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Outbursts in ultra-compact AM CVn binaries

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AM CVn binaries are the most compact of accreting binaries having orbital periods in the range ~5-70 min. They consist of a white dwarf accreting hydrogen deficient material from a degenerate or semi-degenerate star and are predicted to be amongst the verification sources for future gravitational wave observatories such as LISA. Using the recent catalogue of Green et al (2025) I focus attention on the orbital period range in which outbursts are seen from AM CVn's. I examine in more detail the outburst properties of KL Dra which has an outburst every few months and has many sectors of *TESS* data as an open resource. Using observational data on the outbursting systems in general, I compare the outburst recurrence time, duration and amplitude as a function of orbital period with the predictions of the disc instability model. The recurrence time is well described, although there is some evidence that the amount of material in the disc at the end of the quiescence phase is less than earlier model assumptions. The distribution of the outburst duration appears to be dependent on the cadence of the observations and how it is defined. Similarly the amplitude distribution is dependent on cadence and the filter, which causes an apparent spread in distribution. Both of these features need to be systematically studied using consistent benchmarks. AM CVn binaries remain an excellent sources to test models which aim to predict the properties of disc accreting systems.

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1. Introduction

AM CVn binaries are the most compact of accreting binaries (orbital period, $P_{\rm orb}$, $\lesssim$70 min) and consist of a white dwarf accreting material from another white dwarf or semi-degenerate star. The archetype, AM CVn, was identified as having broad double helium absorption lines in the 1950's, but it was not until high speed photometry, which showed a modulation on a period of ~18 min, that it was revealed as a possible very compact binary system (Smak [1]). However, it was only decades later that spectroscopy revealed a $P_{\rm orb}$ of 17.15 min (Nelemans et al. [2]), with a photometric period of 17.52 min being the superhump period which is the signature of a precessing accretion disc.

These ultra compact accreting binaries are important for the following reasons. They have negligible amounts of helium present in their spectrum – they are therefore excellent systems to compare and contrast helium dominated accretion flows with the well studied hydrogen dominated accretion flows seen in cataclysmic variables (CVs). Their compact nature implies they should be strong sources of persistent gravitational waves. Indeed, they are the verfication sources for ESA's Lisa gravitational wave constellation due to be launched in the mid 2030's (see Kupfer et al. [3] and Simone Scaringi's talk at this workshop). Thirdly, their space density is a sensitive test for population synthesis models which predict their number. For a full review of AM CVn binaries in general see Solheim [4]

This short overview is focussed on how the long term behaviour of AM CVn's can be used to test the theoretical models which predict their observational properties. For many years the thermal-viscous disk instability scenario (e.g. Meyer & Meyer-Hofmeister [5]) has been modelled using the Disc Instability Model (DIM) which is the subject of this workshop. Whilst it has been successful in explaining many of the observed properties, it fails in certain aspects, including the prediction that the system will slowly brighten over the quiescent phase, which observations do not show. See Hameury [6] for a recent review of how predictions of the DIM compares with the observational proprties of outbursts from compact binaries, including AM CVn's.

An even earlier model for explaining outbursts from CVs is the Mass Transfer Instability Model (MTIM) which predicted that outbursts were due to episodes of increased mass transfer from the donor star leading to a disc with high viscosity (Bath [7], Bath & Pringle [8]). In the last twenty years, evidence for MTIM in some outbursting systems has increased (see Baptista & Schlindwein [9] for some examples, including the AM CVn system YZ LMi). With the increased number of systems over a range of orbital period, AM CVn binaries can be used to confront both the DIM and MTIM models with observational evidence.

2. How to identify AM CVn binaries

If we aim to understand the long term behaviour of AM CVn's as a function of $P_{\rm orb}$ (and hence test accretion models) we have to understand the biases which are present in their discovery.

At the very shortest period, HM Cnc (5.35 min) and V407 Vul (9.48 min) were discovered using *ROSAT* X-ray observations since they are strong soft X-ray emitters. These are now thought to be 'direct accretors' where the accretion flow impacts the photosphere of the more massive white dwarf directly without the formation of any accretion disc. eRASSU J0608-7040 (6.2 min)

