Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS 529, L28–L32 (2024) https://doi.org/10.1093/mnrasl/slad194
Advance Access publication 2023 December 20

Strongly magnetized accretion in two ultracompact binary systems

Thomas J. Maccarone,[1]⋆ Thomas Kupfer,[1,2] Edgar Najera Casarrubias,[1] Liliana E. Rivera Sandoval,[3] Aarran W. Shaw,[4,5] Christoper T. Britt,[6] Jan van Roestel[7] and David R. Zurek[8]

[1]Department of Physics & Astronomy, Texas Tech University, Box 41051, Lubbock, TX, 79409-1051, USA
[2]Hamburger Sternwarte, University of Hamburg, Gojenbergsweg 112, D-21029 Hamburg, Germany
[3]Department of Physics & Astronomy, University of Texas-Rio Grande Valley, Brownsville, TX, USA
[4]Department of Physics and Astronomy, Butler University, 4600 Sunset Ave, Indianapolis, IN, 46208, USA
[5]Department of Physics, University of Nevada, Reno, 1664 N. Virginia Street, Reno, NV, 89557, USA
[6]Space Telescope Science Institute, 3700 San Martin Dr, Baltimore, MD 21218, USA
[7]Astronomical Institute 'Anton Pannekoek', University of Amsterdam, Science Park 904, 1098 XH, Amsterdam, Netherlands
[8]American Museum of Natural History, 200 Central Park West, New York, NY 10024 , USA

Accepted 2023 December 18. Received 2023 December 14; in original form 2023 September 26

ABSTRACT

We present the discoveries of two of AM CVn systems, Gaia14aae and SDSS J080449.49+161624.8, which show X-ray pulsations at their orbital periods, indicative of magnetically collimated accretion. Both also show indications of higher rates of mass transfer relative to the expectations from binary evolution driven purely by gravitational radiation, based on existing optical data for Gaia14aae, which show a hotter white dwarf temperature than expected from standard evolutionary models, and X-ray data for SDSS J080449.49+161624.8 which show a luminosity 10−100 times higher than those for other AM CVn at similar orbital periods. The higher mass transfer rates could be driven by magnetic braking from the disc wind interacting with the magnetosphere of the tidally locked accretor. We discuss implications of this additional angular momentum transport mechanism for evolution and gravitational wave detectability of AM CVn objects.

Key words: accretion, accretion discs – magnetic fields – binaries: close – novae, cataclysmic variables.

1 INTRODUCTION

Double compact object binaries are one of the primary sources of gravitational waves in the Universe. The subset with two white dwarfs is expected to dominate the sky for the Laser Interferometer Space Antenna (LISA; Amaro-Seoane et al. 2022), which will take advantage of the absence of seismic noise in space to detect gravitational waves at frequencies from 10^{-4} to 1 Hz (Amaro-Seoane et al. 2022). 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 (Amaro-Seoane et al. 2022).

The evolution of close binary stars is driven by three key processes: angular momentum transport (typically from gravitational radiation and/or magnetic braking; Kraft, Mathews & Greenstein 1962; Verbunt & Zwaan 1981); 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 (see Postnov & Yungelson 2014 for a review).

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 (e.g. Nelemans et al. 2001).

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 10^3 G or more for the accretor white dwarfs, because the disc winds from the accretion disc, 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 (Farmer & Roelofs 2010). 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 (Roelofs et al. 2009), 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. In this paper, we show evidence from two sources' X-ray pulsations on the orbital period that they have strong magnetic fields. Additionally, we show that one of them clearly has a mass transfer rate well in excess of that expected from standard binary evolution theory, providing strong evidence that the

⋆ E-mail: thomas.maccarone@ttu.edu

enhanced magnetic braking from the accretor is strongly affecting its evolution.

2 OBSERVATIONS AND DATA REDUCTION

SDSS J080449.49+161624.8 (SDSS J0804) was observed by *XMM–Newton* on 2018 April 16 from 14:28:45 to 17:47:22. For this source, the *XMM–Newton* Guest Observer Facility 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 min orbital period (Roelofs et al. 2009). These results are shown in Fig. 1.

Gaia14aae was observed by *XMM–Newton* on 2023 January 12 from 3:24:58 to 17:39:08. The *XMM–Newton* data are analysed 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 s, corresponding to the readout time for the slower Metal Oxide Semiconductor (MOS) detectors. Following that, we folded the light curves using the FTOOLS efold task. The folded light curves in Fig. 1 are folded on the orbital period of 49.7 min from optical measurements (Campbell et al. 2015).

