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Triggering micromovae through magnetically confined accretion flows in accreting white dwarfs

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ABSTRACT

Rapid bursts at optical wavelengths have been reported for several accreting white dwarfs. In these bursts, the optical luminosity can increase by up to a factor of 30 in less than an hour, before fading on time-scales of several hours, and the energy release can reach $\sim 10^{39}$ erg ('micromovae'). Several systems have also shown these bursts to be semirecurrent on time-scales of days to months, and the temporal profiles of these bursts strongly resemble those observed in Type-I X-ray bursts in accreting neutron stars. It has been suggested that the observed micromovae may be the result of localized thermonuclear runaways in the surface layers of accreting white dwarfs. Here we propose a model in which the magnetic confinement of accretion streams on to the accreting magnetic white dwarf may trigger localized thermonuclear runaways. The model proposed to trigger micromovae appears to favour magnetic systems with both a high white dwarf mass and a high mass-transfer rate.

Key words: magnetic fields – stars: novae, cataclysmic variables – transients: novae.

1 INTRODUCTION

Classical novae (CN) are the result of thermonuclear runaways (TNRs) on the surface layers of accreting white dwarfs (AWDs). After the accumulation of hydrogen from a companion mass donor, ignition conditions are reached near the white dwarf (WD) surface, initiating a runaway thermonuclear explosion (see e.g. Gallagher & Starrfield 1978). Nova explosions result in an increase of up to 10 mag or more at optical wavelengths, have rise times of days, and remain bright for weeks to months (see e.g. Warner 2003). A subclass of novae, namely recurrent novae (RN), are observed to show repeated outbursts on time-scales of years to centuries. The shortest known recurrence time is 1 yr in the system M31N 2008-12a, located in the Andromeda Nebula (Darnley et al. 2016). The physics of novae is well understood, and outburst amplitude and recurrence times are directly related to the mass of the underlying WD and the mass-accretion rate from the donor star (e.g. Starrfield et al. 1972; Shen & Bildsten 2007). Crucially, a CN outburst is always a global phenomenon, in which the accreted hydrogen layer over the whole surface of the WD is burnt after a local ignition. An equivalent

to a nova in a system harbouring a neutron star accretor is a Type I X-ray burst (e.g. Lewin, van Paradijs & Taam 1993). Here the flame also ignites at one location and eventually covers the whole surface (e.g. Strohmayer & Bildsten 2006; Galloway & Keek 2021). When a strong enough magnetic field is present, the flow is channelled on to a smaller fractional area on the surface, and there are indications that this may favour ignition at the base of the accretion column (Goodwin et al. 2021).

Until recently, localized thermonuclear runaways (LTNRs) on AWDs had not been identified. Mitrofanov (1980) and Shara (1982) proposed a mechanism that may allow LTNRs to occur on the surface of AWDs. This mechanism invokes transverse temperature gradients and inhomogeneities in the accreted layers that thermalize on time-scales that are much longer than the thermonuclear runaway time-scale. In this scenario, the freshly accreted material will ignite and be consumed by the propagating flame. This model was initially developed to explain what had already been recognized as accretion-induced dwarf-nova (DN) outbursts (Smak 1971; Warner 1974). It is nonetheless interesting to note that both the rise times and the recurrence times of an LTNR expected from this model can be matched to those observed in DN outbursts of about one day and several weeks, respectively. Orio & Shaviv (1993) later revised this model through numerical calculations to include the effects of mass

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accretion and, importantly, the effects of meridional versus radial energy transport. Extending the analytical model of Shara (1982) to include these effects, Orio & Shaviv (1993) demonstrated that the conditions for triggering LTNRs are possible through temperature inhomogeneities, and are more likely to occur in systems accreting at high rates and on higher-mass WDs. This would give rise to a non-spherical TNR, possibly explaining the observed asymmetries in some nova shells (see also Livio 1995). Importantly, Orio & Shaviv (1993) do not explicitly confirm the presence of the non-spreading LTNR (‘volcanoes’) whose existence was speculated by Shara (1982).

