SUPERHUMPS IN CATACLYSMIC BINARIES. XXI. HP LIBRAE (= EC 15330–1403)

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ABSTRACT

We report photometry of the helium-dominated cataclysmic variable HP Librae during 1995–2001. The main photometric signal varies between 1118.89 and 1119.14 seconds, on a timescale of a few years, and displays a waveform characteristic of "superhumps". After subtracting the main signal, we found a weak residual signal at 1102.70±0.05 s, which we interpret as the underlying orbital period of the binary. The full amplitude of this putative orbital variation is just 0.005 mag, the weakest orbital signal yet found in a CV. The 1119 s signal of HP Lib is a superb match to the well-studied 1051 s superhump of AM CVn, the "mother of all helium CVs".

The superhump shows no change in amplitude or waveform on any timescale, and no essential change in period on timescales shorter than ~3000 cycles. Such great stability makes the star a promising test case for detailed studies of the underlying spiral structure in the disk, the likely cause of superhumps. Comparison of orbital and superhump periods for the family of AM CVn stars supplies evidence that these stars are evolving towards longer orbital period.

Subject headings: accretion, accretion disks — binaries: close — novae, cataclysmic variables

1. INTRODUCTION

O'Donoghue et al. (1994) reported the discovery of EC 15330–1403, an interesting new cataclysmic variable in the Edinburgh-Cape survey for blue stars. The star showed broad, shallow He I absorption lines and a photometric period of 1119 s, and maintained a nearly constant mean brightness near *V*=13.7. These properties made the star an apparent close cousin of the famous AM Canum Venaticorum, the prototype of the interacting-binary-white-dwarf (IBWD) subclass of the CVs.

During each of the last seven years, we have carried out photometric observing campaigns on this star, recently renamed HP Librae. The results are fully consistent with the conclusions of O'Donoghue's initial study; in particular, the photometric signal is an excellent match to the well-studied "superhump" of AM CVn. The remarkable stability of the superhump in HP Lib enables us to count cycles uniquely over each observing season, and thus to study the signal over very long baselines (10^4–10^5 cycles). We also found a weak signal at slightly shorter period (1102.70±0.05 s), which is very likely to be the true orbital period of the binary. Here we report the results of this study.

2. OBSERVATIONS, LIGHT CURVES, PERIODS

The observations consisted of nightly time-series photometry from many telescopes in the network of the Center for Backyard Astrophysics (CBA, Skillman & Patterson 1993), supplemented by contributions from larger telescopes. In all, the observations covered 720 hrs over 185 nights, detailed in Table 1. We obtained a wide range in terrestrial longitude (with observations from the USA, New Zealand, Chile, South Africa, and Israel) in order to resolve ambiguities in daily cycle count, and a wide distribution over each observing season in order to define the precise period without cycle-count ambiguity on longer timescales (weeks to months). The data was predominantly differential CCD photometry with respect to a nearby star, most commonly GSC 5608–294, located about 100" NW of the variable and with *V*=12.93±0.02. We generally used a *V* filter (or rotated filters) with the larger telescopes, and white light with the smaller telescopes. On several occasions we verified that the periodic signal displayed no color dependence, so the data could be merged with no great loss of integrity. This was quite important, because our program of accurate period measurement over very long baselines always requires merging data from disparate sources.

We were tremendously impressed with the stability of HP Lib. The star's mean brightness was always close to *V*=13.70±0.04; we did not see any certifiable departures which exceeded 0.10 mag, and did not see any low-frequency (0.1–5.0 c/day) periodic signals exceeding a full amplitude of 0.04 mag. These upper limits for variation in a long observing record are quite remarkable for a CV. Nor did the properties of the superhump, reported below, show much variation at all. High stability was also noted in the earlier study (O'Donoghue et al. 1994, hereafter O94).

After finding no significant change in the nightly means, we decided to assign *V*=13.70 to every night by *fiat*. This simplified the time-series analysis, and is a convenient normalization for displaying our results. Readers interested in absolute calibration should remember, however, that there is a zero-point uncertainty of ~0.05 mag.

The upper frame of Figure 1 displays a sample light curve of HP Lib, with its characteristic 0.06 mag variation. Essentially all nights look alike. The lower frame shows the mean nightly power spectrum, formed by averaging the 28 nights of long coverage (>5 hrs). The dominant signal at 77.2 c/day appears, along with the four lowest harmonics. By examining longer episodes (~5–10 d) with particularly dense coverage, we were able to study these frequencies more closely, and verify that all are exact integer multiples of 77.20±0.02 c/day. This is explored more carefully in the next section.

Another point worth noting is the broad weak feature in the range 280–320 c/d. This was seen on many individual nights, but does not appear any more strongly in the aggregate since the peaks moved from night to night. This quasi-periodic oscillation (QPO) at P~5 min is a real feature in the star, but we have learned nothing about it and will not comment further on it.

3. PERIOD ANALYSIS

During four years (1995, 1998, 2000, 2001), we had coverage sufficient to study fine-structure effects in the power spectrum. One of the better segments occurred in 2001, with coverage from New Zealand (Rea, McCormick, Velthuis) and Arizona (Halpern) in the most critical time window (JD 2452055–2452064). The raw power spectrum in the upper left frame of Figure 2 shows the powerful fundamental signal, and establishes that it is easy to identify and thus reject aliased frequencies. The remaining frames of Figure 2 show the critical regions of this 9-night power spectrum, with significant detections marked by arrows and labeled with their frequencies (to ±0.02 c/day). The power spectrum has been "cleaned" by removing the aliased frequencies. Aside from the obvious main signal and its harmonics, the interesting features are the signals at 78.35 and 155.57 c/day.

An alternate version of the most interesting part of Figure 2 is shown in Figure 3. Here we have cleaned the power spectra for the superhump only, and have included the entire season's data, not just the densest portion of data. This gives a slightly noisier result (mainly because we remove only the mean superhump period, which is slightly variable), but a more accurate estimate of any stable period which may be present in the residuals. The two seasons with good detections yield ω=78.353±0.004 c/day.

