Optical Studies of Eight AM Herculis–type Cataclysmic Variable Stars

John R. Thorstensen1, Mokhine Motsoaledi2,3, Patrick A. Woudt2, David A. H. Buckley3, and Brian Warner2
1 Department of Physics and Astronomy, 6127 Wilder Laboratory, Dartmouth College, Hanover, NH 03755-3528, USA
2 Department of Astronomy, University of Cape Town, Private Bag X3, Rondebosch 7701, South Africa
3 South African Astronomical Observatory, P.O. Box 9, Observatory 7935, Cape Town, South Africa

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Abstract

We report detailed follow-up observations of eight cataclysmic variable stars (CVs) that are apparently AM Her stars, also called polars. For all, we either determine orbital periods for the first time or improve on existing determinations. The seven for which we have spectra show the high-amplitude radial-velocity curves and prominent He II λ4686 emission lines characteristic of strongly magnetic CVs, and their periods, which range from 81 to 219 minutes, are also typical for AM Her stars. Two objects from the Gaia-alerts index, Gaia18aot and Gaia18aya, are newly identified as CVs. Another, RX J0636.3+6554, eclipses deeply, while CSS 080228:081210 +040352 shows a sharp dip that is apparently a partial eclipse. The spectrum of Gaia18aya has a cyclotron harmonic near 5500 Å that constrains the surface field to ~49 MG or greater.

Unified Astronomy Thesaurus concepts: Cataclysmic variable stars (203); AM Herculis stars (32); Eclipsing binary stars (444); Close binary stars (254); Interacting binary stars (801); White dwarf stars (1799)

1. Introduction

Cataclysmic variable stars (CVs; Warner 1995) are close binary systems in which a white dwarf accretes material from a more extended companion, usually resembling a main-sequence star, which overflows its Roche lobe (critical equipotential surface). The name arose because the first known examples underwent outbursts—classical nova explosions occur when nuclear fuel accumulated on the white dwarf’s surface explodes, and the more common dwarf novae undergo outbursts when gas accumulated in an accretion disk becomes unstable and rapidly accretes onto the white dwarf.

Magnetic CVs—in which the white dwarf is strongly magnetized—can behave quite differently. They are usually much stronger X-ray emitters than nonmagnetic CVs. If the magnetic field is not especially strong, an accretion disk can form far from the white dwarf, but the inner disk is disrupted and the field forces material to fall onto the poles of the white dwarf. Systems of this kind are called DQ Herculis stars (Patterson 1994), or intermediate polars, and they show pulsations in the X-ray and optical bands at the rotation period of the white dwarf and/or the orbital sidebands (e.g., the orbital-spin beat). A still stronger magnetic field can disrupt the formation of an accretion disk entirely; often, magnetic torques force the white dwarf to corotate with the orbit, though the coupling is weak enough that the white dwarf can sometimes be temporarily knocked out of corotation. In these systems, at least some of the matter lost from the companion threads onto the magnetic field and falls directly onto the white dwarf’s magnetic poles via magnetically confined accretion columns. CVs of this kind are classified as AM Herculis stars, after their prototype, and are also called polars (Cropper 1990), because they often show strong circular polarization modulated at the orbital (=rotational) frequency.

It is often easy to recognize an AM Her star even without polarization measurements. When they are accreting actively, their spectra show strong emission lines, with high excitation; the He II λ4686 emission is usually comparable in strength to Hα. Because the emission lines arise largely in the accretion column, their radial velocities are often dominated by infall, which can reach velocities much higher than the white dwarf’s orbital speed. The rotation of the white dwarf changes our viewing angle, leading to large variations in velocity (up to a few thousand km s−1) that are periodic with the white dwarf rotation period, which in corotating systems is the same as the orbital period Porb. The brighter parts of the accretion column can also disappear over the limb of the white dwarf as it rotates, causing the intensity of both the lines and the continuum to vary. As with any binary system, eclipses also occur if the inclination is high enough. Typically, most of the eclipsed flux arises from the bright base of the accretion column (or columns).

We have been observing CVs, mostly spectroscopically, to characterize them and in particular to measure their orbital periods when possible. Here we present a study of eight CVs that are apparently AM Her stars. Table 1 lists the stars discussed here.

In Section 2, we describe the instrumentation and techniques used for our observations, reductions, and analyses. Section 3 gives detailed information on the individual objects. Section 4 summarizes and draws attention to the results we think are most interesting.

2. Techniques

Nearly all of the data presented here are from MDM Observatory, on Kitt Peak, Arizona. Here we only summarize our observing protocols, data reduction, and analysis techniques, because they were mostly similar to those described in previous papers (e.g., Thorstensen et al. 2016; Halpern et al. 2018).

