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Abstract

AM CVn systems are binary star systems with orbital periods less than 70 minutes in which a white dwarf accretes matter from a companion star, which must be either a stripped helium burning star, or a white dwarf of lower mass than the accretor. Here, we present the discoveries of two of these systems in which there is mass transfer from the lighter white dwarf or helium star onto a strongly magnetized heavier white dwarf. These represent the first clear example of magnetized accretion in ultracompact binaries. These systems, along with similar systems that are slightly more widely separated, and that have not started to transfer mass yet, are expected to be the primary source of gravitational waves to be detected by space-based gravitational wave observatories. The presence of strong magnetic fields can substantially affect both the evolution of the binaries, and also the particular wave forms of the gravitational waves themselves, and understanding these magnetic effects is vital for understanding what to expect from the Laser Interferometer Space Antenna.

The next frontier in the search for gravitational waves will be breached by the space-based Laser Interferometer Space Antenna (LISA), which will take advantage of the absence of seismic noise in space to detect gravitational waves at frequencies from 10^{-4} Hz to 1 Hz[1]. In this frequency range, the largest class of detectable sources is expected to be binary stars with pairs of white dwarfs [1]. The LISA verification binaries are objects known, and electromagnetically characterized, at the time of LISA's launch, and these include substantial numbers of double white dwarf binaries, both with and without mass transfer between the two objects[1].

The evolution of close binary stars is driven by three key processes: angular momentum transport (typically from gravitational radiation and/or magnetic braking) [2, 3]; mass transfer (both between components of the binary and expulsion of material from the binary in winds); and evolution of the stars in the binaries themselves. In the AM CVn binaries, the prevailing assumptions in nearly all theory work are that the angular momentum transport out of the system is solely due to gravitational radiation and that the mass transfer is conservative. Still, it has been shown that the standard tracks for AM CVn systems can fail to describe their evolution accurately if there are magnetic fields of 10^3G or more for the accretor white dwarfs, because the disk winds from the accretion disk, in combination with the magnetic field of the white dwarf, will drive magnetic braking angular momentum loss, which could exceed the angular momentum loss from gravitational radiation[4]. This effect should become more important for either higher magnetic fields (since the magnetic braking torques depend on the magnetic field) or longer orbital periods (since the gravitational wave angular momentum losses are slower for longer periods), and magnetic fields of 10^3 G are not exceptionally high for white dwarfs.

Traditionally, it has been hard to find evidence for such magnetic fields in the AM CVn systems. One system, SDSS J080449.49+161624.8 (SDSS J0804), shows a single-peaked helium emission line, something which is often indicative of magnetically dominated accretion in white dwarfs with hydrogen-rich donor stars [5], but clear evidence for magnetic accretion must come in the form of a measurement of modulation of the accretion power on the accretor's spin period. We show here, in figure 1, that this system shows strong modulation of its X-ray emission on the orbital period of 44.5 minutes found by [5]. This system shows a single-peaked X-ray pulsation, suggestive of truncation of the accretion disk relatively far from the white dwarf [6], and hence suggestive of a relatively high magnetic field, of $\sim 10^5$ G or more.

We find a similar X-ray pulsation for another AM CVn system Gaia14aae. Gaia14aae is an eclipsing binary with an orbital period of 49.7 minutes [7]. We fold the data from an XMM-Newton observation on the known orbital period. The folded X-ray light curve is plotted in figure 2 and shows a strong eclipse at the same orbital phase as the ultraviolet light curve obtained from the simultaneous Optical Monitor data from XMM-Newton. On top of the variability from the eclipse, the system also shows a tell-tale double-peaked additional modulation.

The phasing of the non-eclipse orbital modulation, with a strong peak roughly synchronous with the eclipse, removes the possibility of geometric modulations via variable absorption in a disk wind. Such modulations should leave the lowest fluxes just outside the eclipse, not the highest ones, and they would also be stronger in the softer X-rays, where the strongest atomic absorption features are, but we find no strong energy dependence for the amplitude of modulation. Modulations could show this phasing if they involved enhanced emission due to scattering off the hot spot where the accretion stream impacts the outer accretion disk, but such a mechanism could not produce the $\approx 50\%$ amplitude seen, and the double-peaked nature would also not result in this case.