Aside from all the obvious resemblances to AM CVn noted by O94, this structure of the power spectrum is yet another analogy. In particular, in the terminology used by Skillman et al. (1999), the orbital frequency ω should be identified as 78.35, and the fundamental superhump frequency $\omega-\Omega$ should be identified as 77.20. The remaining detections occur at $n(\omega-\Omega)$ for n=2–5, and at $2\omega-\Omega$. The waveforms of the two relevant signals are shown in Figure 4. Especially noteworthy is the very low amplitude of the putative orbital signal, a mere 0.0048±0.0005 mag full amplitude. This is the weakest orbital signal ever seen in a cataclysmic variable; indeed, it is about ten times smaller than the typical upper limit for CVs which *lack* orbital modulations in photometry!

The ascription of the 78.35 c/day signal to an orbital origin is indicated by its evidence for stability, the detailed analogy to AM CVn, and the (almost equally detailed) analogy to many superhumpers which show similar $n\omega-m\Omega$ signals. So we will here refer to it as an orbital signal, despite some doubt which must linger as long as compelling evidence for long-term stability is lacking. Additional evidence for or against an orbital origin is highly desirable to obtain.

It was straightforward — though tedious because of the signal's weakness — to obtain timings of the orbital signal during the observations. Table 2 shows all the detections, along with frequency measurements of both signals. The single-season estimate for P_{orb} is 0.0127627(6) d = 1102.70(5) s. Unfortunately the error in P_{orb} is still somewhat too large to permit unambiguous cycle count from year to year; but we give mean timings for orbital minimum light, which should eventually yield a precise ephemeris spanning many years. The most likely precise period is 0.01276282(1) d, with the other viable candidates at 0.01276326 and 0.01276227 d.

4. TRACKING THE SUPERHUMP

Since the superhump signal dominates the light curve, it is easy to extract a mean timing of maximum light for each night's observation. Indeed, with the mean brightness, power spectrum, and waveform essentially nonvariable, this is practically the entire information content from each night! The full set of 165 pulse timings during 1995–2001 is given in Table 3, and reduced to O–C diagrams (relative to a test period of 0.0129511 d) in the yearly panels of Figure 5. The high density of coverage, coupled with the relatively high coherence of the signal, enables us to track the signal continuously during each observing season (without ambiguity in cycle count, except possibly for one or two lonely points at the beginning or end of a few seasons). The slope changes in Figure 5 show that the signal changes period from year to year, from 0.0129501(2) to 0.0129526(3) d. The timescale for changes is in the range 1–3 years. A few wiggles suggest much faster period changes, but these are of quite short duration (~1 month). These characteristics are an excellent match to the long-term timing properties of the famous 1051 s superhump of AM CVn (compare Figure 5 here with Figure 2 of Skillman et al. 1999).

We studied the yearly O–C diagrams to see if there might be a strict period (in the range 1–5 years) which explains these long upward and downward ramps. There were a few candidates, and we show one in the last panel of Figure 5. But since we do not actually know the cycle count between years, we have little real evidence on this point, and do not discuss it further.

5. DISCUSSION

This study fully supports the interpretation of O94 — that HP Lib is an IBWD which appears to be a very good match to AM CVn. Thus we can appeal to the richly detailed studies of that famous star (Ostriker & Hesser 1968; Faulkner, Flannery, & Warner 1972; Smak 1975; Solheim et al. 1984; Patterson et al. 1992; Provencal et al. 1995; Harvey et al. 1998; Skillman et al. 1999). The orbital periods are very short and similar (1102 versus 1028 s), the He I absorption-line spectra are similar, the magnitude history is similar (virtual constancy), and the broad-band colors are very blue and similar ($B–V \sim –0.2$, $U–B \sim –1.2$). The orbital modulations are very weak, both less than 0.012 mag full amplitude. And the detailed properties of the dominant photometric period in the light curve — the superhump — are similar, with virtually constant amplitude and harmonic structure, and complex sideband frequencies (slightly displaced from the exact superhump harmonics, according to $n\omega–m\Omega$ with $m<n$).

There are some differences, too, which emerge from these long time-series studies. HP Lib has a fractional period-excess (of superhump over orbital period) of 0.0148, compared to 0.0219 in AM CVn. HP Lib has much more power in the fundamental (0.045 mag full amplitude, compared to 0.006 mag) and much less power in the harmonics. Eventually it may be possible to use these numbers — which really are stable properties of the two stars, not merely accidents of the observing window — to infer details about the structure of the underlying accretion disks. At present we confine ourselves to just one property, the value of the fractional period-excess ε.

The origin of superhumps is now known to be in the apsidal precession of the accretion disk in binaries of extreme mass ratio (Whitehurst 1988, Hirose & Osaki 1990, Lubow 1991). The displacement of the superhump period P_{sh} from the orbital period P_{orb} reveals the precession period P_{prec} through

$$(P_{prec})^{-1} = (P_{orb})^{-1} – (P_{sh})^{-1},$$

or equivalently

$$P_{prec} = P_{sh} / \varepsilon.$$

Since ε and P_{sh} can be very accurately measured, this yields a firm value for P_{prec}, namely 0.875±0.016 d. This should be directly, though not necessarily easily, measurable as a period in the star's absorption-line profiles (Patterson, Halpern, & Shambrook 1993).

Since precession arises from a perturbation on the disk from the orbiting secondary, the precession rate reveals the size of the perturbation and thus the underlying mass ratio of the binary. The problem arises in *calibrating* this relation. A recent calibration suggests $\varepsilon=0.216\pm0.018\ q$ (Patterson 2001, 1998), though Murray (2000) rejects this and gives an alternative discussion. Adopting this relation, we estimate $q=0.068\pm0.007$.

There are now 5 AM CVn stars with precise measures of P_{orb} and P_{sh}; this is sufficient to teach us something about superhumps (definitely), and something about helium secondaries (maybe). On the former, the lesson is simple: that *the helium binaries participate in roughly the same type of superhump behavior as their H-rich cousins*, with similar amplitudes, waveforms, and correlations with high/low states. This is fairly well evinced by the detailed studies of individual stars, especially the helium dwarf novae (CR Boo, V803 Cen, CP Eri; references in Table 4).

