp line peaks march through the cyclic velocity curves, also with their own phasing (see Fig. 2). It was, therefore, more difficult than usual to determine the unique velocity period (or indeed that one exists). The spectroscopic period compatible with the photometric period and which gives the best fit to the data (including values from 1979 February by Watts, Greenhill, and Thomas 1980) is 0.228600±0.000005 days. By this we mean that the 4 day period is the beat period of the photometric and spectroscopic, within the given error limits. It was possible to revise the photometric period, by timing maxima during the 1980 November run, to give 0.21631 ±0.00001 days. This in turn yields a beat period of 4.024±0.003 days. Other possible spectroscopic periods, which fit the data marginally less well, are not compatible with this beat relationship.

Independently, times of 4 day maximum can be estimated from Motch's and our data which yield 4.024 ±0.004 days. The exact meshing of these periods over nearly 2 years of observations indicates that they are fundamental clocks in the system and the basic key to understanding its nature.

These figures are compatible with all known data on the system. The 24 hour alias of 0.2286 days is 0.186 days, which presumably accounts for the report by Hill (1980). Our data definitely exclude this period.

The ephemerides of the three periodicities are given in Table 2. Note that the T_0 for the spectroscopic data

TABLE 2

PERIODICITIES IN 2A 0526−328

Data	T_0 JD 2,44 ...	Period (days)	Remarks
Short light curve ...	4,171.46 (1)	0.21631 (1)	T_0 is mean light max.
Radial velocity	4,227.631 (2)	0.228600 (5)	T_0 is Balmer base max. vel.
Long light curve ...	4,191.5 (3)	4.024 (4)	T_0 is light max.

NOTE.—Numbers in parentheses are uncertainties in units of least significant figure.

TABLE 3

ORBITAL SOLUTIONS[a]

Emission Lines	N^b	V_0 km s^{-1}	K km s^{-1}	ϕ_0	σ^c
He II λ4686 peak ...	59	46±15	276±19	0.285±0.020	102
H mean	73	49±6	116±8	(0)	47
He I base...........	41	91±7	103±10	0.966±0.020	43

[a] P=0.228600 days; T_0=2,444,558.631.

[b] Number of data points.

[c] Standard deviation in km s^{-1} per data point per degree of freedom.

