

# PERMANENT SUPERHUMPS IN CATAclySMIC VARIABLES

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## PREFACE

The subject of superhump light variations in “novalike” variables has developed over the last 25 years, and is especially promising since these signals can linger for years — unlike their cousins in dwarf novae. Yet nothing resembling a review paper has ever appeared in print. In 1999 I wrote such a paper in a conference proceeding, but it appeared in a book which very few people can find or access. I’ve received dozens of requests to supply a copy — and apparently it is often cited, although I’m pretty sure that practically nobody has read it. I thought I would improve the situation by “reprinting” this paper now.

## ABSTRACT

I review present knowledge of superhumps in cataclysmic variables other than dwarf novae in superoutburst. The census contains 18 of these stars. There are 14 examples of “positive” superhumps: these have  $P_{\text{sh}}$  slightly exceeding  $P_{\text{orb}}$ , and appear to follow the  $\epsilon(P_{\text{orb}})$  relation familiar from dwarf novae. The empirical distribution of points in the  $\epsilon$ - $P_{\text{orb}}$  plane may furnish a promising method of measuring the underlying mass ratio of the binary. Essentially all high- $M$ -dot novalike variables with  $P_{\text{orb}} < 3$  hr show these waves, and the incidence is still high in the 3–4 hr regime. There are 11 examples of *negative superhumps*, with  $P_{\text{sh}} < P_{\text{orb}}$ . These also probably obey an  $\epsilon(P_{\text{orb}})$  relation, but with a period shift about half as great as observed in positive superhumps. It is plausible that negative superhumps arise from small wobbles of the accretion disk plane.

Two stars (AL Com and CP Eri) show superhumps which are violently positive, with  $\epsilon$  about 4–8 times greater than normal positive superhumps. These stars are also remarkable for their extreme mass ratios, and for flashing superhumps in a state of very low luminosity. These waves may arise from eccentric instabilities at the 2:1 orbital resonance.

## Key words

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

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## 1 INTRODUCTION

1998 marks another 25th anniversary: the discovery of “superhumps” in the light curve of VW Hyi in superoutburst (Vogt 1974; Warner 1975). Since then, detailed studies of this and a few other erupting dwarf novae have led to a more or less standard prescription of how these waves evolve during the eruption. This was reviewed by Warner (1985, 1995) and brought up to date by Taichi Kato in these proceedings. We now have a useful observational record for 47 superhumping SU UMa stars.

To me, it is amazing how monolithic this phenomenon is. When I studied the literature 10 years ago, I thought the empirical support for the “standard” description was rather small — really just *one* well-studied star, VW Hyi itself, with the other ~12 stars poorly documented. Now, ten years and over a thousand nights of photometry later, the roster of stars has quadrupled with maybe 10–20 deserving to be called “well-studied”. And the result is ... well, I’d say that the superhumps in SU UMa stars *do* behave quite similarly and are very well exemplified by VW Hyi. The early optimism that seemed unwarranted to me has basically been proved correct. I think it’s good to label these as *common superhumps*. They’re certainly common; many even consider them to be defining features of a superoutburst.

When we (the Center for Backyard Astrophysics, or CBA) began our study of this subject, Whitehurst’s theory of apsidal precession had recently been published (Whitehurst 1988), and there were preprints rattling around which confirmed and expanded his work (Osaki 1989; Lubow 1991; Whitehurst & King 1991). These theories met with a great deal of acceptance very fast. And yet there seemed to be nothing which explained why superhumping stars had to be dwarf novae. They needed to have accretion disks and a low mass ratio, and perhaps they needed to be bright. But some stars meeting these requirements are not dwarf novae. In principle these could be much better targets, since we need not rely on the serendipity of a well-timed superoutburst.

The literature had a plentiful supply of stars with slightly discrepant periods. Even after rejecting candidates with severe aliasing or very sparse data, there was still a good supply. We started with a campaign on V603 Aql, immediately found superhumps (the same signal discovered by Haefner 1981), and have kept going ever since. We have now found 25 signals of this type. They have become our favorite targets, partly because they allow planned observing campaigns, and partly because they do show, unlike the dwarf novae, much variety in their observed properties. We call these “permanent” superhumps — not implying that they are eternal, but to distinguish them from the common superhumps which have become quite famous (and which I assume are known to readers). Several recent tabulations of common-superhump data are available (Warner 1995; Nogami et al. 1997; Patterson 1998). Here I review permanent superhumps.