3 ANALYSIS

3.1 X-ray fluxes and luminosities

For Gaia14aae, the flux is found to be 3.1×10^{-13} erg/sec/cm^2, from the XMMSAS standard pipeline analysis. Taking the distance from Gaia EDR3 of 258 ± 8 pc (Ramsay et al. 2018; Gaia Collaboration 2021), we find an X-ray luminosity of 2.4×10^{30} erg sec^{-1}. This value is bit lower than that for other AM CVn at similar orbital periods (Ramsay et al. 2006), but X-ray emission may be suppressed due to inclination angle effects (van Teeseling, Beuermann & Verbunt 1996), as it is an eclipsing binary. The source's optical luminosity is similarly likely to be underestimated if one takes $L = 4\pi d^2 F$. Campbell et al. (2015) have found from the temperature of the accreting white dwarf that the accretion rate is about $7.5 \times 10^{-11}\,\mathrm{M_\odot\,yr^{-1}}$. If the system began mass transfer very shortly after the birth of the more massive white dwarf, and hence the temperature reflects the initial conditions for the system and not its quasi-steady state, this could represent an overestimate of the mass transfer rate, but it is also the case that the presence of frequent accretion disc outbursts in a system at such a long orbital period is indicative of a higher mass transfer rate than the $1.5 \times 10^{-12}\,\mathrm{M_\odot\,yr^{-1}}$ expected (Kotko et al. 2012; Campbell et al. 2015). For SDSS J0804, there is not a good white dwarf temperature estimate, so its mass transfer rate must be estimated from its luminosity. The Gaia parallax distance estimate for SDSS J0804 is 999^{+185}_{-134} pc (Bailer-Jones et al. 2021) yielding $L_X = 3 \times 10^{32}$ erg sec^{-1}, a factor of 10–100 times brighter than the X-ray luminosities for other AM CVn at similar orbital periods (Begari & Maccarone 2023). We can take the sum of the X-ray and optical luminosities for the system, and estimate the mass transfer rate, $\dot{m}$ using:

$$\dot{m} = \frac{2RL_X}{GM}, \tag{1}$$

where R is the accreting white dwarf radius, L_X is the X-ray luminosity, and M is the accretor mass. This assumes that the X-rays come from the emission in the boundary layer, and could be an overestimate by a factor of 2 if the X-rays dominate the total accretion flow emission due to a disc truncated far from the white dwarf. This yields a mass transfer rate of about $9 \times 10^{-11}\,\mathrm{M_\odot\,yr^{-1}}$, again, much higher than the predictions from standard binary evolution due to gravitational radiation alone.

We note that such a high accretion rate could be consistent with expectations if the donor were a helium star of significantly higher mass than a white dwarf that fills its Roche lobe for the same period. Given that the chemical composition of the donor inferred from spectroscopy is consistent with a white dwarf and inconsistent with a helium star (Nelemans et al. 2010), this scenario is unlikely to be relevant for SDSS 0804.

3.2 Evidence for magnetic accretion and estimation of the white dwarf magnetic fields

From Fig. 1, both objects clearly show X-ray emission modulated by the spin period. For SDSS J0804, the emission is single-peaked. The orbital solution for this object is not well enough determined for us to determine the phasing of the X-ray peak with respect to the orbital phases. For Gaia14aae, it is clear that the eclipse occurs slightly before the X-ray maximum, and the pulse profile is double-peaked. In both systems, the maximum X-ray flux is about 1.5 times the mean X-ray flux.

For SDSS J0804, the amplitude alone provides strong evidence that the periodicity is due to magnetically collimated accretion. This system is known not to be eclipsing, and the X-ray emitting region of a boundary layer on the surface of the accretor is harder to eclipse than the much larger accretion disc around the white dwarf. Modulations from a disc wind's differential absorption can sometimes yield periodicities in edge-on ultracompact X-ray binaries (e.g. Bahramian et al. 2017), but with very low amplitude.

For Gaia14aae, the system is at high inclination, and does eclipse. Here 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 disc 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 disc, but such a mechanism could not produce the ≈50 per cent amplitude seen, and the double-peaked profile would also not result in this case.

