THE ASTROPHYSICAL JOURNAL, 384:234–248, 1992 January 1

ON THE CERTIFICATION OF AM CANUM VENATICORUM AS A CATACLYSMIC VARIABLE

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Received 1991 March 22; accepted 1991 July 15

ABSTRACT

We rediscuss the evidence that the peculiar faint blue star AM CVn (= HZ 29) is an ultra–short-period cataclysmic binary. The existence of at least two noncommensurate short periods in the light curve, plus the recent discovery of the class of pulsating DB white dwarfs, suggests a need for reappraisal of the binary star model. Reckoned as a cataclysmic variable, AM CVn is extremely unusual: it never erupts, never changes its spectrum, barely flickers, shows suspiciously blue colors, and fails to reveal a stable photometric period despite titanic efforts to discover it. But many of its properties suggest a similarity to the known DB pulsators. We present new photometry and spectroscopy of AM CVn, and also of five DB pulsators, to illustrate this similarity. It is quite possible that a significant fraction of the total light in AM CVn, perhaps most of it, comes from the photosphere of a pulsating white dwarf.

On the other hand, while the original motivations for a binary star model have largely evaporated, several new pieces of evidence in its favor have emerged: the line He II λ4686 in emission, variable line profiles, an ultraviolet spectrum with strong heavy-element absorption features, rapid quasi-periodic oscillations, and the discovery of two apparently similar systems with more impressive binary star credentials (V803 Cen and CR Boo). These are not easy to understand in the context of a single-star model.

The most severe obstacle to accepting AM CVn as a short-period binary is the instability of the photometric period. We suggest that this can be reconciled with a binary star model by postulating the existence of an eccentric accretion disk precessing around the white dwarf. This implies that the absorption-line profiles should be highly modulated not on the presumed 17 minute binary period but on the disk precession period of ~7–12 hr.

Subject headings: novae, cataclysmic variables — stars: individual (AM Canum Venaticorum) — stars: oscillations — white dwarfs

Never try to prove what nobody doubts.—A fortune cookie

1. INTRODUCTION

AM Canum Venaticorum (= HZ 29 = EG 91) was first discovered (Malmquist 1936; Humason & Zwicky 1947) as a faint blue star at high Galactic latitude, and classified by Eggen & Greenstein (1965) as a DB white dwarf. But Smak (1967) discovered the star to be variable with a period of ~17 minutes, and proposed a cataclysmic variable (CV) model, elaborated further by Faulkner, Flannery, & Warner (1972, hereafter FFW). In this now very popular model, a degenerate, low-mass helium star transfers matter to a more massive white dwarf via an accretion disk. The 17 minute period is interpreted as the orbital period of the binary. Because the putative orbital period is extremely short and because the spectrum indicates an extreme deficiency of hydrogen, the model must illustrate a very late stage of binary star evolution. Little is known about the late stages, and therefore the star has become a *cause célèbre* among observers and theorists alike.

But compelling evidence for the duplicity of the star has never been produced. No eruptive behavior has ever been observed; the flux distribution from 0.1 to 1.0 μm is consistent with that of an isolated hot white dwarf; searches for short-period radial velocity variations have been negative; and truly Herculean efforts to uncover a *stable* photometric period have been unsuccessful. Also, a new class of variable white dwarfs has been discovered in recent years, the pulsating DB stars (Winget et al. 1982; Winget 1988). These stars appear to be a rather good match for AM CVn in period, amplitude, spectrum, and flux distribution.

In this paper we reexamine the arguments for classifying AM CVn as a cataclysmic variable, in view of what is now known about pulsating DB white dwarfs. The evidence is still not conclusive. We find that the mean period during 1967–1990 was probably 1051.22 ± 0.03 s. It is possible that this period is stable in the mean, but the evidence does not favor it; in any case, the residuals from a constant-period ephemeris are at

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least as high as $0.15P$, and probably even larger. Such unstable behavior from an orbital clock is hard to understand. A second period of 1023.4 s is also a persistent feature of the light curve; its stability on long time scales is also in question.

There are, however, still some important clues favoring a binary model: weak emission lines, highly and variably asymmetric absorption lines, ultraviolet absorption lines from heavy elements, and transient quasi-periodic oscillations (QPOs). Study of the line profile variations probably represents the best chance of vindicating the binary star interpretation of AM CVn.

2. THE EVER-SHIFTING PHOTOMETRIC PERIOD

2.1. *The Historical Setting*

The basic properties of the rapid periodicity were established by Smak (1967, 1975). Most of the power is at $P = 525$ s, with a slight asymmetry in the minima suggesting (but not proving) that the true period is 1051 s. Despite the commonly assumed orbital origin of the photometric variation, and despite many hundreds of hours of observation, no reliable ephemeris for the periodicity has ever been presented. In Table 1 we collect the various values for the period that have been reported over the years. The lack of agreement is noteworthy, and is particularly disturbing if the period is thought to be an orbital period.

There have been previous suggestions for understanding the disagreements. Krzeminski (1972) hypothesized a third body to explain the wiggles in $O-C$ diagrams, while Patterson et al. (1979, hereafter PRNH) invoked a large $\dot{P}$ term. Neither has proved to have any predictive power. The most recent and complete study is that of Solheim et al. (1984, hereafter SRNK). Those authors made the key discovery that there are two noncommensurate strong periods in AM CVn: the familiar 525 s period, and a previously unsuspected 1011 (or possibly 1023) s period of comparable amplitude. They pointed out that because $1011 \approx 2 \times 525.5$, the effect of the 1011 s signal is to cause an even-odd effect to appear in the light curve, creating a misleading impression that the true period is 1051 s. This suggestion was plausible, but we shall see below that it is not correct.

More important for the present discussion, SRNK also made an ambitious effort to study the long-term behavior of the dominant 525 s signal. They proposed that most previous authors have miscounted cycles, essentially because observations tend to be correlated with the lunar phase, and that with appropriate adjustments to the cycle count, a single, *nearly constant* period (525.52 s) can represent all of the timings. We find this conclusion impossible to accept, for four reasons:

1. Whenever the observations are densely spaced (see Figs. 5 and 6 of SRNK, or Fig. 3 of PRNH), there is very significant "phase jitter" about *any* constant period.
2. Even after clever juggling of cycle counts to obtain the best possible fit, the final fit obtained in Figure 9 of SRNK is far from convincing. The rms residual appears to be ~105 s, and some points, including points of high weight, are discrepant by 180 s. Since the maximum possible departure is 262 s, this is not very reassuring!
3. The analysis presented below does not establish whether there is a stable period; but if there is one, it is probably ~525.61 s.
4. The data presented below demonstrate conclusively that the ephemeris of SRNK, like all previous candidates, displays no predictive power.

TABLE 1

PREVIOUSLY REPORTED PERIODS

Period[a] (s)	Year	Reference
~1050	1962	Smak 1967
1051.05	1967	Krzeminski 1971, 1972
1051.12 ± 0.015	1968	Ostriker & Hesser 1968
1051.05	1971	Warner & Robinson 1972
1051.16	1974	Smak 1975
1051.19 ± 0.02	1976	Patterson et al. 1979
1051.21 ± 0.015	1978	Patterson et al. 1979
1051.0409[b]	1962–1983	Solheim et al. 1984

[a] Here we use the convention of referring to the subharmonic of the dominant period, although doubts have been expressed as to whether it is actually present in the light curve (see Solheim et al. 1984 for a discussion of this). We believe that the discussion in § 2.3 does firmly and finally establish that it is present, however.

[b] Decreasing by 0.0001 s yr^{-1}.

2.2. *New Optical Photometry and Power Spectra*

AM CVn has been on our photometric observing programs for over a decade. In Table 2 we present a list of new observations made during the interval 1979–1990. The McDonald observations were obtained in unfiltered light with a blue-sensitive photomultiplier tube (RCA 8850 or Amperex 56DVP) and a two-star photometer (Nather 1973). The McGraw-Hill observations were obtained in blue light with a 1P21 photomultiplier tube and a single-channel photometer. The Kitt Peak observations were obtained in blue or yellow light with a GaAs photomultiplier tube (RCA C31034a) in the Automated Filter Photometer. The Lick observations were obtained in yellow light with a FW-130 photomultiplier tube mounted in a single-channel photometer at the prime focus of the 0.9 m Crossley reflector, or with the multistar high-speed photometer (Stover & Allen 1987) at the Cassegrain focus of the 1.0 m Anna Nickel reflector.

In order to obtain nearly continuous data streams, we made only occasional interruptions for checks on transparency and sky background. This sacrifices photometric accuracy, but is the preferred technique for the study of short-period oscillations which maintain good coherence. Data reduction was standard; from the raw counts we removed sky background and used a mean extinction coefficient to reduce to counts per second above the atmosphere.

The light curves obtained strongly resemble previously published light curves, with an obvious 9 minute modulation and a usually less distinct wave of ~17 minute period. As pointed out by SRNK, most of the power in the longer period signal is at $P = 1011$ (or 1023) s, not at 1051 s as had been previously believed. The possible presence of weaker signals (at 1051 s, and at other periods) is of considerable importance for the interpretation of the system, and so we have calculated power spectra to identify these signals.

First we calculated discrete Fourier transforms where we have adequately long and densely spaced observations: in 1978 March, 1978 April, and 1990 January. In each case, the results substantially agree with the analysis of the (identical) 1978 March data by SRNK—namely, that $P = 1051$ s is at best a weak feature, and that most of the power in the low-frequency signal is at 1011 or 1023 s. Although we cannot distinguish between these periods directly, we do see a significant peak at

TABLE 2

LOG OF PHOTOMETRIC OBSERVATIONS

UT Date	Telescope	Duration (hr)	$JD_{\odot}$ −2,440,0000 Pulse Minimum
1979 Feb 18	McDonald 0.9 m	2.0	3922.9321
1979 Feb 20	McDonald 0.9 m	1.5	3924.9330
1979 Apr 29	McDonald 0.9 m	1.5	3922.8521
1979 May 10	McDonald 0.9 m	1.0	4003.6444
1979 Jun 15	McDonald 0.9 m	1.1	4039.7028
1979 Jun 26	McDonald 0.9 m	1.5	4050.6649
1979 Dec 25	McGraw-Hill 1.3 m	1.0	4232.7292
1979 Dec 28	McGraw-Hill 1.3 m	2.3	4235.96552
1980 Feb 25	McGraw-Hill 1.3 m	1.1	4294.9313
1980 May 16	McDonald 0.9 m	1.3	4375.84994
1980 May 17	McDonald 0.76 m	1.1	4376.72050
1980 Jul 2	McGraw-Hill 1.3 m	1.0	4422.69103
1981 Jun 27	KPNO No. 2 0.9 m	0.9	4782.6762
1982 Feb 20	KPNO No. 1 0.9 m	2.5	5021.03034
1982 May 28	KPNO No. 2 0.9 m	1.9	5117.69799
1983 Mar 9	KPNO No. 2 0.9 m	1.6	5402.84861
1983 Mar 15	KPNO No. 2 0.9 m	1.7	5408.94950
1983 Apr 16	KPNO 1.3 m	2.2	5440.82640
1983 May 5	KPNO No. 2 0.9 m	0.9	5459.67340
1983 May 6	KPNO No. 2 0.9 m	3.2	5460.75000
1983 May 8	KPNO No. 2 0.9 m	0.9	5462.78217
1988 Feb 28	KPNO No. 2 0.9 m	2.2	7219.79613
1988 Feb 29	KPNO No. 2 0.9 m	1.3	7220.89756
1988 May 17	KPNO No. 2 0.9 m	1.7	7298.71975
1988 May 21	KPNO No. 2 0.9 m	1.2	7302.77084
1988 May 26	KPNO No. 2 0.9 m	2.0	7307.76498
1988 May 27	KPNO No. 2 0.9 m	1.0	7308.81841
1989 Jan 9	KPNO 1.3 m	3.2	7535.91610
1989 Feb 3	KPNO No. 2 0.9 m	1.8	7560.99433
1989 Feb 4	KPNO No. 2 0.9 m	2.2	7561.96754
1989 Feb 7	KPNO No. 2 0.9 m	5.4	7564.9976
1989 Feb 11	KPNO No. 2 0.9 m	2.8	7568.9401
1989 Feb 12	KPNO No. 2 0.9 m	3.1	7569.9253
1990 Jan 24	KPNO No. 2 0.9 m	4.7	7915.87416
1990 Jan 25	KPNO No. 2 0.9 m	5.1	7916.84759
1990 Jan 28	KPNO No. 2 0.9 m	5.3	7919.88947
1990 Feb 24	KPNO No. 2 0.9 m	1.2	7946.80566
1990 Feb 28	KPNO No. 2 0.9 m	0.8	7950.98525
1990 May 18	KPNO No. 2 0.9 m	3.0	8029.67651
1990 May 19	KPNO No. 2 0.9 m	3.1	8030.71142
1990 May 20	KPNO No. 2 0.9 m	0.9	8031.69011
1990 May 25	KPNO No. 2 0.9 m	0.6	8036.63670
1990 May 26	KPNO No. 2 0.9 m	0.7	8037.65828
1990 May 27	KPNO No. 2 0.9 m	0.7	8038.66842
1990 Jun 13	Lick 1.0 m	1.7	8055.75812
1990 Jun 16	Lick 1.0 m	0.9	8058.70307
1990 Jun 17	Lick 1.0 m	1.0	8059.70002
1990 Jun 27	Lick 0.9 m	0.8	8069.7261
1990 Jun 28	Lick 0.9 m	0.8	8070.7175

