OV BOOTIS: FORTY NIGHTS OF WORLD-WIDE PHOTOMETRY

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ABSTRACT

Among the ~1000 known cataclysmic variables, only one appears to belong to the "Galactic halo" - the Population II stars. We report round-the-world photometry of this star (OV Boo) during March-April 2017, when it staged its first certified dwarf-nova outburst. The star is remarkable for its short binary period (66 minutes), high proper motion, metal-poor composition, substellar secondary, sharp white-dwarf eclipses, and nonradial pulsations. Something for everybody…… and it even had the good manners to erupt in northern springtime, when it transits near local midnight. Move over, SS Cyg and WZ Sge; there's a new celebrity in town!

1. INTRODUCTION

As of 2017, several thousand cataclysmic variables (CVs) are known, including ~1200 of known orbital period. Essentially all the orbital periods are short (<1 day), and most are very short (<3 hours). By definition, every CV has a Roche-lobe-filling "secondary star" transferring matter to a white dwarf, and accretion onto the white dwarf powers the luminosity. The "Roche-lobe-filling" condition implies a relation between orbital period and the density of the secondary: $P\sqrt{\rho}$ = constant. A few CVs (~40) have ultrashort periods – in the range 5-40 minutes – and those secondaries must therefore be of very high density. Spectroscopy of these stars shows a nearly pure helium spectrum, and the secondaries are very likely helium white dwarfs. That explains their very high density. This was lucidly explained long ago by Faulkner, Flannery, & Warner (1972).

But the other 97% of CVs show a minimum period of ~80 minutes. In fact there's a big pile-up of CVs right around 77-82 minutes ("period spike"). This is basically because the secondaries are hydrogen-rich main-sequence stars, and the smallest possible star (~0.085 solar masses) has the highest possible density – and hence the shortest orbital period, since $P\sqrt{\rho}$ = constant. So we were quite shocked to find a CV with strong hydrogen emission lines and an orbital period of 66.6 minutes, far below the minimum period. This was SDSS J150722.30+523039.8 (Szkody et al. 2005). Mercifully, the Russians gave it a traditional variable-star name: OV Bootis.

You might think that since 0.085 Mo stars are the densest main-sequence stars, you could explain this oddity by merely hypothesizing a secondary of still lower mass – a brown dwarf. But not so. Lacking the central concentration of more massive "stars" (spherical self-gravitating objects), brown dwarfs are of *lower* density. By way of illustration, consider Jupiter – not quite a brown dwarf, but sufficient to illustrate the point. Jupiter has a mean density around 1 g/cc, like the Sun. But main-sequence stars obey roughly $R \sim M^1$, and hence $\rho \sim M/R^3 \sim M^{-2}$. Get the idea? Low-mass stars have densities far greater than the Sun (~100x greater, for the $R \sim M^1$ assumption). So the secondary in OV Boo is basically a low-mass star... and the spectrum is dominated by hydrogen, so the weirdly short orbital period cannot be explained by supposing it's a helium star.

So we zeroed in on this star and gave it a full photometric and spectroscopic study (Patterson, Thorstensen, and Knigge 2008). We learned the precise orbital period (66.61201 minutes). We learned the masses and radii of white dwarf and secondary, and the orbital inclination. The total eclipse of the white dwarf, along with the very high orbital inclination (85 degrees), permits very accurate measurement of these quantities. Most significantly, we measured the parallax and proper motion, which showed it to have – by a wide margin – the highest proper motion of any CV. This suggested that it might be a member of the Galactic Halo. We followed through with a study of its ultraviolet spectrum, which showed it to be significantly deficient in heavy elements: ([Fe/H] < -1.2; Uthas et al. 2011). This seemed to confirm its credentials as a Population II star – the only one known among all CVs.

Theoretical Pop II stars are slightly smaller, by ~10%, than Pop I stars of the same mass. This is because much of the opacity in the outer layers of Pop I stars comes from "metals" (elements beyond helium), and opacity tends to bloat a star. Pop II stars lack metals. Density scales as M/R^3, so at a fixed mass, that 10% translates to ~ 30% greater density. A 30% increase in ρ means a 15% increase in $\sqrt{\rho}$. Since $P\sqrt{\rho}$ = constant, this means a 15% decrease in P. Thus the minimum orbital period for a Pop II CV should be ~15% shorter, or about 67 minutes.