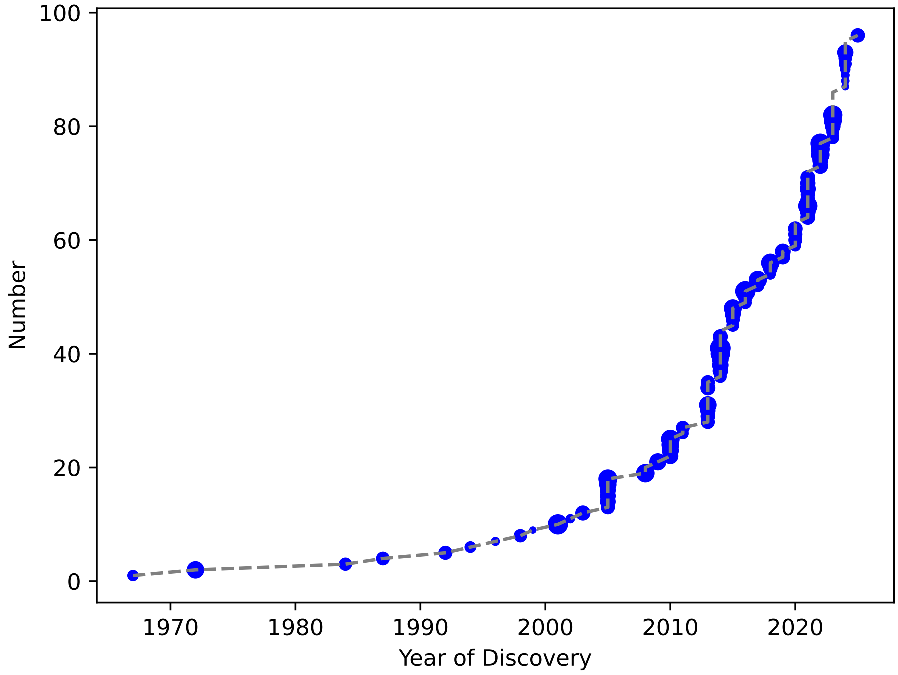

Figure 1: The number of confirmed AM CVn binaries as a function of year where the size of the symbol reflects the stars orbital or superhump period (data taken from Green et al. [10]) For systems with no confirmed or predicted period we have set their symbol size to zero.

discovered in 2024 and 3XMM J0510-6703 (with a longer period of 23.6 min) discovered in 2017 make up their class. Since they do not have accretion discs, we will not discuss them further.

Systems with periods close to ten minute include ES Cet (10.3 min) which was discovered in a UV survey and were subjected to high time resolution photometry by Brian Warner and others which revealed their strong periodic modulation which is due to super-humps in a disc which is always in the hot state (and analogous to the nova-like hydrogen accreting systems). Observations made using ZTF revealed candidates similar to ES Cet with dedicated high cadence observations made using HiPERCAM and other instruments revealing ZTF J0545+3843 (7.95 min). This indicates that wide-field surveys can identify very short period binaries, but followup observations on >2 m telescopes are required to reveal their hydrogen deficient nature and provide data which have a sufficient cadence to model multi-colour light curves.

Using the catalogue of Green et al. [10] we show in Figure 1 the number of AM CVn binaries since the discovery of AM CVn itself in 1967 – by 1990 only four systems were known, rising to 25 by 2010 at the point of the Solheim [4] review. Clear increases in numbers are apparent in 2005 when the SDSS survey identified stars with helium lines and no hydrogen. A sharp rise was also seen in 2013-2014 when transient surveys such as PTF, CRTS and ASASSN, started to identify outbursts from previously unknown binary systems. From 2020, ZTF started to make a series of new discoveries of systems which were outbursting. Because of the sheer number of new candidate galactic transients from surveys such as ZTF, Atlas, Panstarrs and GOTO (to name only a few) there is a serious problem of obtaining spectroscopic data to confirm whether an outburst lacks hydrogen in its spectrum. There are 96 confirmed AM CVn binaries in the catalogue of Green et al. [10]. Given there are two orders of magnitude more predicted AM CVn's than are currently known, it is unclear if many more systems await discovery or that the models which predict their number are seriously incorrect (see Rodriguez et al. [11] for a recent study).

3. The outburst period range

Comparing the long term optical behaviour of AM CVn's with the hydrogen accreting CVs has long been of interest, with the aim being to understand what was causing some systems to appear relatively stable and some which showed outbursts similar to those seen in hydrogen accreting dwarf novae. Work by Smak [12] (when there was two known systems) and Tsugawa & Osaki [13] (six systems) indicated that for systems with $P_{\rm orb}$ $\lesssim$20 min, the mass transfer rate was high and the accretion disc would always be in a hot state. For systems with $P_{\rm orb}$ $\gtrsim$40 min, the disc would always be in a cool state and would not show outbursts.

By the time of the study of Ramsay et al. [14], who had a long term programme on the Liverpool Telescope to monitor AM CVn systems, there were 27 known systems. These authors found that systems with $P_{\rm orb}$=20-45 min showed evidence for outbursts. For instance, KL Dra ($P_{\rm orb}$= 24.5 min) shows outbursts every few months. Using the catalogue of Green et al. [10] we can reassess whether this finding still holds.

Using $P_{\rm orb}$ (or predicted $P_{\rm orb}$ using the Levitan et al. [15] relationship between recurrence time and $P_{\rm orb}$) in Green et al. [10] we split the sources into direct impact accretors; high state systems; outbursting systems and low state systems as defined in the catalogue and show the results in Figure 2. As expected with having significantly more systems, the separation between outbursting systems is not as clear cut as found in Ramsay et al. [14]. (We class GP Com as an outbursting system since Kojiguchi et al. [16] and a poster presentation in these proceedings found an outburst in Harvard plate scans).