The only viable mechanism for this modulation, then, is polar accretion. In the approximation of spherical inflow, the Alfvén radius can be set equal to [8] :

$$r_A = 7.6{\times}10^8\mathrm{cm}\left(\frac{\dot{M}}{7.5\times10^{-11}M_\odot/\mathrm{yr}}\right)^{-\frac{2}{7}}\left(\frac{B}{10^3\mathrm{G}}\right)^{\frac{4}{7}}\left(\frac{R}{10^9\mathrm{cm}}\right)^{-\frac{12}{7}}\left(\frac{M}{M_\odot}\right)^{-\frac{1}{7}}. \tag{1}$$

The fiducial accretion rate above is set based on estimates of the accretion rate from [7] for Gaia14aae, which are additionally in good agreement with the X-ray luminosity. This gives us some bounds on the range of magnetic fields that is plausible for the system. The magnetic field strength must be large enough to disrupt the accretion disk outside the surface of the white dwarf (given that pulsations are seen), but also small enough to allow an outer disk to form (given that outbursts are seen, and that the disc signature shows up in eclipse mapping[7]).

The semi-major axis for the orbit of Gaia14aae should be about 3×10^{10} cm, and the outer radius of the accretion disk is typically 0.2-0.3 times the orbital separation for relatively extreme mass ratio systems [8]. The magnetic field of the white dwarf must then be in the range of about $10^3 - 10^5$ G in order for there to be a disk that forms, and is truncated. Other classes of white dwarfs, including isolated white dwarfs, the accretors in cataclysmic variables [9], and the accretors in the symbiotic stars which are the likely progenitors of AM CVn systems [10] all show substantial subsets with magnetic fields of 10^5 G or more.

We can gain some further, albeit qualitative, insights on the magnetic field strength in Gaia14aae from the presence of a double-peaked X-ray pulse profile. The double-peaked pulse profile implies that the accretor has a relatively weak magnetic field, with the truncation of the thin accretion disk fairly close to the surface of the white dwarf[6]. In principle, the single and double pulse peaks could result from accretion along one magnetic pole or both poles, respectively, but the systematic correlation between number of peaks and inferred magnetic field, and the other evidence for a stronger magnetic field in SDSS0804 than in Gaia14aae both point to variations in the magnetic field, and in the truncation radii, as the determining factor for the pulse profile shape. For the intermediate polar CVs with non-degenerate donor stars, this effect manifests itself as double-peaked pulse profiles showing up for the shorter spin period systems, in which the magnetic torques causing spin-down are weaker. For the ultracompact binaries, the spin period is set by the tidal locking[11] (and these results provide clearer observational evidence than has previously existed for the tidal locking), so it is not a tracer of the accretor's magnetic moment, but the relationship between double-peaked pulse profiles and truncation close to the white dwarf's surface should remain. This, in turn, means that the magnetic field is likely to be in the range of 10^{3-4} G.

The discovery that the accretor in Gaia14aae has a dynamically important magnetic field solves one of its core mysteries. [7] had found that both its current luminosity, and the fact that it showed an outburst, to be indicators that the system is accreting at a higher rate than expected for an AM CVn system of this orbital period under standard binary evolution assumptions. The accretion rates of AM CVn systems can be enhanced by magnetic braking if the accretor's magnetic field is of order 10^3G or more [4] and there is even a quite modest disk wind in the system (to first order, the angular momentum transport does not depend on the rate of mass loss in the wind [4]). Disk winds are clearly present in outbursts of cataclysmic variables[12] and AM CVn systems[13] and there is good evidence even in quiescence that the CVs have strong disk winds[14]. The mechanism by which the accretor's magnetic braking affects the binary orbital evolution is relevant only when the accretor is tidally locked to the orbital period, something which appears to be true for AM CVn systems, but not for standard cataclysmic variables in which there is an accretion disk [4, 15].