Despite the lack of convincing observational evidence on the existence of LTNRs in AWDs, puzzling short-lived high-amplitude variations have been observed in a number of AWDs, most notably in the magnetic system TV Columbae (TV Col; Schwarz et al. 1988; Hellier 1993). High-ionization helium and nitrogen lines were observed to strengthen during these fast bursts, and outflow velocities greater than 3500 km s^{-1} were observed during peak luminosity when P-Cygni profiles developed in UV spectral lines (Szkody & Mateo 1984). At that time, no clear explanation was found for such fast variability, nor for the outflowing velocities.

The *Transiting Exoplanet Survey Satellite* (TESS) has drastically changed the observational status. Its unprecedented monitoring of the optical sky has yielded a number of AWDs in which short-duration, fast-rise–exponential-decay events lasting a few hours grouped in pairs or triples, and with recurrence times of days to months, have been observed. Scaringi et al. (2022) noted these events in the systems TV Col, EI UMa and ASASSN-19bh, and Schaefer, Pagnotta & Zoppelt (2022) noted similar bursts in the recurrent nova V2487 Oph during quiescence. Scaringi et al. (2022) concluded that these bursts are of thermonuclear origin, based on the energetics, rise-time and close resemblance to Type I X-ray bursts in accreting neutron stars, referring to them as *micronovae*. Schaefer et al. (2022) instead came to the conclusion that the bursts are caused by magnetic reconnection events in the accretion disc, possibly due to an extremely active companion.

Here we elaborate and expand in more detail on the possible thermonuclear origin of these fast bursts in AWDs, which may give rise to micronovae events as proposed in Scaringi et al. (2022). In Section 2 we introduce a model in which the surface magnetic fields of AWDs may confine the flow of accreted material on to the WD surface and allow the pressure at the base of the accretion column to reach the critical pressure required to initiate a localized TNR. Section 3 discusses some possible limitations to the model and discusses our results in light of the observations of Scaringi et al. (2022) and Schaefer et al. (2022).

2 MAGNETICALLY CONFINED ACCRETION

The model we propose allows an accretion column on the magnetic poles of AWDs to be confined by the WD magnetic field and to increase in mass over time. As this happens, the pressure exerted on the WD resulting from the column’s weight causes the column base to sink to greater depths. If this magnetic confinement can hold until the pressure at the base of the accreted column reaches $P_{\text{crit}} \approx 10^{18} \text{ dyn cm}^{-2}$, a TNR may start (e.g. Bode & Evans 2008; José, Shore & Casanova 2020). The ignition burns through most of the overlaying accumulated mass in the column. The process can repeat every time the pressure at the column’s base reaches the required pressure to drive a TNR.

In magnetic AWDs with surface magnetic field strengths of $B \approx 10^6 \text{ G}$ to 10^7 G , the accretion flow impacts on the WD magnetic

poles and remains confined by the magnetic pressure $P_B = B^2/8\pi$. This only happens if the ratio

$$\beta = \frac{P_{\text{gas}}}{P_B}, \quad (1)$$

where P_{gas} is the gas pressure of the magnetically confined material, does not exceed a critical β_{crit} . In general, for magnetically channelled accretion on to WDs, P_{gas} is substantially lower than P_B . As the weight of the column increases over time, the pressure at the base of the magnetically confined column (P_{base}) also increases, and the column pressure being exerted radially downwards can translate azimuthally and begin exerting pressure on to the magnetically confined boundary. In this limit, the requirement for material in the accretion column to remain confined becomes

$$\beta = \frac{P_{\text{base}}}{P_B} < \beta_{\text{crit}}. \quad (2)$$

If $\beta > \beta_{\text{crit}}$ then the column pressure substantially distorts the magnetic field lines, and the accretion column may spread on to the WD surface.