2.1. Spectroscopy

Most of our spectra are from the “modspec” spectrograph,4 usually mounted on the 2.4 m Hiltner telescope, though occasionally on the 1.3 m McGraw-Hill telescope. A 600 line mm−1 grating gave 2 Å pixel−1 with either of the two SITe CCD detectors (2048×
Table 1
List of Objects

| Name               | αICRS  | δICRS   | G     | 1/πDR2 (pc) |
|--------------------|--------|---------|-------|-------------|
| Gaia18aot          | 02:11:07.987 | +30:54:06.96 | 18.87 | 513 (+99, −72) |
| PT Per             | 02:42:51.197  | +56:41:31.12 | 18.36 | 185 (+5, −4)   |
| RX J0636.3+6554    | 06:36:22.915  | +65:54:14.77 | 18.86 | 438 (+52, −42) |
| CSS 080228.081210+040352 | 08:12:10.239 | +04:03:51.43 | 18.71 | 1500 (+800, −400) |
| SDSS J100516.61+694316.5 | 10:05:16.583 | +69:41:36.41 | 18.84 | 1640 (+850, −420) |
| SDSS J133309.20+143706.9 | 13:33:09.186 | +14:37:06.93 | 19.71 | ... |
| SDSS J134441.83+204408.3 | 13:44:41.834 | +20:44:08.61 | 18.29 | 591 (+74, −59) |
| Gaia18aya          | 22:04:50.675  | +40:08:38.51 | 18.44 | 430 (+40, −34) |

Note. Positions, mean G magnitudes, and distances from the GAIA Data Release 2 (DR2; Gaia Collaboration et al. 2016, 2018). Positions are referred to the ICRS (essentially the reference frame for J2000), and the catalog epoch (for proper motion corrections) is 2015. The distances and their error bars are the inverse of the DR2 parallax $\pi_{DR2}$ and do not include any corrections for possible systematic errors.
or 1024\(^2\) we used. We reduced these data with IRAF software driven by Python scripts, but extracted the two-dimensional spectra to one-dimensional spectra using our own implementation of the optimal extraction algorithm described by Horne (1986). For wavelength calibration, we derived a pixel–wavelength relation from comparison lamps taken in twilight and then adjusted the zero point using the [OI] \(\lambda5577\) airglow feature, as with this instrument a linear shift accurately compensated the flexure of the Cassegrain-mounted spectrograph as the telescope moved.

The most recent observations are from the Ohio State Multi-Object Spectrometer (OSMOS; Martini et al. 2011) mounted on the 2.4 m, using the blue grism and “inner” slit, which gave 0.7 Å pixel\(^{-1}\) and \(\sim3\) Å resolution. While the reductions were generally similar to modspec, OSMOS required a more elaborate wavelength-calibration procedure because the pixel-to-wavelength scale was less stable. To adjust the wavelength scale, we either measured airglow features (tabulated by Osterbrock et al. 1996) or took short Hg and Ne lamp exposures adjacent to our science exposures.

We measured radial velocities, mostly of H\(_\alpha\), in the individual exposures by convolving the line profile with an antisymmetric function as described by Schneider & Young (1980). The choice of convolution function serves to emphasize different parts of the line profile (Shafter 1983). For the most part, we chose the derivative of a Gaussian as the convolution function, which provides a measure of the “overall” location of the line, including the line core.

The emission lines of AM Her stars display complicated profiles that change through their orbits. We display these by creating two-dimensional images as follows. In most cases, we start by rectifying the spectra, that is, dividing them by a smooth function fitted to the continuum. Cosmic rays and other obvious artifacts are then edited out by hand. We compute the orbital phase of each spectrum, divide the orbital cycle into 100 phase bins and average together spectra that fall within a window of each phase point, using a weighting function that is a truncated Gaussian in phase, centered on the phase point. Finally, we stack the averaged spectra into a two-dimensional image, repeating a cycle to avoid discontinuities. The sources studied here are rather faint, so some of our sources required exposure times of 720–900 s for adequate signal-to-noise ratio; this resulted in some phase smearing. Even so, most of the trailed emission-line spectrograms show a rather sharp component that is brightest as it swings from red to blue. This behavior is consistent with emission from the side of the companion star irradiated by the X-ray and ultraviolet flux from the white dwarf (see, e.g., Schwope et al. 1997, and for a very early example, Thorstensen et al. 1978).

For one of our targets, CSS 080228:081210+040352, we also obtained four spectra with the Southern African Large Telescope (SALT; Buckley et al. 2006); these are described in Section 3.4.

2.2. Photometry

The MDM time-series photometry is from the 1.3 m telescope, mostly with an Andor IKON CCD frame-transfer CCD. Some of the photometric data were taken with a 1024\(^2\) pixel SITE CCD, cropped to a 256\(^2\) pixel subarray to reduce the CCD readout time. The reduction script performed aperture photometry on the program star, a comparison star, and several check stars in each frame.

We also include some time-series photometry from the 1 m telescope at the South African Astronomical Observatory, taken using the Sutherland High-speed Optical Camera (Coppejans et al. 2013) and an Andor iXon 888 EM-CCD camera.