Well, that's pretty good… and consistent with everything else known about this star (high proper motion, low abundance of metals). A remaining question is whether the unusual abundances might have an effect on outbursts. In March 2017, we had an opportunity to find out. This paper reports our time-series photometry over the first 40 days of OV Boo's first recorded outburst.

2. OBSERVATIONAL TECHNIQUES

Most of the data reported here comes from the Center for Backyard Astrophysics, a global network of telescopes cooperating in campaigns of time-series photometry of variable stars (CBA: de Miguel et al. 2016). The network now includes ~20 telescopes, spread sufficiently over the Earth to give very long time series relatively untroubled by local weather and daily aliasing. Our typical telescope is a 35 cm reflector, equipped with a CCD camera and recording images every 30-60 s for many hours per night. Most of the data is unfiltered (white-light, or perhaps more correctly "pink", with an effective wavelength near 6000 A) differential photometry, although we always obtain some coverage in *V* light to express results on a standard scale if needed. Data from several telescopes are then spliced together to form a one-night light curve, with minimal gaps. We take advantage of overlaps in data to determine additive constants which put all our measurements on one instrumental scale (usually that of the most prolific or best-calibrated observer). These constants are usually in the range 0.01-0.05 mag, probably due to variations in transparency and camera sensitivity. Most telescopes use the same comparison star, although we also use data with other comparisons (requiring larger and more uncertain additive constants) if there is sufficient overlap. In this case we frequently used the AAVSO "115" star (GSC 3868-1067, V=11.482) and "143" star (GSC.3868-1068, V=14.290).

Research programs on faint stars with small telescopes often use white light, to enable high time resolution with good signal-to-noise. In the case of cataclysmic variables, it usually makes good astrophysical sense too, since the underlying sources of light are broad-band emitters (accretion disk, white dwarf). It is common practice to report magnitudes as "C" (or often "CV", though we will avoid this term for obvious reasons): the result of differential photometry in clear light, added to the comparison star's known *V* magnitude. This is also our practice. However, because the white-light passbands are typically ~4000 A wide, the effective wavelengths of the variable and comparison stars can easily be 500 A apart. Therefore, C/CV magnitudes are not *V* magnitudes. We nevertheless prefer the C/CV scale and use it here, because it is our natural measurement scale, and because it accurately expresses the true changes in light.

Since an instrumental scale is not fully reproducible, a standard *V* magnitude is more desirable for archival purposes. For "good" comparison stars (B-V<1.0), our *C* magnitudes transform to *V* magnitudes via

$$\Delta V = \Delta C + 0.37\, \Delta(\mathrm{B-V}),$$

which implies ΔV = -0.20 in this case, where the variable is assumed (and observed) to have B-V near 0.0. The latter assumption is pretty good for the great majority of cataclysmic variables accreting at a high rate – including OV Boo in outburst.

Atmospheric extinction is significant for us, because the program stars are usually much bluer than comparison stars (although we avoid very red stars, which are the bane of all stellar photometry). We know from experience that this differential extinction amounts to ~0.06 mag/airmass for most CVs. Nevertheless, in the spirit of keeping human hands off the data as much as possible, we usually make *no correction for extinction*.

The summary observing log for the first 40 days of outburst is given in Table 1. (A "night" denotes a time-series of good quality lasting at least 3 hours.)

3. THE OUTBURST

On 15 March 2017, the star was reported to be at magnitude 11.4 in the photographic sky patrol of Masaru Mukai (no relation to Koji Mukai, the famous X-ray astronomer). This was the first-ever recorded eruption. Within a few hours, telescopes around the world turned to the star, mostly with time-series photometry.

We observed the star during each of the first 40 nights of outburst, averaging ~11 hours per night. The full light curve is shown in Figure 1. We use here and hereafter a **truncated** heliocentric julian date time stamp (true HJD – 2,457.000). The star declined by 0.10 mag/day for the first 30 days – the so-called "plateau" phase of a dwarf-nova superoutburst. Then it suddenly fell another magnitude and resumed the slow decline.