SDSS J0804 must also be overluminous for its orbital period. Our estimate is that its mass transfer rate is about 40 times that of Gaia14aae, and then, if we take the pulse profiles as indicative of a truncation further from the white dwarf surface, it is likely that the magnetic field for SDSS 0804 is at least 10 times bigger than that for Gaia14aae. It thus likely has a magnetic field significantly stronger than the $\sim 10^4$ G of Gaia14aae. The fact that the luminosity is high for the orbital period, even relative to Gaia14aae, and that the magnetic field must be higher than that of Gaia14aae to disrupt the disk, tie in together to support the idea that magnetic braking is relevant for enhancing the accretion rate.

It is even possible for SDS J0804 that it has purely polar accretion, like the AM Her class of cataclysmic variables. The system was already known to have single-peaked emission lines [5], indicating that either the system is nearly face-on, or, more likely, that the accretion disk does not reach very close to the accreting white dwarf. Additionally, the system shows a "spur" in its phase resolved spectroscopic optical emission line profile [5], something also seen in some polar cataclysmic variables, which have no disks [16]. To truncate the accretion disk entirely would likely require $B \sim 3 \times 10^5$ G or more, a level high enough that it might be possible to see some of the higher cyclotron harmonic lines in JWST spectra.

The implications of the evidence for magnetic braking in AM CVn systems for their gravitational wave signatures are important, and may manifest themselves in two ways. First, if the angular momentum transport is strongly affected by magnetic braking, then the period derivatives observed may be faster than those predicted from standard conservative mass transfer models with only gravitational radiation as a means of angular momentum transport. As a result, standard templates used to detect gravitational waves may not have large enough period derivatives for a given orbital period, and the template bank to be used for LISA may need to be larger than currently presumed. Second, if a large fraction of the AM CVn harbor accretors with large magnetic fields, the space density of such systems, especially in the range of periods from about 20–80 minutes, may also be reduced by their faster evolution. These effects are less likely to be important for the shortest period AM CVn systems, because the effects of the magnetic braking are much more weakly sensitive to orbital period than are the effects of gravitational radiation[4]. On the other hand, benefits may exist as well. For systems that are very well characterized in the gravitational wave band, with well-measured amplitudes that make predictions for the strength of the gravitational wave emission, it may be possible to compare the period derivatives that are measured with the ones expected from gravitational radiation alone, and to estimate the accreting white dwarf's magnetic fields from the LISA data.

1 Methods

1.1 Data analysis

SDSS J080449.49+161624.8 was observed by XMM-Newton on 16 April 2018 from 14:28:45 to 17:47:22. For this source, the XMM-Newton GOF has produced standard pipeline light curves with the three detectors summed. We used these light curves, which are from 0.2 to 10 keV, and fold them on the known 44.5 minute orbital period. These results are shown in figure 1.

Gaia14aae was observed by XMM-Newton on 12 January 2023 from 3:24:58 to 17:39:08. The XMM-Newton data are analyzed using standard procedures. After applying standard screening, we extracted light curves from each of the three X-ray cameras. The results shown are for energies from 0.2-10 keV. For each camera, we created an off-source background file, and used the evselect command in the XMMSAS software to produce light curves. We then corrected for exposure duty cycle using lccorr. We then added the three light curves using the FTOOLS task lcmath. The light curves were originally produced with a time resolution of 7.8 seconds, corresponding to the readout time for the slower MOS detectors. Following that, we folded the light curves using the FTOOLS efold task. The folded light curves in figure 2 are folded on the orbital period of 49.7 minutes from optical measurements[7].

1.1.1 X-ray luminosity and the mass transfer rate estimate

For Gaia14aae, the flux is found to be 3.1×10^{-13} erg/sec/cm^2, from the XMM SAS standard pipeline analysis. Taking the distance from Gaia EDR3 of 258 ± 8 pc[17, 18], we find an X-ray luminosity of 2.4×10^{30} erg/sec. This value is bit lower than that for other AM CVn at similar orbital periods[19], but X-ray emission may be suppressed due to inclination angle effects[20], as it is an eclipsing binary.

