Magnetically gated accretion in an accreting ‘non-magnetic’ white dwarf

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White dwarfs are often found in binary systems with orbital periods ranging from tens of minutes to hours in which they can accrete gas from their companion stars. In about 15 per cent of these binaries, the magnetic field of the white dwarf is strong enough (at \(10^4\) gauss or more) to channel the accreted matter along field lines onto the magnetic poles1,2. The remaining systems are referred to as ‘non-magnetic’, because until now there has been no evidence that they have a magnetic field that is strong enough to affect the accretion dynamics. Here we report an analysis of archival optical observations of the ‘non-magnetic’ accreting white dwarf in the binary system MV Lyrae, whose light curve displays quasi-periodic bursts of about 30 minutes duration roughly every 2 hours. The timescale and amplitude of these bursts indicate the presence of an unstable, magnetically regulated accretion mode, which in turn implies the existence of magnetically gated accretion3–5, in which disk material builds up around the magnetospheric boundary (at the co-rotation radius) and then accretes onto the white dwarf, producing bursts powered by the release of gravitational potential energy. We infer a surface magnetic field strength for the white dwarf in MV Lyrae of between \(2 \times 10^4\) gauss and \(1 \times 10^7\) gauss, too low to be detectable by other current methods. Our discovery provides a new way of studying the strength and evolution of magnetic fields in accreting white dwarfs and extends the connections between accretion onto white dwarfs, young stellar objects and neutron stars, for which similar magnetically gated accretion cycles have been identified6–9.

MV Lyrae (hereafter MV Lyr) spends most of its time in an optically bright (\(m_V \approx 12\)) luminosity state. Occasionally and sporadically (typically once every few years), the brightness drops by more than a factor of 250 for short durations (weeks to months), sometimes fading to \(m_V \approx 18\) (Fig. 1a). Other accreting white dwarfs show similar variations in optical brightness and fall into the class of ‘nova-like variables’10–13. The physical mechanism for these sudden drops in brightness is not well established14–16. As the luminosity of these systems is dominated by the release of gravitational potential energy of the gas in the disk, it is clear that the brightness variations are a direct consequence of changes in the mass-transfer rate through the accretion disk in these systems: during the bright phases (‘high states’) the mass-transfer rate can be more than \(10^{-8}\) solar masses per year (M\(_{\odot}\) yr\(^{-1}\)), whereas during the faint phases (‘low states’) it can drop below \(10^{-11}\)M\(_{\odot}\) yr\(^{-1}\) (refs 16, 17).

MV Lyr was continuously monitored during the original Kepler mission in short cadence mode (one flux measurement every 58.8 s) for nearly 4 years, displaying both high and low states during this interval (Fig. 1a). Although its orbital period has been determined by phase-resolved spectroscopy18 to be 3.19 h, the Kepler light curve does not display any coherent periodicity during the full observation, possibly owing to the very low inclination of the system18,19 (\(i = 10^\circ \pm 3^\circ\)). Instead, the Kepler data display all the usual aperiodic variability patterns that have been associated with mass-transferring accretion disks20–22. During an observed low state, MV Lyr displayed quasi-periodic ‘bursts’ of about 30 minutes duration roughly every 2 h,

**Figure 1** | Optical brightness variations in MV Lyr. a, Kepler light curve, 3.89 years long (58.8 s cadence; red points) overlaid onto the long-term V-band and visual light curve (black points) obtained through the AAVSO. b, Portion (60 days long) of the Kepler light curve entering the deep low state, visible between day 20 and day 35 (times starting from barycentric Julian date 2455743 (BJD = 2455743). c, Further zoom of the Kepler light curve during the deep low state showing the clear bursts, approximately 30 minutes long, roughly every 2 hours, overlaid onto a constant (flat) luminosity level.

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which on occasion increased the brightness of the system by a factor of 6.5 ($\Delta m_V \approx 2$, Fig. 1c). The bursts are observed only during the very faintest period, when the light curve reaches a roughly constant minimum brightness level, which we refer to as the deep low state. The bursts disappear as soon as the brightness level rises again from this lowest state.

