40 YEARS OF PERIODIC SIGNALS IN THE ULTRACOMPACT BINARY AM CANUM VENATICORUM

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We've been long on the trail
Of a cataclysmic White Whale.
How hard we have fought
To learn the Pdot…
Now hear the tale.

Abstract

We report the results of 1978-2019 time-series photometry of AM CVn, the prototype of the "double-degenerate" or *ultracompact* class of cataclysmic variable. The star remained faithfully in the range V=14.10-14.25 throughout the ~1400 nights of observation, and flashed its familiar positive and negative superhumps, at periods near 1051 s and 1011 s respectively. These periods, arising from instabilities in the accretion disk, wander erratically in phase, on a timescale of weeks. The 1028.7322 s orbital signal is slightly weaker (~0.003 mag semiamplitude), but is phase-stable over many years. Over a 27-year baseline, timings of orbital minimum show a period decrease of 17± 3 µs/year. This is consistent with evolution driven by gravitational radiation, but only if the secondary is a low-mass helium star, rather than a degenerate dwarf.

1. INTRODUCTION

The now-famous variable star AM CVn was first catalogued as HZ29 by Humason and Zwicky (1947) in their survey of faint blue stars near the north Galactic pole. Smak (1967) discovered a periodic photometric signal at 1050 s, and proposed that the star is actually a cataclysmic variable (CV) with an accreting white dwarf (WD) and an underlying orbital period of 1050 s. Faulkner, Flannery, and Warner (1972, hereafter FFW) presented consistent models of this type, the first quantitative discussion of "ultracompact" binaries. Their Figure 2 -- perhaps the most famous figure in the history of CV research --

showed two simple models with different donor stars: a 0.04 Mo WD, and a 0.4-0.5 Mo star on the helium main sequence. The absence of large radial-velocity variations ruled out the latter, and thus the AM CVn class was born – often called "double degenerates". New members were later found, and now the club includes ~40, ably reviewed by Levitan et al. (2015) and Ramsay et al. (2018). All are CVs with helium-dominated spectra and ultrashort orbital periods, ranging from 5 to 48 minutes. And to the extent that distances (and thus absolute magnitudes) are known, it appears that AM CVn stars obey the pattern that other CVs show: with the most and least luminous being relatively constant in light, while the intermediate class shows outbursts similar to those of their hydrogen-rich cousins.

In order to fit into a very compact binary, the donor star must certainly be very small; but it does not necessarily have to be a WD. This was shown by Savonije et al. (1986), and developed further by Nelemans et al. (2001) and Deloye et al. (2005). "Double degenerate" has flourished as a catchy nickname, but, as recognized even by FFW, need not correctly describe the binary, since P~1000 s still permits some types of helium donors to be nondegenerate. *Ultracompact* is a better term, which includes the binaries with neutron-star or black-hole accretors. Figure 1, which compares the binary to three objects of well-known size, illustrates just how "ultra" is the compactness.
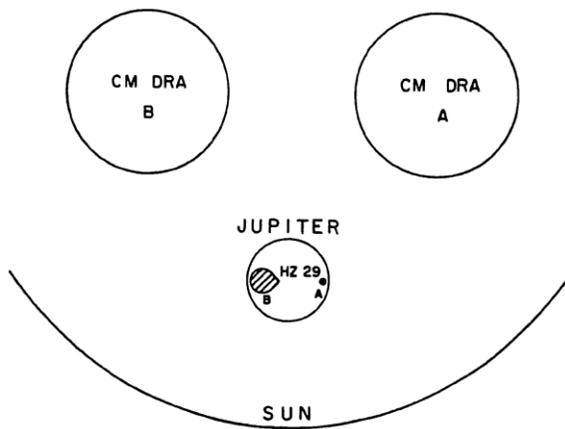
Figure 1. The dimensions of the AM CVn (=HZ 29) binary, compared with several familiar objects of well-measured size. (CM Dra is a famous binary with two M dwarfs.) AM CVn comes by its "ultracompact" name honestly.

A secure measurement of orbital period change can test the donor star's mass-radius relation. If P_{orb} increases, then the donor is probably degenerate, because its radius must increase to keep up with the (likely) increasing binary separation. If P_{orb} decreases, then the donor radius must decrease to maintain stable mass transfer; otherwise, the donor overflows its Roche lobe and the mass transfer runs away.