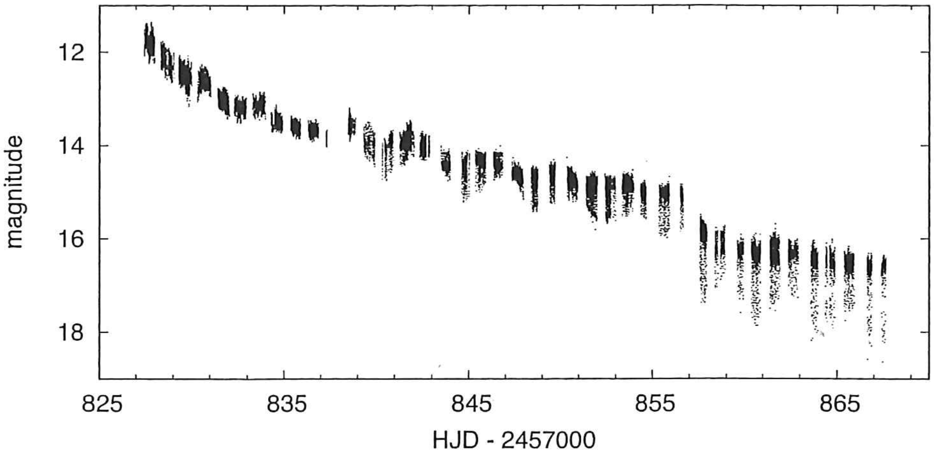

Figure 1. The full light curve over the first 40 days.

The orbital light curve changes smoothly throughout the eruption. This is shown in Figure 2, where we have singled out 4 nights spaced by 10 days, and labelled them with their 3-digit Julian days. Eclipses are seen on every night, but deepen as the star grows fainter. The complex light curve of the first two weeks gradually mutates into a more traditional "superhump" light curve (suggested by the drifting phase of the out-of-eclipse wave between JD 851 and 861).

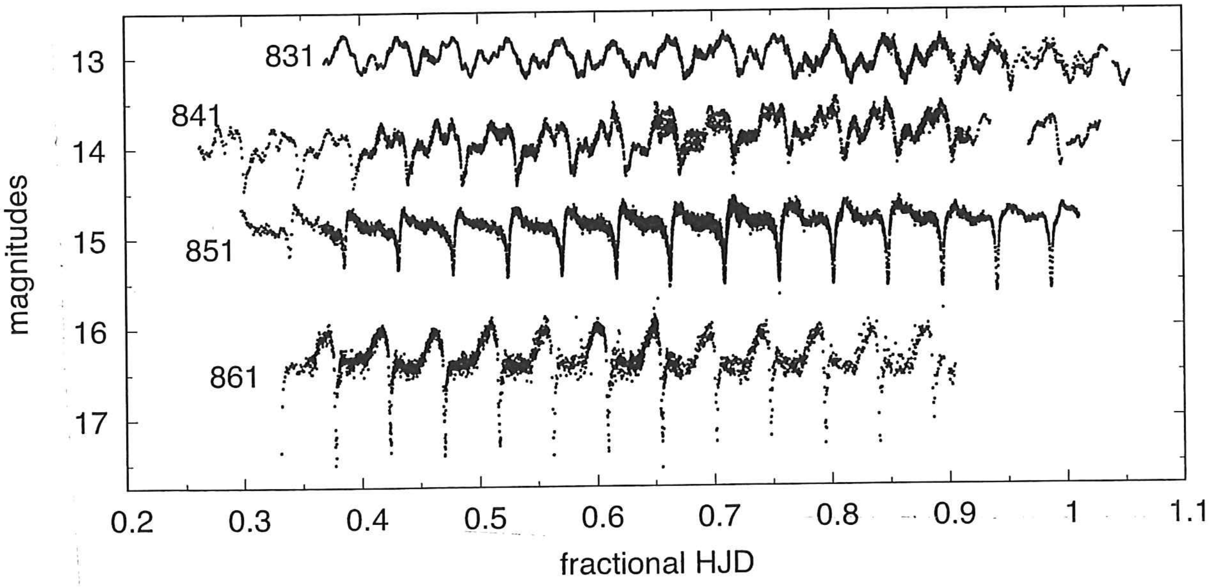

Figure 2. The changing orbital light curve. Light curves are labeled with their 3-digit Julian dates.