Now let us see what can be learned about the helium secondaries. Kepler's third law in

Roche geometry constrains the secondary to obey a period-density relation

$$P_{\rm orb}\,[\rm hr] = 8.75\,(M_2 / R_2^{3})^{-1/2},$$

with M_2 and R_2 in solar units. A cold low-mass white dwarf should approximately obey Chandrasekhar's (1939) relation

$$R_{\rm ch} = 0.0126\,(1 + X)^{5/3}\,M_2^{-1/3},$$

with X=0 here since the helium spectrum attests to a nearly pure helium composition. Coulomb corrections are important for secondaries of very low mass, so we use instead the models of Zapolsky & Salpeter (1969). Interpolation in their tables gives a power-law relation, accurate to 4% over the range 0.01–0.30 $M_\odot$:

$$R_{\rm ZS} = 0.0155\,M_2^{-0.212},$$

still in solar units. We adopt $R_2=\alpha R_{\rm ZS}$ to allow for the possibility that the secondary may be slightly larger (since the degeneracy is not extremely high in these low-mass white dwarfs). Arithmetic then yields

$$M_2 = (0.0069 / P_{\rm orb}^{1.22})\,\alpha^{1.83}, \quad (1)$$

which for α=1 implies M_2=0.029 in HP Lib. The superhump $\varepsilon(q)$ relation then suggests M_1=0.43±0.07 in HP Lib. More generally, we expect the AM CVn stars to lie along a locus in ε–$P_{\rm orb}$ space given by

$$\varepsilon = 0.216\,q = 1.5(2) \times 10^{-3}\,P_{\rm orb}^{-1.22}\,\alpha^{1.83}\,(M_1/0.7)^{-1.0}, \quad (2)$$

with the error set by the uncertainty in $\varepsilon(q)$. [The actual scatter in $\varepsilon(P_{\rm orb})$ will be greater, owing to the inevitable dispersion in M_1.]

How well does this prediction compare to the observational data? This is shown in Figure 6, an empirical plot of ε versus $P_{\rm orb}$. The H-rich stars are the cluster at right, discussed in detail previously (Patterson 1998, 2001). Helium CVs are the family at lower left, with the stars' individual properties given in Table 4. The line at lower left shows the predicted locus for cold white-dwarf secondaries (Eq. 2 with α=1). The upper envelope defines the locus for slightly larger secondaries, in particular the "semidegenerate" helium stars calculated by Savonije et al. (1986), assuming that mass loss is rapid enough to drive the secondaries out of thermal equilibrium. The latter stars correspond approximately to α=1.5.

Also listed in Table 4, and appearing in Figure 6 as open circles, are the two helium CVs which do not show superhumps. They do, however, have limits on q available from spectroscopy. Thus we have a reasonable constraint on q for all seven stars. Inspection of Table 4 and Figure 6 shows that *q appears to decline with increasing P_{orb}*.

That is extremely interesting, because declining q almost surely means declining M_2 (any increases in M_1 can be neglected once M_2 has shrunk to these low values). *And the arrow of declining M_2 must be the arrow of evolution*, because CVs must always evolve in the direction of decreasing M_2. The earliest theoretical studies of helium CVs (Paczynski 1967; Faulkner, Flannery, & Warner 1972) suggested this — that the binaries probably evolve towards longer P_{orb} — but it has been a long wait to find some actual evidence of this.

6. SUMMARY

1. Our main goal was to secure a detailed record of the rapid variability in HP Lib. The 1119 s signal is a very good match to the famous 1051 s superhump of AM CVn, which is now fairly well-understood as the result of apsidal precession of the accretion disk in an IBWD. Like AM CVn, the HP Lib superhump keeps perfect time from night to night, but the period wanders slightly on a timescale of a few months to a few years. The period ranges from 1118.89 to 1119.14 s with $Q = 1 / |\dot{P}| \sim 10^8$. The changes illustrated by Figure 5 seem to be erratic, although this can be usefully tested by future timings over long baselines. The amplitude and waveform of the signal are remarkably constant.

2. Episodes of dense photometric coverage reveal a weak signal at a period slightly shorter than that of the dominant superhump. The best estimate is P=1102.70±0.05 s, with a full amplitude of 0.0047±0.0005 mag. This is consistent with interpretation as the orbital period. The corresponding detection at 1028.733 s in AM CVn is *certifiable* as P_{orb}, because it is demonstrably phase-stable over a timescale of years, and consistent with a periodic motion in the He I emission lines (Harvey et al. 1998; Skillman et al. 1999; Nelemans, Steeghs, & Groot 2001). A similar proof is desirable for HP Lib, but will require similar evidence from additional photometry or spectroscopy. Times of minimum light from Table 2 should eventually supply a period of ephemeris quality.

3. The superhump has ε=0.0148±0.0002, which implies an accretion-disk precession period of 0.875±0.016 d. This period might be directly detected in a study of the absorption-line profiles over a baseline of a few days. A recent ε(q) calibration suggests q=0.07±0.01, or M_2~0.05 $M_\odot$ if the accreting star is a garden-variety white dwarf with M_1~0.7 $M_\odot$. Alternatively, enforcement of the M–R relation appropriate to cold white dwarfs implies M_2=0.041(4) $M_\odot$, M_1=0.60(8) $M_\odot$.

4. There are now 5 AM CVn stars with measured values of superhump period excess. These show a trend of lower ε with longer P_{orb}, happily consistent with the idea that IBWDs really do evolve towards longer period.

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TABLE 1
SUMMARY OF HP LIB OBSERVATIONS, 1995–2001

Telescope	Observer	Nights/hours
CBA–Tucson 0.35m	Harvey	27/139
CBA–Braeside 0.41m	Fried	22/120
MDM 1.3m	Kemp/Halpern	35/106
CBA–Nelson 0.35m	Rea	16/102
CBA–Maryland 0.63m	Skillman	16/55
CTIO 1.0m	Patterson/Kemp	22/54
CBA–Pakuranga 0.35m	McCormick/Velthuis	8/42
CBA–Townsville 0.3m	Butterworth	8/31
SAAO 1.0m/0.75m	O'Donoghue/Patterson	10/27
CBA–Illinois 0.2m	Gunn	4/14
CBA–Awanui 0.25m	Walker	5/12
Wise 1.0m	Retter/Lipkin	5/12
CBA–Concord 0.44m	Cook	3/9
CBA–Belgium 0.24m	Vanmunster	2/6
CBA–Blenheim 0.25m	Allen	1/6
CBA–Adelaide 0.35m	McGee	2/5
CBA–Connecticut 0.2m	Hannon	1/3
CBA–Moscow 0.6m	Shugarov	1/3

TABLE 2
FREQUENCIES AND EPOCHS IN HP LIB

Year	Frequencies (c/day) Superhump	Orbital	Orbital Minimum (HJD, ±0.0007)
1995	77.214(1)		
1996	77.213(1)		
1997	77.208(1)		
1998	77.2165(8)	78.354(4)	2450906.4217
1998	[JD 906–916 segment]		2450906.4218
1998	[JD 920–927 segment]		2450920.4342
1998	[JD 937–942 segment]		2450937.3328
1998	[JD 951–966 segment]		2450951.6914
1999	77.220(2)		(2451328.8233)
2000	77.216(2)	78.350(10)	2451684.7630
2001	77.205(1)	78.349(9)	2452055.9693

NOTE. The superhump is unstable, so a seasonal epoch is meaningless. The nightly epochs are given in Table 3. The 1999 orbital timing is uncertain. We measured 4 independent timings in 1998, which may help in long-term cycle counts.