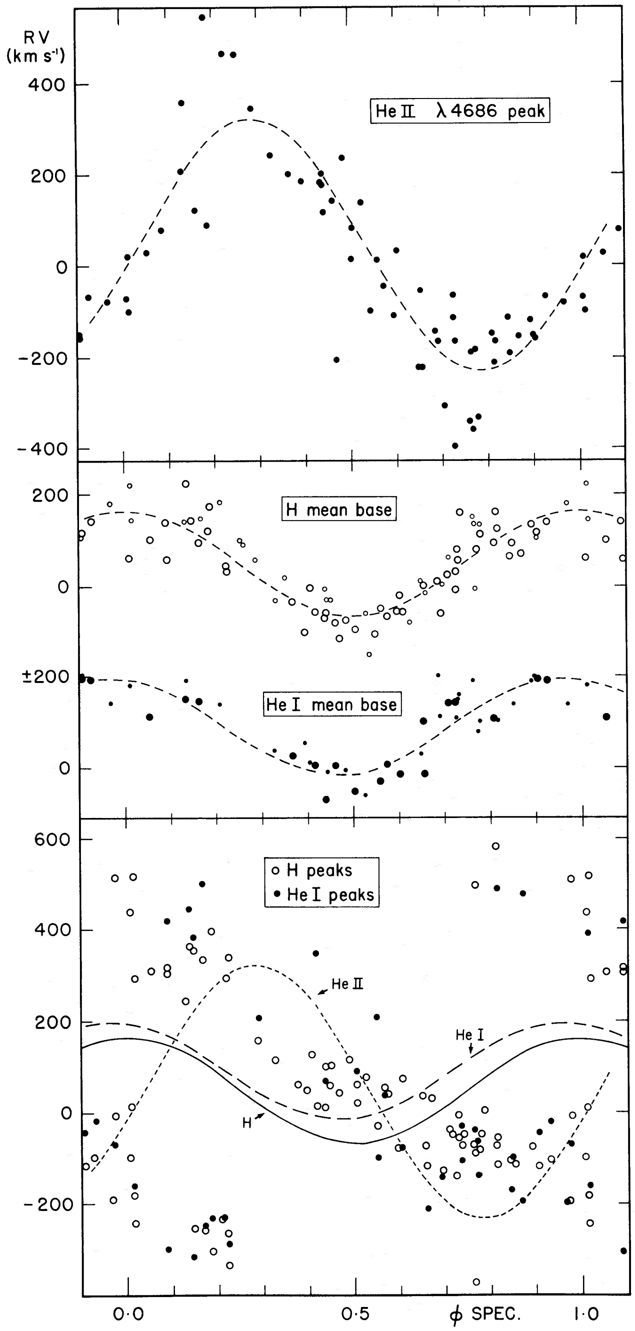

FIG. 2.—Radial velocities in 2A 0526–328 on 0.2286 day period. Curves are best-fit sine functions to data. Size of points indicates weight. Peak and base components can be identified in Fig. 1.

refers to the Balmer line velocity maximum. The best-fitting orbital parameters to the principal velocity curves are given in Table 3 and illustrated in Figure 2. Noncircular solutions did not yield a significantly better fit, and the values of e and ω were not significantly defined. The spectroscopic period was found to be the same, within the quoted error limits, independently in all three data sets, and the value 0.228600 was adopted for all. The Balmer line parameters were derived, including values read from the published velocity curves of Watts, Greenhill, and Thomas (1980).

IV. VELOCITY VARIATIONS AND ORBIT

The scatter in measured velocities is large and mostly attributable to the considerable night-to-night changes in the emission line profiles and intensities. The cyclic nature of the velocities is therefore blurred by significant changes which do not relate to the 0.2286 day clock in the system. Nevertheless, the long-term stability of the behavior shown in Figure 2 (covering nearly 3000 cycles) strongly suggests that it reflects the orbital motion of the binary. The lines of different ionization and excitation appear to arise in different places in the system, as can be seen from the values in Table 3 and Figure 2. The Balmer and He I lines also have sharp peaks which march across the profile in about 1.5 cycles, covering more than 800 km s^{-1} and separated by ~600 km s^{-1}. This is suggestive of matter spiraling away from the system, but its appearance as a sharp emission feature seems to demand either a geometry which occults most of the spiral at any moment or a discrete ejection event every orbital cycle.

The He II λ4686 line has a sharp peak which appears to execute a cyclic motion. It is possible, however, that our measures refer to a cyclic motion of lower amplitude, plus a marching peak similar to the H and He I lines (see Fig. 2, top panel). There *is* a broader base to this line, whose velocity cannot be studied properly because it is blended with C III and N III on one side and He I on the other. In general, the distinction between peak and base is clear (see Fig. 1), but perhaps 10% of the measures are uncertain in this distinction because of profile changes.

The phase shift between He II and the other feature is quite marked and significant, even if we admit the uncertainty in the He II behavior discussed above. The difference between H and He I is less certain in phase, but appears to be real in V_0. Since there are clearly mass-motions in the system, the best estimate of orbital motion of the accreting object would be the lowest measured amplitude. Adopting K of 103 km s^{-1} yields a mass function of 0.026 $M_\odot$. Since the system is not eclipsing, $i < \sim 65°$. At 60°, the mass-losing star is then less than 0.5 $M_\odot$ (for a 1.4 $M_\odot$ white dwarf). If $M_{WD} = 0.5\ M_\odot$, $M_{MS} \sim 0.3\ M_\odot$. At $i = 30°$, the M_{MS} values are about doubled. These are reasonable values for the masses in such a system.

The phase shift and higher velocity amplitude of He II are consistent with its origin in a hot spot in an accretion disk, if the H velocities are orbital.