512 ± 1 s in all three data sets (also evident in Fig. 3 of SRNK), but no excess power at 505.5 s. Therefore, we shall assume that this is the first harmonic of the longer period signal, and that the correct choice for the latter is 1023 s. Inspection of the nightly pulse arrival times during densely spaced observations (1978, 1988, 1990) suggests a more accurate value of 1023.44 ± 0.03 s.

A considerably larger data set is available if we do not require the data to be very densely spaced in time. Considering all good-quality observations from the set of PRNH and this paper, of more than 2 hr duration, we have selected data from five different epochs and averaged the amplitude spectra from the individual nights. The results are shown in Figure 1; the obvious or likely features are labeled in the figure and identified with their periods (in seconds) in Table 3.

There are a number of interesting implications from Table 3:

1. While it can occasionally hide for a few hours at a time, the long-period oscillation appears to be a permanent feature of the light curve.
2. Although a 1051 s signal is not clearly seen (unfortunately it coincides cruelly with a 24 hr alias of 1023 s), an obvious signal at 348 ± 2 s is always present. This could correspond to the sum of the two principal frequencies, which would be expected to occur at $P = 347.2$ s. Or it could be the second harmonic of the unseen fundamental, expected at $P = 350.4$ s.
3. There are also detections at 261 and 210 s. These are probably the third and fourth harmonics of the unseen fundamental.
4. During 1978 and 1990, there was a probable detection at 175 ± 1 s—the fifth harmonic of a putative 1051 s period.
5. In both March and April of 1978, there was a highly probable detection at $P = 289 \pm 1$ s, which does not appear to be related to any of the other periods present in the star.

Combining these five amplitude spectra, with appropriate weighting, we obtain the grand average spectrum seen in the lower right-hand frame of Figure 1. Seven periods are present, at least three of which appear to be noncommensurate (1051, 1023, and 289 s).

We shall return to the interpretation of these signals in § 6.

2.3. *The Mean Waveform*

We have synchronously summed the light curves to find the mean 1051 s waveform. In order to prevent the 1023 s signal from contaminating the summation, we merged data which represent a complete "beat period" of 10.76 hr. Four such complete cycles were identified and studied in the densely spaced observations of 1978 March–April. The results, plotted

TABLE 3

IDENTIFIED FEATURES IN POWER SPECTRUM

	PERIODS (s)						
EPOCH	P_1	P_2	P_3	P_4	P_5	P_6	P_7
1971–1974[a]	1004 ± 29	524 ± 4	349 ± 3	...	262 ± 2	208 ± 2	...
1976 May[a]	1034 ± 17	523 ± 3	348 ± 2	...	...	211 ± 1	...
1978 Mar[a]	1011 ± 13	525 ± 2	350 ± 2	289 ± 2	259 ± 2	...	...
1978 Apr[a]	1029 ± 15	526 ± 2	345 ± 3	289 ± 1	261 ± 1	210 ± 1	...
1990	1024 ± 16	526 ± 4	350 ± 3	...	...	210 ± 1	175 ± 1
All	1021 (± 10)	525.0 (± 1.3)	348.4 (± 1.7)	289.0 (± 1.0)	260.9 (± 1.3)	209.8 (± 0.7)	175.0 (± 1.0)

[a] Minima from these observations have been previously tabulated by PRNH.

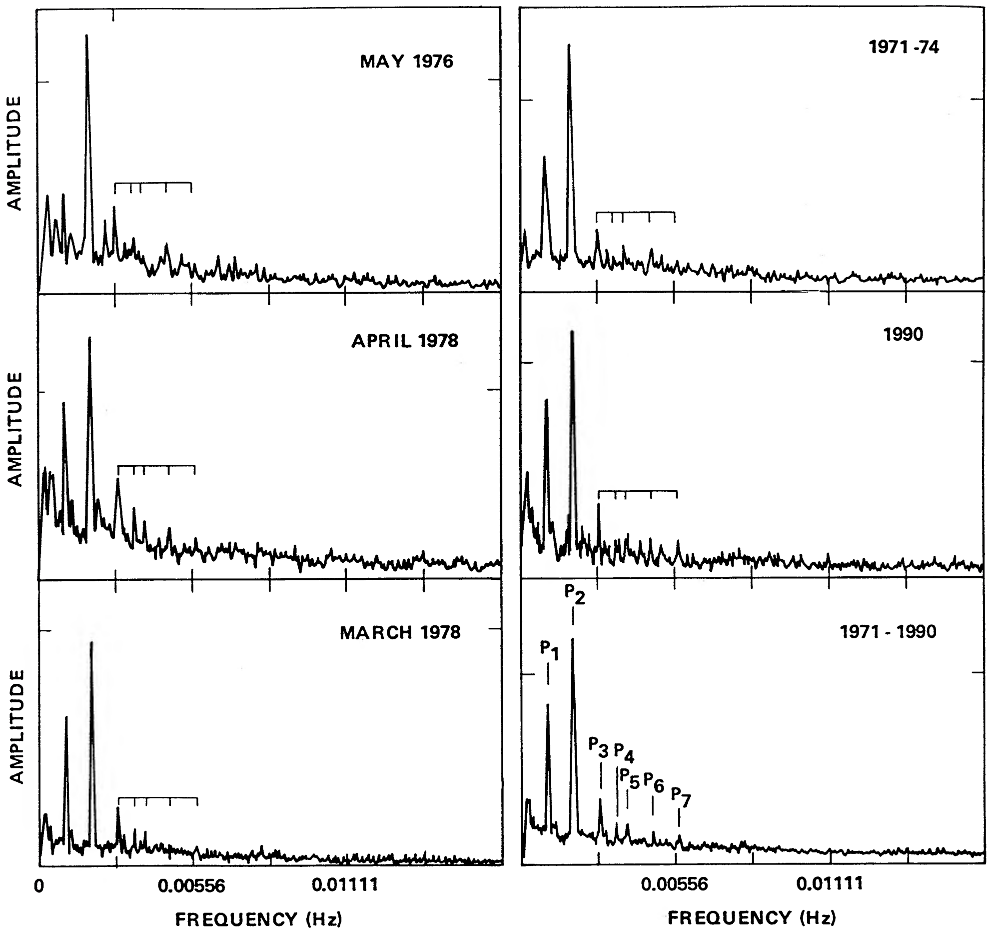

FIG. 1.—Amplitude spectra at five epochs, together with the grand average at lower right. The vertical tick marks indicate the seven periods identified as significant in the summed spectrum, but not all are significantly detected in each frame. See Table 3 for the periods identified in each frame. Horizontal tick marks denote a 1% semiamplitude.

with respect to the period of 1051.15 s shown during this interval (see Fig. 3 of PRNH), are seen in Figure 2. They appear essentially consistent with one another, with the mean waveform presented by Ostriker & Hesser (1968), and with the description of the typical 1051 s waveform stated by Smak (1975) and PRNH. In brief, the maxima and minima are of nearly equal amplitude, but one maximum is somewhat narrower, and the minima are not spaced by 180°. If we designate the trough after the narrow maximum as "primary minimum" (as PRNH did), then secondary minimum occurs at phase 0.55 ± 0.01. The maxima occur at phases 0.28 and 0.79 (± 0.015).

The presence of harmonics of 1051 s (*but not* 525 s), *plus the repeatability of the waveform in this and all other large data sets, furnishes extremely strong evidence that the fundamental period really is* 1051 s, despite the absence of any clear signal in the power spectrum. We note that a waveform of the type observed, with nearly equal maxima and minima, would not be *expected* to yield any power at 1051 s. The slightly non-sinusoidal waveform can be synthesized strictly from the higher harmonics, which are certainly present in adequate supply.

2.4. *Pulse Timings and Period Analysis*

Also included in Table 2 are the derived times of minimum light for the 525 s signal which normally dominates the light curve. Together with the large list of pre-1984 timings compiled by SRNK, and the timings reported by Seetha et al. (1990), these represent the entirety of published timings, as far as we are aware.

First we checked to see whether the long-term ephemeris derived by SRNK predicts the pulse arrival times of Table 2. It does not. Comparing the observed pulse arrival times with the SRNK ephemeris, we find average residuals of 114 s in 1979, 154 s in 1980, 157 s in 1983, 185 s in 1988, and 154 s in 1990. Since an ephemeris based on any randomly chosen period near 525 s would give an average residual of 131 s, this indicates that the ephemeris has no predictive power.

Then, following the long but less-than-hallowed tradition on this star, we sought to make another determination of the period from the pulse timings. Although we have presented strong evidence above that the fundamental period is 1051 s, it seems wisest to study the long-term period behavior by using the 525 s pulse timings, because the 525 s signal usually dominates the light curve. In preparing Table 2, we have fitted a 525.5 s sinusoid to the light curves, ignoring even-odd effects. Since the asymmetry in the minima amounts to only 0.05 cycles, this introduces at most an error of ~ 0.03 cycles.

For a variety of reasons, observers have often reported two timings per night. We have averaged these to obtain one timing per night.