Actually, the light curve changes every night, not merely on the 10-day timescale which Figure 2 might suggest. This is illustrated in Figure 3, where each day looks quite distinct, and where the drifting wave can be clearly seen.

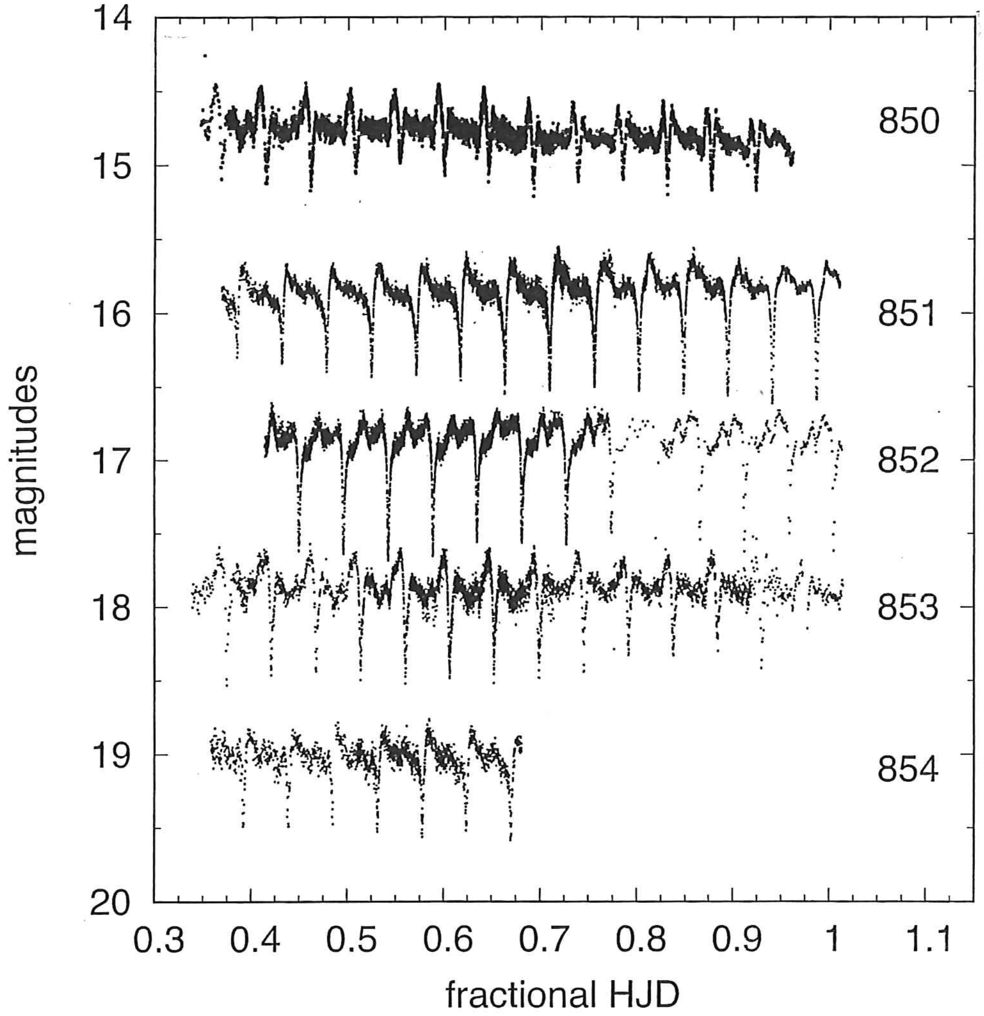

Figure 3. Nightly light curves in one 5-day segment, which illustrates the drifting out-of-eclipse wave. In this figure the magnitudes are correct for JD 850; the others are displaced downwards by 1, 2, 3, and 4 mag, to promote visibility.

