V803 CENTAURI, A HELIUM-RICH DWARF NOVA

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ABSTRACT

We report 1992–1999 photometry of the helium-rich cataclysmic variable V803 Centauri. In its high-brightness state at V=13, the star shows a strong periodic signal with P=1618 s; this resembles the superhumps associated with many dwarf novae. However, it is unusual because the superhump appears to endure through all brightness states, including the very faint state at V=17. The star also becomes occasionally stuck in a "cycling state", in which the brightness varies in the range 13.4–14.5, with a period of 22±1 hr. This appears to be the recurrence pattern of "normal" dwarf-nova outbursts. Thus the underlying physics is probably that of a dwarf nova, but with an accretion disk dominated by helium.

Reckoned as a dwarf nova, V803 Cen presents an interesting test for accretion disk theory, because it appears to display two timescales for eruption recurrence: 0.94 d at V=14.5, and ~5 d at V=17.2. This is roughly consistent with the general idea that recurrence time scales inversely with accretion rate.

Subject headings: accretion, accretion disks — binaries: close — novae, cataclysmic variables — stars: individual (V803 Centauri)

1. INTRODUCTION

The pioneering studies by Smak (1967) and Faulkner, Flannery, & Warner (1972) established that some cataclysmic variables (CVs) consist predominantly not of hydrogen but of helium. This class, the AM Canum Venaticorum stars, contains six members, reviewed by O'Donoghue et al. (1994) and Warner (1995). None of the stars do an excellent job of emulating the prototypes of the various subclasses of hydrogen-rich CVs. Thus we still do not securely know whether these stars are simple analogues of H-rich CVs, or are dominated by somewhat different physics. The question is of some importance, since many exotic phenomena (type I supernovae, production of DB white dwarfs, strong gravitational wave emission) have been ascribed to these stars of very short orbital period (17 to 46 min).

We have carried out studies to test how thoroughly these stars can be interpreted as binaries powered by the same accretion physics as their H-rich cousins. In particular, we wondered why none of these stars were dwarf novae, the most common type of CV. A campaign on CR Bootis (Patterson et al. 1997, hereafter P97) revealed that the star's rapid variability became frequently cyclic with a quasiperiod of 19 hours. The star's characteristics agreed well with the hypothesis that this was simply the cycle time of a dwarf nova. During 1997 and 1999 we conducted similar campaigns on another AM CVn star, V803 Centauri, discovered by Elvius (1975) and known to be a rapid helium-dominated variable with a characteristic photometric period of 1611 s (O'Donoghue & Kilkenny 1989, hereafter OK). Here we report the results.

2. OBSERVATIONS

We obtained ~400 hr of photometric coverage, with the 1.0 m and 0.9 m telescopes of Cerro Tololo Inter-American Observatory, the 0.75 m telescope of South African Astronomical Observatory, and several telescopes of the Center for Backyard Astrophysics. This spanned 122 nights during 1992-1999. A detailed presentation is deferred to a later paper. To this was added 597 visual magnitude estimates (over ~400 nights) accumulated by R.S. during 1995–1999. Roughly speaking, the star was found to be in one of three brightness states:

(1) a "high state" in which the star lingered around V=12.7–13.3 for 3–12 days;
(2) a "low state" in which the star lingered near V=17 for at least 10–30 days; and
(3) a "cycling state" in which the star varied rapidly between intermediate brightness levels (typically V=13.4–14.5).

Over the 5 years well covered, the star appeared to be in the cycling state at least 50% of the time, while spending <10% of the time in very high and very low states. The earlier OK observations show that there is also a moderately high state (V~13.6) in which no pronounced cycling variations occur.

The high states are not always easy to identify, because they are fairly short (~5 d), and because the cycling timescale we report below (~1 d) creates severe problems with aliasing. Nevertheless, we found six certain or very likely high states, with the dates (JD 50431, 50511, 51271, 51349, 51433, 51544) suggesting a recurrence time of ~85 days. In dwarf-nova terminology, this would be called the “superoutburst period”.

Below we describe the star's light curve in each of these brightness states.

2.1 The High State

Our observations may have caught the star in as many as 4 high-state episodes, but long time series were obtained in only one. The upper frame of Figure 1 shows the 8-hour light curve obtained on 3 April 1992, and the lower frame shows the power spectrum, indicating a strong signal near 53.3 c/d (*P*~1620 s) and several higher harmonics. Inset is the mean light curve at the fundamental, showing a 0.049 mag full (peak-to-trough) amplitude. The star’s brightness (*B*=12.95) and strength of the fundamental signal exceeded anything seen on other nights; this suggested to us that this was near maximum of a superoutburst, with the waves describable as “superhumps” (reviewed by Warner 1985, and chapter 3.6 of Warner 1995).

There is also an apparently unrelated (noncommensurate) signal at 491.8 c/d.

A second night of photometry was obtained during this high state, three days later. This gap is too long for a secure cycle count, but the best-fit frequency was 53.36±0.03 c/d, with possible alternatives at 53.03 and 53.68.

2.2 The Low State

V803 Centauri occasionally drops into low states at 17th magnitude. This occurred during the Whole Earth Telescope observation of 1988, when O'Donoghue et al. (1990) identified a periodic signal with *P*=1609±8 s. It also occurred during our observation of May 1999, when we carried out observations from SAAO and CTIO. Figure 2 shows long light curves from this observation, with fast (~1600 s) waves and two eruptive episodes, each of ~1 day duration.

Figure 3 shows an amplitude spectrum of the first 5 days of this coverage, during which the star remained steadily near magnitude 17. A significant signal was detected at 53.60±0.02 c/d (1612±1 s). Figure 2 shows that the signal ebbs to invisibility during the eruptive episodes (“outbursts”), and then is somewhat restored thereafter. Reckoned in intensity units, the signal amplitudes are consistent with approximately steady decline during the 12 days of observation.

The two outbursts suggest a recurrence time of ~5 d. The rise and decay times, and the disappearance of periodic signals and flickering, are consistent with the eruptions seen during the cycling state (see below). They are also consistent with the general behavior of dwarf novae in eruption.