TABLE 3
TIMES OF 1119 S MAXIMUM LIGHT

(HJD 2400000+)					
49860.6413	50221.8145	50873.2407	50942.7085	51331.6488	51697.9003
49861.6512	50232.7582	50874.1861	50947.8758	51332.6459	51698.7543
49862.6617	50273.6320	50880.8554	50949.9217	51334.6664	51699.6744
49863.6584	50274.6419	50892.0191	50951.6956	51335.8576	51700.6597
49864.7077	50275.6263	50896.9143	50952.7191	51355.5807	51702.7309
49867.6689	50279.6809	50906.4206	50952.9006	51359.6724	51705.6829
49886.5174	50303.4993	50907.3788	50955.6718	51361.6672	51705.7476
49887.4755	50312.5021	50907.9873	50956.7211	51396.6337	51706.8099
49888.4727	50467.8422	50908.3502	50957.7181	51427.6091	51719.5786
49889.4829	50534.8306	50908.8162	50958.7154	51622.9459	51935.0239
49890.4799	50541.7612	50909.3860	50961.7070	51650.9159	52010.6673
49891.4772	50564.7396	50909.7354	50962.6007	51657.9476	52043.0858
49893.4721	50568.7289	50909.8005	50966.6152	51675.6758	52044.0706
49896.5285	50570.7240	50910.3573	50976.2625	51680.9856	52045.0682
49904.5194	50592.6113	50910.7587	50982.6598	51681.9699	52046.0656
49905.4779	50594.6971	50910.7717	50987.6585	51684.7676	52055.9621
49907.4855	50608.6843	50911.8207	51029.9042	51684.8971	52056.9591
49908.4831	50616.5711	50912.7922	51032.5458	51687.9277	52057.9697
49925.6559	50619.6927	50913.9704	51041.8055	51688.8474	52058.9671
50134.8851	50622.6713	50914.7996	51061.8667	51689.8330	52059.9773
50135.8827	50623.6427	50915.7192	51220.0077	51690.9582	52060.9748
50136.8798	50625.6881	50916.7424	51252.9155	51691.8907	52062.9564
50195.8348	50626.6862	50920.4333	51266.9148	51692.8626	52063.8766
50196.8061	50628.6806	50937.3342	51305.3608	51692.9009	52063.9547
50208.6952	50630.6623	50938.7718	51320.8358	51696.6695	52066.9718
50209.7439	50866.9593	50939.8336	51328.8260	51697.7189	

NOTE. The typical error for timing maximum light is ±0.0004 d.

TABLE 4
ORBITAL AND SUPERHUMP PERIODS IN AM CVN STARS

Star	V	P_{orb} (s)	P_{sh} (s)	ε	q	References
AM CVn	14.2	1028.7332(2)	1051.2(2)	0.0218(2)	0.101(8)	1, 2
HP Lib	13.7	1102.70(6)	1119.0(1)	0.0148(2)	0.068(6)	3, 4
CR Boo	13–17	1471.3(3)	1487(3)	0.011(2)	0.051(9)	5, 6
V803 Cen	13–17	1612.0(5)	1618.3(8)	0.0041(8)	0.019(5)	7, 8, 9
CP Eri	15–18	1701.2(3)	1715.9(9)	0.0087(4)	0.040(5)	8, 10
GP Com	16.5	2794.05(20)	none		0.02*	11, 12
CE–315	17.5	3906(42)	none		0.02*	13

* These mass ratios were estimated from spectroscopy (small radial–velocity wiggles in emission lines). The others were estimated from the empical ε(q) relation.

REFERENCES. (1) Skillman et al. 1999; (2) Provencal et al. 1995; (3) O94; (4) This paper; (5) Patterson et al. 1997; (6) Provencal et al. 1997; (7) O'Donoghue et al. 1990; (8) Patterson 2001; (9) Patterson et al. 2000; (10) Abbott et al. 1993; (11) Nather, Robinson, & Stover 1981; (12) Marsh 1999; (13) Ruiz et al. 2001.

FIGURE CAPTIONS

FIGURE 1. — *Upper frame*, light curve of HP Lib in *V* light on 9 May 1998. *Lower frame*, mean nightly power spectrum, formed by averaging the 28 nights with long (>5 hr) time series. Significant features are marked with their frequencies in c/day (±0.5). A "QPO" is also evident as the broad excess of power near 300 c/day.