## 2 POSITIVE APSIDALSUPERHUMPERS

Our photometry campaigns on novalike variables often reveal signals at periods a few percent longer than  $P_{\text{orb}}$ . Table 1A contains the basic information on these stars; detailed references are given by Patterson (1998). Stars with only low-precision period measurements ( $> 0.4\%$ ) or unknown  $P_{\text{orb}}$  are excluded, since they do not yet enrich our understanding of the subject. Of ten stars examined with  $P_{\text{orb}} < 3$  hr, every one has yielded such a signal. In the interval 3–4 hr we have found five more, out of about nine searched (the quality of the search varies, so the incompleteness is not well defined). So far we have not found any beyond 4 hr, but we are just starting to search.

There are strong resemblances of these signals to common superhumps. The upper part of Figure 1 shows how the fractional period excess  $\epsilon$  correlates with  $P_{\text{orb}}$  for the novalikes,<sup>2</sup> compared to the distribution for common superhumps (anonymous dots). They certainly look like members of the same family. And the above statistics suggest that there is an association with short  $P_{\text{orb}}$ , as is true for common superhumps.

Detailed study shows significant differences too. An interesting specific difference is the harmonic structure of the superhumps. If the orbital frequency is  $\omega$ , then the superhump frequency can be expressed as  $\omega - \Omega$ . In this terminology, common superhumps generally show their harmonics very near strict integral multiples of the fundamental, i.e., at  $n(\omega - \Omega)$ . But PSHs often flash a more complex harmonic structure, with “harmonics” seen at  $n\omega - m\Omega$ , where  $m$  can be any integer up to  $n$ . The clearest example is AM CVn, whose 1998 power spectrum is shown in Figure 2. The top panel shows the orbital signal at 1028.7 s and the superhump at 1051.2 s, as well as a negative superhump at 1011.4 s. In frequency units, we designate these as  $\omega$ ,  $\omega - \Omega$ , and  $\omega + N$ . The middle panel shows a primary signal at  $2(\omega - \Omega)$ , and small satellite signals at  $2\omega - \Omega$  and  $2\omega - \Omega + N$ . And the lowest panel shows signals at  $3(\omega - \Omega)$  and  $3\omega - \Omega$ . Other observing campaigns have given slightly different results (Provencal et al. 1995; Solheim et al. 1998), but this is the general pattern. This complex sideband structure is probably a rather frequent phenomenon.

Both helium dwarf novae flash superhumps which are clearly common, yet also endure for many thousands of cycles after excitation in the superoutburst. So they are also “permanent”. These provide evidence tending to unite the two phenomena. A good working hypothesis is that permanent positive superhumps might be merely common superhumps that are very slow to die.

### 3 EVOLUTION IN THE $\epsilon$ - $P_{\text{orb}}$ Plane

The correlation of  $\epsilon$  with  $P_{\text{orb}}$  can furnish information on the mass ratio, and possibly evolution, of positive superhumpers. For a first-order calculation, we can assume a main-sequence H-rich secondary and calculate the precession frequency of particles orbiting at

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<sup>2</sup> This term is broadly used to include known old novae as well. Surely, they can lay a reasonable claim to being “novalike,” however narrowly astronomers are inclined to use this term.

the 3:1 resonance in the disk. The predicted trend of  $\varepsilon(P_{\text{orb}})$  is then shown by the curve at the right of Figure 3, which assumes a white dwarf mass  $M_1 = 0.7 M_{\odot}$ . The shaded region shows the effect of allowing a  $\pm 10\%$  uncertainty in  $R_2$  and a  $\pm 25\%$  uncertainty in  $M_1$ , added in quadrature. The theory curve terminates at  $M_2 = 0.08 M_{\odot}$ .