2.3 The “Cycling State” of April 1997

During April 1997, we maintained a worldwide vigil, with coverage from SAAO, CTIO, and CBA-Awanui. The spliced light curve during 2–17 April, seen in Figure 4, shows the main feature: long waves that repeat on a timescale of 0.97±0.02 days. Despite how close the period is to 1 day, the signal is unambiguously identified, because of the multi-longitude coverage[1].

Although the time series of Figure 4 is extremely regular, this appears to be an accident of the observation dates. The extensive visual and CBA-Awanui (CCD) coverage showed that a "superoutburst" began on JD 511 and lasted until JD 516, after which the star varied rapidly until about JD 584–9 (when another superoutburst probably occurred). These variations are somewhat unstable in period, amplitude, and mean brightness. The "round-the-world" time series of Figure 4 is basically a window on a particular photometric state, the *cycling* state, of V803 Cen.

We also searched for the 1600 s signals. In the cycling state, they are ubiquitous but of low amplitude. Near maximum light at *B*=13.4, they fade to ~0.008 mag full amplitude; at minimum at *B*=14.5, they are typically ~0.02 mag full amplitude. Thus they roughly maintain equal amplitude in flux units as the star executes its cycles. The mean nightly power spectrum is shown in Figure 5. Significant features are marked with their frequencies, each with an error of 0.4 c/d. The star shows a dominant signal at 52.5 c/d, six signals near the harmonics, and a noncommensurate signal at 491.4 c/d. It should be noted, though, that the six "harmonics" fall only *roughly* at integer multiples of the fundamental. Also, the 491.4 c/d signal was actually found on only one night (April 3, when it appeared at great strength), unlike the other signals which were more or less regular features of the light curve.

To clarify these matters further, we studied the coherent power spectrum over the full 14-night observation. But the results were very complex, due in part to the signal's poor underlying stability; so we largely defer this discussion to a later paper.

After 17 April, we maintained coverage for 55 more days, primarily with the CBA-Awanui telescope. Variations continued with similar brightness and amplitude; timings of maxima and minima are reported in Table 2. Coupled with the accuracy of the period derived from the multi-longitude studies, this data enabled us to keep continuous cycle count, and thus enabled us to represent the timings with the O–C diagram of Figure 6[2]. The average cycle time over this entire interval was 0.94 d.

3. THE 1600 S VARIATIONS

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[1] The point is worth stressing. Period-finding campaigns from a single site are greatly bedeviled by small systematic effects near 1, 2, or 3 c/d, and 1 c/(observation length). These usually arise from uncorrected differential atmospheric extinction, and harmonics of signals belonging at lower frequency (almost always "noise" signals, since CVs flicker most strongly at low frequency). These problems are greatly mitigated with coverage distributed around the Earth.

[2] Actually there are three intervals (*E*=5–12, 34–41, 53–56) where one cycle may have slipped. However, the polynomial fit to the timings in Figure 7 gave the least residuals (0.05 cycles) of any candidate cycle count, and the mean period obtained from that count agrees with the mean period obtained from the three episodes of certain cycle count. So the cycle count used in preparing Figure 7 is likely to be correct.

OK first reported a photometric signal near 1610 s, later refined by O'Donoghue et al. (1990) to 1611±8 s during an observational campaign carried out in the low state (*V*=17.3). This short-period signal, along with the helium-dominated spectrum, gave the evidence for classification as an AM CVn star.

The observations reported here are consistent with the OK results and interpretation, but extend our knowledge of the 1600 s signal(s). In intensity units, the full amplitude of the detected signal is: 107 at *B*=12.95 (high); 12 at *B*=13.4 (cycling); 12 at *B*=14.5 (cycling); 5.2 at *V*=17.1 (low); 1.8 at *V*=17.2 (low and a week later). Thus the signal is generally associated with the high state, as is always found among the superhumps of SU UMa-type dwarf novae. On these grounds and others (instability in period, high harmonic content), we identify it as a superhump. But, contrary to conventional wisdom about these stars, the signal also exists in quiescence, as well as throughout the intermediate state in which the star rapidly cycles.

A speculation which can cover all the observed behavior is the following. The star has superoutbursts every 85 d, and then excites strong superhumps, like those of Figure 1. These fade in just a few days, followed by a slower fading over (say) 30–60 days. But the accretion light fades on a different timescale (generally faster, with rapid variations superimposed). Thus the superhump remains visible for many weeks after superoutburst, and keeps an approximately constant amplitude in intensity units as the star cycles rapidly. In our coverage, the superhump never disappears, remaining prominent for at least 80 d (4000 binary orbits). But the steadily declining flux in the superhump suggests that re-excitation does not actually occur until the next superoutburst.

An essentially identical pattern appears to hold for CR Bootis. Figure 9 of Patterson et al. (1997) tracks its superhump for at least 4000 binary orbits after the onset of a long outburst. In that case it was even possible to follow the phase continuously over those 4000 orbits. The superhump of V803 Cen is probably a factor >5 less stable, since we had difficulty tracking the phase over even fairly brief gaps in the observational record.

4. IDENTIFICATION OF V803 CEN AS A DWARF NOVA

Records of visual variable-star observers show that V803 Cen is usually in the magnitude range *V*=13.5–15.0. Our observations agree with this: about 70% of our nights are in this range. But these observations also demonstrate that *when the star is in this magnitude range, it often cycles rapidly (timescale of 0.9–1.0 d) from bright to faint*, as seen most vividly in Figure 4. Flickering and short-period variations tend to disappear near the maxima of these waves. The star declines from these maxima at a rate of 5.0 mag/d (0.21 mag/hr), and rises slightly faster.

A plausible hypothesis is that these are simply normal dwarf-nova outbursts (in contrast to the superoutbursts, which are longer, brighter, and featuring powerful superhumps). A simple taxonomic test of this hypothesis can be constructed from two empirical rules for dwarf novae: the period–amplitude relation (Kukarkin & Parenago 1934, recently updated by Warner 1995), and the "Bailey relation" linking decay time from normal eruption to P_{orb} (Bailey 1975, also recently updated by Warner 1987). These correlations are shown in the two frames of Figure 7.

Adopting P_{orb}~P_{sh}=1612 s, A=1.1 mag, T_0=0.94 d, and T_{decay}=0.2 d/mag, we place V803 Cen along with the other helium star, CR Bootis, as the open circles at lower left. Clearly the two helium stars satisfy both relations very well.