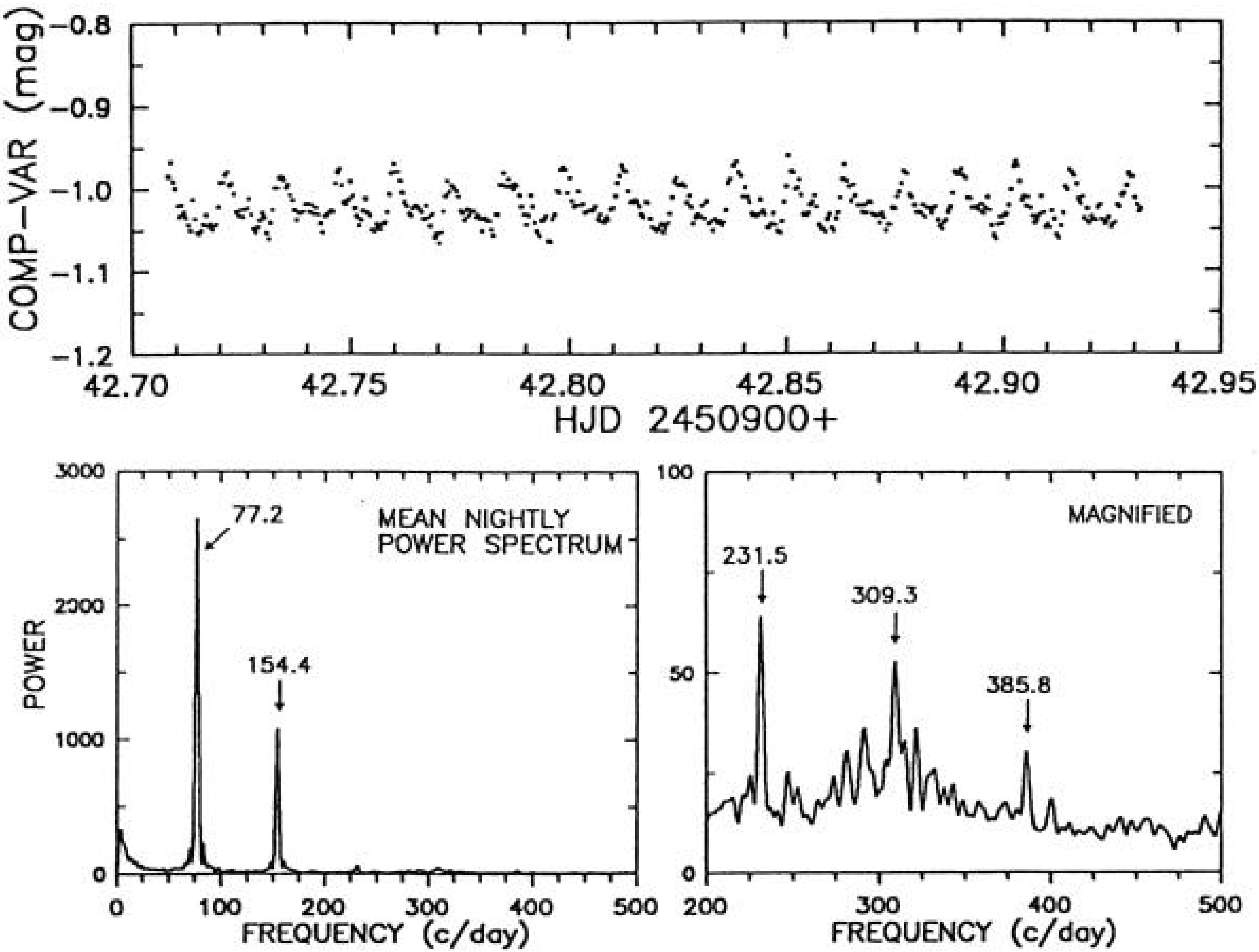
FIGURE 2. — Power spectrum of HP Lib during JD 2452055–2452064, with significant features marked with their frequencies in c/day (±0.02). The upper left frame shows the powerful fundamental, and establishes that the coverage in terrestrial longitude is sufficient to identify and thus reject aliases. The remaining frames show the "cleaned" power spectrum, with aliases removed. The strong peaks at 77.20 and 154.41 rise to a power of 680 and 260, and correspond respectively to a full amplitude of 0.044 and 0.026 mag. The weak features with a power near 10 correspond to a full amplitude near 0.004 mag.

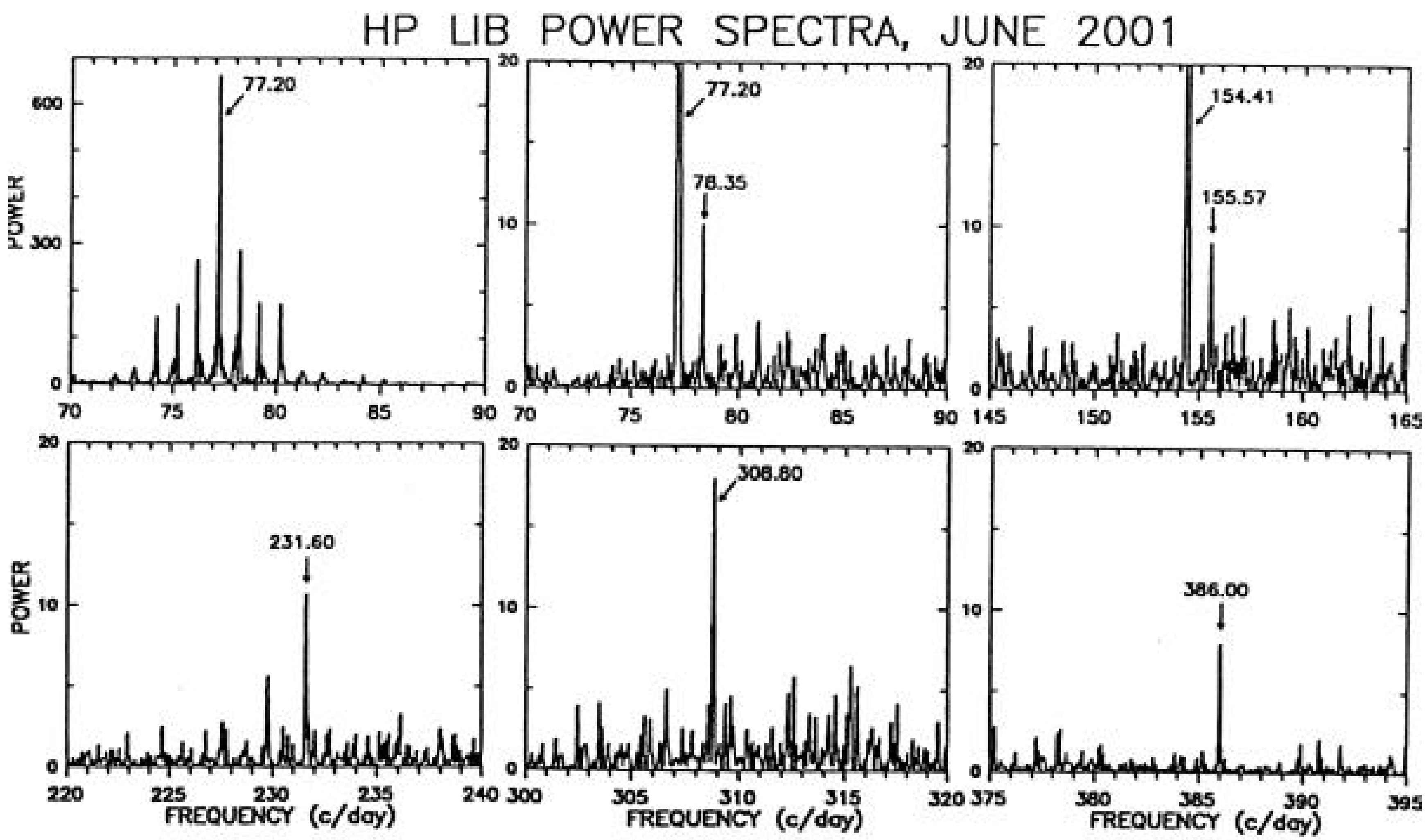
FIGURE 3. — Power spectra for the entire 1998 and 2001 observing seasons, suggesting a stable signal with ω=78.353(4) c/day. Here we have cleaned for the mean 77.20 c/day superhump only, preserving the noise and alias structure so the reader may judge the significance.