Among the verious photometric periods, Harvey et al. (1998) showed that just one (1028.73 s) was precise and stable over a season's baseline, and identified that signal as the long-sought orbital period. Skillman et al. (1999, hereafter S99) verified its stability and gave a long-term ephemeris based on 1992-9 photometry. In this paper we extend that work, and report timings of orbital minimum throughout our 40 years of observation (1978-2019). These timings show that P_{orb} has been decreasing over this interval, with dP/dt ≈ -20 microseconds/year. This strongly suggests that the donor contracts on mass loss, and hence is likely nondegenerate.

2. OBSERVATIONS AND THE PHOTOMETRIC HISTORY

The early studies of AM CVn established the main properties of its periodic signal. The dominant period is 1051.2 s, with most of the power in the first overtone[1] (Smak 1967, Ostriker & Hesser 1968). [[1]Or "second overtone", at 525.6 s. We are grateful to Matt Wood for pointing out the correct terminology, which we have been mangling for years].
This period is somewhat unstable, wandering on a timescale of weeks to months (Krzeminski 1972; Patterson et al. 1979; S99). The signal amplitude is remarkably constant in waveform and amplitude (0.024 mag peak-to-trough, see Figure 5 of S99), and the star's mean magnitude stays within 0.1 mag[2] of *V* = 14.16 (Krzeminski 1972, S99). The colors are extremely blue and nearly constant at *B-V* = -0.21, *U-B* = -1.06 (Krzeminski 1972).
[[2]Because most of our data is unfiltered, and the spectral responses are not standardized, we cannot be quite sure of this. But we have never seen high states, low states, trends within a night's data, or obvious dispersion in the magnitudes from a single observer].

There is another periodic signal, also somewhat unstable, at 1011.43 s (Solheim et al. 1984). The latter signal ranges in full amplitude from undetectable (<0.003 mag) to 0.018 mag, roughly on a timescale of months (S99). A stable period was finally identified at 1028.73 s by Harvey et al. (1998), and this precisely fit the orbital period required by the accretion-disk interpretation of the line profiles (Pat-

terson, Halpern, & Shambrook 1993). S99 verified the signal's stability[2], improved the precision to 1028.7322 s, and gave a long-term ephemeris.

This signal is weak (0.005 mag full amplitude) and difficult to distinguish, in a short time series, from the 1051 s and 1011 s signals. But its proven stability in phase, unlike the more powerful signals, identifies it as the true orbital period. Thus it became possible to identify the triad of periods as following the pattern common in cataclysmic variables: with 1051 s as the positive ("common") superhump, 1011 s as the negative superhump, and 1028 s as the orbital period.

We have continued to study AM CVn with time-series photometry, accumulating ~5000 additional hours during 1300 nights during 1998-2019. This was acquired through the Center for Backyard Astrophysics (CBA) network of small telescopes, scattered around the world. Details of data acquisition and reduction are given elsewhere (Patterson et al. 2013, S99). In order to maximize signal-to-noise, we observed mainly in unfiltered light, which produced an effective wavelength near 6000 A. Occasional use of *V* filters established a rough calibration. Integration times ranged from 10 s to 45 s, and the nightly runs were 2-9 hours long. Our primary comparison star was the *V* = 12.39 star located just 2.7 arcmin south of AM Cvn, the comparison chosen for nearly all earlier studies. Many observers used "ensemble photometry", which increases accuracy. Using the many time overlaps in coverage, we measured the additive constants (usually 0.01-0.08 mag) needed to put all data on a common instrumental scale. Then we removed any small linear trends (usually arising from differential extinction, which in turn arises from the very blue color of AM CVn), merged the data into 3-10 night runs, and calculated power spectra.

Nearly every run showed AM CVn's main features: the positive superhump at 1051.2 s and the negative superhump at 1011.4 s. The large span in terrestrial longitude eliminate daily aliases. In many years the coverage was sufficiently dense and long to parse these signals in more detail, and the results were consistent with the detailed description given earlier by S99 (their Table 2) and Patterson et al. 1992 (their Table 3)[3]. [3We also note that no significant "flares" – such as those reported by Marar et al. (1988) – were observed during our 5000 hours of observation. Nor were any observed during the many hours of earlier coverage (Smak and Krzeminski, private communications). This compares to 30 hours in the Marar et al study. Since the latter employed only a single-channel photoelectric photometer, we prefer the hypothesis of a passing moonlit (terrestrial)

cloud to that of a thermonuclear runaway on a helium white dwarf (Wikipedia entry on AM CVn)].