A more detailed version of this argument was given earlier for CR Bootis (Patterson et al. 1997), comparing the observed slope of the Bailey relation ($T_{decay} \propto P^{0.82 \pm 0.05}$) with the slope expected from the hypothesis that the decay time represents the travel time of the cooling front across the accretion disk ($T_{decay} \propto P^{0.79}$). Thus the test is astrophysical as well as taxonomic.

We conclude that both stars are indeed *bona fide* dwarf novae, with at least their 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 too should show thermal instabilities, due to the partial ionization of helium at T_e~15000 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 V803 Cen and 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, in agreement with this and addressing the issue of instability, have been calculated by Simpson & Wood (1998) and Tsugawa & Osaki (1997).

5. A PLACE IN THE FAMILY

Reclassification of V803 Cen and CR Boo raises some issues of nomenclature. In dwarf novae, "high state" and "low state" are often used as synonyms for the slightly more precise "eruption" and "quiescence". But the most prominent feature of both stars is really the "cycling state" in which the star never closely approaches its true low or high brightness levels. And for both stars there are demonstrated long episodes of fairly steady light, which can be at a somewhat high level (P97, OK, Wood et al. 1987) or very low level (Provencal et al. 1997, O'Donoghue et al. 1990, this paper). That's the most striking feature of all: that the stars move from rapidly cycling states to steadier light which can be fairly high or very low.

This is unusual for dwarf novae. In the thermal-instability model, it suggests that the accretion rate inflicted on the disk by the secondary may vary by a factor of ~10, perhaps even sufficient to transport the disk from being "too cool to erupt" (cool disks are not completely spared the instability, but require a very long time) to a high-$\dot{M}$ state in which the thermal instability is suppressed. We really don't know any hydrogen-rich dwarf novae in which we can document such fickle interest in eruptions. At the high-$\dot{M}$ end, there's a resemblance to Z Cam stars, which flirt between rapid cycling and semipermanent outburst. And at the low-$\dot{M}$ end, some analogy could be made to VY Aquarii and HT Cassiopeiae, which at various times suggest recurrence periods as short as 2 yr, and as long as 20 yr (Patterson et al. 1993, Robertson & Honeycutt 1996). But no hydrogen-rich dwarf nova certifiably does *both* of these things. How wonderful it is that the first solidly identified helium dwarf novae should partake so freely of such a wide range of dwarf-nova behavior! In a flight of wild optimism, we even hope that it may slightly slow the headlong rush towards the Balkanization of dwarf novae.

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TABLE 1
LOG OF OBSERVATIONS

Telescope	Nights	Years	Hours
CTIO 1 m	8	1992–1995	35
CTIO 0.9 m	22	1997–1999	100
SAAO 0.75 m	17	1997–1999	100
CBA–Awanui 0.25 m	70	1997–1999	200
CBA–Otahuhu 0.32 m	8	1998	50
Stubbings 0.32 m	~400	1995–1999	—

TABLE 2
TIMES OF (NORMAL) ERUPTION

Maxima (JD 2,450,000+)			
523.94	544.78	555.62	576.95
524.91	545.92	564.14	577.80
527.78	547.85	565.16	581.45
536.33	548.67	566.10	583.05
537.13	549.66	566.92	585.72
538.06	550.68	567.80	587.50
539.05	551.64	570.30	588.50
541.84	552.60	571.20	589.50
543.80	553.73	572.10	

FIGURE CAPTIONS

FIGURE 1. — *Upper frame*, light curve of V803 Cen in *B* light on 3 April 1992, at 20 s/point. *Lower frame*, power spectrum of this light curve, with significant features marked with their frequency in c/d (errors are all ±0.5 c/d). Inset is the mean light curve folded at the dominant 53.3 c/d frequency.

FIGURE 2. — Long light curves during the low state of May 1999. Absolute calibration is uncertain by ±0.2 mag, but night-to-night uncertainty is no worse than 0.1 mag. Two eruptive episodes occurred, separated by ~5 d.

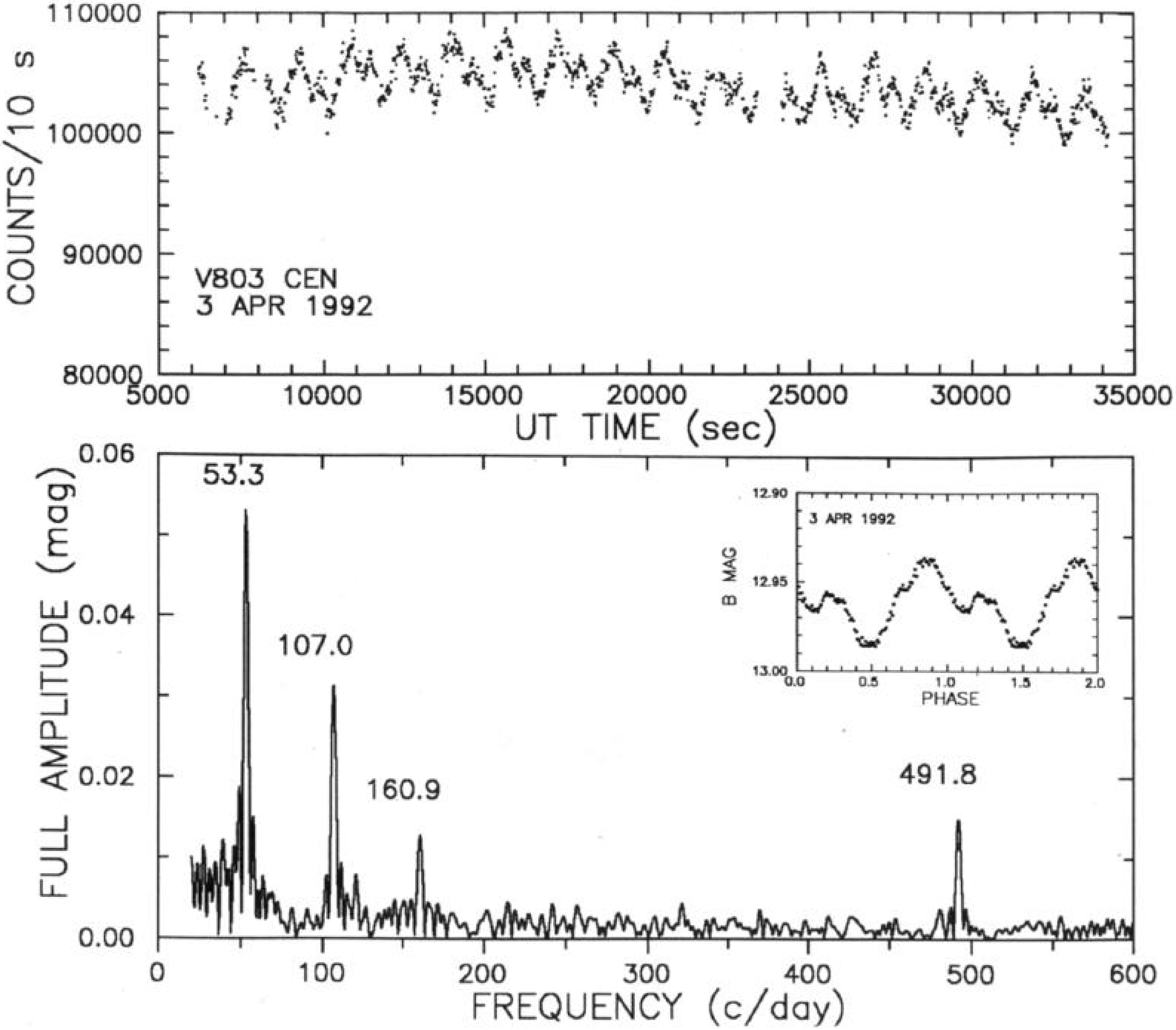
FIGURE 3. — Amplitude spectrum of a 5-night light curve (JD 312–316) in the low state. Significant features are marked with their frequency in c/d. A coherent signal at 53.60±0.02 c/d existed throughout, with a mean waveform given in the inset figure. This signal weakened and lost coherence (though remaining visible) during the remaining 7 nights of low-state coverage.

