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Superhumps in Cataclysmic Binaries. XII. CR Bootis, a Helium Dwarf Nova

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ABSTRACT. CR Bootis is an enigmatic blue variable star with rapid photometric variations and a spectrum dominated by helium. It consists of two white dwarfs in close orbit, with a probable underlying binary period of 1471 s. For years we have marveled at the star's large nightly variations—ramping up or down at a rate of ~ 0.1 mag/hr. An intensive photometry campaign in 1996 showed that this variability is cyclic with a quasiperiod of about 19 hr, and demonstrated the association of 1490-s photometric variations ("superhumps") with extended bright states ("superoutbursts"). During the superoutburst, the 1490-s signal initially decreased with $\dot{P} = -2\times10^{-5}$, but then stabilized at 1487.29±0.02 s after ~ 300–600 binary orbits. Spectroscopy reveals variably asymmetric absorption lines, with the asymmetry migrating on a probable period of 36 hr; this may be the period of accretion disk precession. Neither the helium composition, nor the degeneracy of the mass-losing component, nor the shortness of the period (*all* of the periods) seem to present any barrier to the star in being fully certifiable as a *bona fide* dwarf nova. Stabilization of the superhump period at such a low value (1487.29 s) favors a model in which period changes arise from eccentricity changes rather than mean radius changes in the disk. This naturally explains why decreasing period and decreasing amplitude are strongly linked in the superhumps of dwarf novae.

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1. INTRODUCTION

CR Bootis (=PG 1346+082) is a blue variable star discovered by Green et al. (1982, 1986) in the Palomar-Green survey for ulraviolet-bright objects. Wood et al. (1987, hereafter W87) presented spectroscopy and high-speed photometry, and demonstrated that the star is a short-period cataclysmic binary in which the mass transferred through the accretion disk was predominantly helium rather than hydrogen. This places the star in the "AM CVn" class of variable stars (Smak 1967; Faulkner et al. 1972; Ulla 1994), a suggestion which has been confirmed by all subsequent work. They found variability from magnitude 17.5–13.6, with no definite period. They also found a small-amplitude signal with a fundamental photometric period of 1490 s, but ruled out identification with the actual orbital period since it was not stable from night to night.

An extensive photometric campaign was later carried out by the Whole Earth Telescope (Provencal et al. 1991; Provencal 1994). They discovered a stable signal at 1471.3 s that maintained phase and amplitude despite rapid erratic variations of the total brightness and of the 1490-s signal. They also discovered a rich spectrum of harmonics and sidebands to the periodic signals, which they interpreted as probably the signature of a nonradially pulsating white dwarf.

The 1471-s signal impressed us deeply. Because it maintained phase throughout the star's wanderings in light, we considered it an excellent candidate to be the true orbital period of the binary. This in turn suggested a simple explanation: that the 1490-s variation is a "superhump" signal like those commonly seen in the bright eruptions of SU UMa-type dwarf novae (reviewed by Warner 1985). This hypothesis is more or less testable, since there is a substantial body of empirical data on the properties of superhumps. In 1996 we organized a campaign designed to study the signals and in particular to compare them with superhumps. This paper reports the results. In brief, we found that the 1490-s signals are a fine match for the common superhumps of dwarf novae, and that CR Boo is essentially a "helium dwarf nova" with a recurrence period of ~ 19 hr.

2. PHOTOMETRY

2.1 The Observations

We observed the star for ~ 440 hr over 180 nights during 1988–1996. The longer observations are listed in Tables 1 and 2, omitting snapshots and short time series (some brief ones are included because they were part of a dense data stream). Data obtained with telescopes > 0.8 m consisted of high-speed photoelectric photometry (Table 1), with integration times in the range 3–10 s, and usually a $CuSO_4$ filter which transmitted 3200–5700 Å light ("wide blue"). For the time series obtained with the smaller telescopes, we used CCDs and differential photometry (Table 2). Sparse attention to calibration issues, plus the use of nonstandard filters (to maximize count rate), introduce a typical systematic zero-point uncertainty of ~ 0.1 mag in each dataset. The random error is in the range 0.01–0.03 mag.

The wide blue bandpass defined by the $CuSO_4$ filter yielded Johnson B magnitudes after comparison with observations of hot standard stars in B, V, and $CuSO_4$ filters. Hence those magnitudes are presented in the tabulation of photoelectric data (Table 1). Two of the CCD datasets (Ouda, Wise) were obtained in V light; the others, all unfiltered, were transformed to V as prescribed by Skillman and Patterson (1993). As a primary comparison we used a star located 4′ NE of the variable; multicolor photometry gave $V = 13.76$, $B = 14.99$, $R = 12.98$, $I = 12.35$. Simultaneous observation in V and unfiltered light showed that we obtained the correct V magnitudes for CR Boo by adopting an unfiltered magnitude of 13.01 for the comparison star; in other words, unfiltered light yields close to an R magnitude for our red-sensitive CCDs (KAF-0400, 1600).

In a few cases these "approximately B" and "approximately V" time series overlapped, and we then found $B-V = -0.13$ to -0.20, the typical colors for CR Boo according to W87 and our own snapshot photometry through standard filters.

2.2 The "Eruption" Light Curve and Frequency

We observed on ~ 70 nights during 1988–1993, with results similar to those described by W87: the star varying between 13.6 and 17, usually in the range 14–15, and usually showing periodic signals in the range 1485–1494 s. Most remarkable, however, was the star's very frequent ramping upward or downward in brightness through a single night, followed (as often as not) by the opposite behavior the next night. Figure 1 shows examples. Such a rapid trend (~ 0.1 mag/hr) with a total light variation typically not exceeding ~ 1.5 mag suggests that the underlying time scale for the variation is short. And since our efforts to find that time scale were repeatedly thwarted, we began to entertain a conspiracy theory: we considered that the true time scale might be near 24 hr, that terrible bane of period searchers on this rotating planet.

The solution is to obtain photometry around the clock, without interruptions due to Earth rotation. To accomplish this we organized a six-observatory network to monitor CR Boo intensively in 1996. The season's light curve is shown in Fig. 2. In one way, the results were disappointing: after May 20, the star stayed consistently in the magnitude range 14.2-14.7, basically the "high state" of the star. That light curve was not particularly interesting, since the time scale of the variation did not specifically reward our distribution in longitude. However, coverage of the strong variability seen in the first 10 days paid off handsomely.

A magnified view of the early section of the 1996 light curve is shown in the top frame of Fig. 3. The "ramping" behavior discussed above is obvious. The lower frame shows the power spectrum, indicating a strong signal at $\nu = 1.17$ c/d, with weak aliases at 0.17 and 2.17 c/d. Detailed study of the power spectrum window for these three

TABLE 1

Journal of Observations (Photoelectric Time Series)