In general, the data match the theory fairly well. The H-rich stars of shortest period appear to bend towards lower  $\varepsilon$ , however. This is probably due to the loss of thermal equilibrium in the secondaries (Paczynski 1981; Paczynski & Sienkiewicz 1981). Mass loss proceeds too fast to allow the secondaries to contract, so they remain somewhat larger than they would on the main sequence — implying a smaller  $M_2$  and therefore a smaller perturbation on the disk. This results in the star “bouncing” at a minimum period and then evolving back to long period, now with a much lower  $M_2$ . The H-rich stars of lowest  $\varepsilon$  look like they might have arrived there through a bounce, although it’s also possible that they fall more or less vertically.

At the left of Figure 3 are the helium binaries. These contain secondaries which are helium stars of very low mass. Normally they would be expected to obey a simple Chandrasekhar mass-radius law ( $R \propto M^{-1/3}$ ). This defines the lower bound of the theory curve in Figure 3. But the GR timescale for such binaries is shorter than the secondary’s thermal timescale, so these secondaries may also become larger than a normal white dwarf of that mass — again implying a smaller perturbation on the disk. A mass–radius relation with this assumption was developed by Savonije et al. (1986), and we have used it to calculate an upper bound to the theory curve. The empirical points nestle between these limits and display the expected trend with  $P_{\text{orb}}$ . So these points too appear roughly consistent with a simple theory.

#### 4 NEGATIVE (NODAL?) SUPERHUMPERS

For many years we knew just two CVs which flashed photometric signals with  $P < P_{\text{orb}}$ : TV Col and TT Ari. One interpretation of the signal invoked nodal precession of the disk (Bonnet-Bidaud et al. 1985; Udalski 1987), and this possibility remains viable today. In fact, subsequent work has revealed 9 additional stars with photometric periods slightly less than  $P_{\text{orb}}$ , a condition reasonably called negative superhumps. Table 1B contains the relevant data. All the major classes of disk-accreting CVs are represented. The signals are all “permanent” in not displaying any obvious dependence on eruptive state; but most show amplitude excursions on a timescale of a few weeks, and sometimes they shut down altogether.

The distribution of  $\varepsilon$  with  $P_{\text{orb}}$  is shown in Figure 1, and tracks that of positive superhumps pretty well, with  $\varepsilon_{\text{neg}} \approx -0.5\varepsilon_{\text{pos}}$ . That’s interesting. In the precessional interpretation, it would imply an apsidal precession rate twice as fast as nodal precession — as is true for the Moon (8.8 versus 18.6 yr). Nodal precession is a promising hypothesis for these waves.

Noteworthy is the high incidence of SW Sex stars (Thorstensen et al. 1991) among negative superhumpers. Many aspects of the SW Sex phenomenon can be explained by

supposing that the mass-transfer stream overflows the accretion disk (Hellier 1997), but we still do not understand why this should happen. A tilted disk could explain it naturally.

Table 1 indicates that some stars show both positive and negative superhumps. And six of them (AM CVn, V503 Cyg, V603 Aql, PX And, BH Lyn) show positive and negative superhumps simultaneously. How remarkable it is that these fluid, differentially rotating disks are able to sustain such well-organized motions!

## 5 PRECESSION? OR JUST SUPERHUMPS?

In this review I generally accept the idea that super humps arise from disk precession, with the frequencies related by  $\omega_{sh} = \omega_{orb} \pm \Omega_{prec}$ , where minus signifies a prograde precession, and plus signifies a retrograde precession. That is pure geometry. For ease of discussion and classification I also assume that prograde precession always arises from apsidal motion, and retrograde precession always arises from nodal motion. Is there independent evidence for this?

Well, there's some. A good signature of apsidal motion is periodic skewness in spectral lines (eccentric disks produce skewed lines). To date this has only been reported in two stars, AM CVn and CR Boo; additional searches are warmly recommended! A good signature of nodal precession is the presence of a photometric signal at the precession frequency itself (rather than simply the orbital sideband). We expect a signal at  $\Omega_{prec}$  since the disk wobble changes the visible disk area at this frequency. Effects of this kind are seen in TT Ari, TV Col, PX And, and AH Men. There is no expectation of such a signal in apsidal superhumpers (with the possible exception of edge-on binaries), and we have never seen one, despite extensive coverage. In summary, I think the evidence supports the above classification, but maybe one should substitute "usually" for "always". It's possible that a few Greeks could hide among the Trojans, or vice versa.