FIGURE 4. — The continuous light curve during 1997 April 2–17, spliced from the SAAO 0.75 m, the CTIO 0.9 m, the CBA-Awanui 0.25 m, and the Stubbings 0.32 m. Easily apparent is a quasi-regular variation of ~1.1 mag amplitude and 23-hr period; we interpret this as the "normal eruption" cycle of a helium dwarf nova.

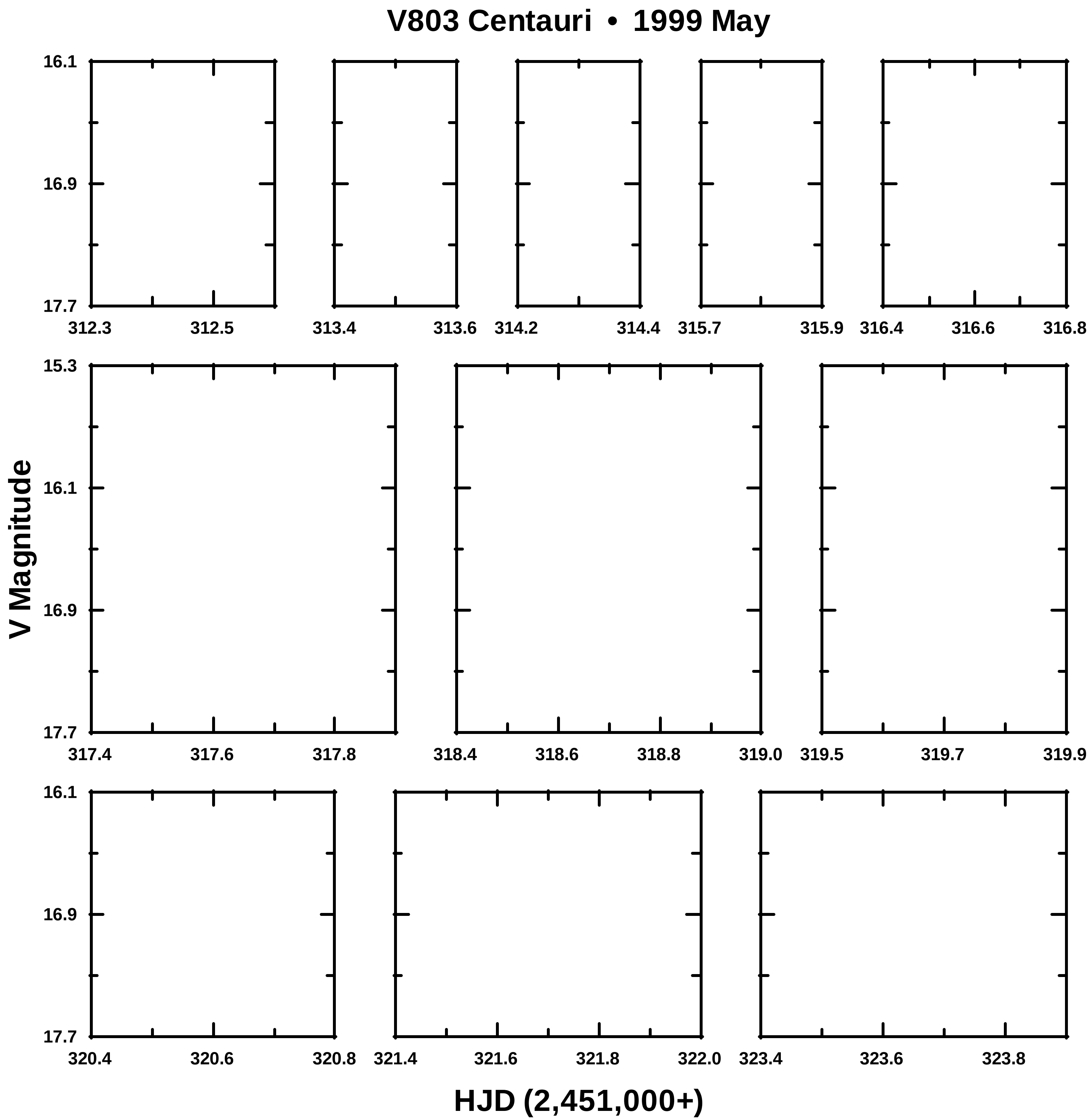
FIGURE 5. — Mean power spectrum of 10 long (>7 hr) light curves during the cycling state. Significant features are labeled with their frequencies in c/d; the error is ±0.5 c/d. The strongest feature, at 52.6 c/d, corresponds to a full amplitude of 0.02 mag.