Given a net positive mass-accretion rate into the magnetically confined accretion column, \dot{M}_{acc} (which takes into account any mass leakage from the column itself), the column mass increases with time t such that

$$M_{\text{col}}(t) = \dot{M}_{\text{acc}} t. \quad (3)$$

Assuming an accretion column with a circular footprint area of radius R_{col} , the fractional impact area on to the WD surface can be defined as

$$f = \left(\frac{R_{\text{col}}}{2R_{\text{WD}}} \right)^2, \quad (4)$$

where R_{WD} is the WD radius. Using this definition, the pressure exerted at the base of the accretion column will increase such that

$$P_{\text{base}}(t) = \frac{GM_{\text{WD}}M_{\text{col}}(t)}{4\pi f R_{\text{WD}}^4}, \quad (5)$$

where M_{WD} is the WD mass and G is the gravitational constant. Over time, the column mass will increase, and numerical magneto-hydrostatic results (Hameury & Lasota 1985) have shown that the accretion column will remain confined by the magnetic pressure P_B as long as

$$\beta(t) = \frac{P_{\text{base}}(t)}{P_B} < \beta_{\text{crit}}, \quad (6)$$

where

$$\beta_{\text{crit}} \approx 7\alpha^2 \quad (7)$$

and

$$\alpha = \frac{R_{\text{col}}}{h}, \quad (8)$$

with h being the height of the accumulated material in the column (see Hameury & Lasota 1985). If $M_{\text{col}}(t)$ is able to become high enough such that the column pressure is equal to or higher than $P_{\text{crit}} \approx 10^{18} \text{ dyn cm}^{-2}$ (e.g. José et al. 2020; Yaron et al. 2005) while remaining magnetically confined (equation 6), then it is reasonable that a TNR may start. When this happens, the TNR, while heating up, may expand along the path of least resistance, which in this case is along the lower-pressure, magnetically confined column material above it, eventually escaping from the WD surface, and burning most of the column mass $M_{\text{col}}(t)$ in the process. It may also happen that the radiation pressure or turbulent dynamics in the column generated

by the hot TNR will break the magnetic confinement, in which case the column material could spread on to the WD surface as it is being ignited. Either way, after the localized TNR takes place, the process of accumulating mass in a magnetically confined accretion column will restart, and another micronova will then be observed with a recurrence time of

$$t_{\text{rec}} = \frac{M_{\text{col}}}{\dot{M}_{\text{acc}}}. \quad (9)$$

The left-hand panel of Fig. 1 shows the column mass required to reach $P_{\text{base}} \approx P_{\text{crit}} \approx 10^{18} \text{ dyn cm}^{-2}$ as a function of the fractional accretion area for AWDs with masses in the range $0.6 M_{\odot}$ up to $1.4 M_{\odot}$. In constructing the figure, we used a mass–radius relationship to determine the WD radius (Nauenberg 1972), and used equation (5) to compute P_{base} . The right-hand panel of Fig. 1 shows the minimum α required to keep the accretion column magnetically confined at least until $P_{\text{crit}} = 10^{18} \text{ dyn cm}^{-2}$ is reached. Both panels show that the magnetic confinement expected from magnetic AWDs ($B > 10^6 \text{ G}$) should be strong enough to build enough pressures at the bases of accretion columns to initiate localized TNRs.