The longer period high state systems are CX361 (22.9 min), which has a Galactic latitude of -1.4°, could be less well observed in wide-field surveys which avoid the plane; TIC 378898110 (23.0 min) (Green et al. [17]) did show a long duration and slow increase of ~0.3 mag but no clear signs of typical accretion outbursts and SDSS J1831+4202 (23.1 min) which has a '?' beside its high state status in Green et al. [10]. All three systems are very worthy of continued followup to search for future outbursts or unusual behaviour.

Those systems showing outbursts now extend from ASASSN-14cc (22.5 min) to SDSS J1137+4054 (59.6 min) with a tendancy for the recurrence timescale to increase for longer period systems (we will discuss this later). However, Duffy et al. [18] used photometry from five wide-field surveys to study the long term behaviour of eight systems in a very narrow period range (22.5 and 26.8 min) and found a diverse set of behaviour implying factors such as formation route, nature of the donor star, metalicity and potentially the magnetisim of the accreting white dwarf, play an important role in defining their long term properties. Systems in a low state stretch from SDSS J0804+1616 (44.5 min) to the longest period AM CVn system we currently know, SDSS

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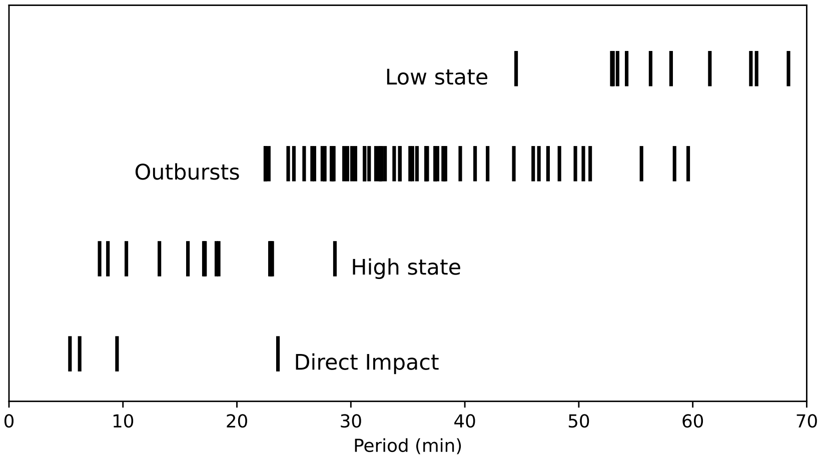

Figure 2: The confirmed systems in the catalogue of Green et al. [10] split into direct imapact, high state, outbursters and low state systems.

J1505+0659 (68.4 min). Searching for (possibly) rare outbursts from these low state systems is strongly encouraged.

4. KL Dra - a case study of an outbursting system

KL Dra was originally identified as a supernova (SN 1998di), although a subsequent spectrum indicated it was not one, but likely a member of the (then) small group of AM CVn binaries. Photometric observations by Wood et al. [19] revealed a period of 25.5 min (super-humps) in a high state and 25.0 min (the likely $P_{\rm orb}$) in the low state. In 2009 Ramsay et al. [14] started a several year photometric study of AM CVn's with the Liverpool Telescope on La Palma. It quickly became clear that KL Dra showed an outburst every few months (Figure 3), indicating it was an excellent source to study the accretion process in these hydrogen deficient accreting systems.

With the advent of wide field surveys such as PTF, studies such as Levitan et al. [15] were able to identify that some bursts were of longer duration than others – i.e. AM CVn's showed normal outbursts and superoutbursts which are seen in various types of hydrogen accreting CVs. One of the many achievements of the *Kepler* mission was to show that superoutbursts in CVs were preceded by a normal outburst with only a small decrease in flux before the start of the superoutburst (e.g. Cannizzo et al. [20]). It was not until *TESS* observations were made of AM CVn outbursts (Duffy et al. [18], Pichardo Marcano et al. [21]), that it was revealed that other systems also show a normal outburst just before a superoutburst.

TESS has now observed KL Dra in dozens of sectors (it is close to the northern ecliptic pole) and we show the light curve obtained in one sector using the *TESS* SPOC pipeline in Figure 4 and shows one normal outburst and a superoutburst. The combined sector-by-sector data show a dozen superoutbursts and three dozen normal outbursts and are a rich resource for studying the accretion process in hydrogen deficient binaries.