The OSMOS spectroscopic target acquisition procedure requires at least one direct exposure to place the slit on the target. We took these through a Sloan g filter and developed an automated program to infer the target’s g magnitude. The script detects the stars in the image, matches them to entries in the PAN-STARRS 1 Data Release 2 catalog, performs aperture photometry, establishes the offset between the instrumental magnitude and the cataloged \(g\) and, from this infers the \(g\) magnitude of the target just before the spectra were taken. Because the offset between instrumental and cataloged magnitude is common to the program and field stars, the procedure is differential. Given adequate signal-to-noise ratio, it is accurate even in thin clouds and poor seeing.

3. The Individual Stars

3.1. Gaia18aot

This source was listed in the Gaia Transient Alerts on 2018 March 7, with an alerting magnitude of 17.32. Its Gaia light curve shows irregular fluctuations, mostly between 18th and 19th magnitude, but sometimes fainter than 20th. The Catalina Real Time Survey (CRTS) Data Release 2 light curve is similar, but also shows a brief flare on 2007 November 2 that reaches 16.0.

Most of our spectra are from 2018 September. The mean spectrum (Figure 1) shows the strong emission in the Balmer, H\(_\alpha\), and H\(_\beta\) lines characteristic of magnetic CVs. The emission-line velocities vary with \(P \sim 114\) minutes, in a nonsinusoidal pattern (Figure 1). We obtained some velocities in 2018 November, 2018 December, and 2019 January.
Combining these, we found $P = 0.078830(2)$ days, with no ambiguity in cycle count.

On the same observing runs, we obtained multiple orbits of the time-series photometry, which are summarized in Figure 2. The object remained in a similar photometric state through all our runs and showed modulation at the orbital period, most notably a rapid decrease in flux around phase 0.2 in the radial-velocity ephemeris and a more gradual recovery around phase 0.7. The small scatter of the phase of rapid decrease over multiple observing runs corroborates the already-secure choice of cycle count.

### 3.2. PT Per

Watson et al. (2016) reviewed the history of this object and characterized it as a “relatively obscure and poorly studied CV.” They analyzed an 18 ks serendipitous XMM-Newton observation of this source from 2011 July and found deep minima in the X-ray light curve, recurring with a 4900 s period. They also obtained optical spectra from the William Herschel Telescope on three successive nights in 2015 April, at airmass $>3$, and in evening twilight, which showed no strong emission or absorption features, but did show weak Zeeman-split absorption at Hα and Hβ, consistent with a magnetic field of $\sim 25$ MG. They suggested that PT Per is a polar and that their optical spectra were taken in a low state. Their observations indicated a relatively small distance, perhaps as near as 90 pc, and indeed its Gaia DR2 distance of $1/\pi = 185(+5, -4)$ pc makes it the closest object studied here.

In 2019 January, we found PT Per in a much more active state and obtained spectra with OSMOS on two successive nights. The spectra (Figure 3, top) showed strong emission
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We took spectra of this star in 2018 February. The mean spectrum (Figure 5, top panel) shows strong emission lines on a blue continuum, with \( \text{He II} \lambda 4686 \) nearly as strong as H\( \beta \). Passing the fluxed spectrum through the \( V \) response function tabulated by Bessell (1990) gives \( V \sim 17.9 \), so we caught the system in a relatively bright state. The emission lines immediately showed large velocity swings on a period just over 100 minutes (Figure 5, middle and lower panels).

The star disappeared from time to time during the spectroscopy, so we obtained time-series photometry on the same observing run (see Figure 6). This showed eclipses \( \sim 2 \) mag deep and lasting \( \sim 6 \) minutes on a \( \sim 103 \) minute period, as well as out-of-eclipse flickering. Over the last two years, we have observed 23 eclipses, including two that were generously observed by Karolina Bąkowska in 2018 April. Table 2 gives the times of the eclipse center, along with the cycle count and residuals from the best linear ephemeris, which are

\[
\text{BJD mid–eclipse} = 2458174.62129(5) + 0.071221298(9),
\]

where \( E \) is an integer eclipse number and the time base is UTC. Nearly all of our time-series photometry was relative to a star \( \sim 81^\circ \) from the program object in position angle \( \sim 63^\circ \), for which Gaia DR2 lists \( \alpha = 6:36:34.75 \) and \( \delta = +65:54:51.7 \). The PAN-STARRS Data Release 2 gives \( g_{\text{PSF}} = 17.07 \) for this star, which we added to our differential magnitudes. During our 2018 February and April observations, the out-of-eclipse magnitude averaged \( g \sim 18.1 \), while for all of our other time-series photometry, it was much fainter at \( \sim 20.1 \).

Figure 7 shows the brighter- and fainter-state eclipse light curves in greater detail. In both the brighter and fainter states, the egress is sharply defined and occurs at a very consistent phase. Our exposures (typically 20 s) do not resolve the sharp rise in egress. In the fainter state, the ingress is also very consistent, but in the brighter state there is significant dispersion in the ingress phase. This suggests that in the bright state, a significant source of light lags behind the trailing side of the white dwarf; a natural candidate for this would be an accretion stream that fades away during the faint state. In some light curves, the ingress starts slightly earlier than in others, suggesting an extra source of obscuration, which might be the outermost parts of the accretion stream.