The only viable mechanism for the modulations in both sources, then, is polar accretion. In the approximation of spherical inflow, the Alfvén radius can be set equal to (Frank, King & Raine 2002):

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

where M_f is the fiducial accretion rate of $7.5 \times 10^{-11}\,\mathrm{M_\odot\,yr^{-1}}$, based on estimates of the accretion rate from Campbell et al. (2015) for Gaia14aae. This gives us some bounds on the range of magnetic fields that is plausible for the system.

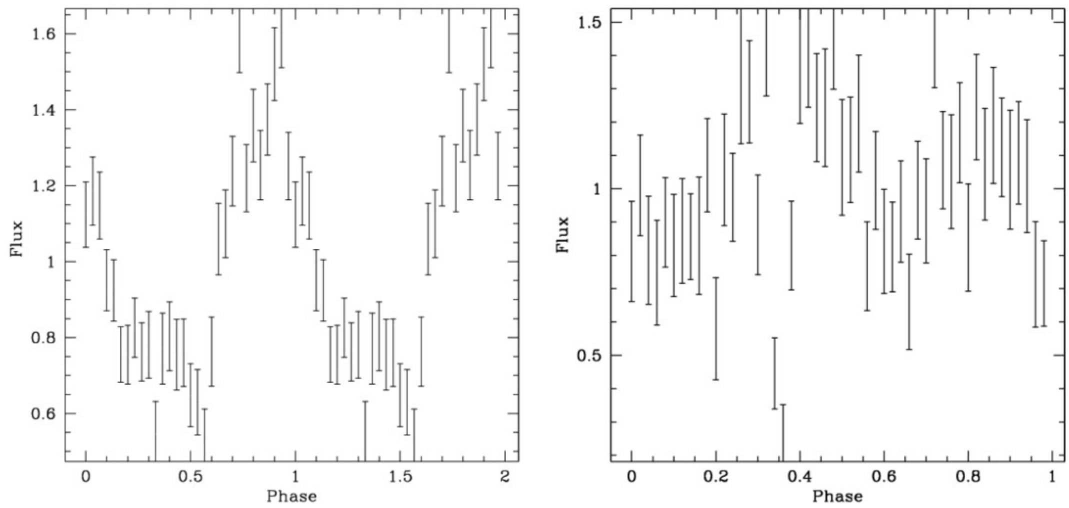

Figure 1. Left: the folded light curve for SDSS J0804 at the 44.5 min period, normalized as a ratio to the mean count rate. Error bars are 1σ. The ephemeris for the folding is set arbitrarily, as it is not well enough known to match. Right: The folded light curve for Gaia14aae at the 49.7 min period, normalized as a ratio to the mean count rate. Error bars are 1σ. The ephemeris for folding is set arbitrarily, as it is not well enough known to match, and the X-ray eclipse lines up properly with that seen by the *XMM–Newton* Optical Monitor. In both plots, the fluxes plotted are ratios to the average flux during the observation.

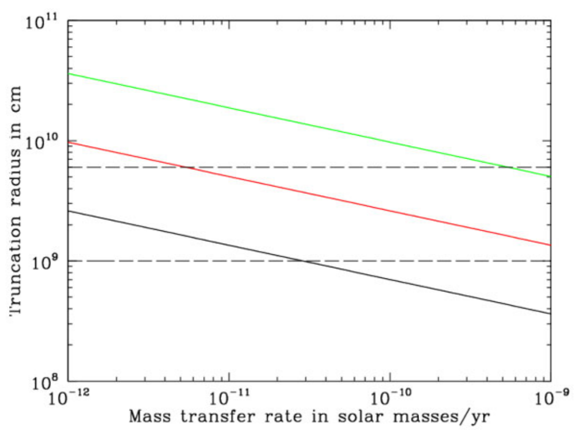

Figure 2. The truncation radius of an accretion disc plotted versus mass transfer rate. The upper dashed line is the approximate circularization radius of an AM CVn with an orbital period in the 45–50 min range. The lower line is an approximate accretor white dwarf radius. The black line represents a magnetic field of 10^3 G, the red line 10^4 G, and the green line 10^5 G. We can see that for the range near 7–9 $\times$ $10^{-11}\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$, the red curve is comfortably between the two radii, yielding a truncated disc, while the green curve is above the circularization radius line, indicating that no disc can form.

3.2.1 *Magnetic field estimation for Gaia14aae*

The magnetic field strength must be large enough to disrupt the accretion disc outside the surface of the white dwarf (given that pulsations are seen), but also small enough to allow an outer disc to form given that outbursts are seen in both sources, and that the disc signature shows up in eclipse mapping (Campbell et al. 2015).