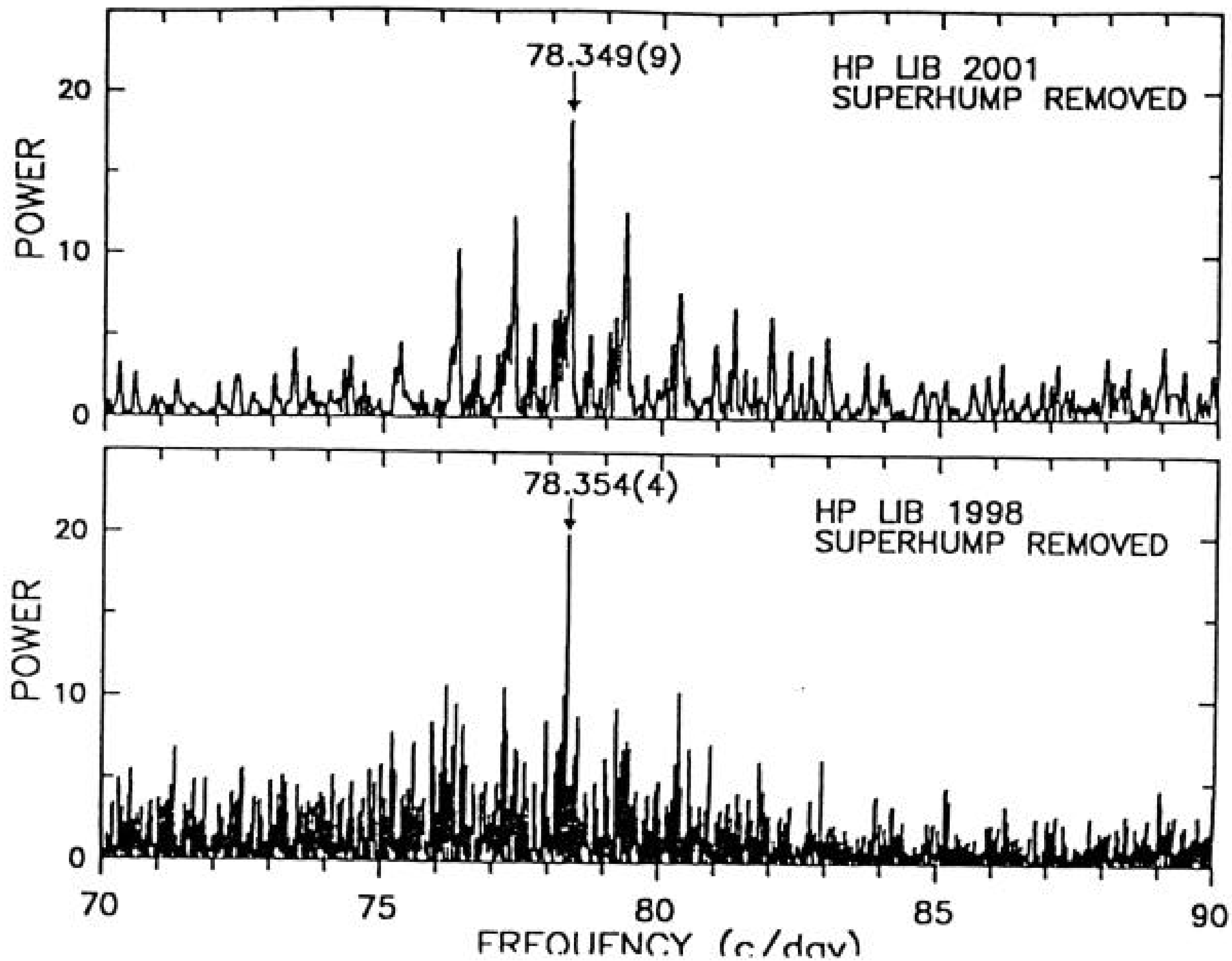
FIGURE 4. — Mean light curves of the superhump (ω–Ω) and putative orbital (ω) signals in 1998 and 2001.