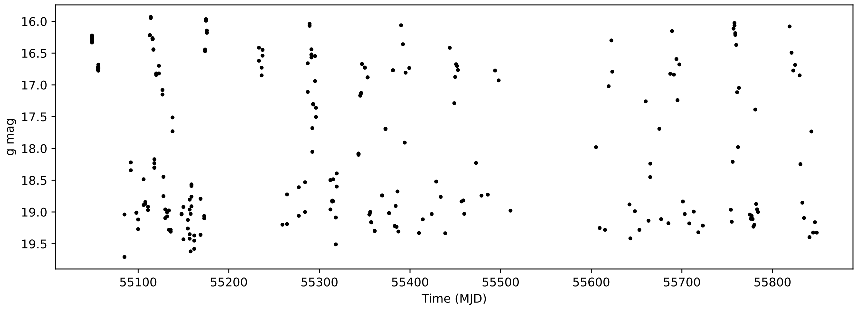

Figure 3: Photometry of KL Dra obtained using the Liverpool Telescope between Aug 2009 and July 2011 (data from Ramsay et al. [14]) showing outbursts every few months.

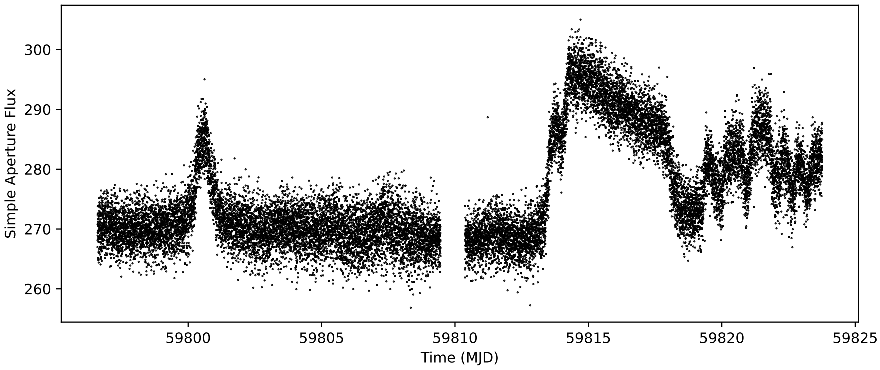

Figure 4: *TESS* data of KL Dra obtained in sector 55 showing one normal outburst and one superoutburst (which immediately follows a second normal outburst) obtained from the *TESS* SPOC pipeline (Caldwell et al. [22]).

Given we could reasonably predict when an outburst of KL Dra would take place, we submitted a ToO proposal to observe it using *XMM-Newton* in X-rays and the UV and were successful in obtaining eight pointings over a superoutburst over Sept-Oct 2011. We show the light curves in the X-ray and UV and also optical data taken over the same time period using the Liverpool Telescope in Figure 5.

A superoutburst was ongoing immediately before the start of the XMM-Newton observations, with the UV flux starting to rise and the X-ray flux being suppressed. By the end of the superoutburst, the UV flux dropped suddenly with the X-rays showing a rise. The X-rays hardened over the course of the bursts, afterwards showing a softening (Ramsay et al. [23]). This is due to the boundary layer between the accretion disc and the white dwarf becoming optically thick and the bulk of the emission is released at UV wavelengths. The same anti-correlation between X-rays and optical is also seen in an outburst from SDSS J141118+481257 ($P_{\rm orb}$ ~46 min, Rivera Sandoval & Maccarone [24]) while the reverse seems to be found in ASASSN-21au ($P_{\rm orb}$ ~58 min) during an outburst which showed an unusually long rise to peak outburst (Rivera Sandoval et al. [25]).

Comparing the characteristics of this KL Dra superoutburst with hydrogen accreting dwarf nova, we find SU UMa also shows hard X-rays to be supressed during optical outbursts (Collins