## 6 COHERENCE

People often ask how coherent these signals are. It's a good question, because accretion disks are highly sheared, encompass a large range of natural timescales, and should not contain a clock of high quality. And indeed, they don't. TT Ari, a very well-studied superhumper, will illustrate the point. The negative superhump period wanders in the range 0.1324–0.1334 d, on a timescale of a few months. This implies a precession period wandering in the range 3.6–4.5 d. Such changes of ~20% are comparable to what one might imagine from a disk in a cataclysmic variable.

The argument is basically the same for positive superhumps, whether permanent or in SU UMa stars. A typical dwarf nova shows a superhump  $\dot{P} \approx 5 \times 10^{-5}$ , indicative of a precession period changing from about 4 to 5 d over the length of a 10-day superoutburst. This implies a quality factor  $Q = 1/\dot{P}$  of about 10.  $Q$ -values in PSH stars tend to be in the range 30–300, presumably because the disks are more stable. The most coherent of all

superhumping stars is AM CVn, whose period wanders over 1051.0–1051.4 s on a timescale of a few months. This implies a precession period in the range 13.3–13.5 hr, or a quality factor  $Q = 10^4$ . Although this is relatively high, it's plausible to find it in this star, the most constant of all CVs (varying only within  $\sim 0.1$  mag on all known timescales from minutes to decades).

Probably there are sloppier precession clocks up there, too. For very low  $Q$  we would have difficulty detecting the signal in a power spectrum. There are a few stars where extensive coverage has yielded only an uncertain detection (thus disqualifying for membership in Table 1); these might indicate a more poorly organized precession.

I realize that the above conflicts with numerous observational papers in the literature. Astronomers studying periodic signals often connect timings to each other with linear ephemerides, and then conclude that the periodic process is very stable. But we (the CBA) tend to produce many more dots to connect, and we find that the dots don't connect. The superhump periods wander. And the implied precession clocks lose memory of phase in less than a few dozen cycles. The sooner you accept this, the happier you will be.

## 7 OUTLIERS AND OUTLAWS

We have a fairly simple story now for the majority of superhumpers, those living in the shaded regions of Figure 3. But some stars refuse to conform. Stars near  $P_{\text{orb}} = 0.06$  d have the aforementioned problems with thermal equilibrium, which is probably an adequate explanation of their substandard  $\epsilon$ . But at least one long-period star, CN Ori, lives far below the mean relation. Why?

Personally I tend to think that  $\epsilon$  is a good indicator of  $q$ , based essentially on the low dispersion in Figure 3. An anomalously low  $q$  could come merely from a high  $M_1$ . A more interesting possibility is that CN Ori is itself a product of period bounce, the result of the secondary's loss of thermal equilibrium as a high angular momentum loss rate is inflicted in the 3–4 hr period regime.

A very lonely point in Figure 3 is V485 Cen, the solitary dwarf nova occupying the territory between the H-rich and the He-rich stars. Augusteijn et al. (1996) pointed out that a CV could reach such an odd period through a mild H-depletion, and cited evidence supportive of that theory from the helium emission-line strengths. That seems plausible, and so I (somewhat nervously) have ignored V485 Cen in the above classification and discussion.

Finally, there are two stars displaying positive superhumps with  $\epsilon$  far in excess of the values shown in Table 1 and Figure 3, in addition to common superhumps which do satisfy the mean relation. I've ignored these waves even more egregiously, omitting them from the table and figures altogether. This signal has  $\epsilon = 0.08$  in AL Com (Abbott et al. 1992; Patterson et al. 1996), and 0.037 or 0.059 in CP Eri (depending on the 1-day cycle count which is uncertain). These values are a factor of 4–7 higher than the  $\epsilon$  of the common superhump in these stars.

The amplitudes appear to be higher,  $\sim 0.20$  mag compared to  $\sim 0.08$  mag for common superhumps. And perhaps most significantly, the waves are found in states of very low luminosity, with the accretion light hovering around  $M_v \sim +12$ . These properties suggest a different origin.