UT Date	(2400000+) HJD Start	(hr) Duration	(s) Δt	Points	$\langle B \rangle$	(mag) Amp	(HJD) $t_{\max}$
1988 May 20	47301.6952	3.81	5	2744	14.79	0.112	301.7057
1988 May 22	47303.7503	2.99	5	2150	16.04	0.100	303.7658
1988 May 23	47304.6815	1.08	5	780	13.40	0.178	304.6824
1988 May 25	47306.8466	1.07	1	3836	13.80	0.069	306.9129
1988 May 26	47307.7036	1.20	5	861	13.85	0.066	307.7162
1992 Feb 10	48662.8295	1.01	10	305	13.50	0.086	662.8459
1992 Feb 11	48663.8234	1.20	10	372	13.62	0.063	663.8281
1992 Apr 7	48719.6480	5.08	10	1533	14.52	0.030	719.6553
1993 Feb 6	49024.7769	2.56	10	763	14.81	0.059	24.7916
1993 Feb 7	49025.8158	1.72	10	558	14.36	0.023	25.8201
1993 Feb 9	49027.7709	2.74	10	888	14.53	0.027	27.7709
1993 Feb 10	49028.8417	1.04	10	312	14.19	$\sim$ 0.018	28.8582
1993 Feb 11	49029.8300	1.37	10	420	14.95	0.031	29.8299
1993 Feb 12	49030.8404	1.16	10	352	14.04	$\sim$ 0.016	30.8555
1993 Feb 13	49031.8342	1.29	10	392	14.93	0.028	31.8479
1993 Feb 14	49032.8479	0.91	10	291	14.31	0.015	harmonics
1993 Feb 19	49037.8547	0.95	10	283	14.06	0.048	37.8601
1993 Feb 20	49038.8718	0.55	10	168	14.03	0.054	38.8793
1993 Feb 21	49039.8105	1.93	10	602	14.30	0.014	harmonics
1993 Feb 22	49040.8425	1.24	10	391	14.84	0.031	40.8446
1993 Feb 23	49041.8393	1.23	10	386	14.22	0.015	41.8423
1993 Feb 24	49042.8425	1.18	10	369	14.50	0.024	42.8451
1993 Feb 25	49043.8489	1.03	10	315	14.59		harmonics
1993 Feb 26	49044.8441	1.15	10	358	14.33	0.023	44.8502
1993 Feb 27	49045.8378	1.39	10	427	14.71	$<$ 0.020	
1993 Feb 28	49046.8399	1.26	10	380	14.69	$<$ 0.024	
1993 Mar 1	49047.8406	1.30	10	398	14.39		harmonics
1993 Mar 2	49048.8403	1.36	10	419	14.97	0.046	48.8498
1993 Mar 3	49049.8456	1.21	10	376	15.19	0.031	49.8559
1993 Mar 4	49050.8349	1.49	10	466	13.94	0.032	50.8496
1996 May 7	50210.5881	4.20	10	693	15.01	$<$ 0.010	
1996 May 9	50212.6476	3.19	10	1086	14.60	$<$ 0.012	
1996 May 10	50213.6357	3.08	10	991	14.22		harmonics
1996 May 11	50214.5074	6.76	5	4348	14.30	0.024	214.5159
1996 May 12	50215.5028	6.51	5	4391	14.85	0.018	215.5094
1996 May 20	50223.5318	2.52	5	1741	14.36	0.049	223.5320
1996 May 22	50225.5188	4.11	5	1842	14.33	0.020	225.5196
1996 May 23	50226.4871	6.34	3	7427	14.37	0.030	226.4880
1996 May 24	50227.5030	1.45	3	1313	14.35	0.042	227.5078
1996 May 26	50229.4749	6.47	3	7535	14.37	0.034	229.4888
1996 May 27	50230.4712	6.35	3	7345	14.47	0.045	230.4855
1996 May 28	50231.4692	6.35	3	7193	14.53	0.025	231.4828
1996 May 29	50232.4698	6.24	3	7390	14.58	0.034	232.4812
1996 Jul 9	50273.4793	3.14	5	2100	14.51	0.041	273.4857
1996 Jul 10	50274.4677	3.34	5	2211	14.58	0.045	274.4678
1996 Jul 11	50275.4826	2.91	5	1663	14.55	0.028	275.4990
1996 Jul 12	50276.4606	3.32	5	2148	14.65	0.048	276.4629
1996 Jul 14	50278.5216	0.39	5	265	14.60		
1996 Jul 15	50279.4680	2.99	5	2066	14.59	0.037	279.4759
1996 Jul 16	50280.4742	2.77	5	1896	14.55	0.030	280.4912
1996 Jul 17	50281.4801	2.59	5	1816	14.55	0.022	281.4908
1996 Jul 18	50282.5177	1.07	5	748	14.48	0.041	282.5242
1996 Jul 21	50285.4866	1.55	5	1004	14.60	0.043	285.5027
1996 Jul 23	50287.4642	2.54	5	1827	14.56	0.028	287.5137

NOTES: May 1988 data obtained with KPNO 0.9-m telescope; the rest with CTIO 1-m telescope. "Amplitude" refers to the full peak-to-trough amplitude. "Harmonics" means that the 1490-s signal was dominated by its harmonics, rendering the amplitude/pulse timing not meaningful. HJD in last column is truncated (first four digits cut off).

frequencies showed that the correct frequency is 1.17 c/d, not either of the aliases. But examination of the light curve also showed that this is not a strict period, since the times of individual maxima and minima wander by amounts exceeding 0.5 cycles.

In 1993 we obtained brief (~1.5 hr/night) light curves on nearly every night during February 6–14 and February 19–March 4. During both intervals the star was seen ramping sharply upward and downward at rates of ~ 0.1 mag/hr, with a total variability range of 1.1 mag.

TABLE 2
Journal of Observations (CCD Time Series)

UT Date	(2400000+) HJD Start	Telescope	(hr) Length	(s) Δt	Points	$\langle V \rangle$	(mag) Amp	(HJD) $t_{\max}$
1992 Mar 24	48705.7514	7	3.93	60	165	16.10	0.15	705.7647
1992 Mar 29	48710.7272	7	2.72	60	131	13.81	0.05	710.7355
1992 Apr 1	48713.6911	7	3.82	60	174	13.76	0.04	713.6993
1992 Apr 5	48717.6989	7	1.78	60	89	15.12	0.07	717.7042
1992 Apr 6	48718.7885	7	2.32	60	131	14.38		
1992 Apr 9	48721.6364	7	1.37	60	8	14.55		
1992 May 20	48762.6006	7	3.78	60	198	14.20	$<$ 0.02	
1992 May 21	48763.5901	7	3.97	60	235	13.65	0.07	763.5929
1992 May 22	48764.5762	7	3.84	60	231	13.49	0.06	764.5914
1992 May 28	48770.6244	7	2.73	60	138	14.42	$<$ 0.03	
1992 Jun 11	48784.5672	7	3.40	60	175	14.34	$<$ 0.02	
1992 Jun 12	48785.5817	7	2.92	60	121	14.10	$<$ 0.04	
1992 Jun 13	48786.5802	7	2.53	60	137	14.34	$<$ 0.034	
1992 Jun 23	48796.5586	7	0.83	60	42	14.40		
1993 Apr 8	49085.6302	7	5.73	60	338	14.96	$<$ 0.03	
1993 Apr 23	49100.6183	7	4.98	60	261	15.03	$<$ 0.04	
1993 Apr 29	49106.5983	7	5.48	45	434	14.27	0.02	harmonics
1993 Apr 30	49107.5724	7	5.77	60	330	13.98	0.062	107.5854
1993 May 2	49109.6747	7	3.11	45	224	14.23	$<$ 0.04	harmonics
1993 May 7	49114.6089	7	4.35	45	214	14.36	$<$ 0.05	harmonics
1993 May 10	49117.7198	7	0.13	45	9	14.43		
1993 May 11	49118.5704	7	4.95	45	392	16.10	0.08	118.5738
1993 May 12	49119.5566	7	4.78	45	332	15.66	0.06	119.5684
1993 May 16	49123.5487	7	4.71	45	267	13.86	0.055	123.5595
1996 Apr 22	50196.1656	4		120	2	14.95		
1996 May 6	50210.1051	4		120	5	14.94		
1996 May 8	50211.6990	2	4.25	70	214	14.50	0.019	211.7053
1996 May 9	50213.1829	4	2.90	120	71	14.85		
1996 May 10	50213.6359	2	3.06	40	247	14.22	0.028	213.6516
1996 May 11	50214.5781	1	2.82	45	164	14.40		
1996 May 11	50214.6880	2	5.70	70	285	14.60	0.023	harmonics
1996 May 12	50215.6986	2	5.07	70	184	15.10	$<$ 0.05	
1996 May 13	50216.5510	2	5.01	45	144	14.40	$<$ 0.022	
1996 May 13	50216.9636	4	3.53	120	8	14.20		
1996 May 14	50217.5450	1	2.03	60	18	14.17		
1996 May 14	50217.6511	2	6.69	70	343	14.16	0.030	217.6642
1996 May 14	50218.0695	4	3.28	120	92	14.37		
1996 May 15	50218.5460	1	1.69	60	98	14.54		
1996 May 15	50219.1012	4	3.12	120	114	14.38		
1996 May 16	50219.7336	2	4.15	70	214	14.33	0.019	219.7449
1996 May 16	50220.0572	4	2.90	120	82	14.25		
1996 May 18	50222.0627	4	2.05	120	76	14.27		
1996 May 19	50222.4105	3	3.29	180	35	14.42		
1996 May 19	50222.5778	1	0.42	60	25	14.35		
1996 May 20	50223.5569	1	0.35	60	22	14.35		
1996 May 20	50223.6641	2	2.48	70	149	14.31	0.025	223.6724
1996 May 21	50224.5483	1	4.45	60	268	14.26	$<$ 0.026	
1996 May 21	50225.0102	4	0.26	120	4			
1996 May 21	50225.4131	3	2.00	120	59			
1996 May 22	50226.1013	4	2.65	120	70			
1996 May 23	50226.5675	1	3.74	60	220	14.36		
1996 May 23	50226.9860	4	4.82	120	125		0.050	226.9910
1996 May 24	50228.0005	4		120	3	14.20		
1996 May 27	50230.6342	2	5.46	70	228	14.48	0.049	230.6411
1996 May 28	50231.6349	2	3.24	70	142	14.55	0.032	231.6396
1996 May 29	50232.6825	2	4.33	70	181	14.64	0.034	232.6880
1996 May 30	50233.6523	2	5.40	70	262	14.69	0.038	233.6537
1996 May 30	50234.2451	6	2.45	180	45	14.79		
1996 May 31	50235.2647	6	1.76	180	32	14.74	0.038	235.2716
1996 Jun 1	50236.0380	4		120	3	14.49		
1996 Jun 1	50236.2338	6	2.98	180	48	14.67		
1996 Jun 2	50236.6465	2	4.37	70	224	14.60	0.050	236.6493
1996 Jun 3	50237.6100	1	1.38	60	85	14.57	0.042	237.6109
1996 Jun 4	50238.7083	2	3.74	70	178	14.59	0.031	238.7127
1996 Jun 6	50240.5559	1	2.87	60	167	14.75	0.029	240.5712