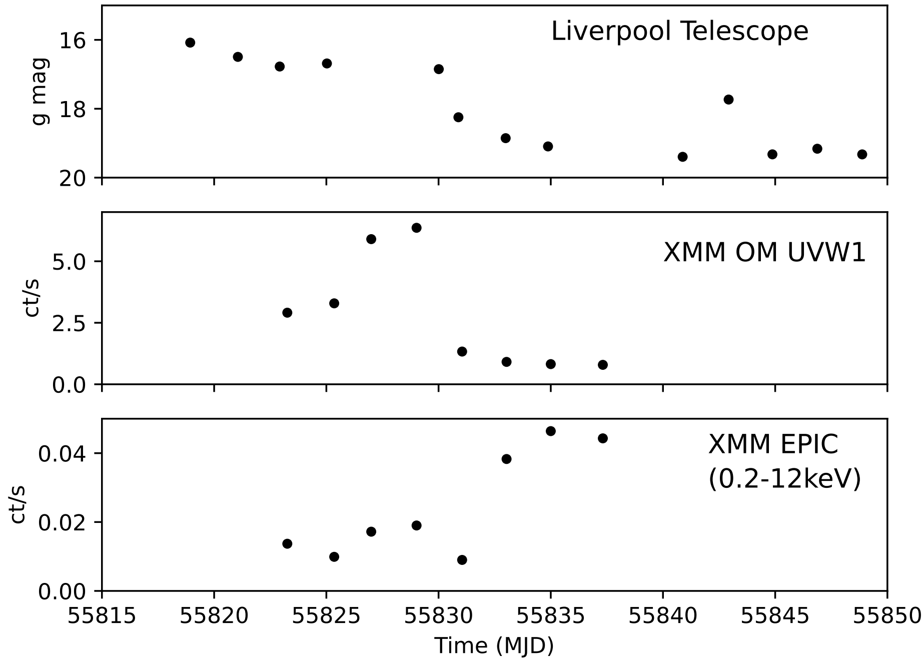

Figure 5: Observations of KL Dra made using the Liverpool Telescope (optical); XMM-Newton OM (UV) and XMM-Newton EPIC (X-rays) (Adapted from Ramsay et al. [23]).

& Wheatley [26]). Hard X-rays are also suppressed during an outburst from SS Cyg although the extreme UV emission follows the optical flux (Wheatley et al. [27]). In contrast, U Gem shows at least one outburst in which the hard X-rays follow the behaviour of the optical and UV emission (Mattei et al. [28]). It is unclear if these differences are due to a viewing angle dependance or other effects.

5. Tests of the disc instability model

With the arrival of systematic programmes to study the long term optical behaviour of AM CVn binaries (e.g. Ramsay et al. [14], Levitan et al. [15]), it became possible to determine if characteristics such as superoutburst recurrence timescale, duration and amplitude were related to $P_{\rm orb}$.

Using data from 11 systems, Levitan et al. [15] found there was a strong correlation between $P_{\rm orb}$ and recurrence time; a slightly weaker correlation with outburst duration and a lesser correlation with outburst amplitude. In other words, systems with longer orbital periods tended to show outbursts separated by longer time intervals and with longer duration than shorter period systems.

5.1 Outburst recurrence time

Cannizzo & Nelemans [29] confronted the observational findings of Levitan et al. [15] with predictions based on the DIM along with various assumptions. They found the correlation between the recurrence time and orbital period was consistent with the predictions of the DIM. Kojiguchi et al. [16] collated a much larger sample of recurrence times of the superoutbursts from 59 systems

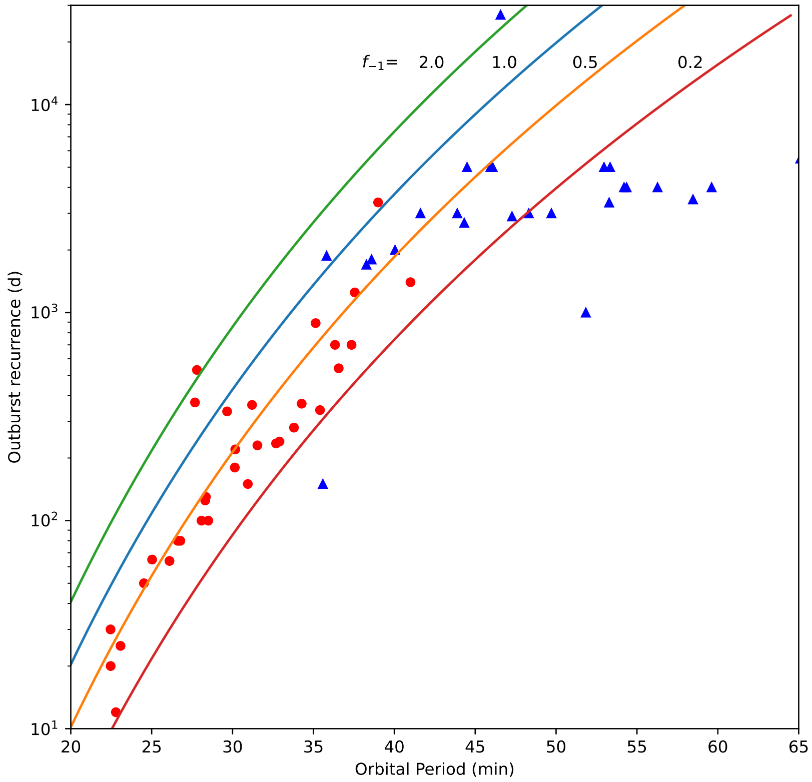

Figure 6: The recurrence time of superoutbursts from the sample of Kojiguchi et al. [16]. We also show the predicted relationship using equation 1 (which is equation 18 of Cannizzo & Nelemans [29]) assuming four different values of f_{-1}.