It's tempting to suppose that the cause is the 2:1 orbital resonance in the disk. This occurs at  $R_{\text{disk}} \sim 0.58a$ , which is beyond the probable radius of disk truncation for most CVs. Only binaries of very low  $q$  could have matter orbiting that far out. But these stars are binaries of very low  $q$ . The value of  $P_{\text{orb}}$  alone requires  $q < 0.1$ , and the observed  $\epsilon$  in the common superhump suggests  $q \sim 0.04$  (Patterson 1998). The large wave amplitude and the large  $\epsilon$  of the "violently positive" superhump are natural consequences, since the tidal force is so large on such big orbits.

## 7 EXHORTATION

I think we're getting some interesting speculations out of all these period measurements. Who knows ... there may be some interesting physics there too! But theorists need to lend a hand. It's at least curious, if not downright miraculous, that so simple a model (perturbation of single-particle orbits) would produce such handsome fits as Figure 3 with no adjustable parameters. Is this merely a coincidence? Maybe. This is an important issue for a more sophisticated calculation. It would also be nice to understand how the disks manufacture the complex harmonic structure of superhumps. And the lowest regions of Figure 3 — probably the Last-Chance Saloon of binary star evolution — surely merit special scrutiny by observers and theorists alike.

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## FIGURE CAPTIONS

Figure 1. Correlation of fractional period excess  $\varepsilon = (P_{\text{sh}} - P_{\text{orb}}) / P_{\text{orb}}$  with  $P_{\text{orb}}$  for all stars. Common superhumps are shown by anonymous dots, and PSHers are shown by name. Negative superhumps are in squares.

Figure 2. Portions of the 1998 power spectrum of AM CVn, after mild spectral cleaning (elimination of aliases of the strongest signals). Each significant detection is shown by an arrow labeled by the period in seconds. The strongest signal, at 525.6 s, rises to a power of 255 (corresponding to a full amplitude of 0.024 mag).

Figure 3.  $\varepsilon(P_{\text{orb}})$  relation for all positive superhumps. Shading shows the regions accessible with a simple theory of perturbed particle orbits, discussed in the text and by Patterson (1998).

TABLE 1

Periods of Permanent Superhumpers

A. Positive Superhumpers				B. Negative Superhumpers			
Star	$P_{orb}$ (days)	$P_{sh}$ (days)	$\epsilon$	Star	$P_{orb}$ (days)	$P_{sh}$ (days)	$\epsilon$
AM CVn	0.011906(1)	0.012166(1)	0.0218(1)	AM CVn	0.011906(1)	0.0117063(6)	-0.0168(1)
CR Boo*	0.017029(2)	0.01723(2)	0.0117(12)	V503 Cyg	0.0777(2)	0.07597(18)	-0.022(5)
CP Eri*	0.019690(3)	0.019862(5)	0.0087(4)	V1974 Cyg	0.08126(1)	0.07911(5)	-0.027(1)
CP Pup	0.06145(6)	0.0625(1)	0.0171(20)	V442 Oph	0.1243(7)	0.12090(8)	-0.027(5)
BK Lyn	0.07498(5)	0.07857(1)	0.0479(7)	AH Men	0.12721(6)	0.12356(6)	-0.029(2)
V1974 Cyg	0.08126(1)	0.08509(8)	0.0471(10)	DW UMa	0.136606(1)	0.1330(5)	-0.026(4)
V348 Pup	0.101839(1)	0.1084(4)	0.0640(40)	TT Ari	0.1375511(2)	0.1329(3)	-0.034(3)
V795 Her	0.108265(1)	0.1165(1)	0.0760(10)	V603 Aql	0.1381(1)	0.1343(3)	-0.028(2)
V592 Cas	0.115063(1)	0.12226(6)	0.0625(5)	PX And	0.146353(1)	0.1415(3)	-0.033(2)
AH Men	0.12721(6)	0.1385(2)	0.0887(16)	BH Lyn	0.155875(1)	0.1490(11)	-0.044(8)
TT Ari	0.1375511(2)	0.1492(1)	0.0847(7)	TV Col	0.22860(1)	0.2160(5)	-0.055(2)
V603 Aql	0.1381(1)	0.1460(7)	0.0572(51)				
PX And	0.146353(1)	0.1595(2)	0.0898(14)				
BH Lyn	0.155875(1)	0.1666(5)	0.069(4)				

NOTE. — \* Superhumps in these two helium stars are essentially common *and* permanent, as discussed in text.