Measures were also made of the Ca II K velocities, but these are so scattered (because of variable profile shape and intensity) that no pattern can be discerned. There is a clumping of velocities coincident with the H and He I peak velocities at ~ -100 km s^{-1}, $\phi_{spec} \sim 75$.

V. LINE INTENSITIES

Before attempting a general discussion, it is instructive to examine the line intensity variations. As noted by Schwartz *et al.* (1979), these are large. We have plotted peak intensities and equivalent widths against phase in all 3 periods for all species of lines. In almost all cases, there is no significant phase correlation at all. Therefore, we show only (Table 4) the range of measured quantities in our data. In general, all strong lines vary in intensity in a highly correlated way, so it appears that the line emission (or continuum) varies irregularly over a factor of 4 or more. The time scales of these changes appear to be days or longer. The absence of a correlation between ϕ_{phot} and line equivalent width implies that continuum and line emission intensities are closely linked over short time scales.

There are some quantities that vary in a phase-locked fashion. The principal one is the Ca II K line, which is stronger by a factor of more than 2, peaking at $\phi_{spec} \sim 0.8$ (see Fig. 3). The He II λ4686 emission has a probable correlation with ϕ_{phot} (Fig. 3), which suggests that it is least coupled to the continuum intensity of all emission lines, and again supports its origin in a removed site, such as a hot spot. He II λ4471 shows a marginal correlation with either ϕ_{spec} or ϕ_{phot}, the distribution among the data points making either one possible. Either λ4471 is low in ϕ_{phot} 0.5–0.9 or it is low in ϕ_{spec} 0.2–0.5.

It is of interest that the Ca II emission peaks when the mass-losing star is at superior conjunction (assuming the H emission orbit to be correct), suggesting an origin on or near the (heated) mass-losing face of that star.

We attempted to estimate the intensities of the Balmer emission peaks as a fraction of the base, to study the peak intensity changes with phase. These are shown in Figure 3. It is notable that the peak is strong in ϕ_{spec} 0.75–0.85, and briefly near ϕ_{spec} 0.44. The peak appears at high positive velocity, weakly at $\sim\phi_{spec}$ 0.8, is strong in phases 0.0–0.2, and then is relatively weak, except for the phase 0.44 event, until it has a negative velocity at phase 0.8 again. It is very weak thereafter until $\phi \sim 0.2$, when it becomes moderately strong before disappearing. These results are somewhat subjective because of the blending in all cases and the extreme variability of all lines at all times. However, they seem relevant in deciding the origin of this peculiar emission.

TABLE 4

Emission Line Characteristics[a]

Line	EW (Å)	Peak (% continuum)
Hβ	4–21	25–110
Hγ	3–15	20–80
He II λ4686 ...	1.5–10	5–60
He I λ4471	0.5–3.5	5–20
Ca II K	0–3.1	0–25

[a]Minimum and maximum values given.

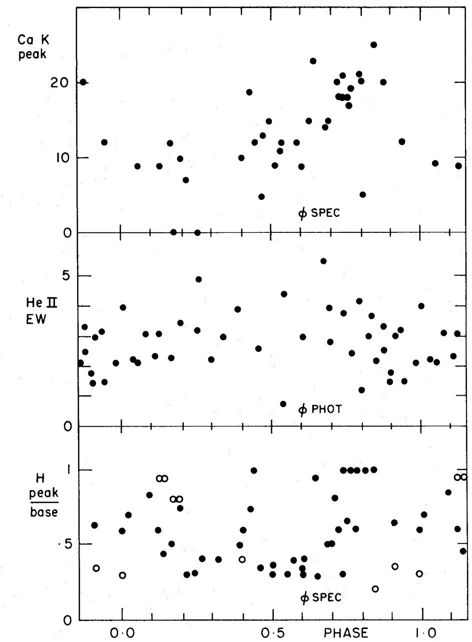

Fig. 3.—Phase-related line changes in 2A 0526−328. No other changes were found on any of the three periods. In the lower panel, the open symbols denote the redward peak when two peaks were present. Note that only one peak is identified in the phase range 0.25–0.75 (see Fig. 2).