(some of which were upper limits) which we reproduce in Figure 6. We also plot the predicted recurrence time using equation 18 of Cannizzo & Nelemans [29]:

$$t_{recur} = (7.59\text{days}) f_{-1} \alpha_{\mathrm{c}-1}^{-0.82} m_1^{0.85} (1+q)^{1.03} (P_{\mathrm{orb}}/1000\text{sec})^{7.51} \tag{1}$$

where f_{-1} is the fraction of of material in the disc at the end of the quiescent phase relative to maximum possible; α_{c-1} is the viscosity paramater, α, of the disc in the quiescent state (both normalised to 0.1); $m_{1,2}$ is the mass of the primary and secondary in solar units, $q = m_1/m_2$.

In Figure 6 we show the prediction from equation 1 where we assume m_1=0.6, q=0.05, $\alpha_{\mathrm{c}-1}$=1, and f_{-1} ranging from 0.2–2.0. We find that most of the systems are contained in the range between f_{-1}=0.2–1.0 indicating $f = 0.02 - 0.1$ which is slightly lower than the expectation of $f \sim 0.1 - 0.3$ (Cannizzo & Nelemans [29]), implying the disc at the end of the quiescent phase has slightly less mass compared to the initial expectations of these model assumptions. (Although Kojiguchi et al. [16] do not include uncertainties on the recurrence time, for KL Dra this is ~10% (Ramsay et al. [14])).

5.2 Outburst duration

Although Levitan et al. [15] did not find as strong a correlation between outburst duration and P_{orb} as for recurrence time, it was still statistically significant. This is maybe due to the sampling rate of the observations or the complex profile of the outbursts which make an accurate determination more uncertain. The duration of the outburst is related to the viscous timescale:

$$t_{viscous} = (15.1\text{days})\alpha_{\text{h}-1}^{-0.8} m_1^{0.34}(1+q)^{0.16}(P_{\text{orb}}/1000\text{sec})^{0.36} \tag{2}$$

which is equation 21 of Cannizzo & Nelemans [29] where $\alpha_{\text{h}-1} = \alpha_{\text{hot}}/0.1$ and other symbols as before.

In Figure 7 we show the duration of outbursts from Levitan et al. [15] together with their observed best fit to their data and also the predicted correlation based on equation 2. We also add the results from Duffy et al. [18] who analysed systems in a similar period range to Levitan et al. [15]. Even if we only consider these samples, which are strongly biased towards shorter period systems, they do not strongly follow the viscous time relationship.

We now examine two outbursting systems with longer orbital periods: SDSS 0807+48 (Rivera Sandoval et al. [30]) which showed a very long rise to outburst (~200 day) and then an apparent more rapid decline from maximum and was classed as having a duration of 390 days. SDSS 1411+48 has shown several outbursts (Rivera Sandoval & Maccarone [24] plus AAVSO data) which indicate a much shorter duration. Both of these systems are shown in Figure 7: SDSS 0807+48 is above the empirical Levitan et al. [15] relationship based on shorter periods while SDSS 1411+48 is slightly above the viscous relationship outlined in Cannizzo & Nelemans [29]. Both are problematic since the rise to maximum in SDSS 0807+48 is highly unusual (perhaps due to a different outburst mechanism) and SDSS 1411+48 has a number of echos or dips in its light curve.

We now return to the shorter period systems, including those previously examined by Levitan et al. [15] and Duffy et al. [18]. Some of these systems were observed using *TESS* (Pichardo Marcano et al. [21]) which revealed detail in the light curves of AM CVn's not seen before, including the fact that superoutbursts are preceded by a normal outburst. Pichardo Marcano et al. [21] determined the mean duration of the superoutbursts in six systems and these are also shown in Figure 7: they are shorter by a factor of five compared to those studies which determine the duration using ground based all-sky surveys. This maybe explained by the fact that Pichardo Marcano et al. [21] defined the duration of the outburst which did not include any dip or echo features that are not always clear in ground based data.

It is worth noting how the superoutburst was defined in Cannizzo & Ramsay [31]. They note the initial rise is set by the thermal timescale[1], τ_{therm}, and then the slow decay is set by the viscous timescale[2], τ_{visc}, followed by a faster decay set by $(\tau_{visc}\tau_{therm})^{1/2}$. They also note 'the relaxation back to the quiescent state can take much longer than what we define to be duration of the outburst'. Finally the same authors conclude that it is not clear whether dips or double outbursts should be included in the outburst duration. However, it should also be noted that the model assumptions which Cannizzo & Nelemans [29] used would not have been able to account for dips and echo outbursts (see §5.4).

The definition of the superoutburst duration in AM CVn's need to be reassessed. For instance, should the duration include the dip phase which can occur after the peak, and subsequent rebright-

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[1] The thermal timescale is the time taken for the disc to change its temperature due to external forces.

[2] The viscous timescale is the time taken for material to move through a disc due to viscosity.