PRNH and SRNK have shown that the pulse arrival times

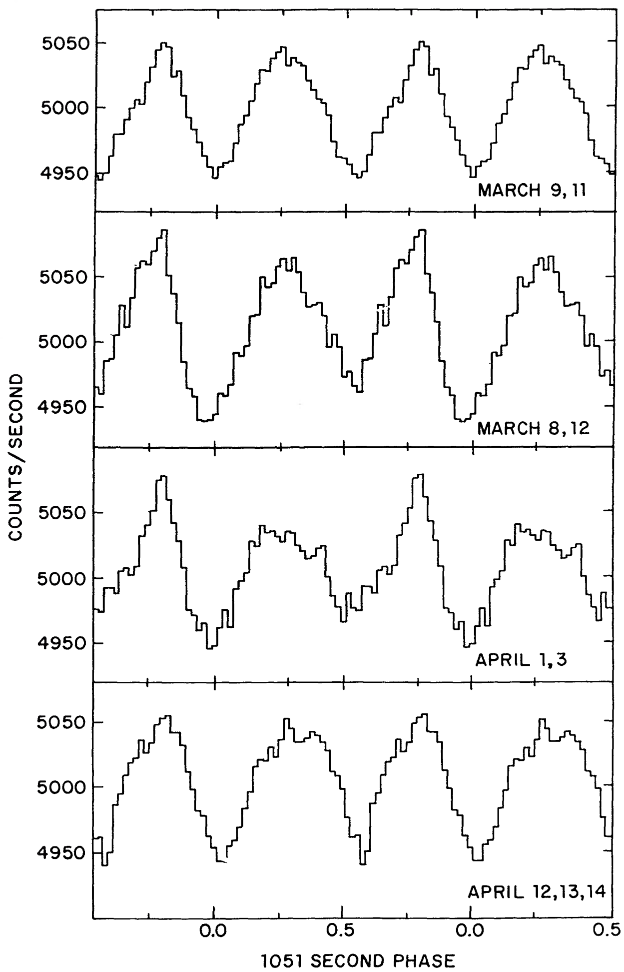

FIG. 2.—Mean light curves of AM CVn in 1978 March/April, folded with the best-fit period of 1051.15 s (see Fig. 3 of PRNH). The count rates have been adjusted to yield the same mean of 5000 counts s^{-1}. In order to minimize contamination by the 1023 s signal, we have selected light curves which span the entire 10.76 hr "beat period," which requires combining nights. The nights selected are identified in the lower right of each frame. There is one feature consistently seen in each waveform (and in every other extensive data set): the displacement of one minimum, which we call the primary minimum, to an earlier photometric phase.

wander with respect to any best-fit period, which severely hampers the accuracy of period determination. And since the observations are essentially never sufficiently dense to specify the time scale and amplitude of the wandering, cycle count is nearly always an extremely serious problem. We approached this problem as follows:

From the published data, we concentrated on eight individual observing seasons: (1) 1978 (PRNH); (2) 1979 (PRNH; this paper); (3) 1980 (Kovacs 1981; this paper); (4) 1982 (SRNK; this paper); (5) 1982/1983 (SRNK; this paper); (6) 1988 (this paper); (7) 1989 (Seetha et al. 1990; this paper); (8) 1990 (this paper).

Starting with the first timing for each season, we prepared $O-C$ diagrams with respect to a range of periods from 524.9 to 525.8 s, in increments of 0.001 s. This covers the entire range of previously suggested periods, with a comfortable margin on either side. We then calculated the rms residual of the timings about the best-fit ephemeris (leaving the epoch free to minimize the variance) for each trial period.

For the eight individual seasons, the results are shown in Figure 3. Each frame shows some complex individual structure, arising mostly from the fact that observations tend to be made at a particular lunar phase. The search for "the true period" meets with mixed results: (1) In 1978, the season of maximum coverage, several periods near 525.60 s give the best fit, but there is really no preferred period. (2) In 1979, 525.64 and 525.67 s are mildly preferred. (3) In 1980, 525.59 and 525.71 s are the best choices, with 525.66 s also permitted. (4) In 1982, 525.50 and 525.52 s are the only good choices. (5) In 1983, 525.63 s is the best choice. (6) In 1988, 525.59 and 525.62 s are mildly favored, with 525.55 and 525.66 s not excluded. (7) In 1989, 525.64 s is the best choice. (8) In 1990, 525.64 and 525.66 s are good choices, with 525.55 s not excluded.

It is hard to see much of a pattern in these results. Perhaps the most striking lesson is that *for most years there is no substantial preference for a particular period over other candidates.* The results from several years (1982, 1983, 1988, 1990) appear promising, but the periods are in conflict. The mean period over the 12 yr interval appears to be ~ 525.61 s, but since each year's "best period" might be strongly influenced by the long-term phase jitter in the timings, the mean period is also somewhat unreliable, for the same reason.

We tried three other methods to find a stable period in these timings:

1. We added together the eight frames of Figure 3, plus two additional frames (not shown) for 1967 and 1976, and weighted each season by the number of timings available. The result, seen in Figure 4, suggests a mean period of $P = 525.61 \pm 0.03$ s (the bottom of the broad dip), with the narrow dip occurring at 525.593 s.
2. We grouped the timings into three long intervals of fairly dense coverage (1978–1980, 1982–1983, 1988–1990), and repeated the period search, yielding Figure 5. A search for coincidences among these various dips did not give any credible result.
3. To fine-tune the test for phase stability still further, we searched for a constant-period representation of the 115 timings accumulated during 1976–1990, using a fine period grid with $\Delta P = 0.000026$ s. The result, seen in Figure 6, reveals no evidence for a stable period.

2.5. *Summary*

The safest conclusion from all this is that, despite the enormity of the observational base, it is still insufficient to define with certainty the "true period" of the 525 s variation—if there is one. The light curve consistently shows a period of 525.57 ± 0.09 s, which appears to maintain good coherence on a time scale of a few weeks, but drifts on longer time scales.[3] Somewhat less safely, we infer that the mean period is 525.60 ± 0.02 s, based primarily on the narrow dip in Figure 4 and its location near the center of a broad dip. We proffer this as the "best period," but in the absence of more definite constraints on the phase jitter, we do not know whether it is truly a

[3] SRNK point out that the 525 s extrema in the light curve can sometimes drift on time scales as short as a few *cycles*. We caution that because the oscillations are *multiperiodic*, examination of short segments of the light curve cannot be trusted to reveal the true phasing of the 525 s clock. Examination of the pulse timing history strongly suggests that phase jitter is not evident in long observations acquired within a narrow time window (~ 1–2 weeks; see Fig. 3 of PRNH). It is likely, in our opinion, that the 525 s clock maintains a strictly stable phase on shorter time scales.

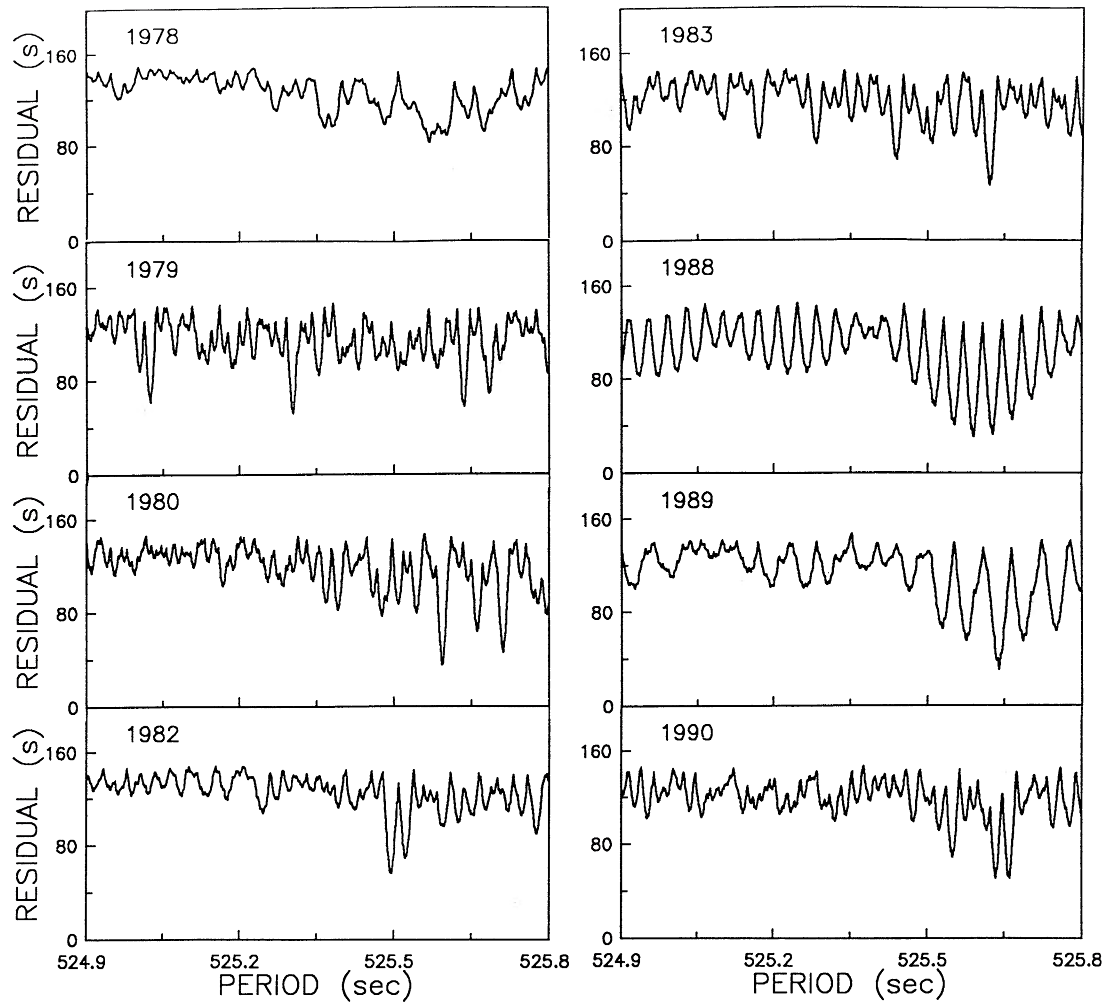

FIG. 3.—Root mean square residual for various trial periods, segregated by observing season. The quasi-periodic wiggles during some seasons reflect the nonrandom distribution of observations. See text for discussion.

stable period. Considerably greater observational vigilance will be required in the future if we are to specify the time scale and amplitude of the phase drift afflicting this star.

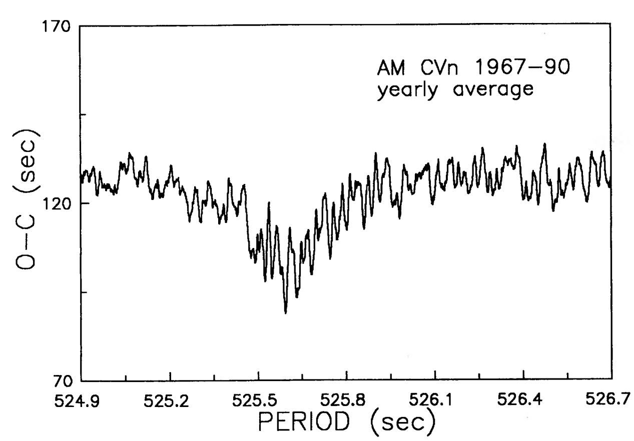

FIG. 4.—Root mean square residual for various trial periods, averaged over all individual observing seasons. The deep minimum occurs at 525.593 s, while the center of the broad dip occurs at 525.60 ± 0.02 s.

3. OTHER PERIODS?

As shown convincingly by SRNK, the light curve is dominated by signals at 525 and 1023 (or possibly 1011) s; and we have seen above that there are also harmonics of a 1051 s period weakly present. Are there still other periods or quasi-periods present in the light curve?

Warner & Robinson (1972) present evidence for transient periods in the range $P = 113–121$ s, of amplitude ~ 0.005 mag. PRNH refer to the presence of ~ 26 s, quasi-periodic oscillations seen on four consecutive nights in 1976 May. In Figure 7 we show the average amplitude spectrum of the light curves acquired on those nights. The amplitude of the signal appears to be ~ 0.01 mag, but is rendered very uncertain by the poor coherence of the signal. Both of these detections appear probable, but neither is on absolutely solid ground. The former occurs at a period uncomfortably close to the known 120 s drive error in the worm gear of the McDonald 2.1 m telescope, while the latter has not been definitely observed on any other occasion, despite the very large observing campaigns waged on this star.