VI. DISCUSSION

We propose that the basic phenomenon giving rise to the multiple periodicity is a nonsynchronized rotation of a moderately magnetic white dwarf of the DQ Her type. The photometric variation is the rotation of the white dwarf, and the spectroscopic period is the orbit. The white dwarf then rotates once within the binary system in 4.024 days. The actual light variation is driven by a beam (the accretion column onto the white dwarf), and the 4 day modulation is the changing illumination of the beam as it sweeps around the binary system. This puts 2A 0526−328 at the extreme end of the DQ Her stars, the next slowest rotation being EX Hya with a 67 minute period.

Predictions are difficult to make from such a model, since it contains many unknown parameters. It is likely that X-radiation is beamed from or modulated by the white dwarf rotation, so that it should show the 5.18 hour period. The expected existence and size of a disk (or ring) are not obvious. With near synchronism there is likely to be only a thin large ring, with matter spiraling into the center from it. However, although the marching peak behavior suggests a spiral, it is clearly phase-locked to the orbit and presumably dynamic rather than magnetic in nature. Since the splitting of the lines is caused by the marching peak, we cannot regard this as evidence on the existence or nature of a disk. The considerable width of the profiles ($\sim$3000 km s^{-1} at times), however, does suggest a ring or disk of considerable geometrical extent.

If the line broadening *is* Keplerian, it corresponds, at $i \sim 60°$, to the surface velocity for a 0.3 $M_\odot$ white dwarf, the velocity at 4 R_{WD} for 0.7 $M_\odot$, or at 25 R_{WD} for 1.3 $M_\odot$. However, since the WD radius varies strongly with mass, these inner radii are all less than 10^{10} cm and are therefore small with respect to the probable size ($\sim 10^{11}$ cm) of the binary.

The absence of clear 4 day spectroscopic phenomena is disappointing. It appears to be masked by the large irregular changes which may relate to a variability in the disk (or ring). One might propose that the 4 day photometric variation is caused by a heating effect on the red star by the beam. This might tie in with the oscillation of the 5.2 hour photometric maximum on the 4 day period by a moving hot spot related to a heating modulated mass flow. We have suggested that He II is connected with a hot spot. Solutions of its velocity curves from data binned near the extremes of the 4 day variation, however, show no significant phase shift ($\Delta\phi = 0.024 \pm 0.022$) or velocity amplitude shift ($\Delta K = 35 \pm 34$) between them. There is a startling difference in V_0: 73 ± 15 at 4 day maximum, and -2 ± 24 at minimum. The Balmer lines show no difference in any parameter.

A 4 day heating modulation should also give rise to color changes and line intensity changes, particularly in Ca II which is (orbital) phase sensitive. No such evidence is found. We are thus driven to consider effects within the disk or ring, such as variable illumination by an obliquely rotating beam attached to the white dwarf.

For the present, we are reluctant to suggest a firm model for the system. Additional photometry and X-ray data will undoubtedly define the system more closely. We commend our findings to the attention of observers and theoreticians.

We wish to thank C. Motch for information and discussions on the photometry, M. Liller for photometric observations, and W. Fisher for work on the spectrophotometry.

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Note added in proof.—P. A. C. and J. R. T. took three more spectra during 1980 December and 1981 January using the same equipment as above. These were reduced for radial velocity using the Berkeley Astronomy Department PDS microdensitometer and an interactive computer program. Since this is different reduction equipment, some systematic differences are likely. The dates of the spectra together with the mean velocities of the centroids of Hβ, Hγ, and Hδ were: JD 2,444,603.588, -21 km s^{-1}; JD 2,444,604.584, $+202$ km s^{-1}; and JD 2,444,605.569, $+70$ km s^{-1}. At these times the radial velocity ephemeris above predicts -43, $+162$, and $+34$ km s^{-1}, respectively, which agrees well given the sizable random and systematic errors likely to be present in the intercomparison of the data.

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