Assuming that the material being burned during micronovae is freshly accreted hydrogen from the companion donor star, the CNO cycle flash will yield $\sim 10^{16} \text{ erg g}^{-1}$ (e.g. Starrfield 1971; Starrfield et al. 1972; Starrfield, Sparks & Truran 1976), and we can adopt this value to convert the radiated energy during micronovae into equivalent column masses M_{col} . Micronovae have been observed to release between 10^{38} and 10^{39} erg (Scaringi et al. 2022; Schaefer et al. 2022), which is $\sim 10^6$ times less than the energies released in classical novae (hence the term *micronovae* describing these events). This then translates to column masses in the range $5 \times 10^{-12} M_{\odot} < M_{\text{col}} < 5 \times 10^{-11} M_{\odot}$. For AWDs with $M_{\text{WD}} \approx 0.8 M_{\odot}$ (typical for AWDs: Zorotovic, Schreiber & Gänsicke 2011; Pala et al. 2022), the corresponding fractional accretion area required by the model would then be $f \approx 10^{-6}$. Although this value is low when compared with those inferred from X-ray observations of other magnetic AWDs (Hellier 1997; Lopes de Oliveira & Mukai 2019), it is still allowed by models of magnetically channelled accretion flows where material precipitates on to the polar cap in discrete filaments (King 1995; Frank, King & Raine 2002). However, AWDs with masses of $M_{\text{WD}} \approx 1.3 M_{\odot}$ are able to achieve the required pressures with accretion fractional areas of $f \approx 10^{-4}$, increasing to $f > 10^{-3}$ for WDs approaching the Chandrasekhar limit. These inferred accretion fractional areas are consistent with those observed in at least one of the systems displaying micronovae (TV Col: Lopes de Oliveira & Mukai 2019). However, the high mass required to achieve $f \approx 10^{-4}$ in TV Col appears inconsistent with that inferred from X-ray spectral observations of $0.74 M_{\odot}$ (Lopes de Oliveira & Mukai 2019). It is interesting to further note that typical mass-transfer rates of $\dot{M}_{\text{acc}} = 10^{-10} M_{\odot} \text{ yr}^{-1}$ for AWDs will achieve $P_{\text{base}} = P_{\text{crit}}$ with a recurrence time of $t_{\text{rec}} \approx 100 \text{ d}$. The energy release and recurrence times match the observations of micronovae in Scaringi et al. (2022). On the other hand, a mass-accretion rate of $\dot{M}_{\text{acc}} = 10^{-8} M_{\odot} \text{ yr}^{-1}$ will yield $t_{\text{rec}} \approx 1 \text{ d}$, which qualitatively matches the observations of the RN V2487 Oph (Schaefer et al. 2022).

There is perhaps a further mechanism that may allow some of the accreted material to reach P_{crit} with wider accretion fractional areas f (and/or shorter time-scales than equation 9). If, as the column mass increases over time, the density at the base of the column becomes comparable to or higher than that of the underlying WD, then this configuration may lead to a Rayleigh–Taylor instability. If and when this happens, freshly accreted column material may be brought to deeper depths, reaching P_{crit} and triggering a micronova. This process

may also lead to partial burning of the accreted fuel, which would then completely burn in sets of smaller bursts as observed in TV Col and EI UMa. Whether high enough column densities can be reached to surpass those of the underlying WD will depend crucially on the column temperature profile. This in turn will depend on the conduction, dissipation from the column walls, and accretion rate, all of which seem to favour high accretion rates to maintain higher column temperatures. Whether the conditions for the instability are reached (i.e. a significant density gradient between the column base and the underlying WD) and up to what depth the instability will develop should be assessed by magnetohydrodynamic numerical calculations.

3 DISCUSSION AND CONCLUSION

Although the model described in Section 2 shows that localized TNRs are possible if the flow of material can remain magnetically confined, it is important to comment on some of its limitations. First, the model assumes that the WD magnetic field lines are solidly anchored at the bottom of the accretion column. This in turn provides the magnetic confinement required for the column to increase in mass over time. Because the exterior layers of WDs are not solid, it is possible that some lateral spreading of the column material on to the surface does occur. In particular, some of the various magnetized plasma instabilities might be at play. We specifically refer to \dot{M}_{acc} as the *net* column mass-accretion rate, which does not necessarily have to be the same as the mass-accretion rate from the disc on to the WD. This is because some of the material may experience either lateral spreading or be accreted outside the magnetically confined column (or both). In this case, we would still expect micronovae to occur, but with longer recurrence times than those computed in Section 2. Also important to address are the effects of the column settling into the WD, because this may decrease the column mass. If the settling time-scale is faster than what can be accreted through \dot{M}_{acc} , then a micronova may be inhibited because the column does not increase in mass over time. Given this consideration, the model appears to favour systems with mass-accretion rates that are higher than the settling time-scale of AWDs. Further modelling to include the effects of settling will allow us to determine whether this is the case.