The positive and negative superhumps wandered in phase on a timescale of a few weeks. Since these wanderings contaminate a search for a weaker *stable* signal, we fit and then subtracted them from each time series. The remaining light curves all revealed a signal at 83.987 c/d (=1028.73 s), which is the orbital signal. Synchronous summations at this period yielded the mean waveforms, which were broadly consistent with each other, and with Figure 6 of S99. There were slight (~0.001 mag) variations in waveform, but the relatively sharp minimum appears to be the best-defined and most stable timing feature. We measured that time in each cluster of data, and record the times in Table 1. However, these should be considered preliminary; a few individual timings may be misprinted or erroneous. We will check this in the final version.

We receive the timings as JD or HJD. The correction to HJD is large, so we present the times as HJD. However, a uniform time base requires a further correction to BJD(TDB). But we omit that correction in this preliminary report, because it is small (leap seconds have been rare in recent years), and because each correction slightly compromises our ability to check for consistency in this large data set relying on contributions from many telescopes. Corrections will be applied at the end of the 2019 observing season, preferably in early morning after two cups of coffee.

We then prepared an O-C diagram, using the first 1992 observation as the epoch and adopting a test period of 0.011906617 days. This is shown in Figure 2, and the quadratic fit indicates a decreasing period, given by the ephemeris:

Minimum light = HJD 2,448,742.56134(14) + 0.0119066194(7)E – 1.6(2)x10^{-13} E^2.

This corresponds to a rate of period change

$$dP/dt = -5.7 \times 10^{-13} \text{ (20 microsec/yr)},$$

or

$$P/(dP/dt) = 5.3 \times 10^7 \text{ years.}$$
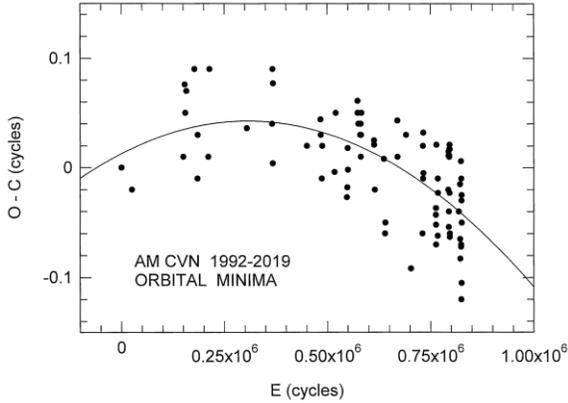
Figure 2. The 1992-2019 O-C diagram for the "eclipse" timings of AM CVn, fit to a parabola. The "sheds water" curvature of the parabola indicates that the period is decreasing, at ~20 µs/yr.

Two comments are appropriate.

(1) The rms disperson of the orbital timings is 0.038 cycles = 39 s. That may seem large, since each timing represents an average over ~300 cycles (of time spanned, corresponding to ~90 cycles of observation). The main culprit here is variability in the amplitude and frequency of the strong negative superhump (at 85.4 c/d, compared to the orbital frequency of 83.99 c/d). This variability confounds a precise removal of the negative superhump. In addition, many runs show a weak signal at the fundamental positive-superhump frequency (82.2 c/d, the "subharmonic" of the famous and obvious 164.4 c/d superhump). The proximity and aliasing potential of these signals to the 83.99 c/d orbital signal is a problem. Finally, the precise waveform of the orbital signal varies slightly.

(2) We observed AM CVn quite frequently in the years prior to the first point (in 1992). These observations were previously described in detail (Patterson et al. 1992). However, we did not come to recognize the importance of the 1028 s signal until 1993, and so the data-taking strategies were not optimum (relatively short time series, with significant aliasing issues). In addition, the absolute time stamps of this early data could not be consistently recovered and checked. So the 1978-1991 data is not used here.

We conclude that the orbital period is decreasing on a timescale of 50 million years.

3. THE DECREASE IN ORBITAL PERIOD

It's very surprising to find AM CVn in a state of orbital-period decrease. Roche-lobe-filling stars (the donors) must satisfy $P^2\rho$ = constant, where ρ is the density of the donor. For P = 1028 s, this implies ρ = 1300 g/cm^3. A thousand times denser than the Sun! That's why the common understanding of the AM CVn class always invokes white-dwarf donor stars. In particular, 1028 s implies M_2 = 0.05 Mo if the donor is a fully degenerate ("cold") white dwarf. But white dwarfs *expand* as they lose matter – and that's a big, big problem. Since $P^2\rho$ = constant, a decreasing period requires an ***increasing*** density. But white dwarfs expand and become *less* dense as they lose matter. Contradiction!

So it's "back to the drawing board".