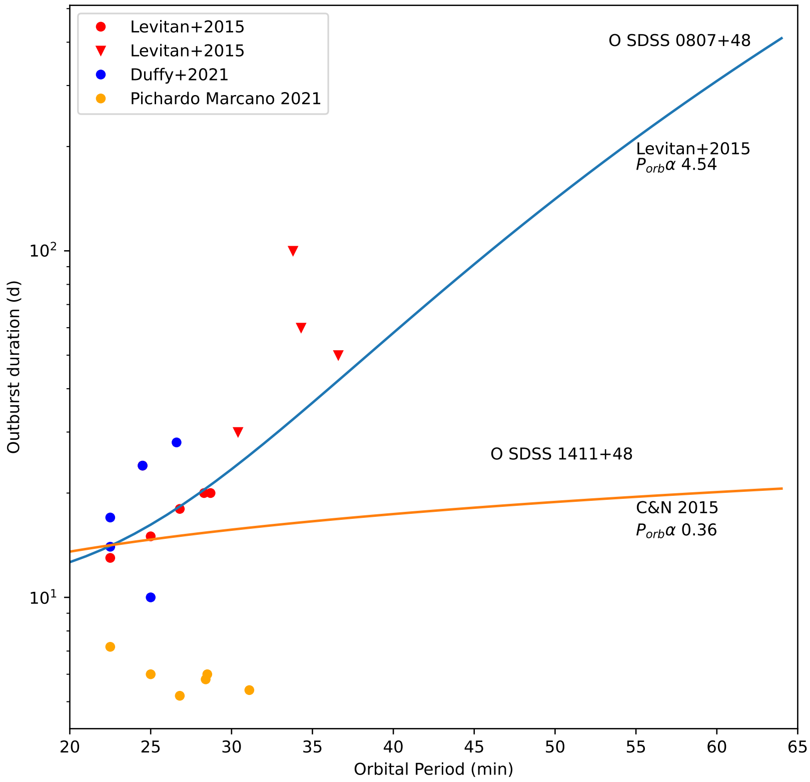

Figure 7: The duration time of superoutbursts and as function of $P_{\rm orb}$ taken from Levitan et al. [15] (including upper limits), Duffy et al. [18] and Pichardo Marcano et al. [21]. We also show the initial empirical fit to the data of Levitan et al. [15] and the predicted relationship of Cannizzo & Nelemans [29]).

ening and any echo outbursts? A systematic study is required which applies a consistent definition of the superoutburst duration.

5.3 Outburst amplitude

Theoretical studies by Mineshige & Osaki [32], Meyer & Meyer-Hofmeister [33], Smak [34] showed that the observed amplitude of dwarf nova outbursts can only be reproduced in simulations if the viscosity parameter, α, was different by approximately a factor of ten, during the cold and hot disc states. (See Coleman et al. [35], Jordan et al. [36] for more recent simulations).

Levitan et al. [15] found evidence of a weak correlation between the outburst amplitude and $P_{\rm orb}$. Since then many more outbursts have been observed from many other sources. One of the main issues with determining the amplitude is the cadence of the observations, which may miss the peak and that a range of filters are used. Similarly, the quiescence brightness is not always well established. We show in Figure 8 the amplitude of systems presented in Levitan et al. [15] and van Roestel et al. [37, 38]. We also show two longer period systems as examples: Gaia14aee (Campbell et al. [39]) and ASASSN-21au (Isogai et al. [40]). Given that the distribution of amplitude versus $P_{\rm orb}$ appears far from being well correlated, a more systematic study of the outbursts of longer period systems is required.

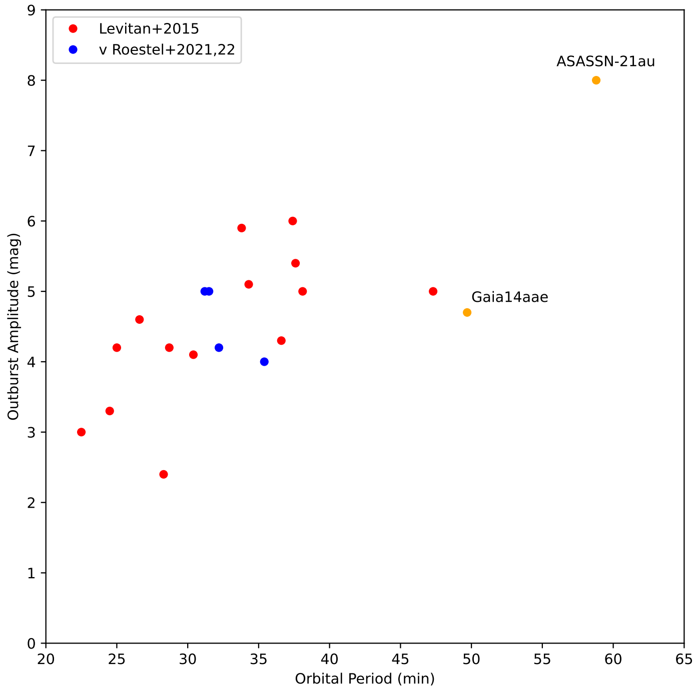

Figure 8: The amplitude of superoutbursts from the samples of Levitan et al. [15], van Roestel et al. [37, 38] plus two longer period systems, Gaia 14aee and ASASSN-21au.