TABLE 2
(Continued)

UT Date	(2400000 +) HJD Start	Telescope	(hr) Length	(s) Δt	Points	$\langle V \rangle$	(mag) Amp	(HJD) $t_{\max}$
1996 Jun 6	50240.6805	2	3.84	70	189	14.66	0.031	240.6912
1996 Jun 6	50241.4151	3	1.36	90	57	14.72	0.031	241.4160
1996 Jun 7	50241.5977	1	1.80	60	98	14.79	0.032	241.6060
1996 Jun 8	50242.5625	1	1.01	60	56	14.77	0.039	242.5702
1996 Jun 9	50243.5643	1	1.50	60	87	14.68	0.055	243.5680
1996 Jun 12	50247.2501	6	1.09	120	25	14.82		
1996 Jun 13	50248.2421	6	1.23	120	26	14.74		
1996 Jun 14	50249.2416	6	1.22	120	29			
1996 Jun 15	50250.2535	6	1.04	120	29	14.73		
1996 Jun 20	50254.7168	8	2.15	112	65	14.61	0.040	254.7232
1996 Jun 22	50256.6927	8	2.54	112	55	14.71	0.040	256.7035
1996 Jun 23	50257.6675	8	3.10	112	102	14.58	0.037	257.6838
1996 Jun 24	50258.6704	8	3.18	112	98	14.63	0.031	258.6833
1996 Jun 25	50259.6999	8	2.13	112	70	14.67	0.020	259.7154

Telescope code:
1 = CBA-East 66 cm
2 = CBA-West 35 cm
3 = CBA-Belgium 25 cm
4 = Ouda 61 cm
5 = CBA-Denmark 25 cm
6 = Wise 100 cm
7 = CBA-East 32 cm
8 = Braeside 40 cm

The power spectrum of the combined time series is shown in the lower frame of Fig. 4. While aliasing is very heavy due to the brevity of the nightly observations, the strongest peaks occur near 1.5 c/d. The highest peak occurs at 1.55 c/d, and the power spectrum window for this signal, seen in the upper frame, yields a fairly good match for the real power spectrum. A comparably good match occurs for the next highest peak in this family, at 1.36 c/d. Detailed comparison of the power spectra, as well as O−C analysis not presented here, shows that the data are not consistent with a truly stable signal—but rather with a clock keeping poor time to a frequency near 1.5 c/d.

We stress again that the nightly 1993 observations are too brief to decide among the several families of aliases. When we studied the spectral windows, we found an equally good fit for the family near 2.5 c/d, and an acceptable fit near 3.5 c/d (other choices were unacceptable). Despite this ambiguity, Fig. 4 still demonstrates that most of the variance in the light curve does not occur over some broad spectrum of frequencies, but in a narrow range near 1.5 or 2.5 c/d. This is an important conclusion: far from being merely a peak in the flickering, the signal dominates the light curve (as also in 1996).

No other data stream provided comparably dense coverage, but when we studied all the data, we found that the light curves could be fairly described thus: (1) a few epi-

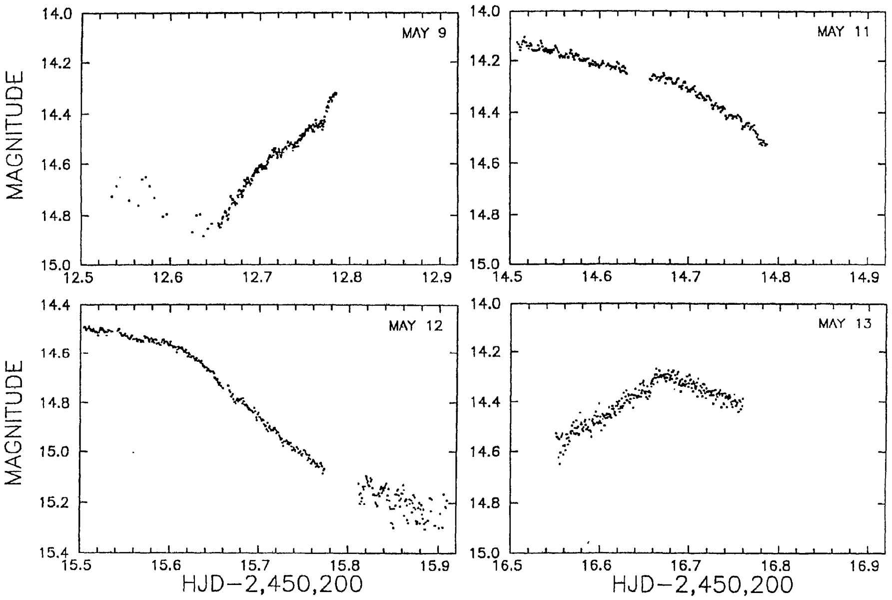

FIG. 1—Nightly light curves in 1996, showing long ramps upward or downward in brightness. Each frame is 0.42-d long and spans 1.0 mag. These slow drifts are very common in CR Boo.

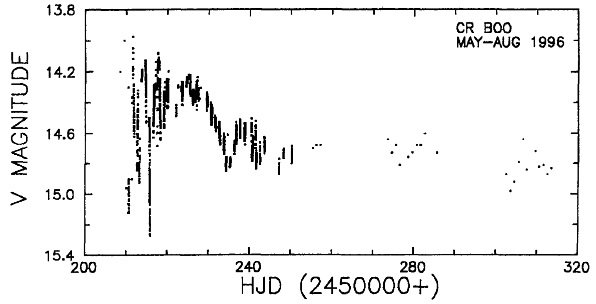

FIG. 2—Light curve of CR Boo in 1996. The star cycled between magnitude 15 and 14 for the first 10 d, followed by a "high state" lasting > 80 d (assuming no downward excursions in light during gaps in the observational record).

sodes of approximately constant light around $B = 14-14.5$; (2) a few brief "very low state" episodes around $B = 16-17$; and (3) frequent meandering in the range 13.5–15.4, with the best frequency always in the range 1.1–1.6 c/d.

Finally, W87 reported that magnitudes from the Harvard Meteor Program showed a power excess at a frequency of 0.20–0.25 c/d (their Fig. 5, reflecting data obtained during the years 1952–1957). Because they averaged magnitudes obtained over a night, high frequencies were severely aliased. In particular, the reported excess of power is also consistent with a signal at 1.20–1.25 c/d. Thus we consider it very likely that for the past 40 yr, CR Boo has been showing quasiperiodic light variations with an amplitude of ~ 1–1.5 mag and a frequency of ~ 1.3 c/d ($P \sim 19$ hr).

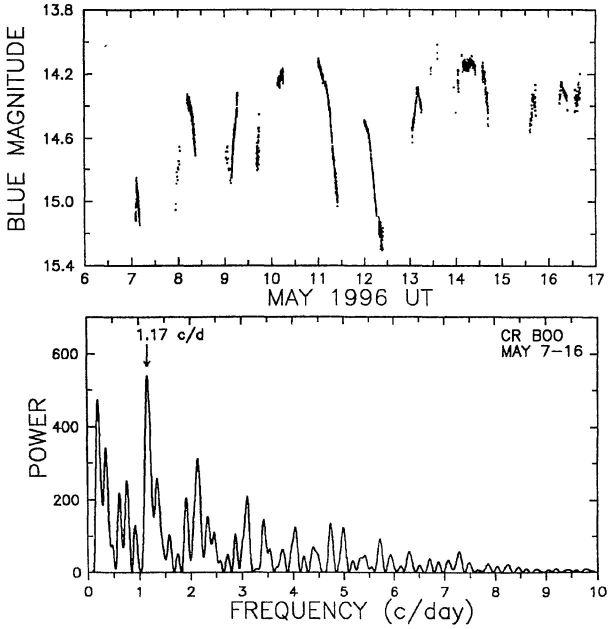

FIG. 3—Upper frame: expanded view of the first 10 d of the 1996 campaign, showing rapid cycling with $P \lesssim 1$ d. Lower frame: power spectrum of this light curve, showing a signal at 1.17 ± 0.04 c/d.