We also note that in the bright-state egress, following the initial rapid rise, the object consistently undergoes a slower, steady brightening. This may be explained by the gradual uncovering of the inner part of the magnetically threaded accretion stream.

The eclipse in the fainter state appears to be that of the white dwarf alone, and we conservatively estimate the full width to be \( 412 \pm 8 \) s. If the secondary star fills its Roche lobe, this implies a minimum \( q = M_2/M_{\text{WD}} \) of 0.11 to 0.13 for an edge-on orbit (Chanan et al. 1976). In nonmagnetic systems, the relationship between \( P_{\text{orb}} \) and \( q \) has been calibrated at short periods (see, e.g., Patterson 2011); dwarf novae at this period have \( q < 0.2 \), which if applicable here implies an upper limit for \( i \) of \( \sim 83^\circ \). Assuming an implausibly large \( q = 1 \) gives \( i \sim 73^\circ \).

Taking \( 90^\circ \leq i < 83^\circ \) constrains the dynamically important quantity \( \sin i \) to an accuracy of better than 3%, so if we did have a reliable measurement of the secondary’s velocity amplitude \( K_2 \), we could in principle determine \( M_{\text{WD}} \) quite accurately. Although the secondary is likely to be extremely

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**Figure 4.** Photometry of PT Per from two successive nights. The phase is treated as in Figure 2. Phase zero corresponds to blue-to-red crossing of the radial velocity. No vertical offset is applied. The large squares, from OSMOS setup images, were taken with a g filter; the time-series points were taken almost unfiltered and were adjusted to agree with the calibrated OSMOS magnitudes obtained simultaneously.

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lines, in contrast to the Watson et al. (2016) spectra. Large, rapid radial-velocity shifts were immediately apparent; an analysis of the velocities over the two nights gives a period \( P \approx 81.0(4) \) minutes, with no cycle-count ambiguity, in reasonable agreement with the 81.7(4) minute period found by Watson et al. (2016). The phase-resolved spectra in the middle panel of Figure 3 shows the large velocity shifts, as well as the asymmetric line wings characteristic of AM Her stars. Large blueshifted velocity excursions are also seen, near phase \( \sim 0.7 \), typical of polars. The H\( \alpha \) radial velocities (lower panel) are modulated almost sinusoidally. The velocity half-amplitude, \( K = 340 \pm 14 \text{ km s}^{-1} \), is much too large to be plausibly orbital, so the infall velocity of the accretion column causes most of the velocity shift.

The high-state data amply confirm that PT Per is an AM Her star, as suggested by Watson et al. (2016). They note that their optical data were taken in a remarkably low state, with no clear emission lines, whereas most AM Her stars continue to show some emission lines even in very low states.

On 2019 January 21 and 22, we used the 1.3 m telescope and Andor camera to obtain the time-series photometry shown in Figure 4. The light curve shows two maxima per orbit, along with some flickering. There is no sign of an eclipse, so the correspondence between the orbital phase plotted and the locations of the stars in their orbits is not constrained. The double-humped light curve indicates that accretion likely occurs onto two poles.

**3.3. RX J0636.3+6554**

Appenzeller et al. (1998) discovered this star as the optical counterpart of a ROSAT X-ray source; they noted it was blue, variable on a timescale of hours, and that one of their spectra showed broad H\( \alpha \) emission at rest velocity. It was listed in the Downes et al. (2001) catalog, but apparently no follow-up studies have appeared. The CRTS Data Release 2 light curve (Drake et al. 2009) shows a short-term variation of about 1 mag superposed on a gradual decline from \( \sim 17.6 \) mag in 2006 to about 20.0 mag in 2013.
faint, similar systems often have a strong, narrow component in their emission-line profiles that arises on the side of the secondary facing the white dwarf. Our spectroscopy shows a hint of this, but at our spectral resolution it is not cleanly defined, so we are unable to draw any useful conclusions.

3.4. CSS 080228:081210 +040352

This object (abbreviated CSS 0812 +04) was detected in 2008 by the Catalina sky survey at a magnitude of 18.8 and listed as an eclipsing CV with a Sloan Digital Sky Survey (SDSS) magnitude of 22.4. However, the PAN-STARRS 1 survey consistently detects it with $18.0 < g < 19.1$, suggesting that SDSS caught it in a state of low mass transfer. We selected this object in 2014 for further photometric and spectroscopic studies after it was identified by one of us, M.M., as a candidate polar based on its long-term CRTS light curve; this is part of a study to identify candidate polars based on long-term photometric behavior. Independently, Oliveira et al. (2020) obtained a survey spectrum and classified it as a magnetic system.