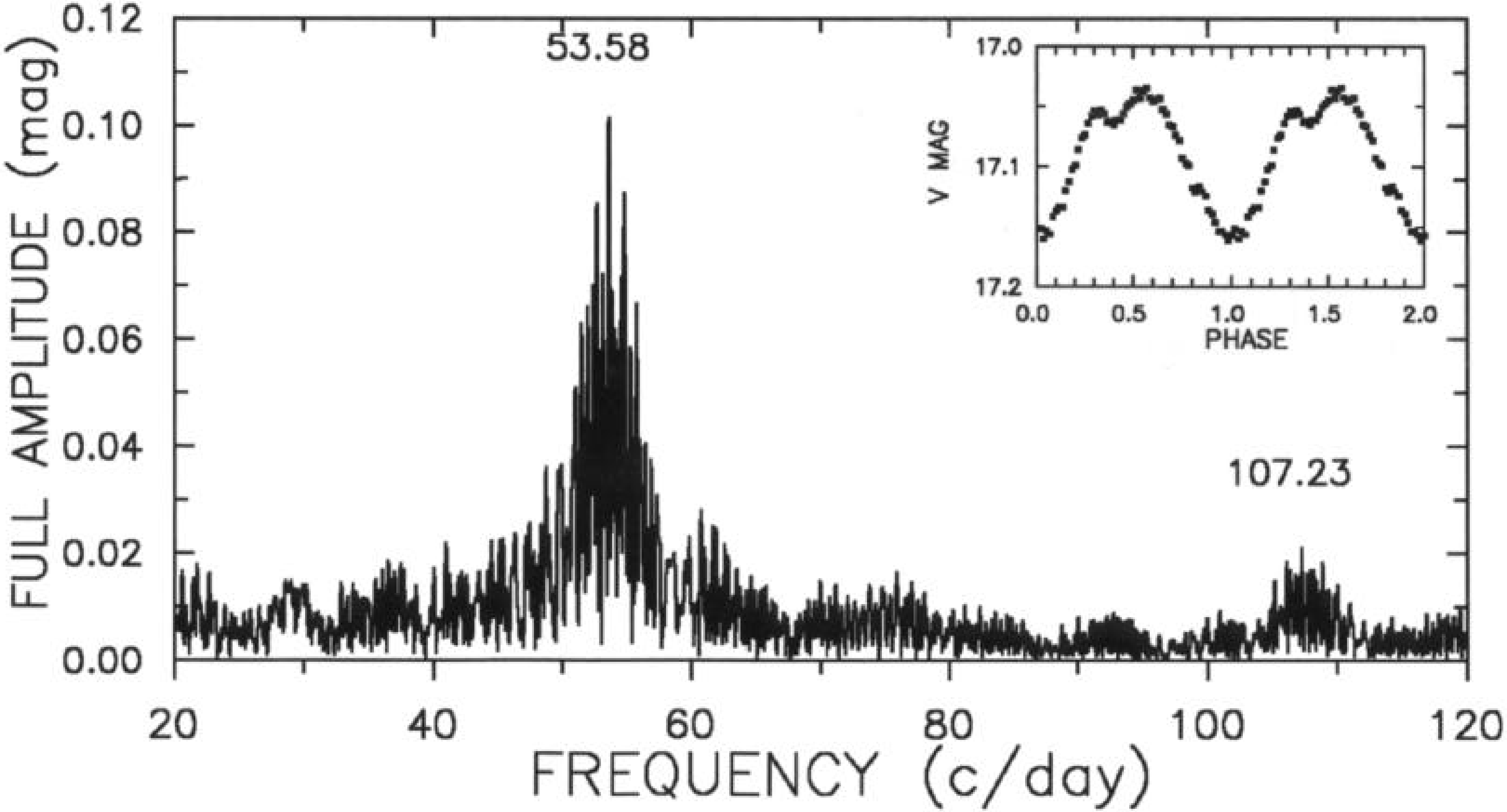
FIGURE 6. — O–C diagram of the eruption maxima, relative to the test ephemeris JD(max) = 2,450,523.92 + 0.95 *E*. The curve is a polynomial fit to the points with the most likely cycle count (see text). The deduced mean period is 0.94 d.

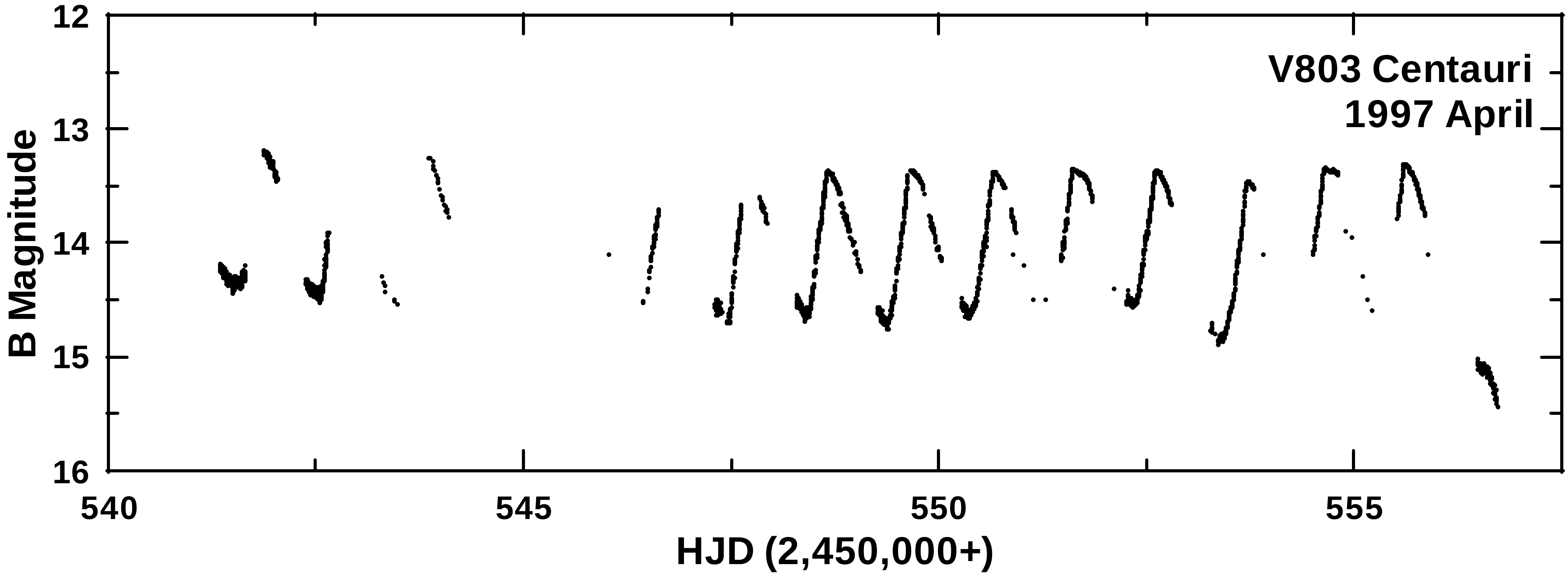
FIGURE 7. — Location of V803 Cen and CR Boo (open circles) in the Kukarkin-Parenago and Bailey relations for dwarf novae. Along with the other supporting evidence, the good fits confer fine credentials as dwarf novae.

