ASASSN-18ey (MAXI J1820+070): KING OF THE BLACK-HOLE SUPERHUMPS

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We report an extensive campaign of V-band time-series photometry of the new X-ray transient MAXI J1820+070 = ASASSN-18ey. About 90 days into its outburst, the star developed large-amplitude photometric waves with a period of 0.690(2) days. These are likely to be ***superhumps*** – characteristic of an eccentric instability in the accretion disk of compact binaries with a low mass ratio. Such waves are common in the high state of cataclysmic variables. Their presence here – along with the luminosity, spectrum, and fast variability of the X-rays – probably establishes the accreting star as a black hole of >4 solar masses.

1. INTRODUCTION

Soft X-ray transients (SXTs) are close binaries in which a black hole or neutron star accretes episodically through an accretion disk. The accretion rates parse naturally into high and low states, and in nearly all cases the binaries are initially discovered when they jump suddenly from obscurity into a high state. In this and other respects they seem to bear a close resemblance to the “WZ Sge” subclass of cataclysmic variables (CVs; Haswell et al. 1997, Uemura et al. 2004), in which the accreting star is a white dwarf rather than a black hole. A very common property of the WZ Sge stars is the appearance of large-amplitude photometric waves (*superhumps*) near maximum light. These waves occur with a period several percent longer then the true orbital period, and are particularly useful because the fractional period excess over P_{orb} enables an estimate of the binary's mass ratio (Patterson et al. 2005, Kato & Osaki 2013).

It would be very desirable to apply that reasoning also to the SXTs. And it seems reasonable, since the eccentric instability (Lubow 1991, Whitehurst & King 1991) producing the superhumps originates in the outer disk, where all these binaries are probably similar. But the number of SXTs sufficiently well-studied to furnish such evidence is still very small. Studies of superhumps in SXTs have not progressed much beyond “some SXTs show some evidence for superhumps”.

A newly eruptive object, anointed MAXI J1820+070, was discovered on 11 March 2018 (Kawamuro et al. 2018), and found to coincide with a 12th magnitude star (ASASSN-18ey) which had been earlier noted on 6 March 2018 as part of the daily summary of transients found by the ASASSN survey (Shappee et al. 2014, Denisenko 2018). A flood of Astronomical Telegrams followed. Within a few days, the X-ray source rose to be among the brightest in the sky, with a hard power-law spectrum,

~100 ms flares, and fast quasi-periodic oscillations. A new radio source appeared, suggestive of a synchrotron-emitting jet. These are the familiar signatures of the "hard state" of a black-hole binary, and in particular the SXTs*. Over the subsequent 12 (and counting) months, the star has been studied intensively by X-ray, ultraviolet, radio, and optical/IR telescopes (e.g., Shidatsu et al. 2018, Tucker et al. 2018). Here we report the results of an observing campaign by the globally-distributed small optical telescopes of the Center for Backyard Astrophysics (CBA).

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*We keep this term for historical reasons, but the term "black-hole X-ray novae" (BHXN) is now more accurate and likely to survive. Transients with a neutron-star accretor have significantly different characteristics (Done 2007).

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2. THE LIGHT CURVE

The data consist of nightly time-series photometry assembled from individual runs by ~20 small (0.2-0.6 m) telescopes scattered around the world. CBA data collection and analysis methods have been discussed elsewhere (Patterson et al. 2013). We obtained ~2000 hours of coverage in V and unfiltered light over 162 of the first 200 nights of the eruption, and converted all data to a V-magnitude scale (using additive constants measured when runs were simultaneous). The nightly runs ranged in duration from 3 to 22 hours, and averaged ~11 hours.. Time resolutions as short as 2-5 s were common in the first few weeks, but we settled on 20-40 s for the remainder of the campaign.

Early in the eruption, our data showed strong and chaotic variability on a timescale of a few seconds, as reported by many observers in X-ray and optical bands. Several X-ray reports cite 100% amplitude variability on a timescale ~100 ms. Such phenomena are somewhat commonly seen among the accreting black-holes (GX339-4, V404 Cyg, KV UMa), but never seen among CVs, whose characteristic timescales for flickering and quasi-periodic oscillations are ~100x slower, and whose characteristic amplitudes are ~10x smaller. Along with the X-ray flux and spectrum, and the radio detection, these observations firmly exclude identification as a CV and strongly support classification as a black-hole SXT.

Figure 1 shows the daily average flux in *V* (our data, except for the very earliest data, mined from the flood of ATel reports) and 15-50 keV X-ray (Swift BAT) bands during the first 250 days of the eruption.