5.4 Outburst echos

In some hydrogen accreting CVs, a series of echo, or rebrightenings, have been seen during the decline from maximum. One famous example is the EG Cnc 1997 outburst which showed six such bursts (Patterson et al. [41]). Hameury & Lasota [42] were able to simulate echo outbursts from several different accreting systems by incorporating time dependent parameters in the DIM model such as a varying mass transfer rate and irradiation of the accretion disc from the hot white dwarf. Several AM CVn systems have also been shown to show echo bursts, including OX Eri (ASASSN-14ei) and V493 Gem (ASASSN-14mv) (see Kato [43] for a review of WZ Sge systems which also touches on echo outbursts including AM CVn systems). As an example, we show in Figure 9 one outburst from Gaia16all observed using *TESS* which showed a series of echo outbursts (see Pichardo Marcano et al. [21] for details). These echo outbursts provide an excellent resource to test the DIM and MTIM models, including those seen from very compact systems and accretion flows which are hydrogen deficient.

5.5 Simulating light curves

Finally we turn to studies which simulate the light curve of AM CVn's over multiple outbursts. Kotko et al. [44] was able to reproduce lightcurves of CR Boo and V803 Cen using a constant viscosity parameter, α, and a mass transfer rate close to the upper critical rate. Kotko et al. [45] explored this in greater detail and found enhanced mass transfer was required, likely due to irradiation of the secondary star, and was able to reproduce the outburst cycle of KL Dra, $\alpha_{\rm cold} = 0.035$, using $\alpha_{\rm hot} = 0.2$. However, it is important to note that normal outbursts were not confirmed

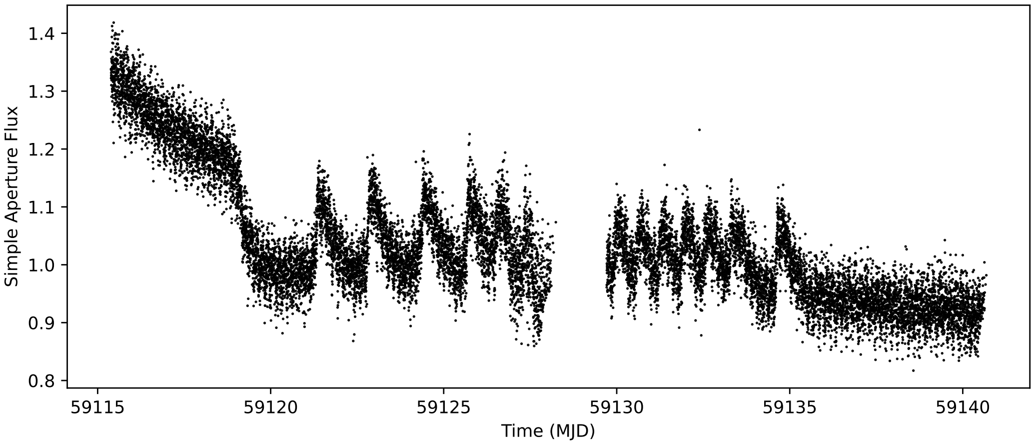

Figure 9: *TESS* observations of Gaia16all made in sector 30 where the light curve was extracted using *TESS*-SPOC pipeline (see Pichardo Marcano et al. [21] for other observations of this source made using *TESS*). This light curve shows a series of echo outbursts after the main outburst.

from KL Dra at that point. The fact they are now known to exist will have an effect on the details of the outburst model. Kotko et al. [45] end by saying: 'When better and richer sets of data will become available the comparison of the DIM with observations will become a precious source of knowledge about accretion disc physics'.

6. Conclusions

With the great increase in the number of AM CVn binaries in recent years, together with their diversity in outburst properties, their population is an excellent test for how hydrogen deficient accretion flows compare with the hydrogen dominated dwarf novae. In particular the recurrence timescale, duration and amplitude of their outbursts can be used to test the predictions of the DIM and MTIM models.

Using the recent compliation of [16] we find that the outburst recurrence timescale is quite well described by the prediction of the DIM, with the caveat that the amount of material in the disc at the end of the quiescent phase is slightly lower than originally expected from the model assumptions. When we compare the duration of the outbursts with the prediction of the DIM and the empirical relationship of Levitan et al. [15] we find that different definitions of the duration make any findings very far from conclusive. A further study is required which compares the duration of outbursts using a consistent benchmark. This is also true for determining the amplitude of outbursts, especially from longer period systems.

With the diversity and extent of outburst behaviours ranging from relatively short orbital periods (~22 min) to long (~60 min) there is great scope for the modellers to predict their light curves using state of the art simulations.

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