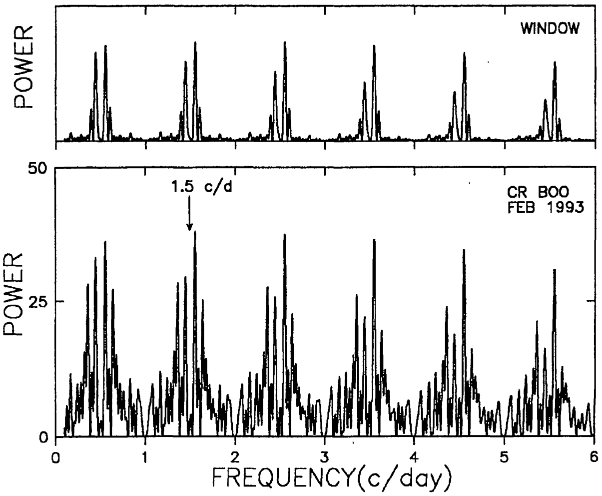

FIG. 4—Lower frame: power spectrum of the 1993 light curve, showing an erratic signal near 1.5 c/d or one of its aliases. Upper frame: power spectrum of an artificial time series containing only a signal at the strongest peak in the real data (1.55 c/d), and sampled exactly like the real data. The similarity of the alias structure establishes that most of the variance in the light curve comes from this signal, which is in the range 1.35–1.55 c/d.

2.3 Nightly Light Curves: 1490-s Pulsations

The upper frame of Fig. 5 shows one of our good-quality nightly light curves, with an obvious periodic signal. We searched every light curve for periodic signals. The results varied, but mainly in the distribution of power among harmonics. In the middle frame of Fig. 5 we present the average amplitude spectrum from the eight longest nights in May 1996 (all in the range $B = 14.1-14.7$). The fundamental and lowest three harmonics are visible, and are labeled with their best-fit periods in seconds.

To study the waveform, we subtracted trends and synchronously summed the light curves at their best-fit periods; some of the results are shown in the lower frame of Fig. 5. Most single-night waveforms show a distinct maximum, but the minima are poorly defined. (This complex waveform corresponds to the strong harmonics seen in the middle frame.) We have used the maxima as absolute timing markers and recorded many times of maximum light in Tables 1 and 2.

The full peak-to-trough pulse amplitudes, also given in Tables 1 and 2, are of interest. In most of our data the highest sustained full amplitudes are ~ 0.08 mag. The signal was basically seen throughout the star's wanderings between high and low states, but the amplitude occasionally fell below our detection limit for a single night's data (full amplitude $\lesssim 0.015$ mag). Figure 6 shows the pulse amplitude in flux units versus the star's total flux (excluding 1988 May 23 as an obvious outlier); the periodic signal is clearly much stronger when the star is bright. By segregating the high-state data, we also reckoned the amplitude greater in a long high state than in a short high state of the same brightness. (But we cannot be certain that the latter is persistently true, since the time series are seldom dense enough to identify the long high states with certainty.)

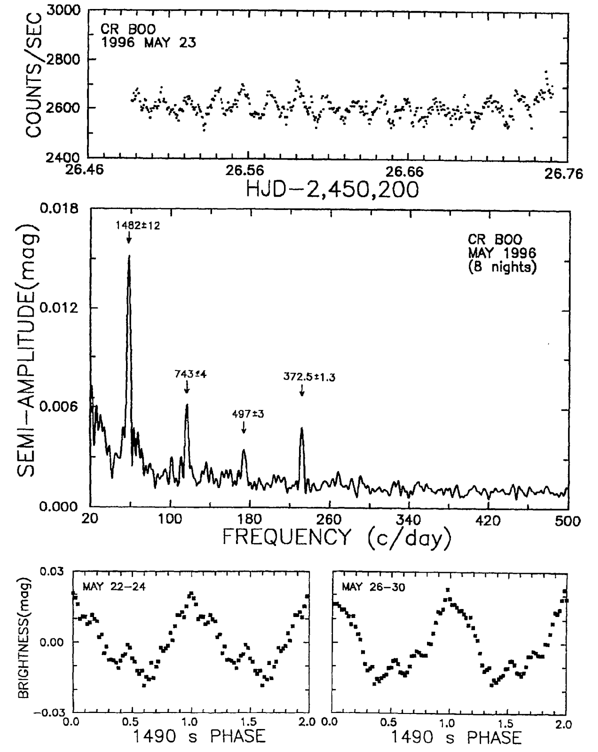

FIG. 5—Top frame: light curve of 1996 May 23, at 48-s time resolution. Middle frame: average amplitude spectrum over eight nights (all long time series); signals are labeled with their periods in seconds. Errors are relatively large because the individual nights span only ~ 6 hr. Lower frame: mean light curves during two intervals in 1996, summed modulo the best-fit periods of 1494.0 s (May 22–24) and 1485.7 s (May 26–30). Errors are about equal to the symbol size.

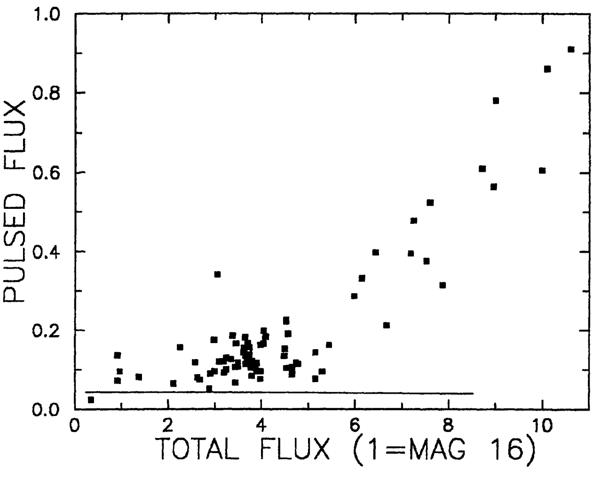

FIG. 6—1490-s pulsed flux (full amplitude) vs. total flux. One point at very large amplitude (1988 May 23: total = 10.97, pulsed = 1.95) is off the scale. The line near the bottom indicates the expected contribution of the 1471-s signal—so we are confident that these measured pulse amplitudes are not strongly contaminated by a 1471-s signal, except at the lowest flux levels. Data are from Tables 1 and 2, supplemented by four points from Fig. 7 of W87.

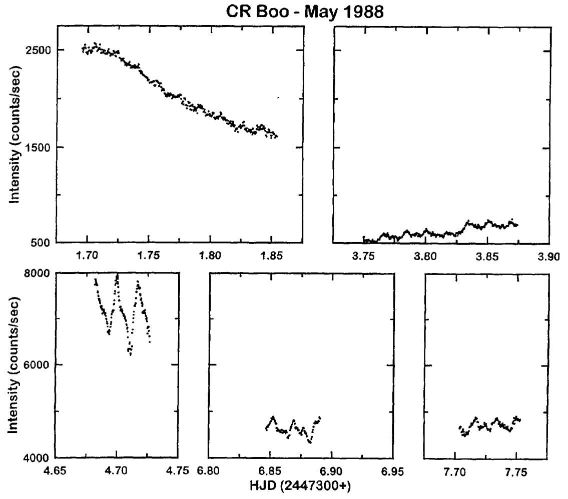

FIG. 7—The early evolution of the 1988 outburst. Strong pulsations were seen just as the outburst started on May 22, and reached full blast (0.18 mag full amplitude) at maximum light on May 23.

The 1988 data deserve a special mention. The reduced light curves are shown in Fig. 7, where May 20 is the first night (HJD 2447301). It appears that a large "eruption" began on May 23, when the star brightened to $B = 13.4$ and showed 0.18 mag pulses. On May 25 and 26 the star remained bright and strongly (0.07 mag) pulsed. It seems likely that this was also an extended high state, a magnitude brighter than that of May 1996.

We closely inspected power spectra of time series with dense coverage, as in Fig. 8. The lower frame shows the power spectrum of the 1996 May 22–24 light curve, with the signal marked by its period in seconds; and the upper frame shows the power spectrum of a time series with that signal artificially inserted and sampled exactly as the real data. The close agreement indicates that the periodicity is a simple one to within limits of measurement. In other words,

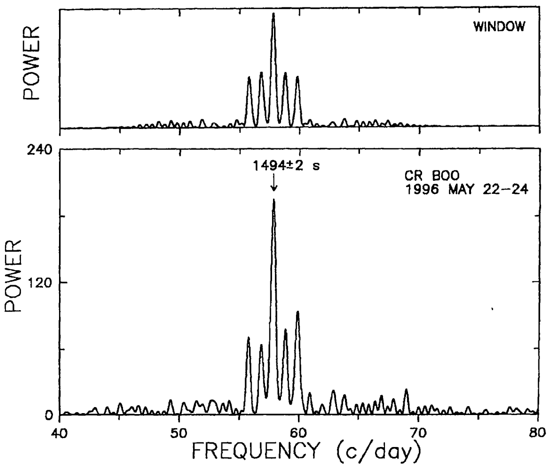

FIG. 8—Lower frame: fine structure of power spectrum near the main signal, for the densest cluster of photometry (1996 May 22–24). Top frame: power spectrum "window" of this time series. The close agreement shows that the apparent fine structure arises entirely from the window.

we did not see credible evidence of secondary periodic signals near the primary frequency or its harmonics; and all "harmonics" were indeed at exact integer multiples of the fundamental.