The $F_X//F_V$ flux ratio is ~500, which is characteristic of accretion onto black holes and neutron stars, rather than white dwarfs (because of the much deeper gravity well). The timescales of these light curves are similar to those of previous SXTs. But the notable feature here, not clearly seen in previous SXTs, is the simultaneous smooth increase in X-ray and V flux around days 300 and 400. These are reminiscent of the “echo outbursts” or “rebrightenings” seen in some SXTs (esp. GRO J0422+32, see Figure 3 of Callanan et al. 1995, and Figure 3 of Goranskii et al. 1996) and in many dwarf novae of short orbital period (e.g. WZ Sge, see Figure 1 of Patterson et al. 2002).

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In December 2018, the star had faded to 17th magnitude, and disappeared in the solar glare. Two months later, Joe Ulowetz's patrol in the morning twilight was rewarded when he glimpsed the star at 15th magnitude and brightening (Ulowetz, Myers, & Patterson 2019). This recovery – apparently yet another rebrightening – takes us to the present. The star is still eminently worth watching!

3. PERIODIC SIGNALS

Until day 230, the nightly light curves were dominated by the chaotic several-second variability (likely containing some yet-faster variations, since our time resolution was 2-4 s)..Around day 240, variations with a timescale of hours first appeared, No stable periodic signal was evident for the next 35 days. Near the “superhump” frequency found sightly later, the semi-amplitude upper limit was ~0.05 mag (and for higher frequencies, much lower). Around day 275, a periodic signal with P ~ 0.7 days became obvious, dominating the light curve over at least the next 100 days Patterson et al. 2018). Figure 2 shows the progression of light curves in 10-day frames, and Table 1 gives the measured times of maximum light in the 0.7 day variation. The mean period is 0.6903(3) days, and the mean waveform is fast-rise/slow-decline, as is characteristic of dwarf-nova superhumps.

. Well-studied SXTs are compact binaries with orbital periods in the range 0.2-20 days, so the detected signal is a natural candidate for the underlying orbital period. However, the phase of the signal slowly drifted as the outburst proceeded, and it was quickly evident that it could not represent the orbital period, Instead, the drift (as well as the waveform) resembled that commonly shown by dwarf-nova superhumps. There are a few precedents for such behavior in previous SXTs; reviews are given by Haswell et al (2001) and Uemura et al. (2004). In some cases the evidence is rather weak; just four detections are described as “certain” by Uemura et al. But they are very common in cataclysmic variables, occurring in essentially *all* short-period CVs (many hundreds) during large outbursts. Thus they would be no great surprise here, since the SXT phenomenon is commonly regarded as the black-hole/neutron-star analogue of CV “superoutbursts” (e.g. Cannizzo 1998, Lasota 2001).

4. THE SUPERHUMP STORY

The identifying features for CV superhumps are these:

(1) They always occur in large outbursts (“supermaxima”), and never in small outbursts.
(2) They generally rise in amplitude as the star brightens, but sometimes after a delay

of ~10-15 days.
(3) When they first appear, they show a characteristic (but not universal) waveform: fast rise, slow decay.
(4) Their periods are a few percent longer than P_{orb}, and slightly change (usually *decrease*) as the outburst proceeds.
(5) They are essentially universal in the long outbursts of binaries with $M_2/M_1<0.35$, and (seemingly) never found in binaries of larger mass ratio.

These are the features of common superhumps in CVs. How does ASASSN-18ey score by these admission criteria?

It scores well with (2) and (3)., and is at least consistent with (1). (5) will have to wait for future studies, since the mass ratio is not yet known. That leaves (4), which is the critical distinction between orbital and superhump periods. True orbital period changes can only occur on long timescales (>10^7 years), while superhump period changes require only a small change in the properties of the accretion disk (e.g. radius). We looked for small period changes by timing the fairly sharp maxima in the nightly light curves. Over the course of the hundred-day duration of the superhumps, the phase drifted by ~0.3 cycles, which corresponds to a timescale P/(dP/dt)~1000 years. Thus they can only represent some transient process, such as an episode of sudden accretion – the usual model for SXTs.

5. OTHER PERIODS?

The only other significant and recurring features in the power spectrum are harmonics of the superhump frequency. We then subtracted the mean superhump (with second harmonic) from each 10-day interval, and searched the residual time series for a periodic signal. We did not find any, to a semi-amplitude upper limit of 0.03 mag. This could be considered an upper limit for an *orbital* signal.

We did see a weak but possibly significant signal near 0.6883 days in the last 60 days of our 200 days of coverage. Under the assumption that this represents the true orbital period, the superhumps appear at a period 1.5% longer – or, in the language of superhumps, with a period excess ε = 0.015.

We mention this just for the record. No other evidence yet favors this interpretation. The amplitudes and shapes of the periodic signal change somewhat during the outburst, but do not seem to be linked to the date of that slope change in the O-C. That casts doubt on the “orbital-period”: interpretation.