Our mean spectrum from 2017 March (Figure 8) shows strong He II $\lambda$4686 emission and also emission at $\lambda$5411, which are typical of magnetic CVs. Four additional spectra were taken with the Robert Stobie Spectrograph (RSS; Burgh et al. 2003; Kobulnicky et al. 2003; Smith et al. 2006) on the Southern African Large Telescope (SALT; Buckley et al. 2006) on 2016 January 4 and 5, February 10, and March 1. The RSS was used in long-slit spectroscopy mode with a slit width of $1''5$. The PG900 VPH grating was used, set to an incidence angle of

![Figure 5. Top: mean spectrum of RX J0636.3+6554. Middle: phase-resolved spectra of RX 0636.3+6554 in the region of Hα and He I $\lambda$6678. Phase increases from the bottom, and two cycles are shown for clarity. The horizontal discontinuities are caused by incomplete phase coverage, and the noise near phase 0 is largely caused by the eclipse. Lower: velocities of Hα folded on the orbital ephemeris, showing large velocity swings and a nonsinusoidal modulation.](image)
The wavelength calibration was done using Ar lamp exposures taken immediately following the observations, and relative flux calibration was achieved using standard stars LTT 377 and LTT 4364, depending on the night of observation. The SALT spectra are shown in Figure 9.

Radial velocities taken over two nights gave \( P = 162.0 \pm 0.3 \) minutes. The velocity half-amplitude \( K = 131 \pm 14 \) km s\(^{-1}\) is much smaller than expected for an AM Her star.

Figure 10 shows a sampling of our time-series photometry. Many of our light curves show a very short dip, resembling a partial eclipse. This feature appeared insignificant until we found the spectroscopic period, which made it evident that dips on successive nights were separated by integer multiples of the orbital period. We were able to connect dips found in 2014, 2017, and 2019 with a unique ephemeris, \( \text{BJD sharp dip} = 2457844.6379 \pm 0.11241902 \) (Table 2).

Table 2  
RX J0636.3+6554 Eclipse Centers

| \( E \) | Time   | \( O - C \) | Date      |
|-------|--------|------------|-----------|
| 0     | 8174.62125 | –3        | 2018 Feb 25 |
| 1     | 8174.69239 | –11       | 2018 Feb 25 |
| 28    | 8176.61553 | 4         | 2018 Feb 27 |
| 29    | 8176.68680 | 8         | 2018 Feb 27 |
| 56    | 8178.60964 | –3        | 2018 Mar 1 |
| 70    | 8179.60681 | 2         | 2018 Mar 2 |
| 647   | 8220.70147 | 0         | 2018 Apr 12 |
| 688   | 8223.62175 | 18        | 2018 Apr 15 |
| 3710  | 8438.85216 | –13       | 2018 Nov 16 |
| 3724  | 8439.84923 | –15       | 2018 Nov 17 |
| 3753  | 8441.91472 | 9         | 2018 Nov 19 |
| 3754  | 8441.98586 | –15       | 2018 Nov 19 |
| 4088  | 8465.77391 | –4        | 2018 Dec 13 |
| 7840  | 8732.99620 | –6        | 2019 Sep 6 |
| 8485  | 8778.93416 | 14        | 2019 Oct 22 |
| 8486  | 8779.00504 | –16       | 2019 Oct 22 |
| 8499  | 8779.93109 | –1        | 2019 Oct 23 |
| 8512  | 8780.85697 | –1        | 2019 Oct 24 |
| 9299  | 8836.90813 | 0        | 2019 Dec 19 |
| 9662  | 8862.76148 | 1        | 2020 Jan 14 |
| 9663  | 8862.83294 | 22       | 2020 Jan 14 |
| 9718  | 8866.74993 | 6        | 2020 Jan 18 |

Note. Observed times of mid-eclipse. The first column gives the eclipse number \( E \), and the second the barycentric Julian date minus 2,450,000, on the UTC system. The penultimate column gives the residual compared to the best-linear ephemeris (Equation (1)) and the last the calendar date in UT.

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Figure 11 is a close-up view of the dip, with data from 13 nights plotted. The dip appears to be stable in phase, about 250 s wide, and typically about 0.6 mag deep. Its consistency suggests it is caused by a grazing eclipse of the bright accretion column by the secondary star. A compact accretion column disappearing momentarily over the limb of a rotating white dwarf might, in principle, mimic the dip’s appearance, but such events tend to have more gradual ingresses and egresses, and not to be as consistent.
3.5. **SDSS J100516.61+694136.5**

Wils et al. (2010) discovered this object (hereafter SDSS 1005+69) by mining data from SDSS, Galaxy Evolution Explorer (GALEX), and various astrometric catalogs for dwarf nova candidates. They noted strong emission lines, including He II $\lambda$4686 comparable to H$\beta$, in the SDSS spectrum and suggested that it is a magnetic CV, varying from 17.9 through 21.2 mag.