Both of these papers also cite the existence of "flickering" in the light curve, and rely on this as a significant clue in favor of a binary star model. But the evidence is not so clear. In Warner

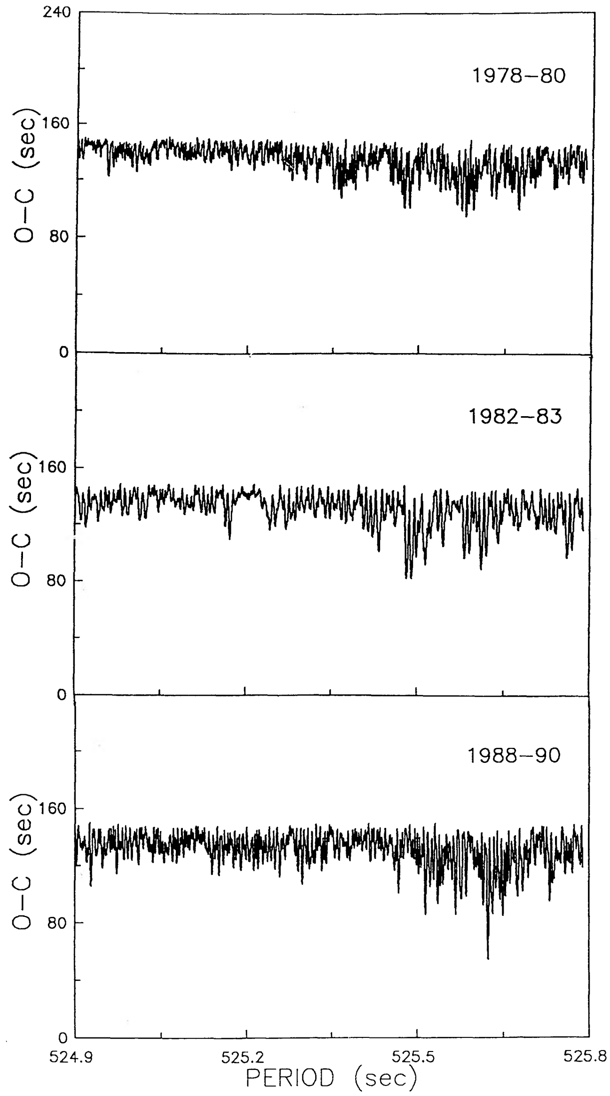

FIG. 5.—Root mean square residual for various trial periods, using three intervals of dense coverage: 1978–1980, 1982–1983, 1988–1990.

& Robinson (1972), the light curves in Figures 1–3 certainly show short-time-scale activity at the $\sim 1\%$ level, and the power spectra in their Figure 5 show a rise in power at low frequencies; both of these are hallmarks of true flickering in cataclysmic variables. But they are also characteristic signatures of slightly nonphotometric conditions; and because the light curves were obtained without reference to comparison stars, one cannot place full trust in them. In PRNH, the light curves were obtained with a two-star photometer (Nather 1973), which allows high-speed monitoring of transparency changes; but they were obtained with smaller telescopes, so they did not show such clearly defined rapid wiggles. Furthermore, to the extent that flickering is present, it may arise from a superposition of many relatively coherent short-period signals.

We do not mean to assert flatly that there is no flickering in the light curve. However, if it is present, we are struck by two remarkable facts about it:

1. Its amplitude is smaller than in any other cataclysmic variable we have observed (a few erupting dwarf novae come close, however).

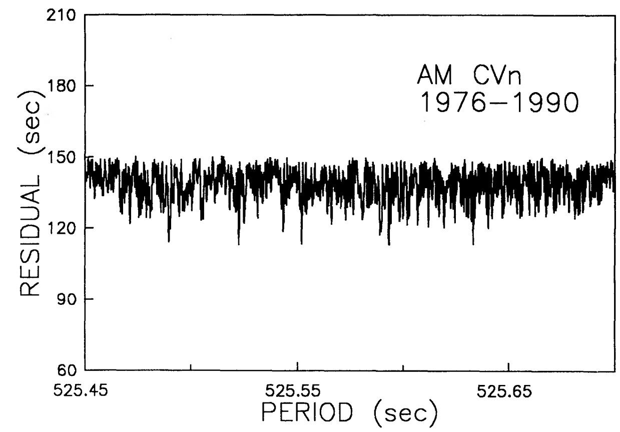

FIG. 6.—Root mean square residual for various trial periods, using the 1976–1990 timings. The lack of any pronounced dip attests to the absence of a stable period.

2. Its power spectrum is considerably flatter than that of any other cataclysmic variable we have observed. The power in the apparent continuum rises approximately as $P(f) \propto f^{-0.95}$. Most CVs show much steeper spectra, rising typically as $P(f) \propto f^{-2.5}$ (see, e.g., Patterson & Richman 1991).

Both the QPOs and the flickering should probably be reckoned as mild arguments in favor of a binary star model, but with the caveats we have mentioned. We shall return to this subject in § 6.

4. SLOW VARIABILITY, BROAD-BAND COLORS, AND FLUX DISTRIBUTION

4.1. *Variable, Maybe, but Mighty Quiet*

Apart from the rapid periodicities, is AM CVn a variable star? Smak (1967) gives $V = 14.18$, $B-V = -0.21$, $U-B = -1.03$. Other reports on these magnitudes are 14.07, -0.19, -1.03 (Krzeminski 1972); 14.14, -0.244, -1.01 (Smak 1975); 14.12, -0.20, -1.06 (this work; see Table 4 below). Because the star varies rapidly by a few hundredths of a magnitude, and because there is no suitable comparison star nearby

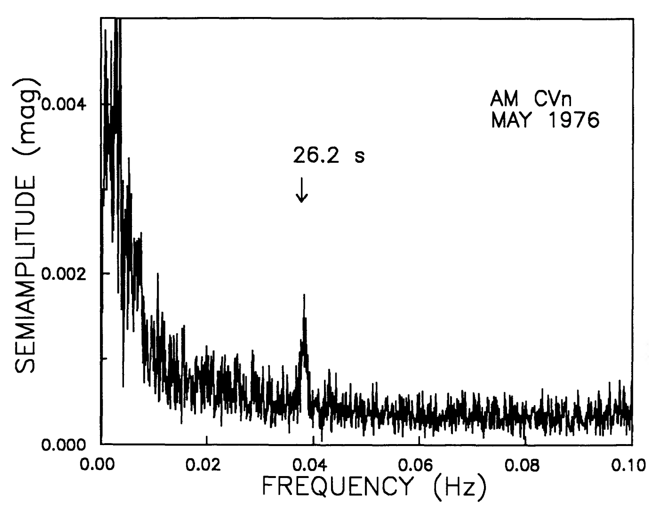

FIG. 7.—Average amplitude spectrum during four consecutive nights in 1976 May. A highly significant peak at 26 s is marked by the arrow. The great breadth of the peak indicates either a "quasi-periodic" oscillation or underlying fine structure not resolved here.

of similar color, systematic errors of ~ 0.05 mag are easily possible. This suggests that the spread in the above measurements may be entirely due to measurement error. On the other hand, the outlier point is the V measurement of Krzeminski (1972), whose observing practices appear to have been the most methodical. We conclude that AM CVn *may* show long-term variability with an amplitude of up to 0.1 mag, but this is not a secure result; long-term constancy is also possible.

Many more measurements (hundreds) have been made by observers carrying out high-speed photometry. But in this approach, a very broad bandpass and a mean extinction coefficient are usually employed, making it difficult to put the magnitudes on a standard system to an accuracy better than ~ 0.2 mag. Even more measurements (thousands) have been made unwittingly by spectroscopists, because AM CVn is, oddly enough, on a frequently used list of spectrophotometric standards (Oke 1974). Because these measurements are not routinely reported anywhere, they do not provide a secure basis for further discussion. But with no reported discrepancies, and with rather accurate agreement whenever calibrated magnitudes are derived, we consider it unlikely that AM CVn has ever swerved from its mean magnitude by more than ~ 0.2 mag in the last 25 years.

4.2. *Colors*

To study the possible connection between AM CVn and helium-rich white dwarfs, we have also obtained $UBVRI$ photometry of five pulsating DB white dwarfs. The observations were obtained on 1990 May 27 and 28 with the automated filter photometer at the Cassegrain focus of the No. 2 0.9 m telescope of Kitt Peak National Observatory. A focal-plane aperture of 14″ diameter was used. The V-magnitudes are somewhat suspect, since no attempt was made to average over the rapid variability of these stars, but the colors should be generally reliable since the filters were spun rapidly. Each magnitude is obtained from averaging 3–6 separate measurements of 10 s per filter, with equal time spent on measuring the sky. The results are given in Table 4.

One star, PG 1654+160, showed a distinctive red upturn, and the red-sensitive acquisition TV for the KPNO 2.1 m telescope revealed a star 3″ from the white dwarf. We obtained a spectrum which showed the deep TiO absorption bands characteristic of an M dwarf. Photometry of this star provided us by B. Zuckerman and E. E. Becklin showed $V-K = 5.3$, suggesting a spectral type of about M4. Adopting this color and spectral type, we have subtracted the estimated contributions of the red dwarf through each filter, to arrive at the corrected magnitudes in the last line of the table.

4.3. *The Color-Color Plane*

The colors cited above for AM CVn are in satisfactory agreement; an average gives $B-V = -0.21$, $U-B = -1.03$. For a cataclysmic variable, these colors are suspiciously too blue; the $U-V$ color of -1.24 exceeds that of any other known CV by ~ 0.2 mag. We illustrate this in Figure 8. Here we have collected all the available UBV colors of "high-$\dot{M}$" CVs (i.e., those showing absorption or at most weak emission in their spectrum) and plotted them as circles in a color-color diagram. Also plotted are the colors we have measured for the DB pulsators (*star symbols clustered at upper left*) and the mean colors of the helium-rich stars CR Boo and V803 Cen (*triangles*).

Note that AM CVn, at the upper left, stands well separated from the normal hydrogen-rich CVs,[4] but mingles among the DB pulsators. A weighted average of the five white dwarfs in Table 4 gives $B-V = -0.17$, $U-B = -1.08$, $V-R = -0.09$. These colors agree with those of AM CVn within the scatter of the measurements.

But since the color temperature of AM CVn is obviously quite high, it is admittedly not strongly constrained by these UBV colors. Perhaps a more important question is, do the *ultraviolet* (1000–3000 Å) fluxes resemble those of a pulsating DB white dwarf?

4.4. *Ultraviolet Flux and Colors*

The brightest DB pulsator is GD 358, and for this star two high-quality *IUE* spectra have been obtained, described by Liebert et al. (1986; images SWP 25310, LWP 5415) and Koester et al. (1985; images SWP 14015, LWR 10668). As shown in Figure 5 of Liebert et al., the short-wavelength fluxes are in very close agreement, while the long-wavelength fluxes (obtained with different cameras) differ by $\sim 10\%$. This appears to be due to the slow degradation of the LWR camera (Sonneborn & Garhart 1986). After correcting for the degradation and averaging the long-wavelength spectra together, we used Table 2 and Figure 5 of Liebert et al. to form fluxes over 240 Å intervals, and show the resultant flux distribution (including the UBV data of our Table 4) with open circles in Figure 9.

[4] We exclude stars showing strong emission lines (e.g., dwarf novae in quiescence) from this plot, because broad-band magnitudes are misleading for such objects. A typical dwarf nova shows a substantially redder $B-V$ color in quiescence (say ± 0.3), presumably due to the cooler temperatures prevailing in the accretion disk, but sometimes an even bluer $U-B$ (up to -1.1), due to the presence of the Balmer jump in emission. Even if these stars are included, there is still no CV showing colors similar to those of AM CVn.