To search for periodic behavior in these light curves, we first removed the sharp eclipses. We defined the eclipse portion as spanning from orbital phase 0.9 to 1.1, because that is the eclipse duration commonly found in other deep-eclipsing CVs. Then we took power spectra of segments of the overall light curve. These are shown in Figure 4. In the first 10 days of eruption, the dominant signal occurs at 21.6409 (12) cycles/day – about 0.1% displaced from the known orbital frequency. This signal is commonly found in the dwarf novae of extremely short orbital period, and is called the "outburst orbital hump" (because it occurs very close to ω_{orb}, and is a signature of superoutburst) or "early superhump" (because it is restricted to the early part of superoutburst). It fades after ~10 days, and is replaced by a dominant signal around 21.33(3) cycles/day. In Figure 4 we have parsed the latter signal into "plateau" and "post-plateau", and report their frequencies respectively as 21.3562(20) and 21.3182(20) cycles/day. This wave, dominating the raw light curves, is the famous ***common superhump*** – a universal and indeed defining signature of the "WZ Sge" class of dwarf novae. The frequency resolution is not sufficient to establish whether these are different phenomena, or just one process wandering slightly in frequency, or phase, or even amplitude. Fourier analysis is a powerful tool, but is confounded if its assumptions (constant frequency, phase, and amplitude) are not satisfied.

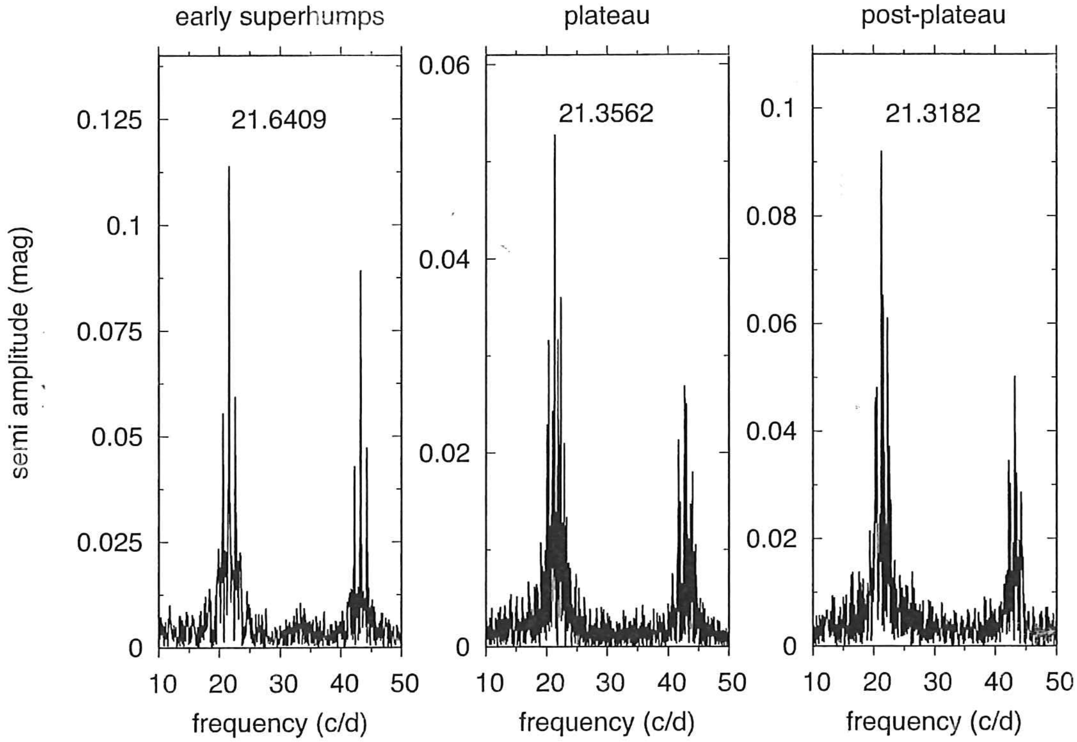

Figure 4. The amplitude spectra, parsed into three segments in time. Each peak is labeled with its frequency in cycles/day, and the fine structure in the first segment reflects the alias pattern in all of them. Therefore the signal is quite complex after the first 10 days, and the division into plateau and post-plateau may be artificial.