6. MASSES FROM PERIODS

The traditional method for measuring masses in binaries requires a double-lined spectroscopic binary which eclipses (or is of known inclination). This luxury is essentially never available for CVs, which are generally not double-lined and of poorly known inclination, Nevertheless, the period and Roche-lobe-filling constraints enable a measurement of the mass ratio in CVs, and the measurements indicate essentially that common superhumps are guaranteed in binaries with a mass ratio q<0.3, and forbidden for significantly higher q (Patterson et al. 2005). That paper also establishes a simple relationship between q and the fractional period excess ε of superhump period over orbital period:

$$\varepsilon = 0.18q + 0.29\, q^2,$$

where ε is defined as $(P_{sh}-P_{orb})/P_{orb.}$

The precise value of P_{orb}, and therefore ε, will probably have to wait another year or two, when the eruption light fades sufficiently to reveal the binary structure within. But if the superhumps are anything like those seen in CVs, then the two numbers we do know (P_{orb} near 0.7 d, and q<0.3) enable us to make a preliminary estimate of masses.

An empirical main sequence is known for the donor stars in cataclysmic variables (Figure 3 of Knigge 2006). For long orbital periods (>8 hours), it is close to an ordinary main-sequence relation [$R/Ro = (M/Mo)^{0.9}$]. This implies that to fill the Roche lobe of a 0.69 d binary, the secondary should have M_2 ~1.4 Mo. This is permitted by the brightness at quiescence (V = 18.5) and the estimated distance constraint of 3.1 (+1.5, -0.8) kpc (Tucker et al. 2018). And since $q = M_2/M_1 < 0.3$, this implies that the mass of the primary (M_1) should exceed 4 Mo.

On the (somewhat unlikely) assumption that 0.6883 d represents the orbital period, then the ε(q) relation implies M_1~20-30 Mo. Successful measurement of the orbital period will straighten this out!

7. SUMMARY

1. In luminosity, spectrum, and X-ray and optical light curve, ASASSN-18ey appears to be a fairly typical SXT, with a black-hole accretor. About 90 days into its outburst, it began to show 0.7 day large-amplitude waves in its optical light curve. These lasted for at least 80 days, were somewhat variable in period, and greatly resembled the superhump variations seen in cataclysmic variables and a few other SXTs. They are by far the best exemplar of superhumps among the SXTs.

2. Most superhump lore concerns “common” superhumps, which show positive period excesses of a few percent, and are born in episodes of greatly increased accretion. The obvious periodic signals in ASASSN-18ey are apparently of this type. Considerable evidence among the CVs suggests that these arise from an eccentric

instability at the 3:1 resonance in the accretion disk. This explains why they are only found in binaries with a mass ratio q <0.3 (because only in *those* binaries can the disk extend as far out as the 3:1 resonance).

3. The mean photometric period is 0.694 (2) d, and it decreased with P/(dP/dt) = 2×10^3 years. It is this period change which decisively establishes the signal as a superhump (rather than an orbit, which would be vastly more stable).

4. We did not succeed in measuring the underlying orbital period of Maxie (as we now call it, since it has been so good to us). That will apparently have to wait until the star reaches or approaches quiescence – at which point both spectroscopy and photometry will probably be able to measure it. Compared to dwarf novae, everything about this binary – the masses, the duration of outburst, the characteristic energies of the emitted photons, the characteristic frequencies of fast (and, for that matter, slow) variability – is 10-20 times bigger!

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FIGURE CAPTIONS

Figure 1. ***Upper frame*****, daily average 15-50 keV (Swift BAT) flux the first ~240 days of the eruption.** ***Lower frame*****, daily average V magnitudes from CBA data (averaging over the 17-hour variation). Superposed on the slow decline, around days 285 and 400, are apparently linked echo outbursts in both X-ray and optical light. The event near day 285 coincides with the birth of superhumps, to an accuracy of ~5 days.**

Figure 2. ***V*****-band light curve over the first 30 days in which the periodic signal dominated the light curve. However, the periodic signal may have appeared, at lower amplitude, as early as day 272.**

TABLE 1 - TIMES OF MAXIMUM LIGHT IN THE 0.7 DAY CYCLE (HJD 2,458,000+)

273.41	274.85	276.93	278.46	279.93	280.517	281.949
282.651	284.701	285,430	286.856	287.538	289.641	291.722
292.426	293.800	294.490	295.179	295.871	296.558	298.612
300.667	301.369	302.752	303.433	304.101	304.793	305.429
307.568	309.610	311.680	312.380	313.765	314.463	315.122
316.481	317.858	318.588	319.947	320.641	321.994	322.693
323.378	324.742	325.428	326.806	327.493	328.868	329.545
330.980	331.653	332.327	332.994	333.679	334.408	335.717
336.454	337.826	338.521	340.562	342.644	345.439	346,787
347.444	349.573	350.910	351.596	352.981	353.610	355.719
356.423	358.563	359.839	362,643	364.638	365.333	367.488
369.572	370.904	371.555	372.953	373.628	374.370	378.476
379.300	382.63	384.62	385.41	386.74	389,52	