TABLE 4

UBVRI PHOTOMETRY

Star	V	$B-V$	$U-B$	$V-R$	$R-I$	Estimated Errors (UBV)[a]
AM CVn	14.12	−0.20	−1.06	−0.06	−0.08	(0.02)
GD 358	13.63	−0.16	−1.09	−0.05	−0.14	(0.02)
PG 1456+103	16.41	−0.16	−1.08	−0.13	+0.15	(0.04)
PG 1351+489	16.82	−0.25	−1.08	−0.00	[b]	(0.05)
PG 1115+158	16.74	−0.11	−1.05	−0.18	[b]	(0.05)
PG 1654+160	16.28	+0.10	−1.00	+0.60	+1.00	(0.04)
PG 1654+160 (corrected)	16.62	−0.17	−1.08	...	...	(0.10)

[a] In general, the errors in R and I are about twice as large.

[b] No reliable I measurement was obtained.

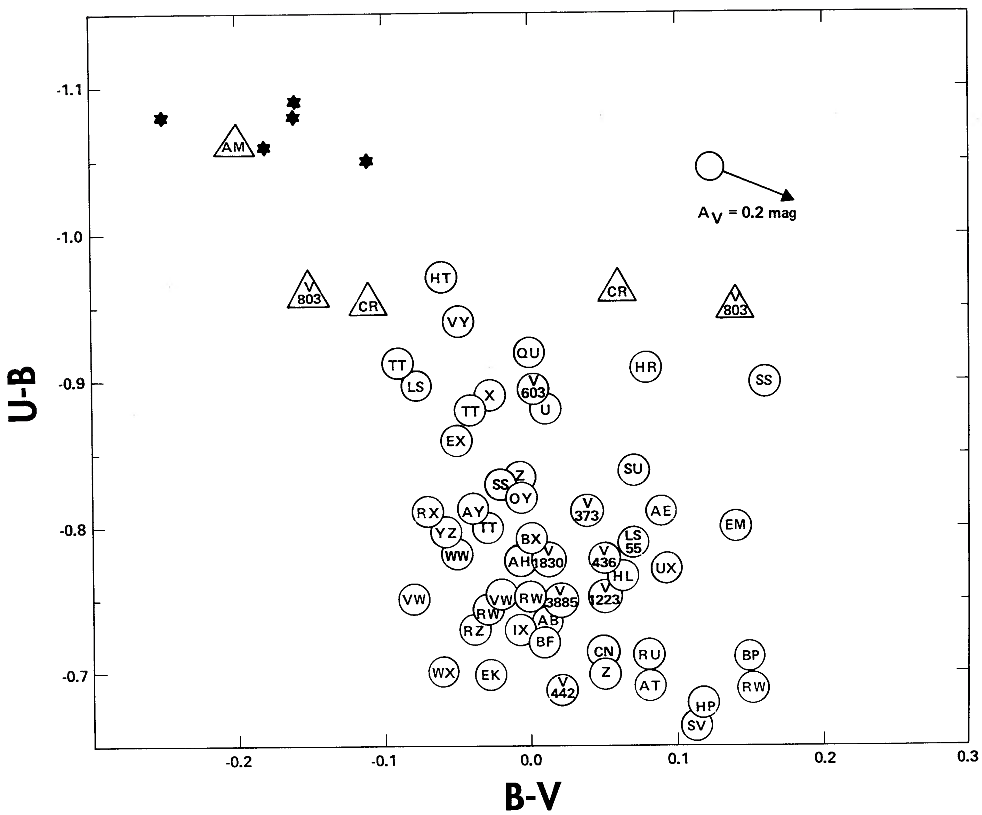

FIG. 8.—Color-color plane for high-$\dot{M}$ CVs (*circles*, labeled with their given names), pulsating DB white dwarfs ("star" symbols), and the helium-rich stars AM CVn, CR Boo, and V803 Cen (*triangles*). The latter two stars change their colors significantly between high and low states, becoming bluest when brightest; we show both sets of colors here. The interstellar reddening vector is shown at upper right.

Also shown in Figure 9, as triangles, are the corresponding fluxes for AM CVn, scaled up by 0.48 mag to normalize the two distributions at U. We have derived the short-wavelength fluxes by measuring and averaging spectra I, II, and III presented by Solheim & Kjeldseth-Moe (1987). (Spectrum IV is otherwise normal but shows continuum fluxes about twice those of the other spectra; we have excluded this as being suspect, in view of the star's long history of near-constancy.)

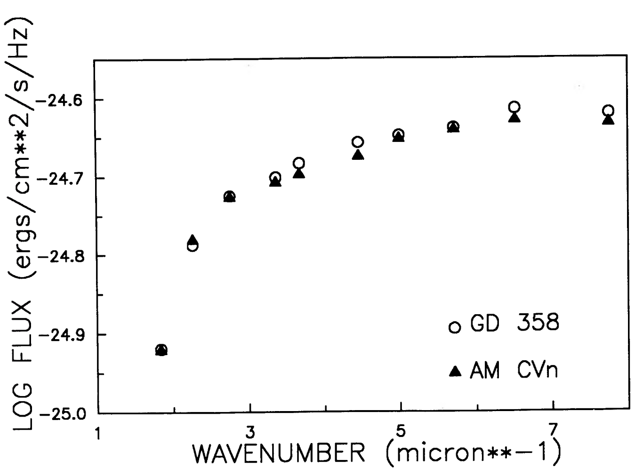

FIG. 9.—Flux distributions of AM CVn and GD 358, assuming no interstellar reddening. The scale is calibrated for GD 358; AM CVn has been scaled upward by 0.48 mag to account for the difference in brightness (this normalizes the two curves at U).

We have derived the long-wavelength flux by extracting image LWR 15583, a 60 minute exposure on 1983 March 26, from the *IUE* archives, and correcting for the sensitivity degradation of the camera. No reddening correction has been applied; since AM CVn is at extremely high Galactic latitude (79°), and the broad-band colors are already extremely blue, reddening is likely to be quite low.

We note from Figure 9 that throughout this wavelength range the flux distributions agree within ~0.03 mag. This is within the calibration uncertainty of the *IUE*. Thus we arrive at a striking result: the broad-band flux distribution of AM CVn is indistinguishable from that of GD 358.

How typical is GD 358 of the DB pulsators? Except for GD 358, all of the known DB pulsators are rather faint for the *IUE*, and the data are somewhat noisy. Liebert et al. (1986) present continuum flux distributions for all five DB pulsators listed in Table 4. We have used their data to estimate fluxes in a short-wavelength bandpass (SW: 1280–1680 Å) and a long-wavelength bandpass (LW: 2400–2800 Å), and combined these with the flux in the U bandpass (3400–3800 Å) to form an ultraviolet color-color plot. This is illustrated in Figure 10, which includes a correction for the degradation of the LWR camera. Four of the five pulsators, plus AM CVn, are seen to occupy a quite well-defined region of the diagram, suggestive of a temperature ~25,000 K.

The one exception is PG 1115+158. Liebert et al. (1986) argued that the short-wave spectrum of this star by itself shows a continuum slope consistent with the other DBs, but that the flux was probably depressed by a poorly centered exposure. Interstellar reddening could also be a culprit, but this is less

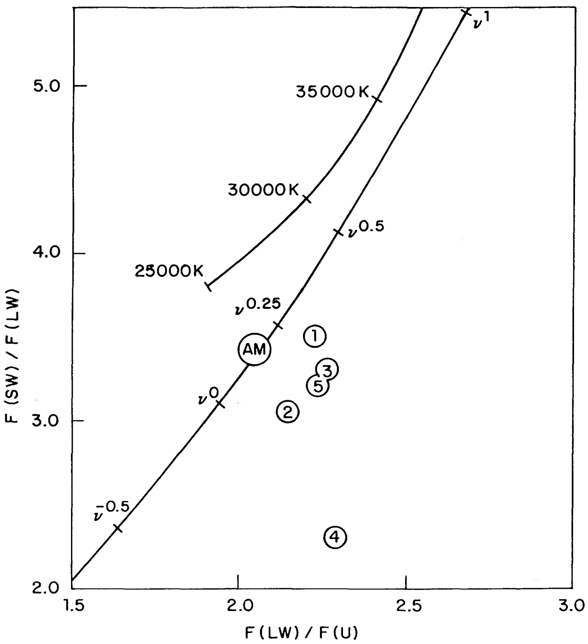

FIG. 10.—Ultraviolet color-color plane for AM CVn and pulsating DB white dwarfs. The curves represent the colors expected from flux distributions of power laws ($F_\nu \propto \nu^\alpha$) and white dwarf model atmospheres of pure helium (Wesemael 1981). The DB white dwarfs are coded in order of their appearance in Table 4.

likely, since the H I measurements in this direction suggest that it is a fairly transparent line of sight (Heiles & Burstein 1984; Table 5 of Liebert et al. 1986).

We conclude from Figures 9 and 10 that in its ultraviolet continuum slope AM CVn is an excellent match for the DB pulsators.

4.5. *The Ultraviolet Spectrum*

Nevertheless, the detailed ultraviolet spectrum is quite different. GD 358 shows no spectral features in this region, while AM CVn shows strong absorption features unlike those seen in any other solitary white dwarf. We have extracted six well-exposed short-wavelength spectra from the *IUE* archives, and present the average spectrum, together with the single long-wavelength exposure, in Figure 11. The spectra show broad absorption features of N V λ1240, Si III λ1300, Si IV λ1400, C IV λ1549, and He II λ1640. The N V line has an equivalent width of about 6 Å, while the others have EW $\approx$ 2 Å. These lines are much broader and stronger (by a factor of $\sim$10 in equivalent width) than the metal lines occasionally seen in the spectra of hot white dwarfs. In addition, we find:

1. The continuum flux appears to be constant within measurement error.
2. No emission is present, and there is no definite evidence for spectral variation.
3. There is some evidence for a $\sim$4 Å violet shift in the C IV and He II absorption lines. This resembles the profile sometimes seen in face-on accretion disks and early-type stars, and is often interpreted as a sign of mass loss. But at this resolution, it could also arise from the same effect that produces the absorption-line asymmetries in visible light (whatever the effect is).

5. OPTICAL SPECTROSCOPY

Optical spectra have been presented by Greenstein & Matthews (1957), Robinson & Faulkner (1975), and Williams (1983). They show He I absorption lines, characteristic of a typical DB white dwarf but shallower and somewhat asymmetric in profile. Robinson & Faulkner (1975) searched for radial velocity variations at the 17.5 minute period and found none, to a limit of $K < 30$ km s^{-1}. They suggested that the asymmetry could arise from the presence of weak, broad emission, but no emission has ever been clearly seen in the optical spectrum.