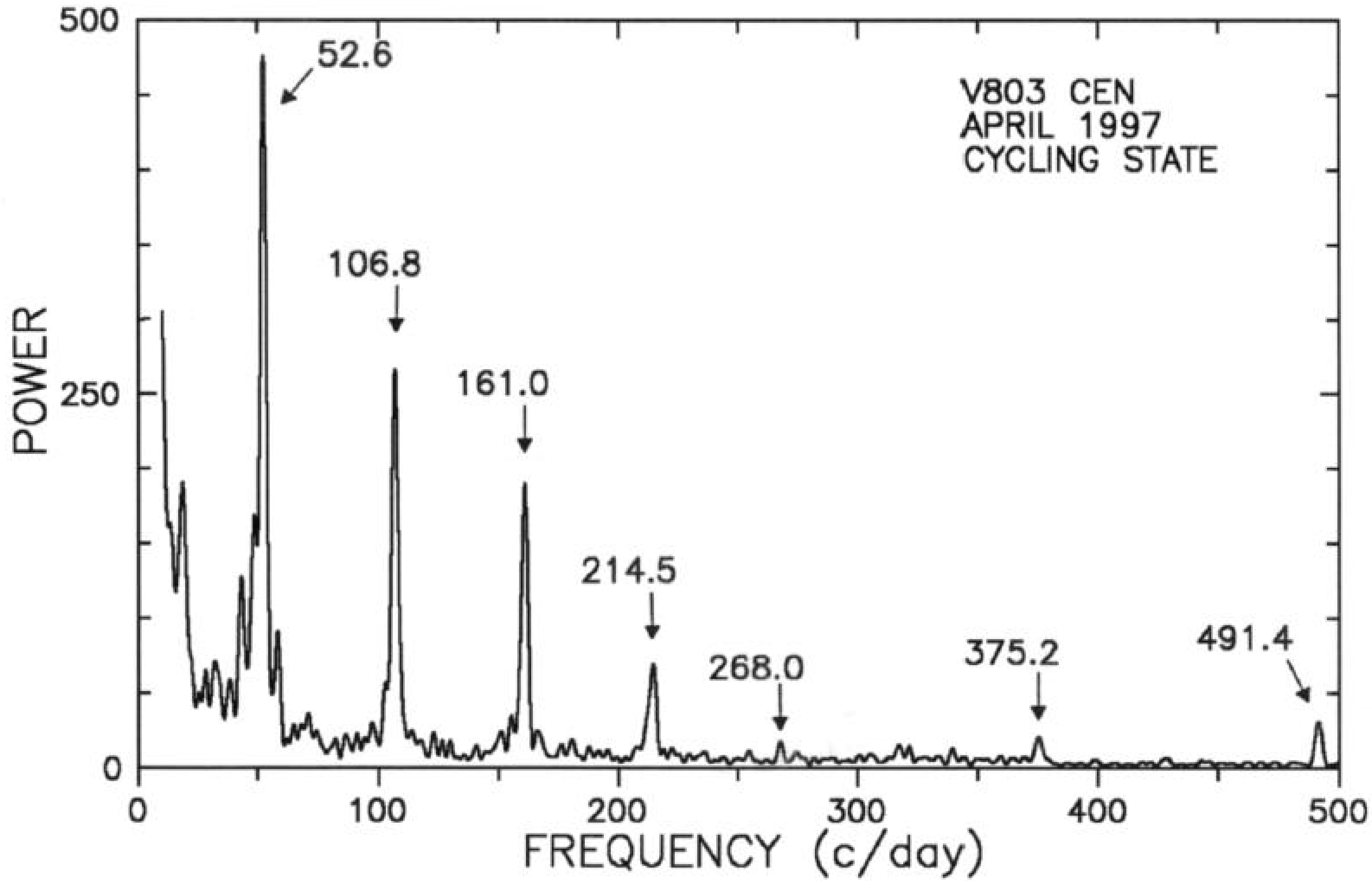


COUNTS/10 s
110000
100000
90000
80000
5000
10000
15000
20000
25000
30000
35000
UT TIME (sec)
V803 CEN
3 APR 1992
FULL AMPLITUDE (mag)
0.06
0.04
0.02
0.00
0
100
200
300
400
500
600
FREQUENCY (c/day)
53.3
107.0
160.9
491.8
B MAG
12.90
12.95
13.00
3 APR 1992
0.0
0.5
1.0
1.5
2.0
PHASE