Eclipses are present in all light curves, but are relatively shallow, broad, and distorted (asymmetric) in the early portion of the outburst. After JD 838, they become more consistent and appear to show a regular pattern, seen in Figure 5. Here we have established a fiducial epoch of mid-eclipse (HJD 827.70155) as the expected precise time of the first mid-eclipse, based on the 2008 ephemeris. We measure the center of the sharp component seen near the bottom of every eclipse, and record the average of (usually) three consecutive eclipses. The wiggles in Figure 5 suggest a wave of ~75 orbital cycles, or 3.5 days. This appears to be the beat period between orbit and superhump, which is 3.48 days for the compromise frequency we adopt (21.33 c/d).

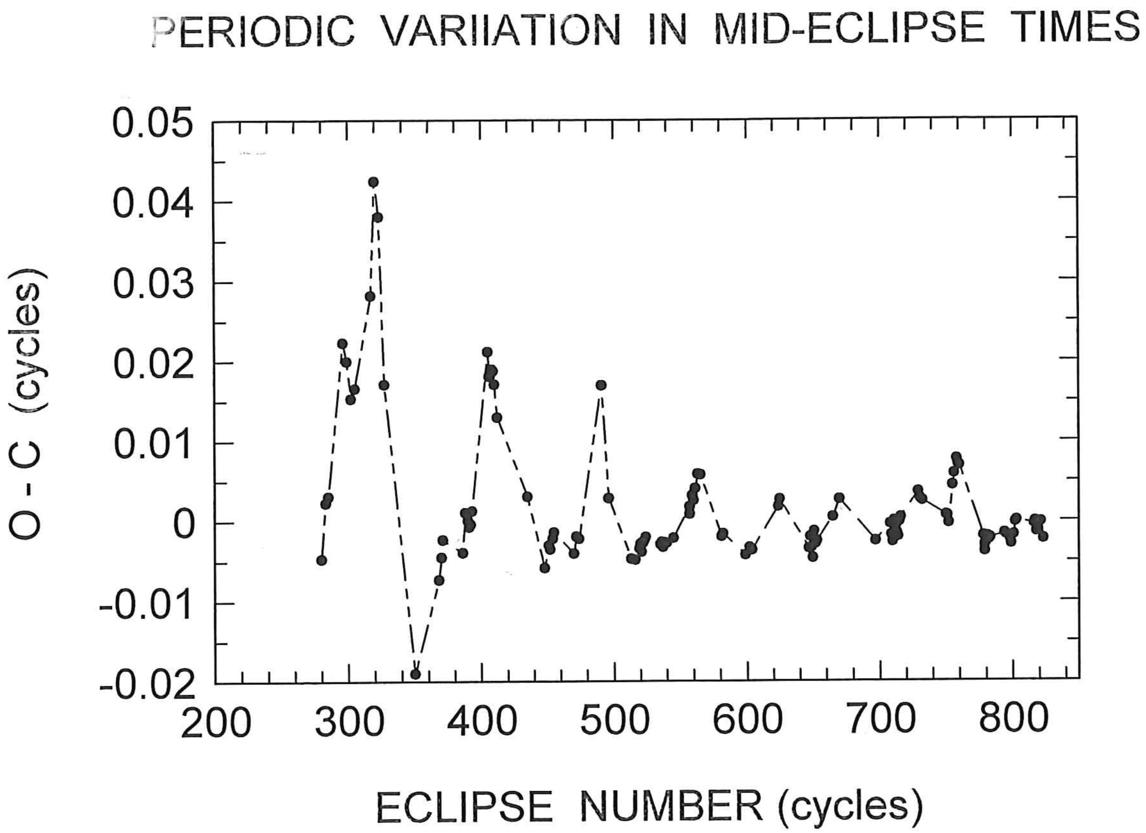

Figure 5. O-C departures from the expected time of mid-eclipse (defined as the middle of the sharp eclipse), based on the ephemeris HJD 827.70155 + 0.046258341 E. There is a wiggle with a timescale ~75 cycles = 3.5 days.