The Gaia parallax distance estimate for SDSS J0804 is $999\pm^{185}_{134}$ pc[21] yielding L_X=3×10^{32} erg/sec, about 50 times brighter than the X-ray luminosities for other AM CVn at similar orbital periods. We additionally note that the two systems presented in this paper both have optical magnitudes of $g \approx 18-19$ in quiescence, with SDSS J0804 typically about half a magnitude brighter, but that the X-ray flux from SDSS J0804 is about 10 times as high. This, too provides evidence that in SDSS J0804, the accretion disk is truncated far from the white dwarf, so that the optical luminosity of the accretion disk is reduced because the optical disk fails to reach the innermost parts of the gravitational potential of the white dwarf. For SDSS J0804 there is not a good literature estimate of the white dwarf temperature, so a mass transfer rate cannot be estimated from that. For SDSSJ0804, the optical luminosity is about 20 times higher than for Gaia14aae, and the X-ray luminosity is about equal to the optical luminosity, so that the bolometric luminosity is about 40 times higher. If we take that as a rough scaling for the mass transfer rate, as well, we can estimate that $\dot{M} \approx 3 \times 10^{-9} M_{\odot}$/yr for this system, well above the predictions based on evolution solely due to gravitational radiation.

1.2 Implications of magnetic braking for the size and period distribution of the AM CVn population

The standard theory of AM CVn evolution consists of systems moving to longer period as the donor white dwarf loses mass, and expands due to its degenerate nature. The rate at which the mass loss takes place is set by finding the mass loss rate at which the angular momentum transport due to gravitational radiation yields an orbit that expands such that the donor star remains exactly in Roche lobe contact with the accretor. Adding a new mechanism to transport angular momentum outside the binary will have two direct effects: (1) it will lead to more rapid orbital evolution of the system and (2) it will lead to more rapid mass transfer.

These two effects, in turn, mean that the period distribution of AM CVn systems should be heavily skewed toward longer periods that predicted, and that the long period systems should be systematically brighter than expected. Given the severe challenges in discovering the longest period AM CVn, this may then help explain the apparent dearth of AM CVn in observed samples [22] relative to model predictions.

Standard theory predicts that the systems at periods longer than about 40 minutes should be in "stable low states", in which there are no outbursts. Gaia14aae was thus already enigmatic because of its outbursting behavior [7]. Its outbursting behavior *is* consistent with its accretion rate inferred from both the temperature of the white dwarf and the X-ray luminosity in quiescence. Notably, all AM CVn systems with orbital periods longer than 49 minutes are systematically brighter than the predictions from standard models[18], perhaps indicating that this magnetic braking effect is ubiquitous, and just harder to measure in the other long period systems due to lower quality X-ray data.

This, in turn, suggests that the accretion rate in Gaia14aae must be higher than that from model tracks that include only gravitational radiation[23] by a factor of about 30. If the solution is that magnetic braking dominates the angular momentum transport in this system, then the magnetic field should be about 10^4 G, following figure 2 of [4]. This is in good agreement with the finding of the double-peaked pulsations in the X-rays.

In turn, one would expect that the single-peaked pulsations and higher accretion rate in SDSS0804 imply a magnetic field closer to 10^5 G (or, perhaps, even higher). A magnetic field of that size, which truncates the accretion disk relatively far from the surface of the white dwarf, can suppress the disk instability model by turning the region in which the hottest part of the accretion disk would exist into a region with accretion along the magnetic poles, that comes out as X-rays. Dwarf nova outbursts are rare, possibly non-existent, in the intermediate polar class of cataclysmic variables for this reason [24], and completely absent in the polar class, in which no accretion disk forms.

Interestingly, if $\sim 10^4$ G is a typical value for the magnetic fields in AM CVn, the magnetic braking would start to be the dominate source of angular momentum transport only for systems with periods longer than about 20 minutes. It is most likely that there exists a broad range of magnetic fields in the AM CVn systems just as there does for cataclysmic variables with hydrogen-rich donors. Relatively few of these objects are the subjects of long observations with sensitive X-ray telescopes, and it is likely that performing such observations would reveal some more of these objects.

The effects of magnetic braking may be profound for both the orbital period distribution of the AM CVn systems, and for the gravitational wave search approaches with LISA. If the effect is important at periods as short as 20 minutes, it will affect some of the strongest mass-transferring gravitational wave sources for LISA. The space densities of these systems will be reduced, as they will move through their orbital period evolution significantly faster than predicted by models with pure gravitational wave evolution.