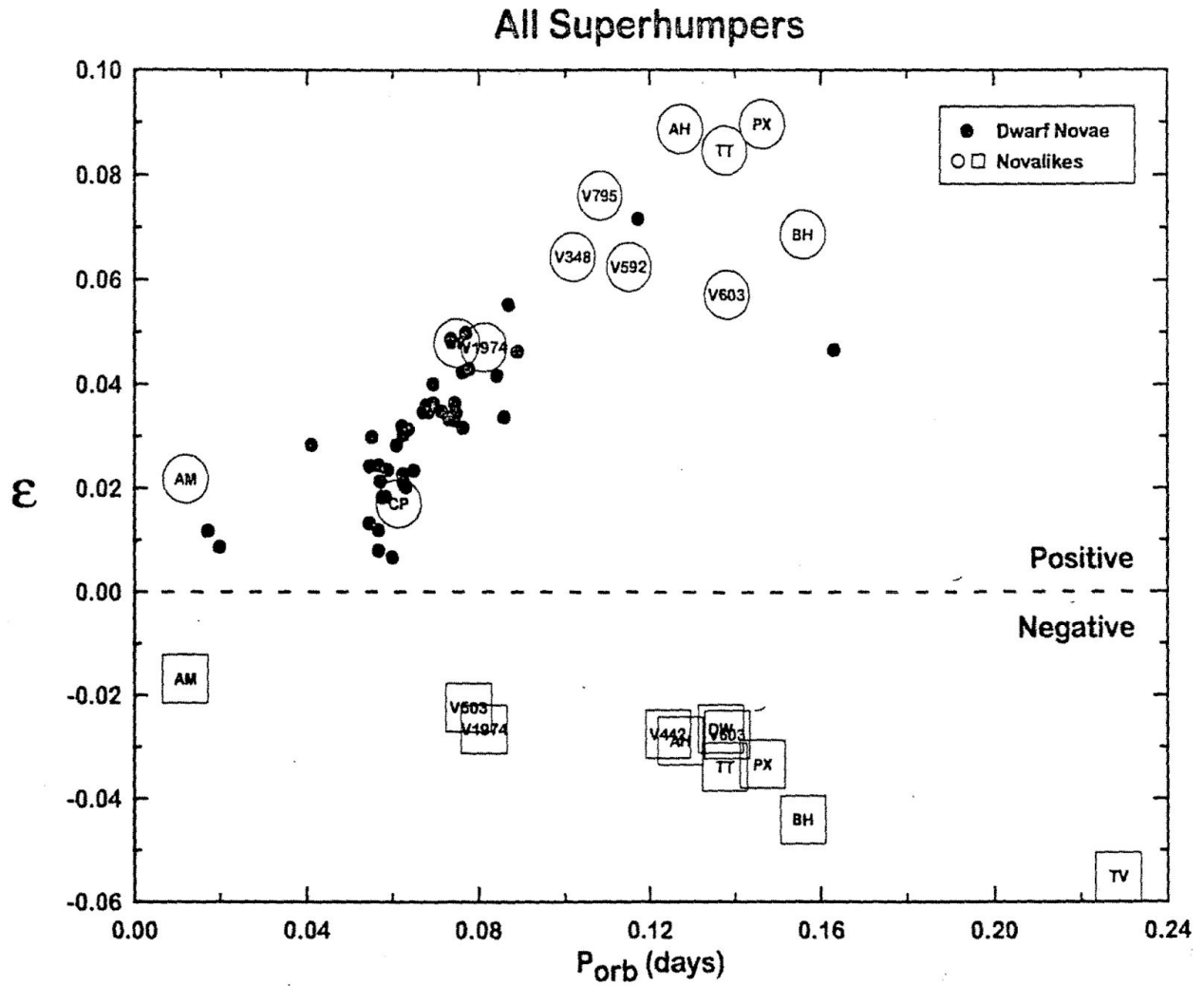


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