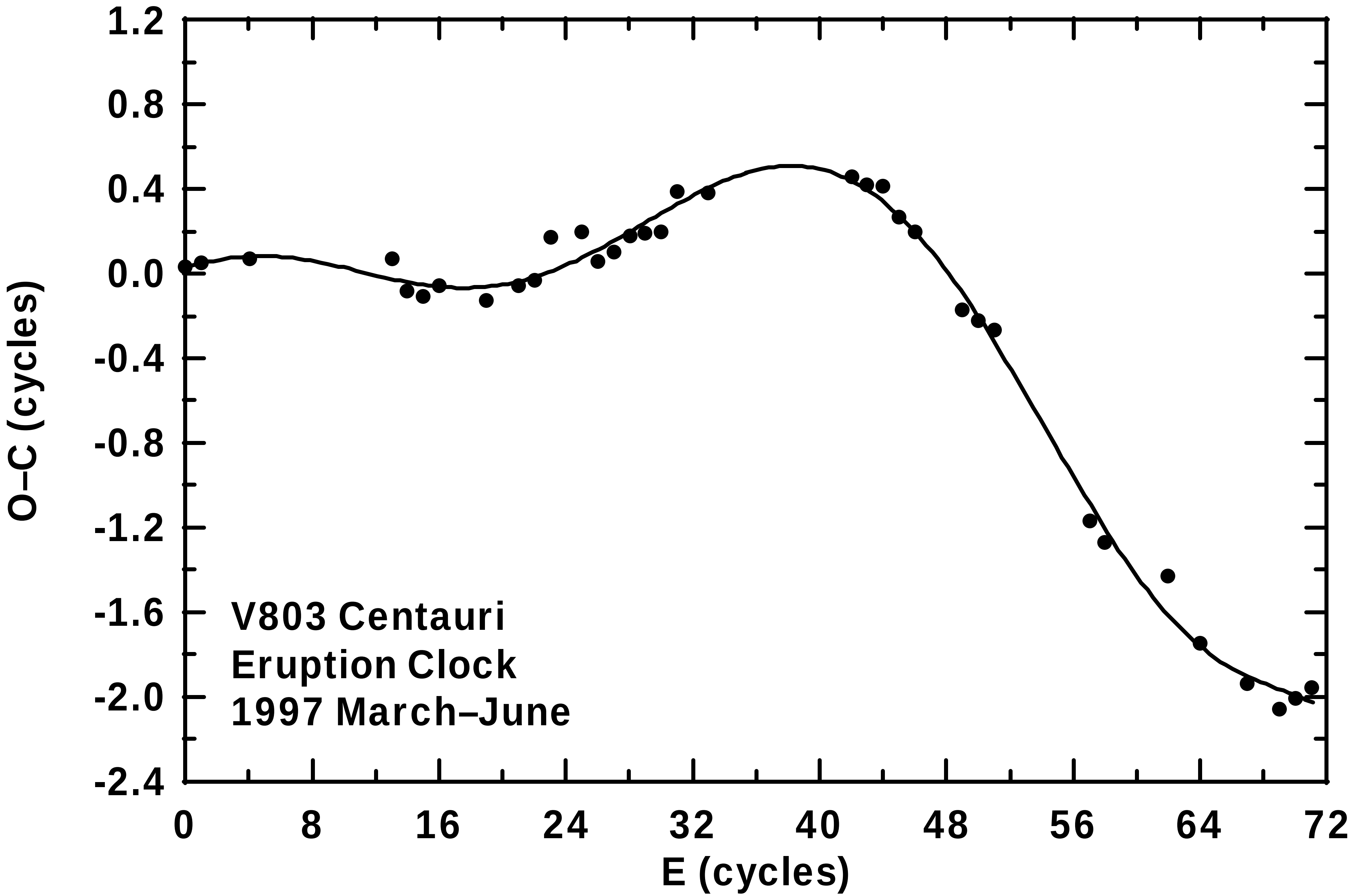

V803 Centauri • 1999 May
V Magnitude
HJD (2,451,000+)
16.1
16.9
17.7
15.3
312.3
312.5
313.4
313.6
314.2
314.4
315.7
315.9
316.4
316.6
316.8
317.4
317.6
317.8
318.4
318.6
318.8
319.0
319.5
319.7
319.9
320.4
320.6
320.8
321.4
321.6
321.8
322.0
323.4
323.6
323.8