The semimajor axis for the orbit of Gaia14aae should be about 3×10^{10} cm, and the outer radius of the accretion disc is typically 0.2–0.3 times the orbital separation for relatively extreme mass ratio systems (Frank, King & Raine 2002). 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 disc that forms, and is truncated (see Fig. 2). Other classes of white dwarfs, including isolated white dwarfs, the accretors in cataclysmic variables (Pala et al. 2020), and the accretors in the symbiotic stars which are the likely progenitors of AM CVn systems (Sokoloski & Bildsten 1999) all show substantial subsets of the objects 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 disc fairly close to the surface of the white dwarf (Norton et al. 1999). 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 SDSS 0804 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 (Kupfer et al. 2016; 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.

3.2.2 *Magnetic field estimation for SDSS J0804*

SDSS J0804 must be overluminous for its orbital period, relative to other AM CVn systems, and relative to theoretical models (Nelemans et al. 2001). It is even possible for SDSS J0804 that it has purely polar accretion, like the AM Her class of cataclysmic variables. The system was already known to have single-peaked optical emission lines (Roelofs et al. 2009), indicating that either the system is nearly face-on, or, more likely, that the accretion disc 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

(Roelofs et al. 2009), something also seen in some polar cataclysmic variables, which have no discs (Rosen, Mason & Cordova 1987). Following Equation (2), the magnetic field would need to be about 10^5 G to truncate the accretion disc outside the circularization radius.

4 DISCUSSION

4.1 Magnetic braking and enhanced accretion

The discovery that the accretor in Gaia14aae has a dynamically important magnetic field solves one of its core mysteries. Campbell et al. (2015) 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. SDSS 0804 is similarly overluminous, and hence similarly is likely to be displaying enhanced accretion.

The accretion rates of AM CVn systems can be enhanced by magnetic braking if the accretor's magnetic field is of order 10^3 G or more (Farmer & Roelofs 2010) and there is even a quite modest disc wind in the system (to first order, the angular momentum transport does not depend on the rate of mass-loss in the wind (Farmer & Roelofs 2010). Disc winds are clearly present in outbursts of cataclysmic variables (Cordova & Mason 1982) and AM CVn systems (Wade, Eracleous & Flohic 2007) and there is good evidence even in quiescence that the CVs have strong disc winds (Hernández Santisteban et al. 2019). 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 disc (Roelofs et al. 2006; Farmer & Roelofs 2010).

4.2 Implications of the magnetic braking scenario for angular momentum transport mechanisms in AM CVn systems

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 harbour accretors with large magnetic fields, the space density of such systems, especially in the range of periods from about 20–80 min, 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 (Farmer & Roelofs 2010). On the other hand, benefits may exist as well. For systems that are very well characterized in the gravitational waveband, 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.

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 (van Roestel et al. 2022) relative to model predictions.

Standard theory predicts that the systems at periods longer than about 45 min should be in 'stable low states', in which there are no outbursts (Kotko et al. 2012). Gaia14aae was thus already enigmatic because of its outbursting behaviour (Campbell et al. 2015). Its outbursting behaviour *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 min are systematically brighter than the predictions from standard models(Ramsay et al. 2018), 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 both Gaia14aae must be higher than that from model tracks that include only gravitational radiation (Deloye et al. 2007) by a factor of about 50. 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 Farmer & Roelofs (2010). This is in good agreement with the finding of the double-peaked pulsations in the X-rays. If the accretion rate is overestimated by assuming the white dwarf temperature is reliable for estimating it, then significantly lower magnetic fields could be accommodated.

The single-peaked pulsations SDSS J0804 imply a magnetic field of $\sim 10^5$ G. A magnetic field of that size, which truncates the accretion disc relatively far from the surface of the white dwarf, can suppress the disc instability model by turning the region in which the hottest part of the accretion disc 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 (Hameury & Lasota 2017), and completely absent in the polar class, in which no accretion disc forms.

This would seem to be at odds with the results of Farmer & Roelofs (2010), which shows a dependence of approximately $\dot{M} \propto B^2$, so that an accretion rate about 100 times that of Gaia14aae would be expected, given the 10 times higher magnetic field. In the context of a scenario where mass transfer is enhanced by magnetic braking, one possibility is that there is an accretion disc in SDSS 0804, and the magnetic field is well below 10^5 G. Another is that the effects of magnetic braking at a given magnetic field and the accretion rate in Gaia14aae have been overestimated by similar amounts. A final possibility is that the magnetic braking process is fundamentally different in the absence of actual disc formation.