This failure could be interesting, because the quiescent light curve has a strong signal at 1471.3 s (Provencal et al. 1991, 1997; Provencal 1994). We never saw that signal. Our best upper limit was 0.007 mag full amplitude, obtained during May 22–30 when the star averaged $B = 14.4$. If the flux in the signal is constant, then Provencal's detection at 0.11 mag and $V = 17.1$ implies that we should have seen a full amplitude of 0.009 mag. This conflict is probably too small to cause worry, though, in view of the strong evidence of the "staying power" of the 1471-s signal in Provencal's study.[3]

2.4 Tracking the 1490-s Pulse Timings

The several long time series enabled us to follow the 1490-s pulses continuously over weeks. For each night, we studied the time series and estimated time of maximum light, peak-to-trough amplitude, and average blue magnitude. In a few cases the signal was dominated by a higher harmonic, in which case we could not estimate a 1490-s pulse maximum.

We studied the 1996 timings with O−C diagrams and Fourier analysis. Prior to May 20, the pulses showed random scatter; the clock wandered on a timescale shorter than a day. Within a day of May 20, the clock improved in quality, and the amplitude grew by about a factor of 3. The clock quality and amplitude remained high for the rest of the campaign. The upper frame of Fig. 9 shows the O−C residuals in the interval May 20–June 9; the curvature indicates a period decreasing from 1494 to 1487.2 s over ~ 8 d, then remaining essentially constant ($|\dot{P}| < 10^{-6}$). The middle frame explicitly shows the evolution of the period (essentially the slope of the O−C) in this interval; the period was deduced by three-night fits, with two nights between fits, so there is mild oversampling. The bottom frame shows the O−C for the entire interval May 27–July 23, and the straight-line fit indicates a constant period of 1487.29±0.02 s. The ephemeris during this interval is

$$\text{Pulse maxima} = \text{HJD } 2{,}450{,}230.4712 + 0.017214\, E, \tag{1}$$

and the upper limit on period change is $|\dot{P}| < 3\times10^{-8}$.

We also tried O−C analysis of previous data sets. During February and March 1993, the 1490-s clock definitely did not remember phase from night to night. The results for 1988 were inconclusive; the first three nights of the "eruption" followed a period of 1494±2 s, consistent with the value seen at the same stage in 1996, but the pulse wandered far from schedule on the last night. However, since the latter rests on only two pulses, and since the period seen at the same stage in 1996 (the place of fastest curvature in the upper frame of Fig. 9) changed rapidly, we do not give much weight to this.

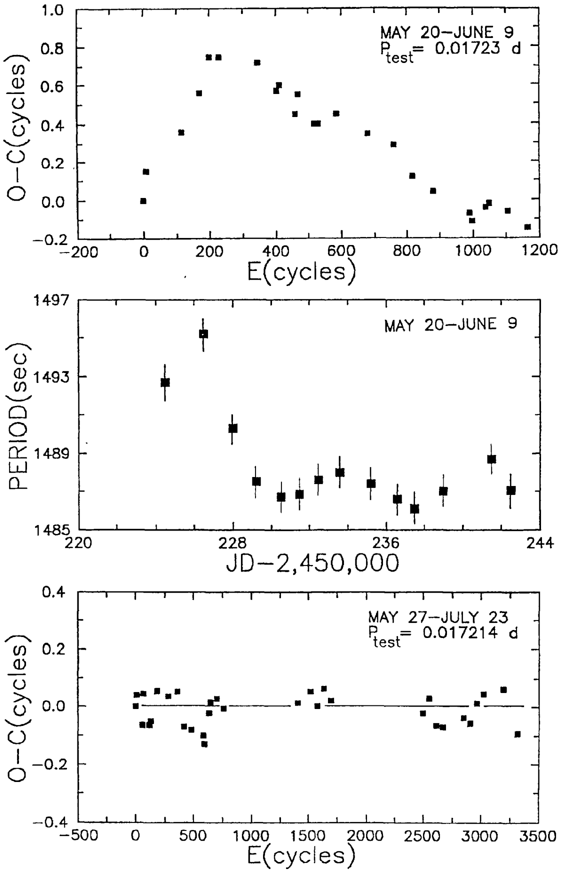

FIG. 9—Studies of the 1490-s signal during the 1996 long eruption. The top frame shows the O−C diagram during May 20–June 9, and the downward-sloping curve implies a period decrease from 1493 to 1487.3 s (with most of the decrease occurring early). The middle frame explicitly shows that period decrease. The bottom frame shows the O−C diagram during May 27–July 23, where the straight-line fit demonstrates period stability.

Since the waveform is not stable, could it be that the period wanderings are merely the result of a changing waveform? We studied this with ~ 40 pairs of consecutive nights, by comparing periods found by Fourier analysis and O−C pulse timings. The result was simple: O−C residuals of the pulse maxima tracked the Fourier analysis quite faithfully. This raised our confidence that O−C residuals were indeed tracking the period, apart from the occasional hopeless night when harmonics dominate.

Finally, our desultory coverage over the years, mostly when the star was rapidly cycling, showed that pulse maxima could not be tied together with any stable period, even on successive nights. This was also the conclusion of W87. We conclude that the 1490-s signal is generally of poor quality ($\dot{P} \sim 10^{-4}$) but improved by at least a factor of 1000 during the one well-observed long high state in 1996.

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[3] And a close look at Tables 1 and 2, along with Fig. 6, shows high pulse amplitudes in the low state. But those occasions were sufficiently rare and scattered that period uncertainties were ~ ±25 s, insufficient to distinguish between the two periods of interest. Considering Provencal's result, it's plausible that these are actually detections of the 1471-s signal.

2.5 The "S" Word

Experienced students of dwarf novae will realize that there is a one-word summary for the above-described properties of the 1490-s signal. The word is *superhumps.* Many will have been caught uttering that word immediately on seeing Fig. 7. More conservative folks might need to be reminded of the phase-stable candidate orbital signal at 1471.3 s. With a degenerate secondary the Roche-lobe geometry yields an expected fractional period excess of 0.015 (Patterson et al. 1993), consistent with observation. Despite its exotica (helium composition, degenerate secondary, ultrashort period), CR Boo displays essentially garden-variety superhumps in its light curve.

3. SPECTROSCOPY

3.1 The Moving Lines

When it is bright, CR Boo shows broad, asymmetrical helium absorption lines (W87). Such lines are likely to be formed in the accretion disk, with asymmetry possibly arising from the eccentricity of the disk. In particular, theory predicts that the asymmetry should cycle between the blue and red wings with a period equal to the disk's period of apsidal advance ("precession"), which should be the beat period of orbit and superhump (Patterson et al. 1993, hereafter PHS). With $P_{\rm orb} = 1471$ s and $P_{\rm sh} = 1487-1493$ s, this yields an expected period of 28–38 hr for the absorption-line asymmetries.

During 1993 May 10–17 we searched for this effect. From two telescopes (the Kitt Peak National Observatory 2.1 m and the South African Astronomical Observatory 1.9 m) we studied the spectral variations, accumulating 500 spectra averaging 2 min each. The interval 3500–5800Å was covered. We condensed the spectra into approximately 50-min sums, in order to suppress any variability near the probable orbital period. The grand average spectrum is shown in the top frame of Fig. 10, showing the broad He I lines and also a broad feature near 5170 Å, probably arising from the Fe/Mg blend seen in late-type stars.

We then calculated the skewness of the helium absorption lines in each spectrum, and the power spectrum of the resultant time series, as described by PHS. We concentrated on the three cleanest lines: λ4388, λ4471, and λ4922. The average for the three lines is presented at the bottom frame of Fig. 10. The line core ($|v| < 1000$ km s) shows a periodic term at 36.4± 2.8 hr. In the middle frame is the power spectrum of an artificial time series containing just one signal at the candidate period, sampled exactly as the real data. The similarity of lower and middle frames shows that most of the other power spectrum peaks are aliases of the fundamental signal; this raises the credibility of the result and suggests that most of the variance truly occurs at the fundamental frequency.