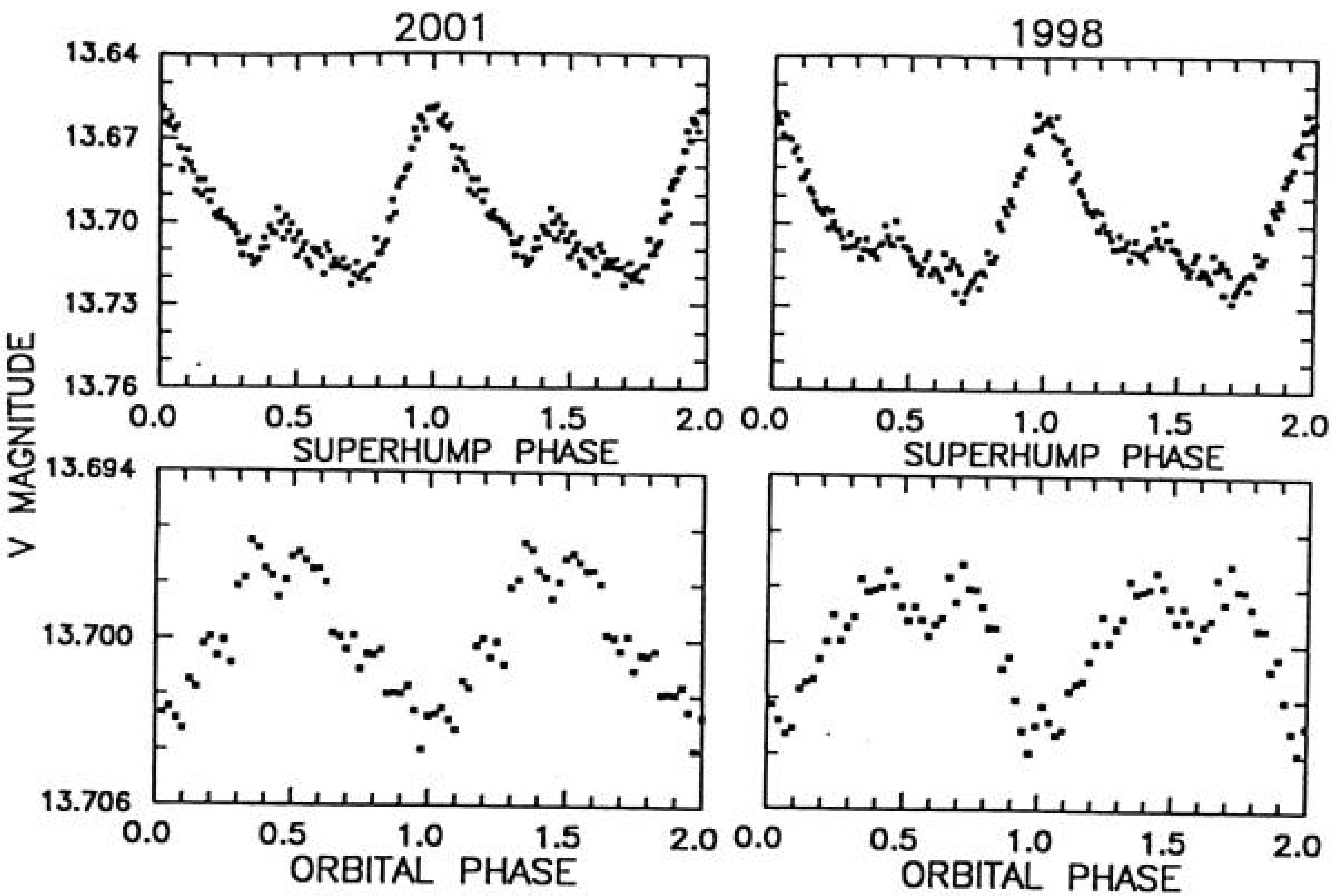
FIGURE 5. — The yearly O–C diagrams show the superhump's departure from a test period of 0.0129511 d. The first timing of each year is taken as the epoch for that year, though occasionally assigned O–C=+1 or –1 as needed for illustration. The cycle count is essentially well-determined during each year. The changes in slope show the obvious period changes. However, the changes are sufficiently large that the cycle count between years is not securely known. One possible choice for the complete 7-year cycle count is given in the last frame.

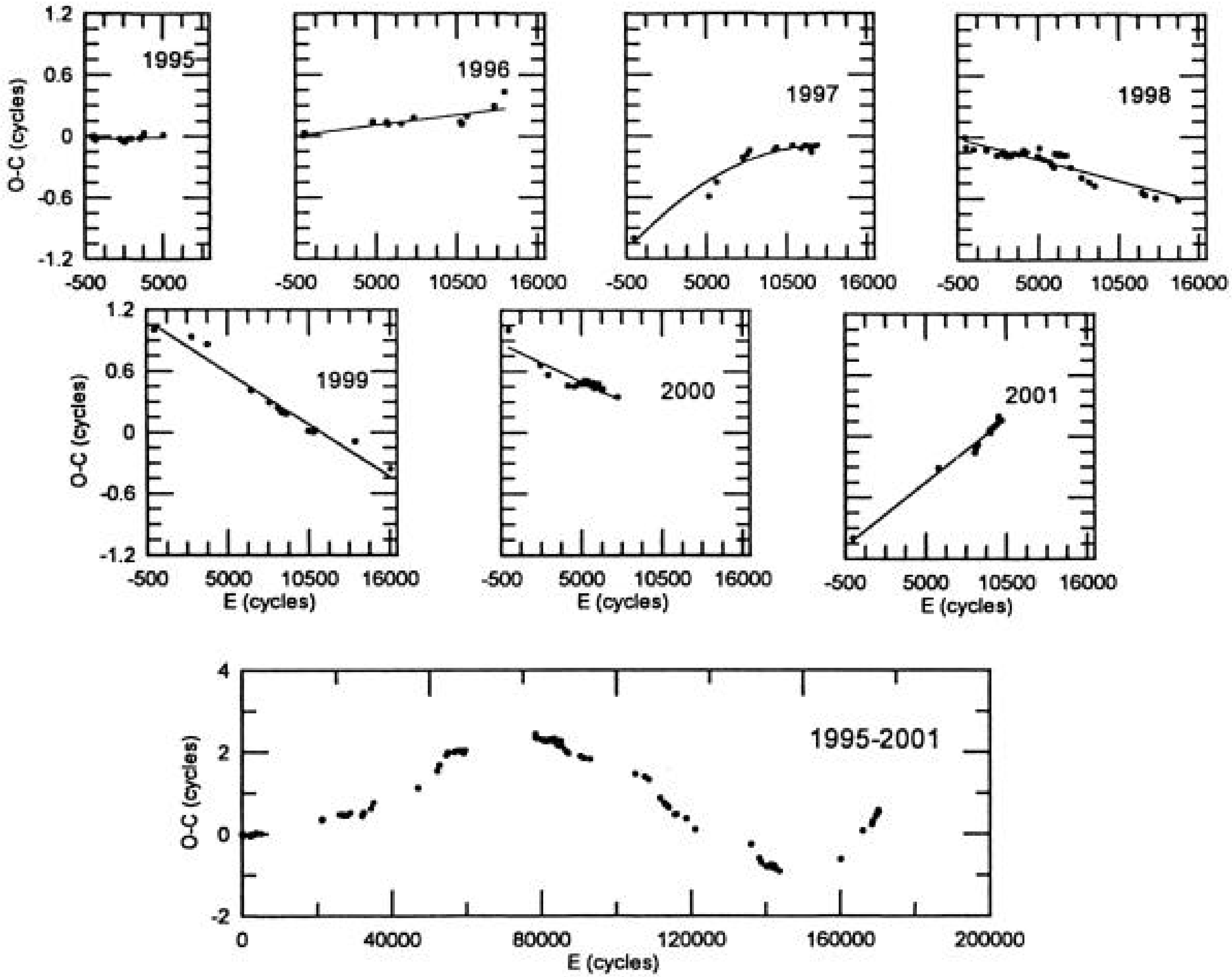
FIGURE 6. — ε versus $P_{\rm orb}$ for CVs with positive (apsidal) superhumps. H-rich CVs, mainly dwarf novae, are the family at upper right; the curve through these points is the evolutionary model favored in a previous discussion ("enhanced" GR, Patterson 2001). He-rich CVs are the family at lower left; the line is the predicted locus (Eq. 2 with α=1) if the secondaries are cold white dwarfs and M_1=0.7 $M_\odot$.