To understand the constant minimum brightness level exhibited in the deep low state, we transform the Kepler light curve of MV Lyr into V-band magnitudes using archival simultaneous observations obtained by the American Association of Variable Star Observers (AAVSO). This allows us to estimate the brightness level of MV Lyr in the deep low state to be $m_V \approx 17.5$, which is compatible with emission originating only from the white dwarf and secondary star component, with negligible accretion disk contribution. Our estimate is also consistent with previous Far Ultraviolet Spectroscopic Explorer (FUSE) observations of MV Lyr during a previously detected deep low state$^{19,23}$ which did not seem to display any bursting behaviour. The time-averaged magnitude during which MV Lyr reaches the deep low state observed with Kepler is $m_V \approx 16.7$. This includes the observed quasi-periodic bursts, and translates to a time-averaged mass accretion rate onto the white dwarf of more than about $10^{-11}M_\odot\text{ yr}^{-1}$ (see Methods).

The combination of the duration, the recurrence time, the large amplitude and the lack of coherence associated with the quasi-periodic bursts (Fig. 2) excludes an origin of rotation or pulsation in either the donor star or the white dwarf. One possibility seen in simulations is that Papaloizou–Pringle instabilities are generated within the boundary layers of accreting objects$^{24}$. However, the observed burst recurrence behaviour and the similar burst luminosities cannot be reconciled with current simulations. The most likely mechanism is magnetically gated accretion bursts, arising from the interaction between the inner edge of the accretion disk and a dynamically important white dwarf magnetic field$^{4,5,25}$. Such bursts can occur when the magnetic field is strong enough to disrupt the disk close to the star, moving the inner edge of the accretion disk outside the 'co-rotation radius'—the point at which the Keplerian frequency of the disk matches the rotation rate of the white dwarf. This creates a centrifugal barrier that inhibits accretion onto the white dwarf (Fig. 3). In some cases, the magnetic field is not strong enough to expel most of the accreting gas from the system (as is the case for a 'magnetic propeller' such as AE Aquarii$^{26}$), and, as a result, gas in the disk piles up and gradually pushes against the magnetic field (the 'trapped disk' scenario$^5$). Once a critical amount of mass has

![Figure 3](link)

**Figure 3** Schematic depiction of the accretion flow in MV Lyr during phases of magnetically gated accretion cycles. **a**. During the deep low state, accreting gas around MV Lyr is not able to penetrate the centrifugal barrier created by the interaction between the magnetic field of the fast-rotating white dwarf and the inner accretion disk. The inner disk is thus truncated just outside the co-rotation radius $R_{\text{co}}$, preventing the launching of a strong 'propeller' outflow. Consequently, material gradually piles up around the truncation radius, exerting more pressure against the magnetic barrier. **b**. The gas disk eventually pushes inside the co-rotation radius, removing the centrifugal barrier and allowing a burst of accretion onto the white dwarf surface. When the reservoir is depleted, the magnetosphere again pushes outwards, and the cycle repeats on timescales comparable to the viscous timescales at the variable truncation radius of the disk.

![Figure 2](link)

**Figure 2** Power spectrum and flux distribution of MV Lyr in the deep low state and regular low state. **a**. Power spectra during the interval for which the light curve (black line) is in the deep low state between 930 and 944 (BJD − 2454833), compared with the interval 955 to 969 (BJD − 2454833). Owing to an observational gap in the Kepler light curve during the deep low state, we present the average of two power spectra, each of equal length (6.2 days) for both the deep low state and the regular low state. The quasi-periodicity is visible in the deep low state as a broad forest of peaks, distinct from the regular low-state power spectrum, shown red. The dashed grey line marks a 2.1-hour frequency for reference. **b**. Flux distribution of the corresponding light-curve intervals used to compute the power spectra. The flux distribution in the deep low state (grey) is skewed to lower fluxes, abruptly cutting off at about 2,000 electrons per second. The flux distribution in the regular low state (red) can be described using a log-normal function, consistent with the accretion-induced flickering observed in most accreting sources$^{20–22}$.© 2017 Macmillan Publishers Limited, part of Springer Nature. All rights reserved.
depends on both the magnetic field strength and the spin period (P\text{spin}) of the accretor. This three-parameter combination determines whether the inner disk (R\text{in}) is truncated close to the disk co-rotation radius (see Methods). The figure shows the MV Lyr constraints on the critical mass-transfer rate and white dwarf spin period (or, equivalently, inner disk truncation radius), varying the white dwarf magnetic field strength. The horizontal dashed lines mark the strongest constraint given by the outer disk circularization radius (R\text{circ}) and the white dwarf radius (R\text{WD}). The vertical dashed line marks the upper limit on the mass-transfer rate in MV Lyr during the low-state period (approximately 300 days) observed with Kepler. Our constraint on the mass-transfer rate obtained using the time-averaged flux in the deep low state is shown by the light-grey-shaded region. The dark-grey-shaded region shows the additional constraint on spin period inferred from the rotational velocity of the white dwarf of 150–250 km s^{-1} and inclination of 3°. The diagonal solid lines mark the critical mass-transfer rates at varying magnetic field strengths for the white dwarf, adopting M\text{WD} = 0.73 M\odot and R\text{WD} = 0.0125 R\odot for reference.