Apsidal advance of an eccentric disk provides a plausible explanation for this effect. The skewness period would then be the actual precession period, as also seen in AM CVn. In CR Boo, however, the argument is slightly more interesting, because there is an independent signature of $P_{\rm orb}$: the phase-stable 1471-s signal at quiescence.

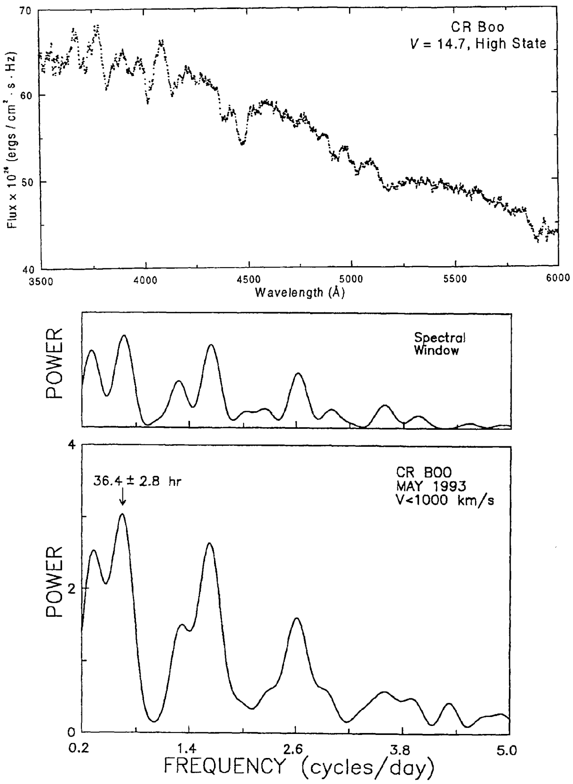

FIG. 10—Upper frame: grand average high-state ($V = 14.7$) spectrum of CR Boo in May 1993. The usual broad He I absorptions are present, and a feature at 5170 Å probably due chiefly to Fe II. Lower frame: power spectrum of the skewness time series (for λ4388, λ4471, and λ4922 combined), with the fundamental signal marked by its period in hours. Middle frame: power spectrum of an artificial time series containing only this signal and sampled exactly like the real data; the similarity shows that the other peaks are aliases, and that most of the variance in the time series arises from the signal at 36 hr.

An important caveat is needed. Some spectra were obtained under nonphotometric conditions, so we do not accurately know the variations in light. Since the star frequently shows variability on a roughly similar time scale, and was in fact known to be varying strongly during this week (see Table 2), we cannot rule out the possibility that the skewness changes[4] arise from gross spectral changes as the star wanders from bright to faint states. We looked for such an effect and did not see it (at least we did not see traces of emission, the most obvious peril to the experiment); but with clouds and short exposures, our data are poorly suited to constrain this. It would be desirable to repeat the search with more and better data, preferably when the star is in a prolonged high state.

3.2 A Low-State Spectrum

The one low-state spectrum presented by W87 showed a very blue continuum and helium lines in weak emission (at

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[4] The skewness changes in this particular time series. Bright-state spectra show large skewness changes with no significant changes in brightness, so this is definitely not true in general.

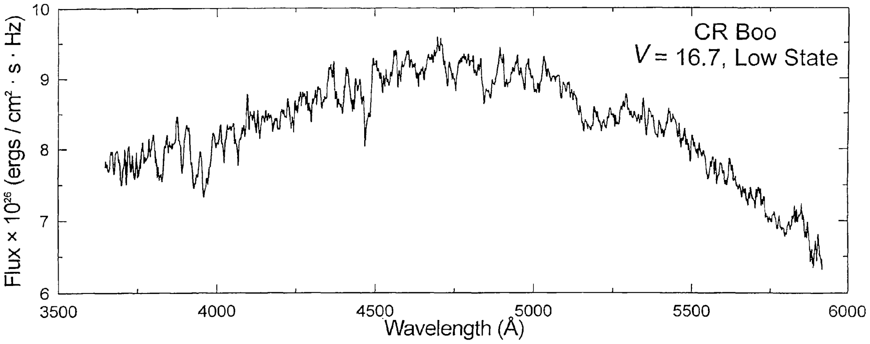

FIG. 11—Spectrum of CR Boo near minimum light ($V = 16.7$), showing a cool continuum and low-excitation absorptions as well as a few remaining He I lines.

$V = 16.9$). Appearance of emission lines in the low state is a standard feature of dwarf novae, so we obtained additional spectra to see if this correlation persisted. On one occasion during spectroscopy, the star became quite faint. On 1993 May 14 it declined to $V = 16.7$, and we obtained three consecutive 50-min exposures. The sum of these exposures is shown in Fig. 11.

This is a very peculiar spectrum. All lines are still in absorption, but the apparently dominant features are of both high (He I) and low (Ca II, Fe II/Mg I) excitation, and absorption is seen at 4860 Å, very likely due to H. We studied the possibility of contamination by moonlight, by extracting the night-sky spectrum along the tall slit. The spectrum showed the usual solar features (e.g., very strong G band, Ca I, and Na D absorptions) but did not resemble that of Fig. 11. The features in Fig. 11 are also quite broad (30–35 Å), characteristic of white dwarfs and accretion disks but not normal stars. So we concluded that the spectrum is not significantly contaminated by moonlight or any field star which might be lurking undetected very close to CR Boo. The measured total width of He I 4471 is 34 ± 5 Å, compared to 65 ± 6 Å in the high state.

4. DISCUSSION

4.1 Evidence from the Light Curve

The light curve description given above in Sec. 2.2 certainly resembles that of many dwarf novae. In particular, the sharp dichotomy between short ($T_{\rm rec} \sim 19$ hr) and long ($T_{\rm rec} \gg 20$ d) eruptions is characteristic of SU UMa-type dwarf novae. During their long eruptions, such stars also sprout photometric variations at a period slightly greater than $P_{\rm orb}$–the famous "superhumps". So does CR Boo: 1488 s implies a mean period excess of 1.2% if $P_{\rm orb}$ is taken to be the phase-stable 1471-s signal, and we know from our data that the former signal is indeed much enhanced during the long bright states. Thus the evidence truly favors interpretation of CR Boo as a "helium dwarf nova."

4.2 Evidence from Spectroscopy

The spectral pattern in dwarf novae is very consistent: emission when faint, absorption when bright. This also seemed true in the one low-state spectrum showed by W87. Yet our spectrum at a similarly low flux showed absorption. The continuum slopes also disagree: that of W87 was even bluer than at high state ($T > 30{,}000$ K), while ours was fairly red ($T \sim 5000$ K). Interpretation of this could be complicated by the appearance of white dwarf photospheric features, and by variations in the white dwarf's surface temperature due to recent episodes of heating by accretion. These complications are known to affect spectra of a few well-studied dwarf novae in quiescence. For CR Boo the data are certainly too sparse to assess these factors, so all we can say at this point is that the spectral changes do not contradict the dwarf-nova hypothesis.

4.3 Other Evidence from the Office of Dwarf-Nova Credentials

We can also test for membership by using two empirical rules for dwarf novae, the period-amplitude relation (Kukarkin and Parenago 1934; recently updated by Warner 1987), and the "Bailey relation" linking decay time from normal eruption to $P_{\rm orb}$ (Bailey 1975; also recently updated by Warner 1987). These correlations are shown in the two frames of Fig. 12. Using the values cited above ($P_{\rm orb} = 1471$ s, $A = 0.9$ mag, $T_{\rm rec} = 19$ hr, and $T_{\rm decay} = 0.4$ d mag), we place CR Boo as the solitary point at the lower left in both frames. Clearly the star satisfies both relations very well.