We obtained a single spectrum in 2012 January and 2015 April, but did not find the system bright enough to study. We enjoyed better luck in 2018 February and March and obtained spectra on three nights. The top panel of Figure 12 shows the mean spectrum, which includes the He II emission characteristic of magnetic CVs. The H$\alpha$ emission-line velocities are strongly modulated at an unambiguous period of 218.6(4) minutes; the modulation is nonsinusoidal with a rapid rise and a more gradual decline in each cycle. The phase used in the lower panel of Figure 12 is based on a sinusoidal fit to the velocity data and is essentially arbitrary. Using the 1.3 m telescope, we obtained time-series photometry contemporaneous with our 2018 spectroscopy, and also on two nights in 2020 January (see Figure 13). The comparison star was at $\alpha = 10^h05^m14^s34$, $\delta = +69^\circ43'23''4$, 108" from, and almost due north of, the target; the PS1 DR2 lists $g = 15.53$, $r = 14.98$ for this star. The light curves show a rise starting around phase zero and a slower decline, but no definite eclipse. The spectroscopic orbital period is not precise enough to specify phase for the 2020 data; to prepare the figure, we assumed the minimum around phase zero is stable in phase and adjusted the period slightly to force its phase to align with the 2018 data.

For the light curves taken on 26 February and 2018 March 1 (top panel of Figure 13), we see evidence of possibly periodic...
fluctuations on $\sim 800$ s timescales. We therefore produced periodograms of the 2018 light curves using Gatspy, a Python implementation of the Lomb–Scargle method (VanderPlas & Ivezic 2015). The results are shown in Figure 14, which clearly show period peaks at 810 s and 771 s, respectively, both of which have formal false-alarm probabilities below 1%. In addition, the periodogram of the four combined nights clearly shows the presence of the orbital period and its harmonic (Figure 15). The fact that the two shorter period peaks are not separated by the orbital frequency would seem to rule out an intermediate polar interpretation, where the two frequencies could be due to the beat and spin modulations, respectively. We therefore conclude that the system probably exhibits quasiperiodic variability from time to time.

The photometric variations seen in polars have variously been characterized as flickering, fluctuations, and sometimes quasiperiodic oscillations (QPOs). The latter are variations that show some degree of coherence over a number of cycles of the QPO period. The discovery of $\sim$Hz frequency QPOs in the visible light of polars is now over 30 yr old (e.g., Middleditch 1982) and at the time resulted in a flurry of theoretical studies. The commonly held understanding is that they are due to plasma oscillations in the magnetically confined accretion columns. Until recently, only five systems were known to exhibit such QPOs, with the sixth (V379 Tel) being the only discovery in over two decades, despite attempts to find more examples (H. Breytenbach et al. 2020, in preparation). Longer-period QPOs were also seen in AM Her (Bonnet-Bidaud et al. 1991), at 250–280 s, while more recently a $\sim 320$ s QPO was detected in IGR J14536–5522 5.4 (Potter et al. 2010). The origin of these longer-period QPOs is still debated, with proposed sites suggested near the L1 point (King 1989), the
Figure 10. Differential photometry of CSS 0812+04, from three different observing runs, aligned on the sharp dip ephemeris (Equation (2)).

Figure 11. A magnified view of the sharp dip, showing differential magnitudes from 13 different nights. The data were aligned by subtracting the median value of each night’s magnitudes. The lower scale is in cycles and the upper in seconds (see Equation (2)).
stream coupling region, or within the magnetically confined flow, close to the white dwarf surface (Bonnet-Bidaud et al. 1991).

In polars, the QPOs seem to occur with typically a period of a few seconds (accretion column oscillations) or with periods of many minutes. The latter are larger amplitude and are quite a common feature of polars, often seen by eye in the light curves, as seems to be the case for SDSS J100516.61+694136.5 (see Figure 13), where they can appear to show some sort of coherence, but are not necessarily obvious in power spectra; they are often referred to as “QPO like” (Potter et al. 2010).

3.6. SDSS J133309.20+143706.9

Schmidt et al. (2008) published time-series spectroscopy and polarimetry of this object not long after it was discovered in SDSS. The detection of circular polarization firmly established it as an AM Her star. The radial velocities of Hα varied with \( K \sim 250 \text{ km s}^{-1} \) on a period of \( 2.2 \pm 0.1 \text{ hr} \). Southworth et al. (2015) obtained time-series photometry on three nights, but were unable to improve on the period.

On five consecutive nights in 2016 February, we obtained time-series photometry with the 1.3 m telescope and Andor camera. The light curves (Figure 16) consistently show a flat-topped brightening that recurs on a period of 0.08814(4) days, or 126.92(6) minutes, consistent with the radial-velocity period found by Schmidt et al. (2008). The daily cycle count is unambiguous.

We also have time series from 2016 June 10 and from 2017 June 21 and 22. The 2016 June time series shows a brightening toward the end that is similar to those seen in the other light curves, but does not cover the decline. The 2017 June light
Figure 13. Light curves of SDSS 1005+69 from two observing runs. The differential magnitudes have been adjusted by the comparison star’s $r$ magnitude. The lowermost trace in each panel is plotted without a vertical offset, and successive traces offset upward by 1.0 mag. The period is not known to the accuracy shown but is fine-tuned to align the light curves from the two observing runs.