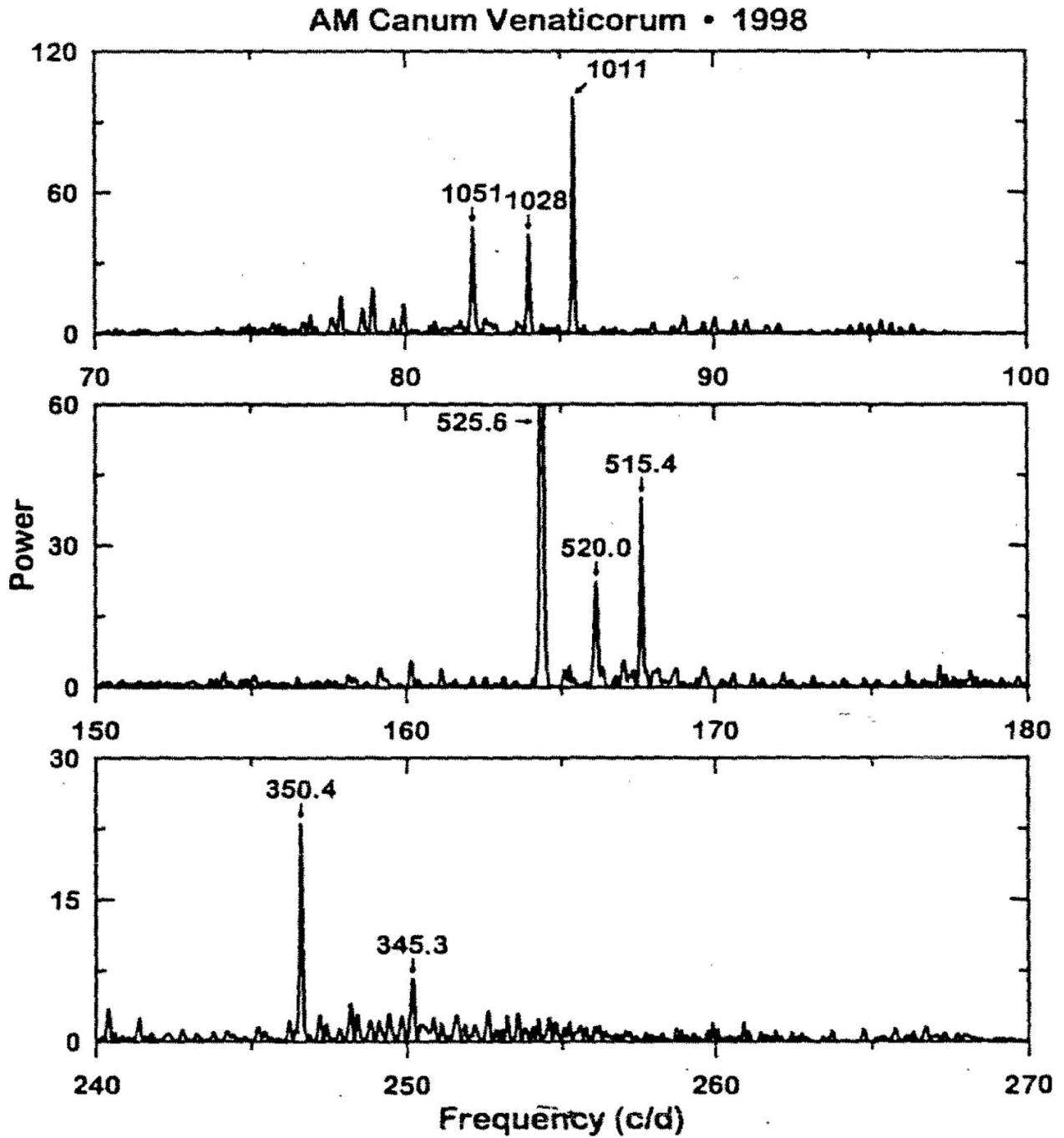


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