In the thermal instability model of dwarf novae, the decay time represents the travel time of the cooling front across the accretion disk, and hence is proportional to $R_{\rm d}/\alpha_{\rm hot}$. Observations suggest that disk radii in eruption are generally in the range $(0.4\text{–}0.5)a$, and if we combine this with Kepler's Third Law, we expect

$$T_{\rm decay} \propto P^{0.67} M_1^{1/3} \frac{(1+q)^{1/3}}{\alpha_{\rm hot}}, \tag{2}$$

where M_1 is the white dwarf mass, and $q = M_2/M_1$ is the mass ratio. The quantity $(1+q)$ varies from about 1.1 at $P = 1.4$ hr to 2 at $P = 7$ hr, implying a dependence like $(1+q) \propto P^{0.37}$. Thus we get

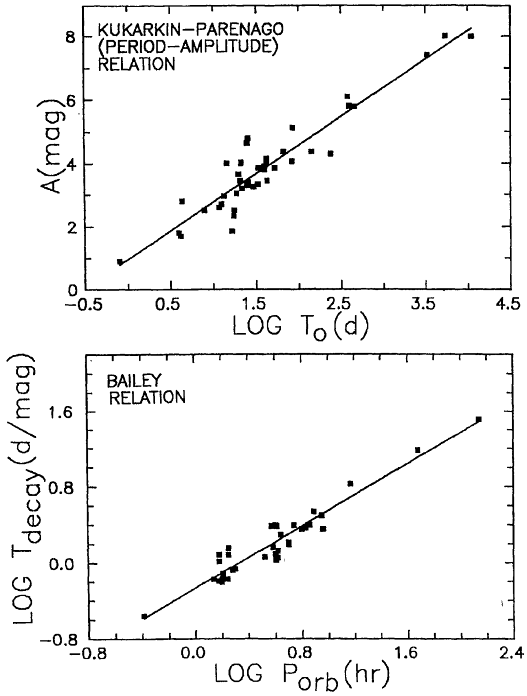

FIG. 12—Empirical relations for dwarf novae. Upper frame: Kukarkin–Parenago relation, linking eruption amplitude A to recurrence period T_0. Lower frame: the "Bailey relation," linking the decay time from normal eruption to underlying orbital period. Most points are taken from Warner (1987, 1995), with more recent data added. CR Boo is in both frames the solitary point at the lower left. Lines show the best fits to all points.

$$T_{\mathrm{decay}} \propto P^{0.79} \frac{M_1^{1/3}}{\alpha_{\mathrm{hot}}}. \quad (3)$$

The empirical Bailey relation of Fig. 12 gives $T_{\mathrm{decay}} \propto P^{0.82}$, so this is in fine agreement if the dispersion in white dwarf masses and hot-state viscosities is not large.

The Kukarkin–Parenago relation is trickier, since it requires separate theories for luminosity produced during eruption and quiescence, the recurrence time interval, and often a significant subtraction of nonaccretion light. Therefore, we forego the effort here. But at least the location of CR Boo in the figure gives prima facie evidence of belonging to this family of points.

We conclude that CR Boo is indeed a *bona fide* dwarf nova, with at least its short eruptions powered by the same mechanism, probably a thermal instability of the helium-dominated accretion disk. The existence of such stars was essentially predicted long ago by Smak (1983) and Cannizzo (1984), who pointed out that helium disks as well should show thermal instabilities, due to the partial ionization of helium at $T_e \sim 15{,}000$ K. Smak concluded that the two helium CVs known at that time, AM CVn and GP Com, avoided the instability by remaining, respectively, much hotter and cooler than that critical temperature. The dwarf nova nature of CR Boo implies that there is indeed an intermediate region of instability, and hence basically fulfills the prediction.

More recent models of helium accretion disks, addressing the issue of instability, have been calculated by Wood and Simpson (1996) and Tsugawa and Osaki (1997).

4.4 CR Boo as a Dwarf Nova

Classification of CR Boo as a dwarf nova raises some issues of nomenclature. The above evidence shows that CR Boo is a "helium Z Cam star" (standstills slightly below maximum light) and a "helium ER UMa star" (very frequent short maxima) as well as a helium SU UMa star (superoutbursts punctuated by common superhumps). But we beg readers to resist urges for further subclasses. The very fact that a single star manages to be all these things (at least; there may be more) is pretty good testimony to over-Balkanization in the class assignments of dwarf novae, and even a vague remembrance of the history of that unhappy peninsula should counsel us not to go down that road.

There are more subtle issues. In dwarf novae, "high state" and "low state" are often used as synonyms for the slightly more precise "eruption" and "quiescence." But 1996 showed basically a "cycling state" in which the star never particularly approached its true low or high brightness levels, followed by a state which was somewhat high but more importantly long (>90 d). So while the star does have high and low states, it is really more distinctive in the way that it moves from rapidly cycling states to much steadier light which can be fairly high (as in 1996) or very low (as in the observations reported by Provencal 1994).

That is quite unusual for dwarf novae. We really do not know any hydrogen-rich dwarf nova in which we can document such fickle interest in eruptions. This might be explained by postulating large changes in $\dot{M}$ from the secondary, which could strongly alter the eruption characteristics as desired. But that does not seem promising, as the actual brightness of CR Boo is not strongly variable. Another possibility is that the $\dot{M}$ window for thermal instability in helium disks is relatively narrow (i.e., fairly modest changes in $\dot{M}$ might carry a star from the stable cold to the stable hot equilibrium). A third possibility, and probably the best, is that the $\dot{M}$ window is small because the disk is small. This at least is a consequence of the disk-instability theory (Cannizzo 1993).

It would be awfully nice to know the recurrence period for superoutbursts in CR Boo. A very rough estimate, based on the longevity of the 1996 superoutburst and our success in certifying such events in 1988 and 1996 with our frequency of observation, is in the range 100–300 d. However, this estimate could go much lower (to 25–40 d) if the 1996 event was anomalous or if it consisted of several events not quite resolved by our coverage. In fact, since available evidence suggests episodes of rapid cycling, long high states, and fairly long low states, it is not even entirely obvious how to learn the recurrence period.

5. SUPERHUMP PERIOD CHANGES

The superhump period changes in May–July 1996 were quite interesting. Essentially all well-studied dwarf nova superhumpers have shown monotonically decreasing periods, but we have not yet learned much about what happens very late in the outburst. Most commonly, the outburst ends after 8–15 d, and the superhumps disappear without revealing their plans. Does the period decrease asymptotically to $P_{\rm orb}$? Linearly to $P_{\rm orb}$ and then die? Linearly to $P_{\rm orb}$ and then track $P_{\rm orb}$? Linearly or asymptotically to $P_{\rm orb}$ after suffering a 0.5 cycle phase shift ("late superhumps")? Linearly or asymptotically to some other value? There is some observational support for each of these pictures, but available data are too sparse to commend any one of them strongly over the others.

We covered the 1996 superoutburst of CR Boo with time-series photometry for 60 d, giving a long base line. With a likely $P_{\rm orb}$ of 1471 s, this means about 3500 orbital cycles, contrasting with just 50–150 orbital cycles for the typical "well-observed" outburst. And this (orbital cycles) seems like the relevant time unit for an accretion disk, since the superhump phenomenon must surely be in its heart a dynamical property of the disk.

After the rapid period decrease at the beginning of the superoutburst, the lower frame of Fig. 9 shows that the period seemed to stabilize at 1487.3 s. Is this actually a stable period? Well, the probability of such a good fit arising by chance from a clock losing correlation from night to night is $<10^{-20}$. The probability of the three monthly segments defining a tight line by accident is $<10^{-3}$. Thus we can securely conclude that the clock was stable over at least 3500 cycles. This proves that accretion disks can settle into a more or less stable superhump period during a long and sustained high state.[5] Fairly stable superhump periods in some novalike variables (BK Lyn, V795 Her, V603 Aql, AM CVn) have already provided good evidence for this, but we have not previously had the luxury of actually observing a star in the act of stabilizing (top frame of Fig. 9).

6. UNDERSTANDING THE STABILIZATION OF THE SUPERHUMP PERIOD

6.1 Paradoxes in the Conventional Wisdom

The issue of period stabilization deserves a closer look. It is commonly assumed (but has never been proved) that the observed period decreases in superhumping dwarf novae arise from changes in the disk radius. The early rapid decrease is attributed to rapid disk contraction which results from the increased tidal torque when the eccentricity becomes large as a result of the (largely unrelated) instability at the 3:1 orbital resonance in the disk. For CR Boo we then need to explain the eventual stabilization at a fractional period excess $\epsilon[\equiv(P_{\rm sh}-P_0)/P_0]$ 30% smaller. In the restricted three-body problem with Roche-lobe geometry, perturbed orbits show a precession rate given approximately by

$$\frac{P_{\rm prec}}{P_0}=\frac{4}{3}\frac{(1+q)^{1/2}}{q}\frac{(1-e^2)^2}{(R_{\rm disk}/a)^{3/2}}, \qquad (4)$$

to lowest order in the eccentricity e (Danby 1988). $P_{\rm prec}$ is related to ϵ by

$$\frac{P_{\rm prec}}{P_0}=\frac{(1+\epsilon)}{\epsilon}, \qquad (5)$$

so the observed change in ϵ (0.0154–0.0108) implies that $P_{\rm prec}/P_0$ changed from 66 to 93. For small e, this requires a disk radius change of 24%. $R_{\rm disk}$ should settle down to a value 24% smaller than the radius for the 3:1 instability.