Nearly all CVs, and certainly the short-period ones, have a low-mass star losing matter to a high-mass star. With angular-momentum conserved, this mass-transfer expands the binary and increases P_{orb}. But there must be a ***driver*** of mass transfer. In ultracompacts, the natural driver is gravitational-radiation (GR), which operates at a precisely known rate – dependent on M_1, M_2, P_{orb} – and removes angular momentum from the binary. ***Thus there is always a competition between a GR spiral-in term and a mass-transfer spiral-out term.***

This calculation has been made many times for AM CVn stars. Under the assumptions commonly adopted, the result is always that spiral-out wins. So all AM CVn stars are expected to be increasing their periods. But measured values of dP/dt are now available for four members of the class; 3 out of 4, including the prototype, are decreasing their periods (at 5, 9, and 17 minutes). Something is seriously wrong.

In the final version of this paper, we will show what that something probably is: the assumption of a WD mass-radius relation. In particular, we calculate that a 0.2 Mo donor (rather then 0.05, which the cold-WD theory requires) will have much more spiral-in and less spiral-out. As required! The trick is to be willing to completely surrender the traditional assumption of a "cold" WD as the donor star.

4. SUMMARY

1. We present the analysis of time-series photometry of AM CVn over a 40-year baseline (1978-2019). This comprises ~1300 nights (~5000 hours) of data, The star always stayed within ~0.1 mag, and usually within 0.05 mag, of its mean brightness (V = 14.18). It's by far the least cataclysmic and least variable of any known CV.

2. The star displayed its usual cornucopia of periodic signals (about a dozen, mostly higher harmonics and precessional sidebands of the fundamental signals), consistent with our earlier analysis of 1992-8 data (S99). The strongest are the positive and negative superhump, at 1051.2 s and 1011.4 s respectively. We separated each season's data into a few clusters with a relatively dense distribution in time, measured the phase and amplitude of the superhumps in each cluster, and then subtracted them separately from each cluster. We then computed the power spectrum of the residual time series, and always found a signal at 1028.7 s. Unlike the superhumps, this signal maintains a stable phase over years, and is the true orbital period.

3. Over the 40-year baseline, the timings of orbital minimum-light show a period decrease of 20 ± 4 μs/yr. A decreasing P_{orb} implies a decreasing orbital separation, which implies a decreasing radius for the donor star. This is inconsistent with the traditional belief that the donor is a normal ("cold") WD. Instead, the donor's radius probably decreases slightly ("semi-degenerate") as it loses mass. "Hardly degenerate at all" might be even more accurate; seemingly, $\rho_2 = M_2/R^3$ must increase as M_2 decreases, implying R_2 proportional to $M_2^{>0.33}$. The secondary is probably a low-mass helium star, not a WD.

4. Under the plausible theory that evolution is driven by GR angular-momentum loss, we can obtain the observed dP/dt with numbers like $M_2 = 0.2$ Mo and dM/dt = 10^{-9} Mo/yr. The GR theory fails if M_2 is substantially less or dM/dt substantially more.

5. ACKNOWLEDGEMENT

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TABLE 1 – (Provisional) Orbital Minima (HJD – 2,400,000)

48742.5612	49041.7147	50526.6726	50570.3826
50589.7425	50617.5923	50855.7963	50938.6413
50945.6310	50977.6733	51211.9952	51252.8096
51292.6620	52349.68235	52364.6729	52368.6026
52369.5673	53102.76483	53117.6844	53123.6486
53129.6504	53840.90405	53844.66631	54104.89700
54176.78582	54499.75634	54507.49544	54535.6422
54903.86634	54941.61096	55259.6715	55272.6141
55282.6280	55291.6887	55565.9466	55568.8635
55576.8052	55590.5338	55644.56545	55657.68665
55660.57961	55667.87855	55679.54737	55712.63617
56040.37710	56042.72365	56064.65418	56326.69531
56359.81871	56365.35541	56709.71873	56717.76868
56721.47116	56727.60332	57109.42322	57438.54630
57444.85828	57449.47783	57458.66908	57466.46866
57466.46866	57469.56370	57826.74985	57829.59560
57830.50033	57834.46500	57840.68135	57880.60356
57882.54462	57887.67625	58182.81750	58190.81912
58195.54527	58200.59377	58210.59600	58213.44176
58216.28737	58218.28780	58221.33538	58226.53904
58228.35980	58231.23062	58475.80374	58488.84120
58525.66865	58529.64482	58531.63300	58540.49320
58550.60166	58555.37493	58558.38730	58560.56554
58562.54350	58564.40080	58566.35244	58568.35368
58570.53260	58572.34218	58574.40245	58584.35640
58586.35716	58588.59496	58590.49937	