Two new spectra were obtained in 1990 June with the "UV Schmidt" spectrograph mounted on the Lick Observatory 3 m Shane reflector. A 1200 line mm^{-1} grating blazed at 5000 Å was used to cover the spectral range 4300–5100 Å at a disper-

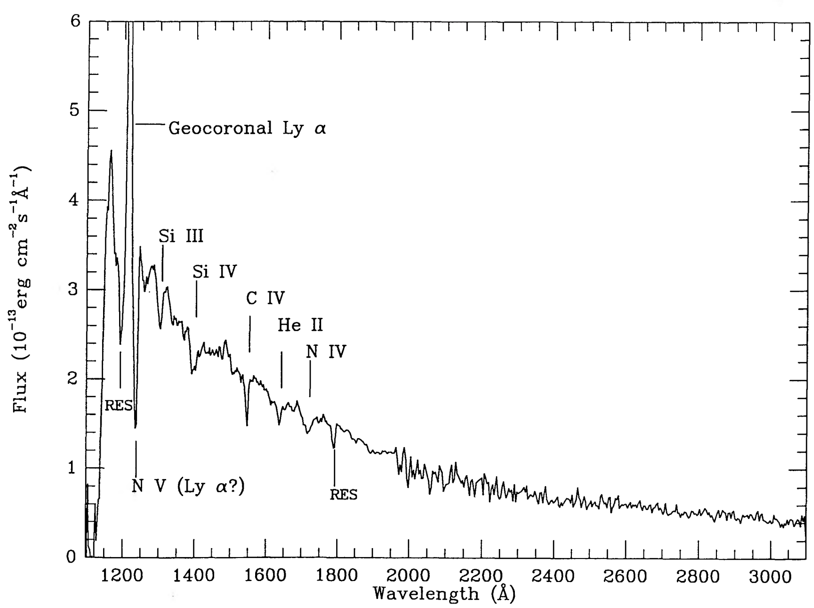

FIG. 11.—Mean *IUE* spectrum, with probable identifications of spectral features. The fluxes are unreliable for wavelengths shorter than the geocoronal Lyman-α emission.

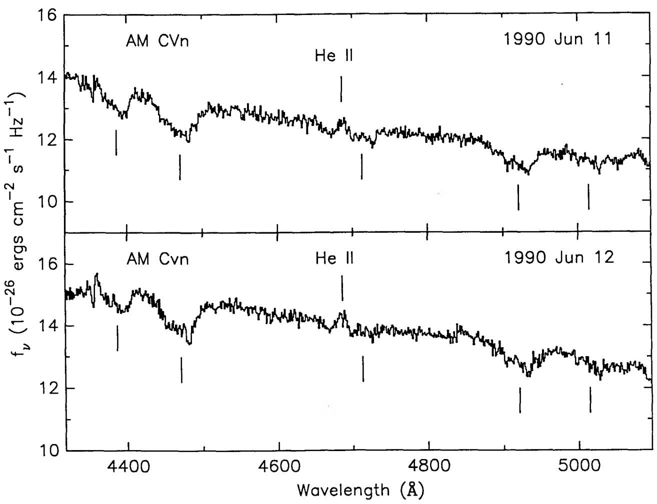

FIG. 12.—Optical spectra of AM CVn. Tick marks below each spectrum indicate the expected location of He I absorptions (at zero velocity), and the tick mark above each spectrum indicates the location of He II λ4686, also at zero velocity. Note that the line λ4713, of unexpected weakness, is partly filled in by 4686 Å emission. Some contamination due to imprecise removal of the night-sky line Hg I λ4358 is also apparent. Fluxes are not quite reliable, owing to light losses at the slit.

sion of 1 Å pixel^{-1} on a TI CCD. Because of the nonuniform focus across the chip, the spectral resolution ranged from 2.5 to 4 Å. Observation of the star BD +26°2606 provided a flux calibration (Oke & Gunn 1983). Two exposures were obtained, of 26 and 20 minute duration, with arc lamps observed after each exposure.

The resultant spectra, shown in Figure 12, substantially resemble previously published spectra, with two noteworthy differences:

1. The He I absorption features are asymmetric, with their troughs displaced to the red by ~12 Å; this is opposite to the sense of the asymmetry seen in the spectrum of Robinson & Faulkner (1975).

2. A weak emission feature, partially buried in the He I λ4713 absorption, appears at 4686.8 ± 1.2 Å; this is presumably a He II line. The feature is about 15 Å in total width and 0.5 Å in equivalent width. The actual equivalent width is probably much larger, though, because in other spectra (not shown) the 4713 Å line is the strongest absorption feature seen in this part of the spectrum. Making this correction, we estimate an equivalent width of 2–4 Å. Despite its weakness, we believe it is entirely trustworthy, because no 4686 Å feature was present either in our flux standard star or any other star we observed on these nights.

During the same observing run, we also obtained spectra of known pulsating DB white dwarfs for comparison. These are shown in Figure 13. The spectra are fairly similar to each other, showing only He I absorption lines. The lines are quite different from those of AM CVn; they have larger equivalent widths, relatively sharp cores, and are much more symmetrical. The exception is the line λ4713, which in all of our spectra shows a small but consistent asymmetry, with the sharp core slightly blueshifted relative to the broad absorption.

6. INTERPRETATION

6.1. *The Periodic Variations*

It is the short-period variations, and especially the persistent 525/1051 s signal, that has conferred celebrity status on AM CVn. Faulkner, Flannery, & Warner (1972) interpreted this as the orbital period of a highly evolved and ultracompact binary system, consisting of two white dwarfs. This remains a widely accepted view today. SRNK propose a slight variant, in which 1051 s (or 525 s) is the white dwarf's rotation period, and some other short period, not identified, is the orbital period. Does the evidence still support either of these views?

6.2. *The Problem of the Wandering Period*

Most of the evidence gleaned from high-speed photometry now seems difficult to reconcile with either view. The lack of stability in phase is very well documented, and is very remarkable! This essentially rules out an orbital origin. A rotational origin also seems very unlikely, because the asynchronous magnetic rotators, or DQ Her stars, are also very stable clocks. All but two are essentially perfect, keeping time to within measurement error, and showing only long-term $\dot{P}$ effects. The two miscreants (DQ Her: Patterson, Robinson, & Nather 1978; FO Aqr: Imamura & Steiman-Cameron 1988) have displayed slow phase drifts of $\sim 0.1 P_{\rm rot}$ on a time scale of years. AM CVn sports at least 3 times as large a drift, on a time scale of *weeks*.

The DQ Her stars are also characterized as a class by relatively strong X-ray emission, probably due to an accretion shock at the white dwarf's magnetic pole, and by strong optical and UV emission lines. These credentials are lacking in AM CVn. It is true that the star has been reported to be a source of very hard X-rays, with a flux F(260–1200 keV) = 7.3×10^{-10} ergs cm^{-2} s^{-1} (Coe, Engel, & Quenby 1978). However, there are also rather stringent upper limits on the X-ray flux [F(80–180 keV) < 6×10^{-11} ergs cm^{-2} s^{-1} from *HEAO* A-4, Levine et al. 1984; F(0.2–4.0 keV) < 2×10^{-13} ergs cm^{-2} s^{-1} from the *Einstein Observatory*]. Without some very extreme assumptions about source variability or the X-ray spectrum, it's hard to reconcile these numbers. With no confirmation forthcoming in the 15 years since the hard X-ray detection, we have to regard it as suspect.

A remaining possibility is white dwarf pulsation. The stability of the pulsational clock in white dwarfs appears to be highly variable. Some are known to show great stability, never changing phase in ~10 years of observation (e.g., R548, Stover et al. 1980; G117-B15A, Kepler et al. 1982). Others casually change their periods from one night to the next (e.g., HL Tau 76, Warner & Nather 1971). And in at least one case, a pulsating white dwarf showed a nearly constant period and amplitude over an observing season, yet appeared to drift slowly in phase on a time scale of weeks to months (G29-38, Winget et al. 1990). This latter behavior is reminiscent of what we observe in AM CVn.

6.3. *The Case for Pulsation*

A number of arguments can be arrayed in favor of the pulsation hypothesis:

1. The observed periods (200–1100 s), well within the range of known pulsating DB white dwarfs.

2. The long-term constancy of the mean light. This is more or less necessary from a bare photosphere, but is surprising if the light is dominated by accretion.

3. The very low amplitude of the random flickering.

4. The consistency of the flux distribution with a single photospheric temperature, which is unexpected from an accretion disk with its characteristic *range* of temperatures.

5. The location of AM CVn within the DB instability strip, as defined by its optical/UV colors.

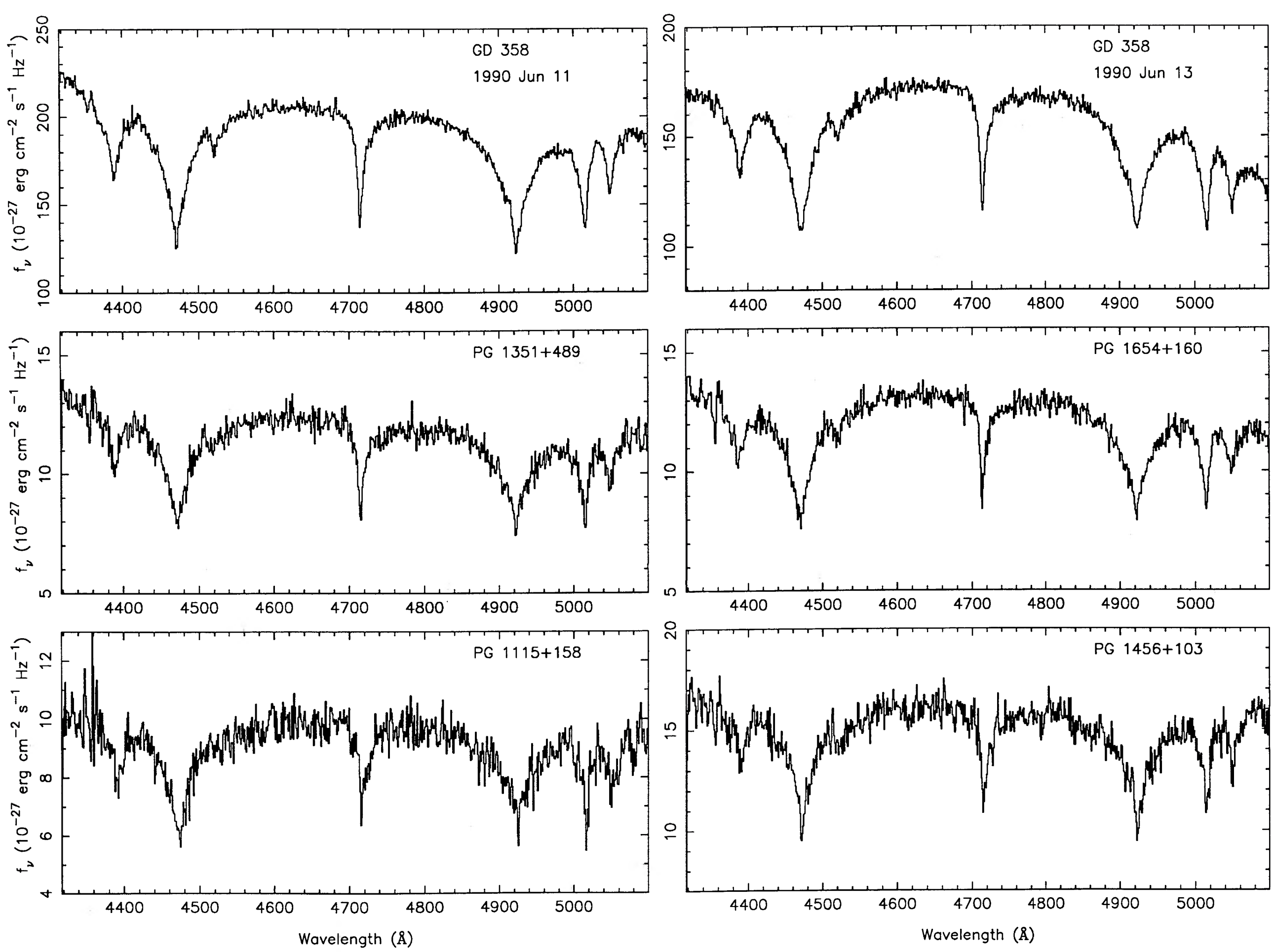

FIG. 13.—Optical spectra of pulsating DB white dwarfs. The only features observed are Stark-broadened He I absorption lines; a few lines, especially 4713 Å, show narrow cores.