The depth at which a magnetically confined TNR occurs may determine how much radiation and its associated wavelength from the TNR escapes to reach observers. Deeper TNRs may yield fainter and redder micronovae than those occurring closer to the WD surface. In this respect, it is important to note that higher-mass WDs achieve $P_{\text{base}} \approx P_{\text{crit}}$ closer to their surfaces than lower-mass WDs. Thus, higher-mass WDs not only provide more reasonable accretion fractional areas, but also may allow more radiation to escape because the TNR occurs at shallower depths. The model in Section 2 also appears to disfavour magnetic AWDs with relatively low surface magnetic field strengths ($B < 10^6 \text{ G}$) because these systems require columns that are extremely short and wide with $\alpha > 10^4$ to be able to confine the column material magnetically (see Fig. 1, right-hand panel).

One may ask why the micronovae do not ignite the whole WD outer layer, leading to a classical nova explosion. If, following the trigger of a localized TNR, the hot fluid is ejected following the magnetically confined boundary, the heat may be dissipated outside the WD. Depending on the surface composition of the WD, the temperature reached by the outer layers may also be too low to trigger unstable burning. Observations of TV Col during one of its micronova events, for example, show clear evidence of fast outflows

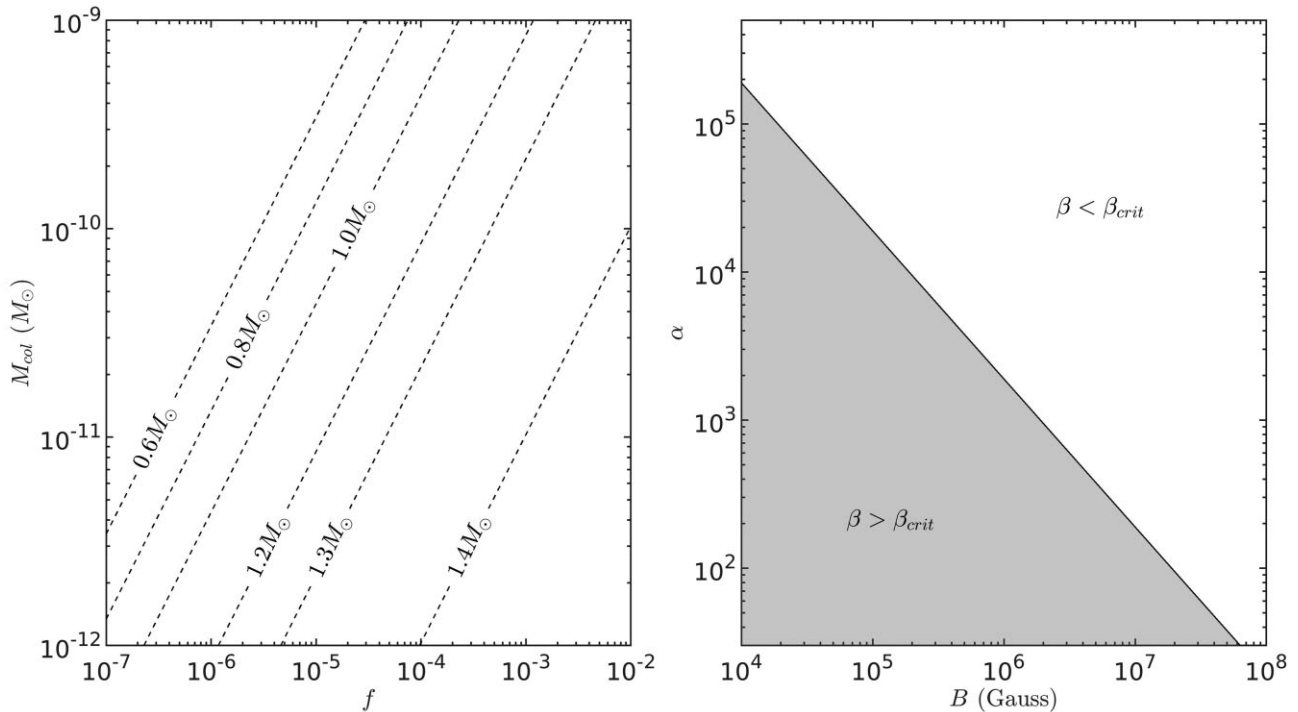


Figure 1. Left-hand panel: Range of column masses (M_{col}) required to reach $P_{\text{base}} \approx P_{\text{crit}} \approx 10^{18}$ dyn cm $^{-2}$. The plot has been computed with a range of WD masses as indicated by the dashed lines. Right-hand panel: Constraint on keeping the accretion column magnetically confined up to $P_{\text{crit}} = 10^{18}$ dyn cm $^{-2}$. The grey shaded region shows where the column pressure will be too high and break the magnetic confinement.

only during the peak of the bursts (Szkody & Mateo 1984), suggesting that the ejection of material is driven by the micronovae themselves. If this material is part of the burning column material, this would act as a substantial sink of heat.