Actually, the fingerprints of "3.5 days" are all over the light curves. The upper frame of Figure 6 shows the mean brightness of the star during the plateau phase. A 3.5 day wiggle is apparent. The lower frame shows the eclipse depth in magnitudes (mid-eclipse minus mean light for the full orbit). An obvious 3.5 day modulation is present, with an apparent phase change during the transition to post-plateau.

4. EXULTATION... AND INTERPRETATION

We were very surprised to see how accurately we could time the eclipses. The timings appear to have a dispersion of just 4-5 s, relative to the overall trend (the "damped sinusoid" in Figure 5. Our telescopes are small, the star is faint, the eclipse is brief, the integration times are long (usually 30-40 s), and the sharp eclipse must be measured amid a broad eclipse which is variable and asymmetric. Formidable problems!. But we had some advantages: the short P_{orb} implies many eclipses; the sharpness of the eclipse makes it easier to measure the mid-point; and we had very frequent overlaps in coverage, yielding the advantage of "crowd-sourcing" ".

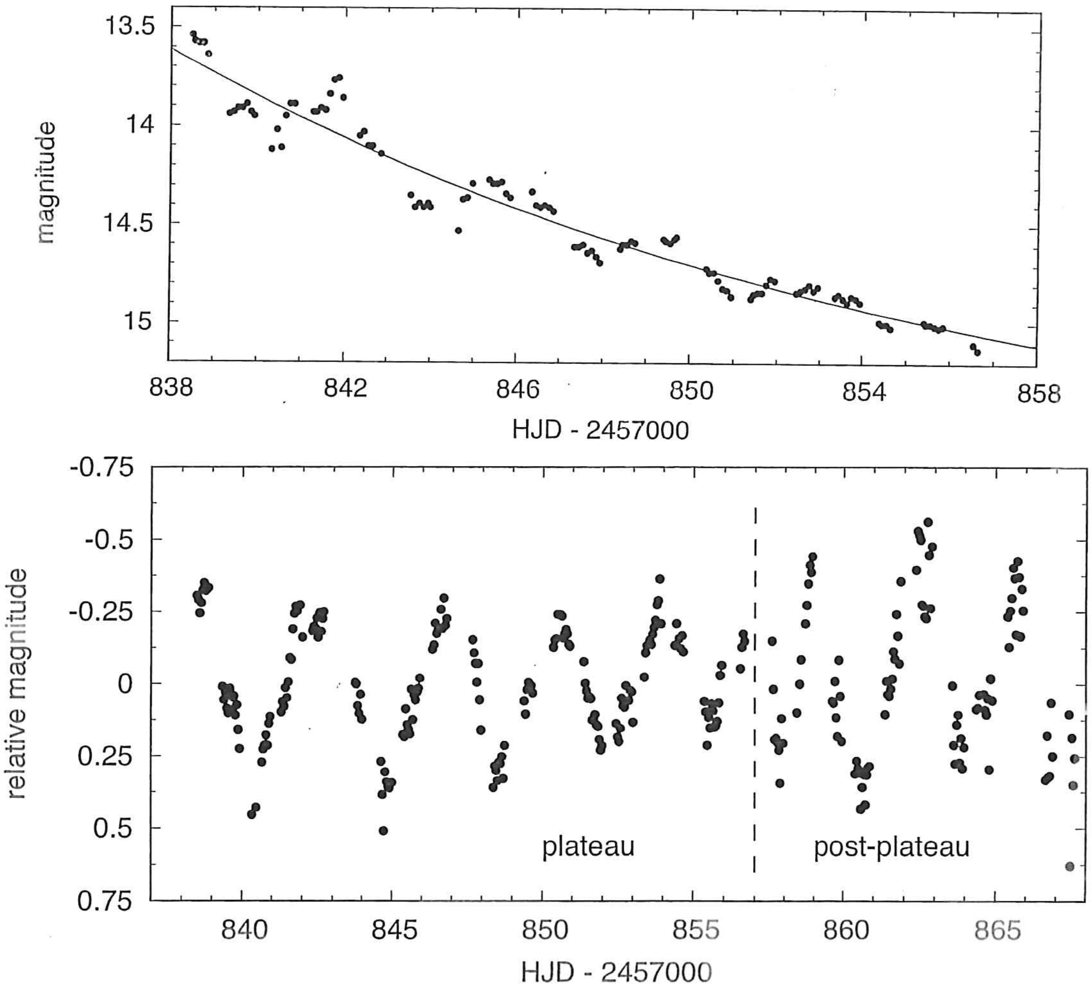

Figure 6. *Upper frame*, the average out-of-eclipse magnitude per orbit, relative to the overall exponential decline. *Lower frame*, the eclipse depth for each orbit (post-plateau measures are noisy because of the faintness and brevity of mid-eclipse).