6. The relatively low phase coherence of the principal signal, as discussed above.

7. Most important, the fact that the variations are *multiperiodic*. Noncommensurate periods are a characteristic signature of nonradial pulsation in many kinds of stars, certainly including white dwarfs. To obtain such noncommensurate periods in a standard CV geometry, one may have to resort to ad hoc assumptions (e.g., near-equality of periods and amplitudes from both orbital and rotational modulation, plus yet another mechanism to produce the 289 s signal).

6.4. *The Case for Accretion Light*

Taken at face value, these arguments constitute fairly impressive support for the hypothesis that the white dwarf photosphere is a significant contributor to the total light. On the other hand, within the context of an accretion disk model, excuses can be found for the first five of these arguments:

1. As shown by FFW, this period range is also reasonable for an interacting binary white dwarf, assuming one of them is of very low mass ($\sim 0.04\ M_\odot$).

2. There is probably some long-term variability, and a bare photosphere ought to show none.

3. Considered as an optically thick accretion disk (to yield the absorption lines), AM CVn should be in a state of high $\dot{M}$, essentially something like a dwarf nova stuck in outburst. Dwarf novae in outburst often show low flickering.

4. If the orbital period is very short, the range of radii in the disk is small, and there is less opportunity for the flux distribution to demonstrate its inconsistency with a single temperature. To verify this, we have calculated theoretical fluxes and colors from blackbody disks, assuming $M_1 = 0.9\ M_\odot$. In the upper frame of Figure 14, we show the flux distribution for an outer disk radius given by $\log R = 10.2$ cm, and accretion rates given by $\log \dot{M} = -8.5$ and $-8.3\ M_\odot\ \mathrm{yr}^{-1}$ (*dots and plus signs, respectively*). In the lower frame, we show a color-color plot of a family of models with a disk radius given by $\log R = 10.4$, 10.2, and 10.0 cm, and accretion rates given by $\log \dot{M} = -9.0, -8.75, -8.5, -8.25\ M_\odot\ \mathrm{yr}^{-1}$. It seems clear that these small disks can in fact mimic a single temperature fairly well.

5. Since the disk is helium-rich, it should avoid the normal dwarf nova instability that arises from the increase in opacity with the ionization of hydrogen. However, it is reasonable to conjecture that in a helium-rich disk, a similar instability may arise at the temperature corresponding to the maximum opacity of He I transitions, which occurs at $T \sim 25{,}000$ K. This would explain the coincidence with the colors of DB pulsators; but of course it needs to be checked with model calculations for helium-rich disks.

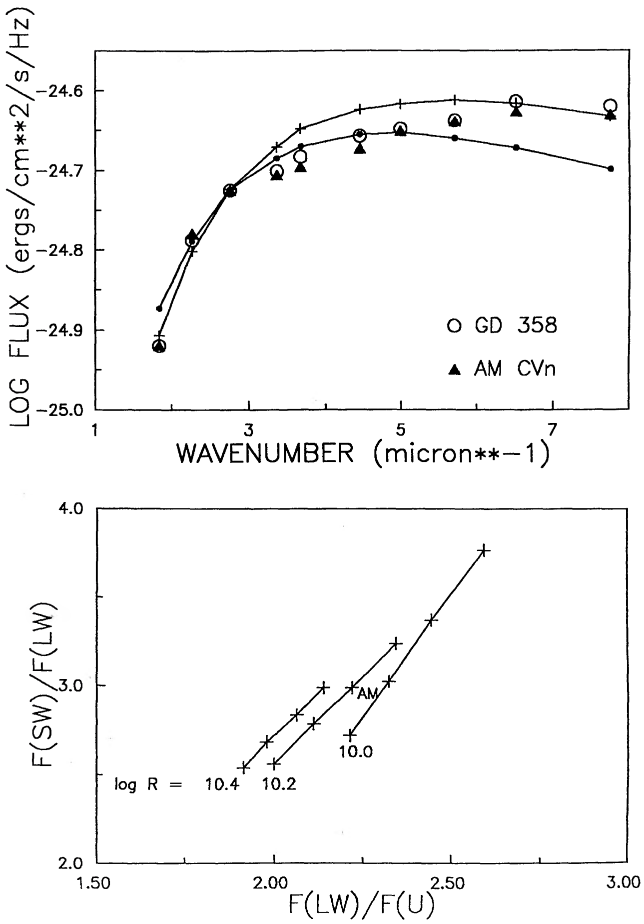

FIG. 14.—*Upper frame:* reproduction of Fig. 9, with two blackbody disk models superposed: $\dot{M} = 2 \times 10^{17}$ g s^{-1} (*dots*) and 3×10^{17} g s^{-1} (*plus signs*); log $R = 10.2$ cm and $M_1 = 0.9\ M_\odot$ have been assumed. *Lower frame:* ultraviolet color-color plot, as in Fig. 10, of three families of disk models, with outer radii given by log $R = 10.0$, 10.2, and 10.4 cm. The plus signs are at accretion rates given by log $\dot{M} = -9.0$, -8.75, -8.5, $-8.25\ M_\odot$ yr^{-1} (*from bottom to top*).

Thus, of the seven arguments we regard as favoring pulsation, the first five can probably be considered weak or moderate. In our judgment, though, the last two are really quite strong.

On the positive side of the ledger, there appears to be only one clue in the light curve that really indicates the contribution of an accretion disk: the rapid quasi-periodic oscillations presented in § 3. This is especially true of the 26 s signal, which is of much shorter period than anything previously seen in pulsating white dwarfs, but would be a typical member of the zoo of short-period oscillations seen in cataclysmic variables (Robinson & Nather 1979; Patterson 1981).

6.5. *Evidence from Spectroscopy*

The optical and UV spectra of AM CVn are profoundly difficult to explain as arising from a bare, uncontaminated white dwarf photosphere. The single DB pulsators show a pure He I absorption spectrum, with features marked by little asymmetry and deep, narrow-line cores. AM CVn shows significantly different line profiles (shallower, more asymmetric, clearly variable), a wide range of elements and ionization states (He I, He II, N V, C IV, Si III, Si IV), and even some emission (He II). Essentially *all* of the spectroscopic features, other than the continuum slope, are unusual or unprecedented in single white dwarfs. They are, however, fairly similar to the spectra of high-$\dot{M}$ accretion disks, as seen in cataclysmic variables, with the proviso that helium rather than hydrogen is the dominant element.

6.6. *Guilt by Association*

Since Smak's 1962 discovery of the short-period variability of HZ 29, two other stars have been added to the roster of short-period variables with helium absorption lines: CR Boo (=PG 1346+082; Wood et al. 1987), with a period of 25 minutes, and V803 Cen (=AE-1; Elvius 1975; O'Donoghue, Menzies, & Hill 1987; O'Donoghue & Kilkenny 1989), with a principal period of 27 minutes. The similarity of these stars to AM CVn is impressive: they are hot and blue with shallow, asymmetrical He I lines, and their optical light curves show noncommensurate, closely spaced periods. But most important, both of these stars show "high" and "low" states, differing by 3–4 mag. As pointed out by Wood et al. (1987) and O'Donoghue et al. (1987, 1990), it is this behavior which points so ineluctably at an accretion origin for the light observed in the high state. For how can a solitary white dwarf, with its meager supply of fuel and deep gravitational well, manage to power an outburst of this size?

On the same nights when we obtained spectra of AM CVn and the five pulsating white dwarfs, we also observed CR Boo. The spectrum, shown in Figure 15, is basically indistinguishable from that of AM CVn, including even a weak He II emission feature at zero redshift. Inspection of Figures 12 and 15 together certainly does build confidence in the hypothesis that these are the same type of object.

Now this argument from analogy is mitigated somewhat by the fact that AM CVn itself has never shown any large-amplitude variability, despite much more extensive observation. But the photometric and spectroscopic resemblances among these three stars are really quite striking, and we agree with Wood et al. and O'Donoghue et al. that these "eruptions" furnish additional evidence supporting a binary star model for AM CVn. We also note from Figure 8 that CR Boo and V803 Cen in their bright states are the cataclysmic variables most resembling AM CVn in broad-band colors.

6.7. *Noncommensurate Periods and Unholy Disks*

AM CVn is a helium-rich high-gravity object showing noncommensurate periods and colors placing it in the known DB instability strip; this is normally considered adequate grounds

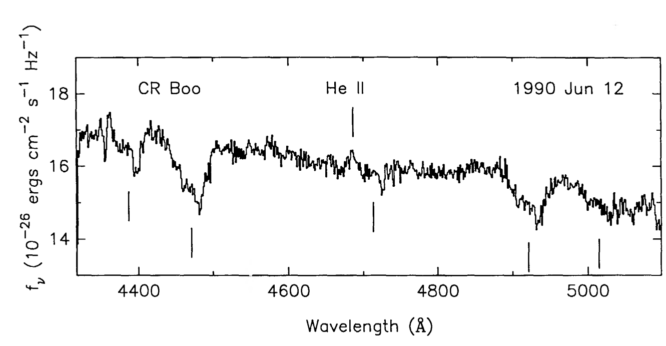

FIG. 15.—Spectrum of CR Boo = PG 1346+082, essentially a "dead ringer" for the spectrum of AM CVn—including the weak He II emission. Tick marks have the same meaning as in Fig. 12.

for certifying a star as a pulsating white dwarf. Yet there is little spectroscopic resemblance to a white dwarf, especially in the ultraviolet where the spectra reveal quite strong lines from a wide range of elements. Is there a way to explain both of these facts at once?

If we suppose that AM CVn is basically a DB white dwarf with a rotationally supported *disk* (of unspecified nature and origin) around it, we can make some progress. Multiperiodic variations can be ascribed to the white dwarf pulsations, with perhaps some reprocessing in the disk. The presence of heavy-element absorption lines, especially the strong N v $\lambda1240$ feature, *requires that the dominant ultraviolet light source, whether white dwarf or disk, be not subject to the gravitational settling which renders most white dwarf spectra monoelemental or featureless.* The latter requirement is difficult, but perhaps not impossible, for a single star; for example, very rapid rotation would counteract settling, would broaden out sharp cores in the absorption lines, and could, for a while, maintain an "excretion disk" by flinging out gas in the equatorial plane.

6.8. *Noncommensurate Periods from Accretion Disks*

In a binary star model, the advantages of the disk are preserved, the energy released by accretion through the disk provides a natural way to power a fairly hot continuum source, and the origin of the disk is much more clear (mass transfer from the companion). The optical/UV spectra and the quasi-periodic oscillations are then unsurprising, as they resemble features commonly seen in cataclysmic variables.

However, in such a model we still have to understand the noncommensurate periods in the light curve. *Can it be a normal pulsating white dwarf surrounded by a normal luminous gravitationally powered accretion disk?* Not likely. The problem is that the accretion disk is invoked to provide nearly all the continuum light at 1240 Å; since the disk is hot, optically thick, and larger than the white dwarf, it must then also dominate at longer wavelengths. This is not necessarily fatal, since the observed pulse fraction in AM CVn is quite low (1%), suggesting a possible dilution by unpulsed light. But it means that we have to accept that the accretion disk has colors *coincidentally* close to a known instability strip, and it raises the serious question: if the observed periods arise from pulsation, then what *is* the orbital period? It ought to be short, since the star being cannibalized is made of helium. But the amplitude limits on a short period other than 1023 and 1051 s are very stringent, about 0.002 mag. It is hard to imagine how a close interacting binary can hide its orbital signature at that level of accuracy.