Table 4
Summary of Findings

| Name                | Measurement       | $P$ (days) | $T_0$       | $K$ (km s$^{-1}$) | $\gamma$ (km s$^{-1}$) | Remarks     |
|---------------------|-------------------|------------|-------------|-------------------|------------------------|-------------|
| Gaia18aot           | Spec.             | 0.078830(2)| 58443.7138(11) | 218(15)$^*$       | 10(12)                 | New CV      |
| PT Per              | Spec.             | 0.05625(3) | 58504.7576(3) | 340(14)           | −9(9)                  | High state  |
| RX J0636.3+6554     | Spec.             | 0.07122(7) | 58174.6790(7) | 328(24)$^*$       | −12(14)                | New AM Her  |
| Eclipse             | Spec.             | 0.071221298(8) | 58174.62129(5) | ...               | ...                    |             |
| CSS 080228:081210+040352 | Spec.             | 0.11247(17) | 57841.820(2)   | 131(14)           | 72(10)                 | New AM Her  |
| Dip                 | Spec.             | 0.11241902(2) | 57844.6379(2)  | ...               | ...                    |             |
| SDSS J100516.61+694136.5 | Spec.             | 0.1518(3) | 58174.979(5) | 111(17)$^*$       | 16(14)                 | New period  |
| SDSS J133309.20+143706.9 | Bump ingr.   | 0.08812(4) | 57434.8816(6) | ...               | ...                    | New period, firm |
| SDSS J134441.83+204408.3 | Spec.             | 0.070592(4) | 57456.8785(7) | 273(17)           | −50(12)                | Improved period |
| Gaia18aya          | Spec.             | 0.0834482(16) | 58391.7142(9) | ...               | ...                    | New CV      |

Note. A summary of the measurements presented here. Sinusoids, where fitted, are of the form $v(t) = \gamma + K\sin 2\pi(t - T_0)/P$. Epochs are barycentric Julian dates minus 2,400,000, in the UTC time system; these can be converted to TDB with sufficient accuracy by adding 69 s.

$^*$ Nonsinusoidal velocity curve; parameters are formal best fits only.
curves show clearly defined brightenings similar to the others. Only one choice of long-term cycle count fits all the brightening ingress times comfortably, and it implies

$$\text{BJD of brightening} = 2457434.8817(4) + 0.0881118(3)E \quad \text{(provisional).}$$ (3)

We label this as provisional because of the lack of redundant timings on the longer baselines; the less precise value from 2016 February is firmly established. One reason for caution is that the three brightenings seen in Southworth et al. (2015) arrive early in this ephemeris by $\sim 25$ minutes, in contrast to the MDM timings, which all align to better than 2 minutes.

### 3.7. SDSS J134441.83+204408.3

Szkody et al. (2011) found this object (hereafter SDSS 1344 +20) in the SDSS data and noted its apparently magnetic nature. In a short series of spectra, they found the radial velocities of $\text{H}$\(\alpha\) and $\text{H}$\(\beta\) varying on a period of $\sim 115$ minutes, with semi-amplitudes $K \sim 400$ km s$^{-1}$. Szkody et al. (2014) present further observations, including photometry and spectroscopy showing changes of photometric state.

We observed this star most intensively in 2016 February and March. In the mean spectrum (Figure 17), $\text{He}$\(\text{II} \lambda 4686\) is less prominent than usual in AM Her stars, about half the strength of $\text{H}$\(\beta\). The continuum is strong and blue. Hot continua usually show a smooth upward sweep toward the blue; this continuum may have a very broad hump from $\sim 5100$–$5700$ Å. If real, this might be a cyclotron feature.

As Szkody et al. (2011) found, the radial velocities of $\text{H}$\(\alpha\) are strongly modulated, and with our more extensive data set we determine $P_{\text{orb}} = 101.652(6)$ minutes. The cycle count between nights and between the two observing runs is unambiguous; the relatively small uncertainty reflects the 21 day span of the time series.
Figure 18 shows light curves taken on three different observing runs; the spectroscopic ephemeris used to compute the phases is only valid for the 2016 February data, so the phases in the top and bottom panels are arbitrary. Not all of the runs used the same comparison stars, but the magnitude scales have been adjusted using the different stars’ $r$ magnitudes from PAN-STARRS. No periodic behavior is evident, though the intervals of rapid fluctuation seen in the middle panel are both centered on a brief interval before phase zero. We speculate that the V-shaped $\sim$0.5 mag dips seen near phase zero in the 2016 data, when the object was brighter than for the other observations, could be a partial grazing eclipse of an accretion hot spot. The data from 2018 February 26 show a brightening by $\sim$2 mag over less than one orbit; note that Szkody et al. (2014) observed significant changes in the light curve from night to night.

3.8. Gaia18aya

The Gaia light curve for this source shows it varying between 18 and 19 mag, except for a few days in 2018 April when it triggered an alert at a magnitude of 17.52, and a pair of detections at 17.27 on 2018 May 25.

The mean spectrum (Figure 19) shows the usual emission lines, but the most striking feature is a cyclotron emission
harmonic centered around \(\sim 5500\ \text{Å}\). The cyclotron harmonic clinches the AM Her classification. The H\(\alpha\) radial velocities from 2018 September establish an unambiguous orbital period near 120 minutes. We obtained more observations in 2018 November, December, and January, which constrain the period uniquely to 120.165(3) minutes.