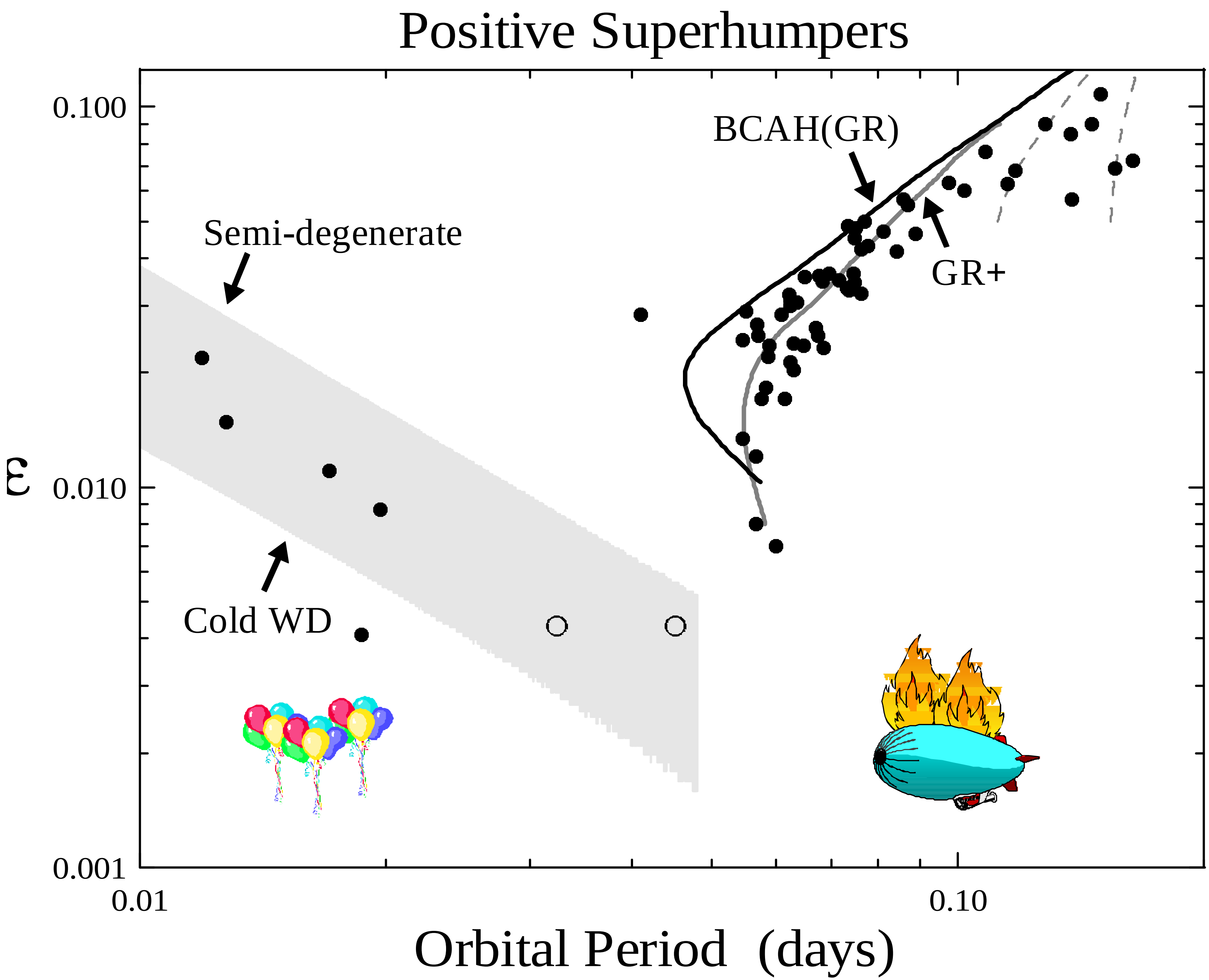

COMP−VAR (mag)
−0.8
−0.9
−1.0
−1.1
−1.2
42.70
42.75
42.80
42.85
42.90
42.95
HJD 2450900+
POWER
3000
2000
1000
0
77.2
154.4
MEAN NIGHTLY
POWER SPECTRUM
100
200
300
400
500
FREQUENCY (c/day)
MAGNIFIED
231.5
309.3
385.8
50
FREQUENCY (c/day)


HP LIB POWER SPECTRA, JUNE 2001
POWER
FREQUENCY (c/day)
77.20
78.35
154.41
155.57
231.60
308.80
386.00


78.349(9)
HP LIB 2001
SUPERHUMP REMOVED
POWER
20
10
0
78.354(4)
HP LIB 1998
SUPERHUMP REMOVED
POWER
20
10
0
70
75
80
85
90
FREQUENCY (c/day)


2001
1998
V MAGNITUDE
13.64
13.67
13.70
13.73
13.76
0.0
0.5
1.0
1.5
2.0
SUPERHUMP PHASE
13.694
13.700
13.706
ORBITAL PHASE


1995
1996
1997
1998
1999
2000
2001
1995-2001
O-C (cycles)
E (cycles)
1.2
0.6
0
-0.6
-1.2
-500
5000
10500
16000
4
2
-2
40000
80000
120000
160000
200000


Positive Superhumpers
ε
0.100
0.010
0.001
0.01
0.10
Orbital Period (days)
Semi-degenerate
Cold WD
BCAH(GR)
GR+