There is another interesting possibility, which *does* seat the noncommensurate periods in the disk itself. We are impressed by the observational fact that during episodes of high $\dot{M}$ ("supermaxima"), nearly every dwarf nova of short orbital period displays photometric humps ("superhumps," reviewed by Warner 1985) at a period slightly in excess of $P_{\rm orb}$. Among the various models proposed to account for superhumps, one has been particularly successful: the eccentric precessing disk model, proposed by Vogt (1982) and developed further by Whitehurst (1988) and Osaki (1985, 1989). In this model, viscosity in the disk is assumed to be high enough to transport gas of high angular momentum to a large radius in the disk, where a tidal instability occurs, if the mass ratio ($M_{\rm wd}/M_{\rm secondary}$) of the binary exceeds ~ 4. The line of apsides in the eccentric disk then precesses around the white dwarf, and the tidal stresses in the disk then vary with a period slightly longer than the orbital period, yielding a superhump. This model makes many impressive predictions: it locates the superhump light at large radius in the disk, it produces superhumps independent of binary inclination, it imprints a very special pattern on the absorption-line radial velocities, and it confines the phenomenon to stars of short orbital period (where the instability can exist because the mass ratio is expected to be high). These predictions are generally in good accord with observational constraints for short-period dwarf novae.

Although this theory has been invented for dwarf novae, there appears to be no reason why the same mechanism would not apply to any cataclysmic variable, as long as two conditions hold: (1) the viscosity must be sufficiently high to maintain a disk of large radius, and (2) the mass ratio must exceed ~ 4. For noneclipsing systems it is generally impossible to obtain a good estimate of disk radius, but available estimates from light curves of eclipsing stars suggest that, in CVs generally, the disk radii are at least 70% of the Roche lobe radii (Sulkanen, Brasure, & Patterson 1981; Horne 1985; Cook & Warner 1984; Wood, Irwin, & Pringle 1985). This suggests that condition 1 may be readily satisfied. If the secondary in AM CVn is a lobe-filling white dwarf, its mass should be $\sim 0.04\ M_\odot$ (FFW). Thus, for a "typical" white primary of 0.6 $M_\odot$, the mass ratio is 15 and condition 2 is easily satisfied.

The model supposes that 1051 s is the superhump period, and 1023 s is the true orbital period. The ratio $P_{\rm sh}/P_{\rm orb}$ is then 1.027, in fine agreement with the range of 1.02–1.04 expected for a system of this mass ratio (see Fig. 11 of Hirose & Osaki 1990). And, most important, the phase jitter in the timings of the 1051 s clock can be understood qualitatively, since the precession period depends on the angular and epicyclic rotation frequencies of gas at the outer edge of the disk—which can vary with changes in $\dot{M}$ and viscosity.

O'Donoghue & Kilkenny (1989) have proposed essentially the same model for V803 Cen.

7. SUMMARY

1. We present a new and extensive set of high-speed photometry which demonstrates the multiperiodic nature of the light curve but is inconsistent with any simple ephemeris for the dominant 525 s signal. The mean period during 1976–1990 was probably 525.61 s. The exact value of the period appears to be stable on time scales of days, perhaps weeks, but not months.

2. Analyzing the most densely spaced observations, we find that the most likely choice for the long period is 1023.44 ± 0.02 s, although the 24 hr alias period of 1011.43 s cannot be ruled out.

3. Based on the presence of signals near 350, 262, and 210 s, and on the highly repeatable double-humped waveform (with a primary minimum consistently offset by 0.04 cycles), we are confident that there is also a weak fundamental signal at 1051.2 s, even if it is not seen in the power spectrum. We consider this issue to be settled beyond reasonable doubt.

4. In its flux distribution and light curve (on *all* accessible time scales), AM CVn is very unlike the vast majority of cataclysmic variables but is strikingly similar to the pulsating DB white dwarfs. This underlines the possibility that the white dwarf photosphere may contribute a significant fraction of the total light.

5. However, essentially all of the optical/UV spectral features (shallow, asymmetric, and variable lines; a variety of elements and ionization states; and a He II emission line) are very difficult to understand if they arise in an uncontaminated white

dwarf photosphere. Whether or not the white dwarf pulsates, it appears to be necessary to sprinkle gas enriched in heavy elements into the environment (disk? extended atmosphere?) in which the absorption lines are formed. The spectra certainly demand high He/H and N/C ratios, which in turn demand a highly evolved donor star.

6. The preponderance of evidence does favor a binary star model. The direct evidence from AM CVn itself is quite ambiguous, but we are influenced considerably by the arguments made by Wood et al. (1987) and O'Donoghue et al. (1987) for CR Boo and V803 Cen—in particular, the large luminosity variations present in those stars.

7. It is striking that the colors of AM CVn indicate $T \sim 25{,}000$ K, where helium contributes maximum opacity, just as the typical colors of erupting dwarf novae ($B-V \sim 0$, $U-B \sim -0.8$) indicate $T \sim 15{,}000$ K, where hydrogen contributes maximum opacity. Since unstable mass flow through a hydrogen-rich disk is probably linked to this maximum in hydrogen opacity (Hoshi 1979), it is plausible that the same is true for a helium-dominated disk in AM CVn. A detailed model of such a disk, including an analysis for thermal stability, would be of great interest.

8. Interpreted as a binary, AM CVn must consist of two compact stars with a high mass ratio (FFW; Robinson & Faulkner 1975). During their bright outbursts, dwarf novae of high mass ratio are known to exhibit luminosity variations ("superhumps") with a period that is slightly longer than the orbital period and is slightly unstable. This leads us to consider the eccentric precessing disk model of Whitehurst (1988) and Osaki (1989), with 1023 s identified as the orbital period, 1051 s as the superhump period, and 10.8 hr as the disk precession period.

9. There is hope for testing this model. To be validated as the orbital period, the 1023 s clock should prove to be very stable. Our observations suggest that it is *comparably* stable to the 525 s clock, but they do not answer the question adequately (i.e., test for phase stability on long time scales).

10. Finally, the expected disk precession period of 10.8 hr implies a similar period for the modulation of the line profiles (Vogt 1982; Honey et al. 1988). Since the line asymmetry in AM CVn is large and variable, spectroscopic observation over a few nights with wavelength resolution less than 5 Å should suffice to carry out this test.

We thank Al Grauer and Howard Bond for donating to the pile of observations, and Rob Robinson for digging out the workhorse 1978 March data—a bit brown around the edges, but still worth mining. This research was supported in part by NSF grant AST 89-16995. This work is Contribution No. 444 of the Columbia Astrophysics Laboratory.

REFERENCES

Coe, M. J., Engel, A. R., & Quenby, J. J. 1978, Nature, 272, 37
Cook, M. C., & Warner, B. 1984, MNRAS, 207, 705
Eggen, O. J., & Greenstein, J. L. 1965, ApJ, 141, 83
Elvius, A. 1975, A&A, 44, 117
Faulkner, J., Flannery, B., & Warner, B. 1972, ApJ, L79 (FFW)
Greenstein, J. L., & Matthews, M. S. 1957, ApJ, 126, 14
Heiles, J., & Burstein, D. 1984, ApJS, 54, 33
Hirose, M., & Osaki, V. 1990, PASJ, 42, 135
Honey, W. B., Charles, P. A., Whitehurst, R., Barrett, P. E., & Smale, A. P. 1988, MNRAS, 231, 1
Horne, K. 1985, MNRAS, 213, 129
Hoshi, R. 1979, Prog. Theor. Phys., 61, 1307
Humason, M., & Zwicky, F. 1947, ApJ, 105, 85
Imamura, J. N., & Steiman-Cameron, T. Y. 1988, AJ, 96, 1420
Kepler, S. O., Robinson, E. L., Nather, R. E., & McGraw, J. T. 1982, ApJ, 254, 676
Koester, D., Vauclair, G., Dolez, N., Oke, J. B., Greenstein, J. L., & Weidemann, V. 1985, A&A, 149, 423
Kovacs, G. 1981, Acta Astron., 31, 207
Krzeminski, W. 1971, in IAU Colloq. 15, New Directions and New Frontiers in Variable Star Research, ed. W. Strohmeier (Veroff. Remeis-Sternw. Bamberg, Vol. 9, No. 100), 78
———. 1972, Acta Astron., 22, 387
Levine, A. M., et al. 1984, ApJS, 54, 581
Liebert, J., Wesemael, F., Hansen, C. J., Fontaine, G., Shipman, H. L., Sion, E. M., Winget, D. E., & Green, R. F. 1986, ApJ, 309, 241
Malmquist, K. G. 1936, Stockholm Obs. Ann., Vol. 12, Part 7
Nather, R. E. 1973, Vistas Astron., 15, 91
O'Donoghue, D., & Kilkenny, D. 1989, MNRAS, 236, 319
O'Donoghue, D., Menzies, J. W., & Hill, P. W. 1987, MNRAS, 227, 347
O'Donoghue, D., et al. 1990, MNRAS, 245, 140
Oke, J. B. 1974, ApJS, 27, 21
Oke, J. B., & Gunn, J. E. 1983, ApJ, 266, 713
Osaki, V. 1985, A&A, 144, 369
———. 1989, PASJ, 41, 1005
Ostriker, J. P., & Hesser, J. E. 1968, ApJ, 153, L151
Patterson, J. 1981, ApJS, 45, 517
Patterson, J., & Richman, H. 1991, PASP, 103, 735
Patterson, J., Robinson, E. L., & Nather, R. E. 1978, ApJ, 224, 570
Patterson, J., Robinson, E. L., Nather, R. E., & Handler, F. 1979, ApJ, 232, 819 (PRNH)
Robinson, E. L., & Faulkner, J. 1975, ApJ, 200, L23
Robinson, E. L., & Nather, R. E. 1979, ApJS, 39, 461
Seetha, S., et al. 1990, in Accretion-powered Compact Binaries, ed. C. Mauche (Cambridge: Cambridge Univ. Press), 139
Smak, J. 1967, Acta Astron., 17, 255
———. 1975, Acta Astron., 25, 371
Solheim, J. E., & Kjeldseth-Moe, K. O. 1987, Ap&SS, 131, 785
Solheim, J. E., Robinson, E. L., Nather, R. E., & Kepler, S. O. 1984, A&A, 135, 1 (SRNK)
Sonneborn, G., & Garhart, M. P. 1986, *IUE* NASA Newsletter, No. 31, p. 29
Stover, R. J., & Allen, S. L. 1987, PASP, 99, 877
Stover, R. J., Hesser, J. E., Lasker, B. M., Nather, R. E., & Robinson, E. L. 1980, ApJ, 240, 865
Sulkanen, M. E., Brasure, L. W., & Patterson, J. 1981, ApJ, 244, 579
Vogt, N. 1982, ApJ, 252, 653
Warner, B. 1985, in Interacting Binaries, ed. P. P. Eggleton & J. E. Pringle (Dordrecht: Reidel), 367
Warner, B., & Nather, R. E. 1971, MNRAS, 152, 219
Warner, B., & Robinson, E. L. 1972, MNRAS, 159, 101
Wesemael, F. 1981, ApJS, 45, 177
Whitehurst, R. 1988, MNRAS, 232, 35
Williams, G. A. 1983, ApJS, 53, 523
Winget, D. 1988, in Advances in Helio- and Asteroseismology, ed. J. Christensen-Dalsgaard & S. Frandsen (Dordrecht: Reidel), 305
Winget, D., et al. 1990, ApJ, 357, 630
Winget, D., Robinson, E. L., Nather, R. E., & Fontaine, G. 1982, ApJ, 262, L11
Wood, J. H., Irwin, M. J., & Pringle, J. E. 1985, MNRAS, 214, 475
Wood, M. A., Winget, D. E., Nather, R. E., Hessman, F. V., Liebert, J., Kurtz, D. W., Wesemael, F., & Wegner, G. 1987, ApJ, 313, 757