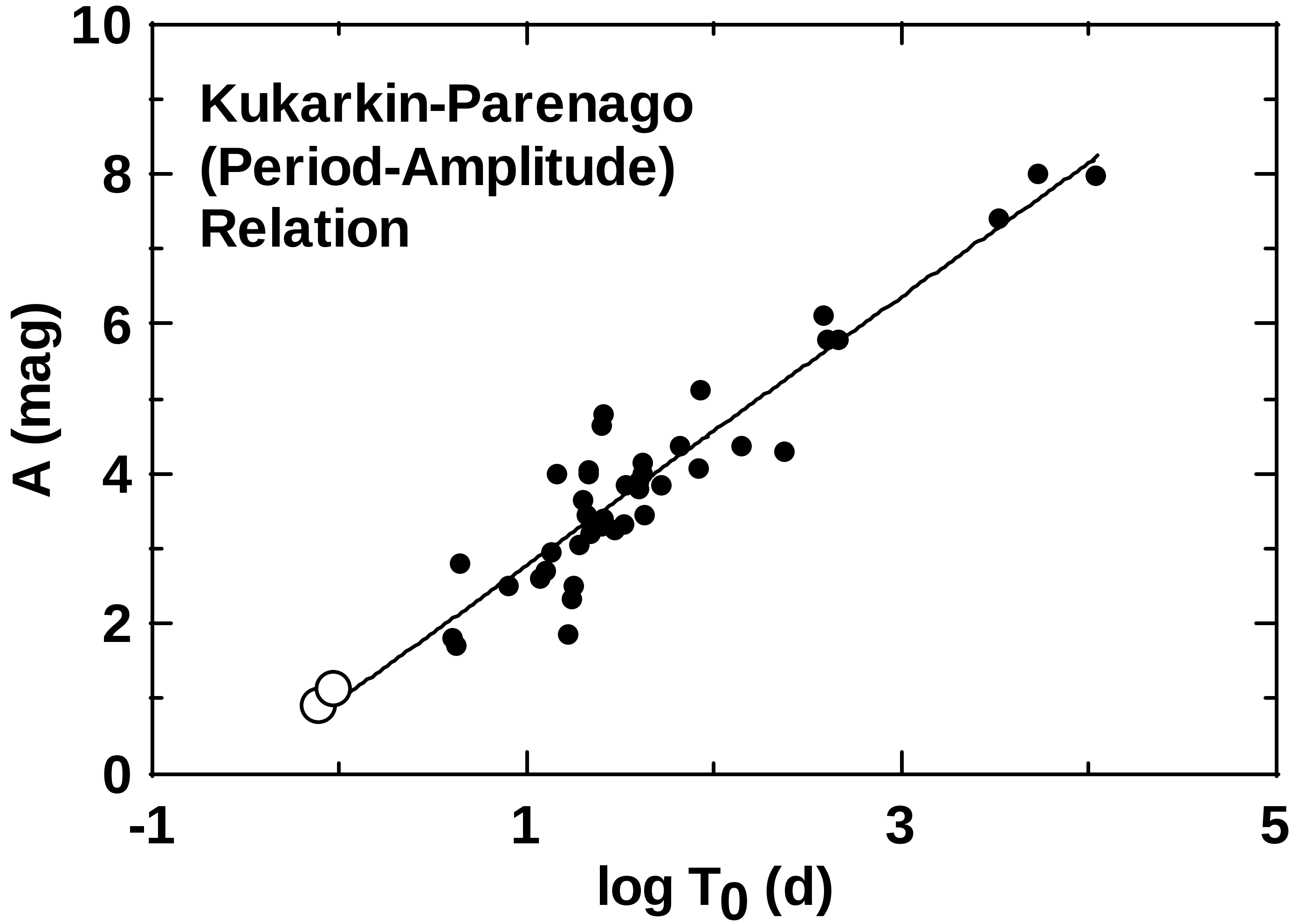

53.58
107.23
V MAG
PHASE
FULL AMPLITUDE (mag)
FREQUENCY (c/day)


V803 Centauri
1997 April
B Magnitude
12
13
14
15
16
540
545
550
555
HJD (2,450,000+)

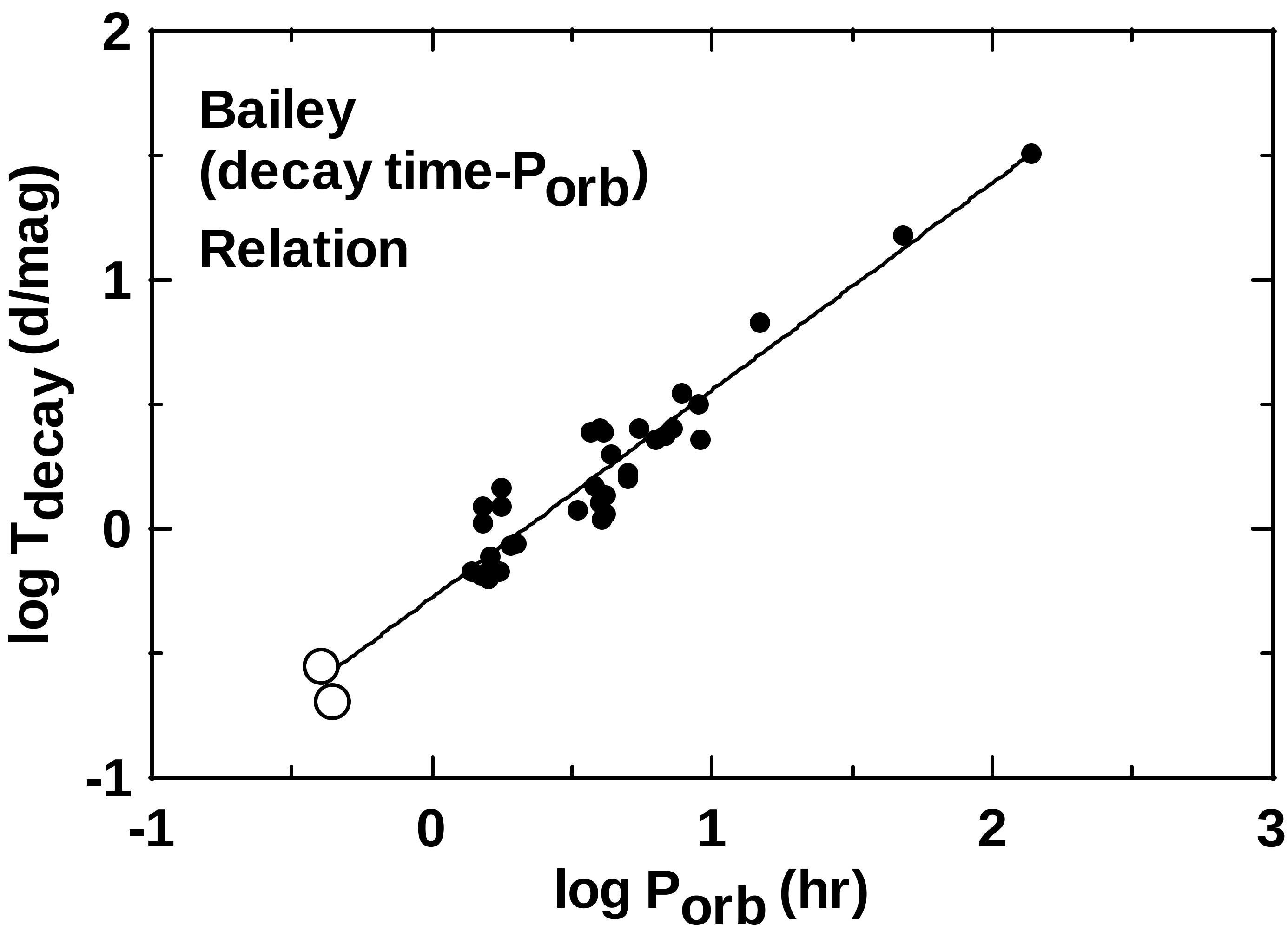


V803 CEN
APRIL 1997
CYCLING STATE
52.6
106.8
161.0
214.5
268.0
375.2
491.4
POWER
500
250
0
0
100
200
300
400
500
FREQUENCY (c/day)


1.2
0.8
0.4
0.0
-0.4
-0.8
-1.2
-1.6
-2.0
-2.4
O–C (cycles)
0
8
16
24
32
40
48
56
64
72
E (cycles)
V803 Centauri
Eruption Clock
1997 March–June



Kukarkin-Parenago
(Period-Amplitude)
Relation
A (mag)
log T_0 (d)
10
8
6
4
2
0
-1
1
3
5



Bailey
(decay time-P_{orb})
Relation
log T_{decay} (d/mag)
log P_{orb} (hr)
2
1
0
-1
-1
0
1
2
3