Finally, it is important to comment on the reasons why some magnetic AWDs appear to display micronovae while some do not, and why at least one system displays both classical novae and micronovae. Following the simple model in Section 2, the requirement to trigger a micronova is that $P_{\text{base}} \approx P_{\text{crit}}$, and this is achieved with small accretion fractional areas for lower-mass WDs in order to explain the observed energies released. It is thus possible that AWDs displaying micronovae have high WD masses. This would provide reasonable accretion surface areas consistent with observations. However, the WD masses required to obtain reasonable accretion surface areas appear higher than those inferred from X-ray observations (Lopes de Oliveira & Mukai 2019). In some systems, it may further be that the combination of mass-transfer rate, surface magnetic field, WD spin, and spin-to-orbit alignment provides unfavourable conditions to achieve $P_{\text{base}} \approx P_{\text{crit}}$ within t_{rec} as defined in equation (9). This situation can be further complicated if the impact area of the magnetically confined accretion flow varies over time. For example, the high-mass-transfer-rate system V2487 Oph could accrete outside its magnetically confined region for most of the time, either because of changes in the mass-accretion rate or because of other factors relating to where material latches on to the magnetic field lines. In this case, fresh material would spread on to the WD and accumulate mass in preparation for the next global nova eruption. If and when material is able to remain magnetically confined to a small enough fractional area for at least t_{rec} then we may observe micronovae.

Among the four AWDs confirmed so far to display micronovae, two (EI UMa and TV Col) belong to the magnetic class of interme-

diare polars (IPs: Thorstensen 1986; Hellier & Buckley 1993). It has been suggested that V2487 Oph harbours a magnetic AWD, although no coherent pulsations have been detected so far (Hernanz & Sala 2002), while ASASSN-19bh is a recently identified system with a suspected magnetic WD accretor (Scaringi et al. 2022). The orbital periods of EI UMa (6.4 h) and TV Col (5.5 h) are long, and V2487 Oph is a recurrent nova with a likely orbital period of 1.2 d (Schaefer et al. 2022), which all point to high-mass-accretion-rate systems. Therefore, magnetically confined TNRs in these AWDs appear to be a feasible mechanism. Furthermore, the RN V2487 Oph is expected to harbour a high-mass WD, and a high-mass accretor has also been considered to explain the detected large positive superhumps in TV Col (Retter et al. 2003), and by extension those detected in EI Uma (Scaringi et al. 2022). We have also found reports in the literature of two further systems that appear to have displayed a micronova in the past. The IP V1223 Sgr (orbital period of 6.4 h) was observed to display a single burst lasting several hours (van Amerongen & van Paradijs 1989), while three bursts each lasting less than a day with a recurrence of ~ 60 d were observed in the IP DW Cnc (orbital period of 86.1 min) during a high-accretion state (Duffy et al. 2022). The model presented in Section 2 requires relatively small accretion fractional areas on to AWD, as well as relatively high mass-accretion rates and WD masses. Future observations of the systems mentioned here, especially in between successive micronova events (and specifically at X-ray wavelengths), will allow us to test these expectations further.

While various mechanisms explaining the rapid bursts have been proposed (Schaefer et al. 2022; Shara 1982), a quantitative model has not yet been developed. The model presented here has the potential to explain both the observed burst energies and recurrence time-scales. Detailed time-dependent magnetohydrodynamic simulations of accretion columns in magnetic AWDs are required to further test

the model presented here as a mechanism for triggering microminorae. Further multiwavelength and long-term monitoring of microminorae will also be crucial in testing the model and in identifying the true origin of microminorae.

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DATA AVAILABILITY

There are no new data associated with this article.

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