4.3 Tides?

An alternative means of affecting the evolution of AM CVn systems relative to the standard gravitational wave scenario is via tides. This appears unlikely for two reasons: tides tend to reduce, rather than increase accretion rates (Biscoveanu, Kremer & Thrane 2023), and tides are unlikely to lead to dramatic difference between systems at a given orbital period, especially for longer period systems that have had longer to synchronize (Biscoveanu, Kremer & Thrane 2023).

4.4 Implications for long-term evolution of AM CVn systems and their orbital period distribution

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 min. 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 min, 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.

ACKNOWLEDGEMENTS

We thank Matthew Green for useful discussions and an anonymous referee for comments that improved the quality of this article. TK acknowledges support from the National Science Foundation through grant AST #2107982, and from the National Aeronautics and Space Administration through grant 80NSSC22K0338. Co-funded by the European Union (ERC, CompactBINARIES, 101078773). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Council. Neither the European Union nor the granting authority can be held responsible for them.

DATA AVAILABILITY STATEMENT

All new data presented in this Letter are accessible from the *XMM–Newton* archives.

REFERENCES

Amaro-Seoane P. et al., 2023, Living Rev. Relativ., 26, 2
Bahramian A. et al., 2017, MNRAS, 467, 2199
Bailer-Jones C. A. L., Rybizki J., Fouesneau M., Demleitner M., Andrae R., 2021, AJ, 161, 147
Begari T., Maccarone T. J., 2023, JAAVSO, 51, 227
Biscoveanu S., Kremer K., Thrane E., 2023, ApJ, 949, 95
Campbell H. C. et al., 2015, MNRAS, 452, 1060
Cordova F. A., Mason K. O., 1982, ApJ, 260, 716
Deloye C. J., Taam R. E., Winisdoerffer C., Chabrier G., 2007, MNRAS, 381, 525
Farmer A., Roelofs G., 2010, preprint (arXiv:1006.4112)
Frank J., King A., Raine D. J., 2002, Accretion Power in Astrophysics: 3rd Edn. Cambridge Univ. Press, Cambridge, p. 398
Gaia Collaboration, 2021, A&A, 649, A1
Hameury J. M., Lasota J. P., 2017, A&A, 602, A102
Hernández Santisteban J. V. et al., 2019, MNRAS, 486, 2631
Kotko I., Lasota J. P., Dubus G., Hameury J. M., 2012, A&A, 544, A13
Kraft R. P., Mathews J., Greenstein J. L., 1962, ApJ, 136, 312
Kupfer T., Steeghs D., Groot P. J., Marsh T. R., Nelemans G., Roelofs G. H. A., 2016, MNRAS, 457, 1828
Nelemans G., Portegies Zwart S. F., Verbunt F., Yungelson L. R., 2001, A&A, 368, 939
Nelemans G., Yungelson L. R., van der Sluys M. V., Tout C. A., 2010, MNRAS, 401, 1347
Norton A. J., Beardmore A. P., Allan A., Hellier C., 1999, A&A, 347, 203
Pala A. F. et al., 2020, MNRAS, 494, 3799
Postnov K. A., Yungelson L. R., 2014, Living Rev. Relativ., 17, 3
Ramsay G., Groot P. J., Marsh T., Nelemans G., Steeghs D., Hakala P., 2006, A&A, 457, 623
Ramsay G. et al., 2018, A&A, 620, A141
Roelofs G. H. A., Groot P. J., Nelemans G., Marsh T. R., Steeghs D., 2006, MNRAS, 371, 1231
Roelofs G. H. A. et al., 2009, MNRAS, 394, 367
Rosen S. R., Mason K. O., Cordova F. A., 1987, MNRAS, 224, 987
Sokoloski J. L., Bildsten L., 1999, ApJ, 517, 919
Verbunt F., Zwaan C., 1981, A&A, 100, L7
Wade R. A., Eracleous M., Flohic H. M. L. G., 2007, AJ, 134, 1740
van Roestel J. et al., 2022, MNRAS, 512, 5440
van Teeseling A., Beuermann K., Verbunt F., 1996, A&A, 315, 467

This paper has been typeset from a TEX/LATEX file prepared by the author.