But then why should the superhumps continue? Is it a relic of having earlier been driven hard by the 3:1 instability? This is hard to believe. CR Boo was still vigorously superhumping 3000 orbits later. And its close cousin AM CVn has been displaying superhumps and absorption-line asymmetries for at least 35 years (since discovery), or one million orbits. This seems compelling evidence that eccentricity was being maintained by some continuing mechanism—presumably at the 3:1 resonance. And if that is so, then the disk was presumably much ($\sim 20\%$) larger during the early stages of superoutburst.

But that too is hard to understand. Figure 7 shows that superhumps develop very rapidly, reaching maximum amplitude in one day; that is indeed the general pattern among dwarf novae. They also generally appear with a predictable value of ϵ ($=0.01-0.05$, varying from star to star but not varying from outburst to outburst of a given star).[6] Both the very rapid development and the exactitude of the new period tend to indicate a resonant process. This suggests that the 3:1 resonance is reached right at the start of the outburst.

Both arguments seem good to us (well, to most of us); but to accept them both, we simply cannot blame period changes on changes in disk radius.

6.2 Eccentricity, the Savior

The alternative is eccentricity. To account for the observed change through eccentricity, $e=0.4$ is needed, or slightly more since some eccentricity must remain after the period has stabilized.

This makes considerable sense. The rapid onset of superhumps gives evidence that an eccentricity machine is operating powerfully at that time, and observations also show (for CR Boo and the entire family of superhumpers) that the hump amplitudes are highest at onset. Although the precise mechanism for superhump light generation is still unknown, it seems reasonable that if they are powered by eccentricity, then greater eccentricity implies greater amplitude. Thus if we want to attribute superhump period

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[5] It should put to rest the much-cited argument that precession models cannot produce high period stability (Zhang et al. 1991). Such arguments are misleading because they overlook the fact that superhumps acquire their moderately high stability mostly via the infinitely stable orbital clock which underlies them. For example, CR Boo early in superoutburst showed $\dot{P}_{\rm sh}=-2\times10^{-5}$, but the corresponding $\dot{P}_{\rm prec}[=-(P_{\rm prec}/P_{\rm sh})^2\dot{P}_{\rm sh}]$ is just 10^{-1}. They are also contradicted by the many observations of high stability ($|\dot{P}_{\rm sh}|=10^{-8}-10^{-6}$) in superhumping CVs.

[6] See Vogt (1982), Warner (1985), Warner (1995), or just trust us on this one. All observers of superhumps become quickly amazed at how the stars manage to produce exactly the same anomalous period in each superoutburst.

1997PASP..109.1100P

changes to changes in e, we obtain for free a natural explanation of the pattern of amplitude change.

That seems a nice return on investment. And while some might be distrustful of the required e (> 0.4), any version of a precessing-disk model probably needs e that high, in order to reproduce the hump amplitudes sometimes observed at onset, ranging as high as 0.5 mag. The efficiency of light production in the outer disk is just too low to get a large amplitude from a small eccentricity. Therefore, we think this theory has a fair chance of being right.[7]

7. COMPARISON WITH THE WHOLE EARTH TELESCOPE RESULTS

The conclusions of this paper concerning the 1490-s signal are very different from those presented in the report of the Whole Earth Telescope observation (Provencal et al. 1991, 1997; Provencal 1994). One reason is that the WET data were obtained primarily in the very low state; our data ranged over many states but were primarily based on the high state. Another important reason lies in the methods of data analysis. The WET study used Fourier analysis, which dissects the light curve into component sinusoids of fixed amplitude and frequency. We studied our light curves to see if we could use it too, but decided that in general we could not; usually there is too much variation in frequency and amplitude from night to night. During the 1996 superoutburst the signal became much more stable, and we trusted a limited use of that technique. But no stable fine structure was seen within the 1490-s signal or any of its harmonics, so we never found any reason to invoke white dwarf pulsation or rotation or any other mechanism for producing truly stable short-period signals. Indeed, the 1490-s signal seems to us to be a textbook case of a common superhump, such as those frequently found in dwarf novae of extreme mass ratio. Since we believe on quite independent grounds that CR Boo is a dwarf nova of extreme mass ratio, we basically found nothing remarkable about the 1490-s signal.

We do, however, trust the WET detection of the 1471.3-s signal. That signal was seen by the WET authors at large amplitude, and dominated the power spectrum in the low state. It maintained an essentially constant phase and amplitude (in flux units) as the star went through several mini-outbursts. This is the pattern that has been well documented in following the quiescent orbital modulations in the two best-studied dwarf novae of all, U Gem and VW Hyi. We believe it is characteristic of the very low state, and think it likely to signify the true binary period.

8. SUMMARY

(1) We report the results of a long optical campaign on CR Boo in 1996. The most important result was quasiperiodic cycling, with $P \sim 19$ hr, between high and low states during the first two weeks. This behavior and this period were verified in a 1993 campaign, and may also be present in the Harvard Meteor Program data covering the years 1952–1957. It thus appears to be a long-lived time scale in the star.

(2) After the first 10 d of the 1996 campaign, the star brightened to $V = 14$ and declined very slowly $(\sim 0.02$ mag/d) over the next ~ 90 d. Signals with $P = 1486-1494$ s were then seen on essentially every night. Over the first five days of this long bright state, the period decreased with $\dot{P} \sim -2\times 10^{-5}$. The period then stabilized at 1487.29 ± 0.02 s. The initial low coherence of the signals, their slight period excess over the presumed $P_{\rm orb}$, and their association with long bright maxima, all suggest identification as "common superhumps," a familiar syndrome of dwarf novae.

(3) These signals were seen at all stages in the eruption cycle. But they were much stronger in long high states, and strongest at the very beginning of these states—again consistent with the properties of common superhumps.

(4) Possession of common superhumps and a strong long/short dichotomy in the eruption types are characteristic of SU UMa-type dwarf novae. The dominance of helium in the accretion disk (and therefore also in the mass-losing secondary) appears not to have impeded the star in acquiring the standard credentials for dwarf nova status.

(5) The stabilization of the superhump period is interesting. Common superhumps of dwarf novae all have $|\dot{P}| \sim (1-10)\times 10^{-5}$; yet permanent superhumpers frequently show signals $\sim 100-1000$ times more stable. In 1996 CR Boo may have revealed the time scale (300–600 orbits) for the disk instability creating superhumps to relax to a steady condition.

(6) Period stabilization at such a low value creates paradoxes in understanding the superhumps as the result of excitation at the 3:1 orbital resonance. The paradoxes disappear if we attribute period changes to eccentricity changes in the disk, with $e > 0.4$ required at superhump onset. This may well be the dominant cause of $\dot{P}_{\rm sh}$ in all the common superhumps of dwarf novae.

(7) The light curve of CR Boo displays at different times several familiar syndromes of hydrogen-rich dwarf novae (Z Cam, SU UMa, etc.). Those syndromes are known to be associated with states of high and low $\dot{M}$. Yet CR Boo itself has only fairly modest luminosity variations, suggesting no great changes in the mass transfer rate. Perhaps this arises because the disk is very small (so that the stable cold and stable hot equilibria are accessible or nearly accessible with only small changes in $\dot{M}$).

(8) Persistence of superhumps in the low state is slightly unusual among dwarf novae, but not entirely so. The best-studied dwarf nova superhumpers (VW Hyi, TU Men, V1159 Ori) show signals enduring at least a few days after the outburst ends; CR Boo seldom (never in our data) stays faint this long. Still, the 1993 data showed superhumps

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[7] Of course we do not allege that $R_{\rm disk}$ never changes! Eclipsing dwarf novae have provided quite firm evidence for 20%–40% decrease in $R_{\rm disk}$ as the stars drop from eruption to late quiescence (Paczynski 1965; Smak 1984; O'Donoghue 1986; Anderson 1988; Zola 1989; Wood et al. 1989), but we allege that this contraction occurs well after the initial era of superhump period changes, which lasts only $\sim 50-200$ orbital cycles. It is still possible that the later era of period changes is briefly dominated by change in $R_{\rm disk}$ rather than e (as long as the superhumps quickly die, which they generally do; otherwise one cannot understand the sustained excitation at a smaller radius).

throughout a 30-day interval including no superoutburst, indicating either great longevity or, more likely, repeated re-manufacture of new superhumps in short eruptions. Either option would have to be considered unusual. CR Boo evidently has a somewhat better superhump machine than most dwarf novae.

(9) When bright, the star displays asymmetric helium absorption lines. The skewness of these lines varies rapidly, and suggests a periodicity of ~ 36 hr, the approximate beat period of superhump and (candidate) orbit. This is consistent with the hypothesis that the superhump originates from an eccentric accretion disk precessing with $P \sim 36$ hr.

(10) In the very low state ($V = 16.7$), the spectrum was quite different. Helium absorption lines of about the same strength ($EW \sim 3-5$ Å) persist, but are accompanied by other broad absorptions of low excitation. The origin of these features remains unknown.

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