2 Author contributions

TJM conceived of the project, wrote both the data proposal and the first draft of the paper, contributed to the interpretation, especially in terms of the magnetic braking scenario, and did the final data analysis. TK contributed to the proposal and paper writing and first proposed the interpretation of the pulsations as magnetism. ENC did the first run-through of the data analysis for Gaia14aae. LERS, JCvR, AS and DZ contributed to the proposal writing and to the paper editing.

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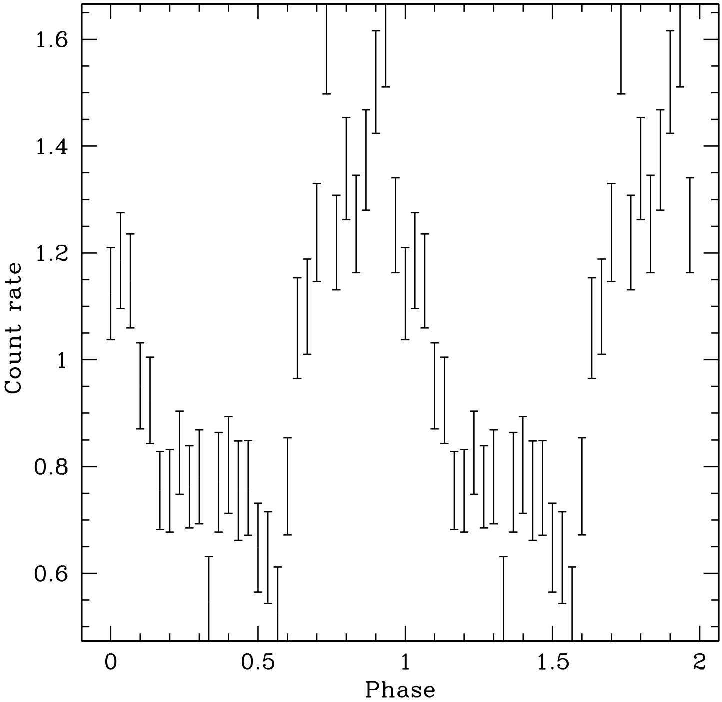

Fig. 1 The folded light curve for SDSS J0804, normalized as a ratio to the mean count rate. Error bars are 1σ. The ephemeris for the folding is set arbitrarily.

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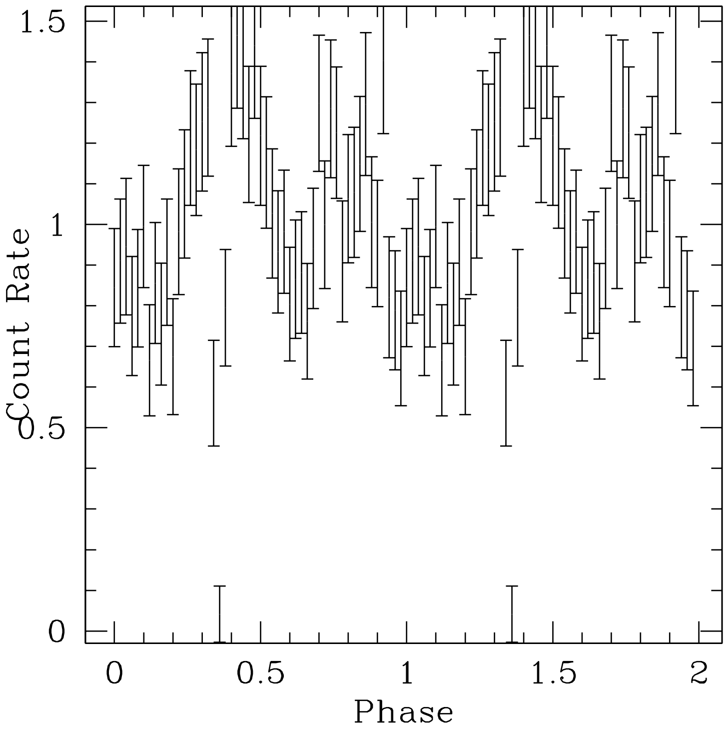

Fig. 2 The folded light curve for Gaia14aae, normalized as a ratio to the mean count rate. Error bars are 1σ. The ephemeris for folding is set arbitarily and the X-ray eclipse lines up properly with that seen by the XMM-Newton Optical Monitor.

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