The cyclotron emission hump varies in strength with the orbital period. This can be seen in Figure 20, which is similar to the middle panel of Figure 19 but with a wider wavelength range. In both these figures, the spectra were not rectified (normalized to a continuum) before being averaged and stacked; rather, flux-calibrated spectra were used, so variations in flux can be seen.

Figure 21 shows the time-series photometry. During 2018 September, the variation is irregular without obvious periodicity, but in 2018 November, the source was somewhat brighter and varied smoothly with the orbital period.

The wavelength of the \(n\)th cyclotron harmonic is

\[
\lambda_n = \frac{(10700\ \text{Å})}{nB_8},
\]

where \(B_8\) is the magnetic field in units of \(10^8\ \text{G}\) (\(10^4\ \text{Tesla}\)). The \(\sim 5500\ \text{Å}\) feature is the only harmonic we clearly observe, which implies that the allowable magnetic fields for different assumed cyclotron harmonics in the range \(n = 2\sim 7\) vary from 28 to 97 MG. If the cyclotron feature at \(\sim 5500\ \text{Å}\) is associated with the \(n = 6\) (32 MG) or 7 (28 MG) harmonic, this implies that the shorter and longer wavelength harmonics at \(n \pm 1\) (\(\sim 4800\) and \(\sim 4700\ \text{Å}\), and \(\sim 6400\) and \(\sim 6600\ \text{Å}\), respectively) should be detectable in our spectra. For \(n = 5\) \((B = 39 \text{ MG})\), we should also see the \(n = 4\) harmonic at \(\sim 6900\ \text{Å}\). The fact that we see no other cyclotron features corresponding to these wavelengths is evidence that \(n < 5\). If we take \(n = 4\), then the

\[\lambda_4 = \frac{(10700\ \text{Å})}{4B_8} = \frac{2675\ \text{Å}}{B_8}.\]
neighboring harmonics should occur at \( \sim 4400 \) Å \((n = 5)\) and \( \sim 7300 \) Å \((n = 3)\), respectively. From Figure 19 (top panel), we see the flux increases from \( \sim 7000 \) Å to the red limit at \( 7400 \) Å, consistent with a broad cyclotron line at \( \sim 7300 \) Å. Similarly, the flux also increases for wavelengths \( \leq 4900 \), to the blue limit of our spectra at \( 4550 \) Å, also consistent with the expected cyclotron line at \( \sim 4400 \) Å. So this is all consistent with identifying the clearly observed hump at \( \sim 5500 \) Å with the \( n = 4 \) cyclotron harmonic from a \( B = 49 \) MG magnetic white dwarf. Lower harmonics, at \( n = 2 \) or 3, are also admissible, with higher field strengths, though the \( n \pm 1 \) harmonics are now well outside the wavelength range of our spectra.

A good far-red or near-infrared spectrum could help determine the field strength by clearly identifying the lower harmonics and allowing for subtraction of the underlying secondary star flux, which is likely an M-type star given the \( \sim 2 \) hr orbital period.

4. Conclusions

Figure 22 shows a histogram of the orbital periods of AM Her stars listed in the final release (version 7.24) of the Ritter & Kolb (2003) catalog of cataclysmic binaries. The periods of the stars discussed here are also indicated. They all have periods typical of the population.
Table 4 summarizes our findings. We classify three objects (Gaia18aot, RX J0636.3+6554, and Gaia18aya) as AM Her stars for the first time; the two Gaia sources are also newly recognized as CVs. For six of the objects we determine $P_{\text{orb}}$ for the first time, and for two more (PT Per and SDSS 1344+20) we improve significantly on previous period determinations. We confirm that PT Per is a magnetic CV, as Watson et al. (2016) suggested.

Three of our objects have especially interesting light curves. RX J0636.5+6554 eclipses deeply. CSS 0812+04 shows a sharp dip that is stable in phase and appears to be a partial eclipse. Finally, SDSS 1333+14 persistently shows a distinctive bump consistent with the appearance of an otherwise self-occulted accretion spot.

The spectrum of Gaia18aya has an apparent cyclotron emission hump near 5500 Å, which constrains the magnetic field to be greater than $\sim$49 MG.

It is worth noting that magnetic CVs appear to be underrepresented in various listings. Pala et al. (2020) constructed a volume-limited sample of 42 CVs within 150 pc, as judged by Gaia DR2 parallaxes, and found that over 30% were magnetic, and that 11 out of the 42 in the total sample were polars, including the prototypical polar, AM Her.

High-cadence synoptic sky surveys have found very large numbers of new CVS (see, e.g., Breedt et al. 2014), but they are clearly biased toward dwarf novae, which show distinct, large-amplitude outbursts. The objects in this paper no doubt...
represent a very sizable population of more subtly variable AM Her stars, as yet unrecognized.

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ORCID iDs
John R. Thorstensen @ https://orcid.org/0000-0002-4964-4144
Patrick A. Woudt @ https://orcid.org/0000-0002-6896-1655

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