As of this writing, the eruption is only 40 days old, and the star is still ~2 magnitudes above quiescence. There could be surprises just around the proverbial corner. But the periods found in our analysis are well-determined and free from aliasing, because of the large geographic spread in longitude, and because the length of coverage (40 days) is sufficient to establish the longer period (3.5 days). The outburst orbital hump ("early superhump") occurs at a period 0.1% shorter than P_{orb}; the plateau superhump occurs at a period 1.22% longer than P_{orb}; and the post-plateau superhump occurs at a period 1.40% linger than P_{orb}. From the mass ratio M_2/M_1 = 0.069(2) measured by Patterson, Thorstensen, and Knigge (2005), and the calibration of Patterson et al. 2005 [their Equation (8)], one would ***expect*** a superhump period excess of 1.38(10)%.

So that all looks pretty good. What exactly *are* superhumps?

They are large-amplitude photometric waves, with a period 1-5% longer than P_{orb}, and seen in the large eruptions ("superoutbursts") of many dwarf novae. They were discovered as early as 1972, but their origin remained puzzling until theorists made a breakthrough discovery (Whitehurst & King 1991, Lubow 1991). These studies showed that an eccentricity instability develops at the 3:1 resonance in an accretion disk. Quiescent disks are generally too small to reach that resonance. But when accretion starts, some material must spiral outward to balance the angular momentum lost by the inward-spiralling gas. It reaches the 3:1 resonance, and the disk becomes elliptical. The elliptical orbits are then perturbed by the orbiting secondary, and the orbits precess forward – for the same reason that planets in the solar system precess forward in their elliptical orbits (perturbed mainly by Jupiter). The secondary star then aligns with the disk's line of apsides on a period *slightly longer than* P_{orb}. This is the 67.5 minute superhump period, and the precession period itself is the beat period between the 66.6 m orbit and the superhump. And, happily, that equals 3.5 days.

That's the theory, anyway. The deep eclipses in OV Boo allow us to test the general correctness of these ideas. If the accretion disk is a precessing ellipse, then the center-of-light moves slowly around the white dwarf, and the eclipse times will show the signature of that slow precession. Figure 5 shows just this effect... and we may eventually be able to learn the degree of ellipticity, and how fast it decays.

OV Boo in superoutburst is a pretty good match for WZ Sagittae, the poster-child for all short-P_{orb} dwarf novae. The resemblance is sufficiently thorough that we can, with some confidence, answer our original questions: does the Population II composition affect the creation or properties of outbursts? No, and probably no.

But our observations and analysis are far from over. Bootes has a long observing season, and ours will be filled with extensive photometry and spectroscopy.

Of course, 666 is widely regarded as an ominous and evil number. We take no position on that subject... but for us, 66.6 (minutes) proved to be a very lucky number indeed. So are AST16-15456 and HST-GO-13630, the NSF and NASA grants that keep us going in this enterprise.

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TABLE 1 - OBSERVER'S NIGHTS/HOURS (first 40 nights)

de Miguel	20/132
Cejudo	24/122
Licchelli	29/108
Dvorak	16/104
Vanmunster	18/82
Stone	18/81
Lemay	12/80
Cook, L.M.	18/73
Kroes	13/72
Cook, M.J.	11/68
Ulowetz	11/66
Barret	8/57
Campbell	7/49
Roberts	7/49
Boardman	5/27
Wood	4/32
Wallgren	4/32
Collins	8/31
Seargeant	4/31
Dubois	9/23
Slauson	4/19
Buczynski	4/16
Thorstensen	4/14
Mich. State	4/11
Cooney	2/12
Novak	2/8
Halpern	2/7
Brincat	1/3