Figure 4 | Magnetically gated accretion instability plane. Magnetically gated accretion burst cycles occur when the mass-transfer rate through an accretion disk drops to, and is sustained at, a critical value. The critical mass-transfer rate (\dot{M}_\text{crit}) depends on both the magnetic field strength (B) and the spin period (P\text{spin}) of the accretor. This three-parameter combination determines whether the inner disk (R\text{in}) is truncated close to the disk co-rotation radius (see Methods). The figure shows the MV Lyr constraints on the critical mass-transfer rate and white dwarf spin period (or, equivalently, inner disk truncation radius), varying the white dwarf magnetic field strength. The horizontal dashed lines mark the strongest constraint given by the outer disk circularization radius (R\text{circ}) and the white dwarf radius (R\text{WD}). The vertical dashed line marks the upper limit on the mass-transfer rate in MV Lyr during the low-state period (approximately 300 days) observed with Kepler. Our constraint on the mass-transfer rate obtained using the time-averaged flux in the deep low state is shown by the light-grey-shaded region. The dark-grey-shaded region shows the additional constraint on spin period inferred from the rotational velocity of the white dwarf of 150–250 km s^{-1} and inclination of 3°. The diagonal solid lines mark the critical mass-transfer rates at varying magnetic field strengths for the white dwarf, adopting M\text{WD} = 0.73 M\odot and R\text{WD} = 0.0125 R\odot for reference.

accumulated, the centrifugal barrier induced by the rotating magnetosphere can be overcome, and material accretes onto the white dwarf, releasing a burst of energy through accretion.

the critical mass-transfer rate required for triggering magnetically gated accretion burst cycles depends on both the spin period of the white dwarf (and thus the co-rotation radius) and its magnetic field strength (Fig. 4). In the case of MV Lyr, we can constrain the mass-transfer rate \dot{M} to be between 10^{-11} M\odot yr^{-1} and 2 \times 10^{-10} M\odot yr^{-1}. The lower limit arises from the observed time-averaged luminosity in the deep low state. The upper limit arises from the total low-state duration of about 300 days, during which no thermal-viscous outburst was observed (see Methods). The inferred mass-transfer constraint, we are able to place very conservative constraints on both the white dwarf’s spin period and the magnetic field strength by requiring the disk truncation radius to lie between the disk circularization radius and the white dwarf surface. For a system such as MV Lyr (M\text{WD} = (0.73 \pm 0.1) M\odot and R\text{WD} = (0.0125 \pm 0.0025) R\odot), with an orbital period of 3.19 h, the inferred magnetic field of the white dwarf is then constrained to be between 22 kG and 1.3 MG. The exact value of the field strength depends primarily on the rotation period of the white dwarf (Fig. 4).

Because MV Lyr is seen nearly face-on, and the spin axis of the white dwarf is probably nearly perpendicular to the orbital plane, measurements of the projected rotational velocity of the white dwarf at the surface are bound to be small, even for a rapid white dwarf spin. High-resolution spectra obtained with FUSE during a previous low state have been used to infer a projected white dwarf rotational velocity of ~150–250 km s^{-1}. Together with the observed system inclination (i = 10° ± 3°), this translates to a white dwarf spin period in the range 19–98 s, and an associated magnetic field strength between 22 kG and 130 kG.

The observation of magnetic gating in MV Lyr connects this source to other magnetic accretors, such as young stellar objects and neutron stars, for which similar bursts have been seen. For example, EX Lupi, an accreting young star, is the prototype of the ‘Exor’ stellar class, which undergo large-amplitude accretion variations that have been attributed to magnetic gating. In EX Lupi, the burst recurrence time of several years corresponds well with viscous timescales in the inner disk region and implies a magnetic field of about 10^6 G. Observations comparing the inner disk during and after the accretion burst also revealed a depleted inner accretion disk after the burst. Magnetic gating is also thought to be responsible for very-large-amplitude accretion bursts with a recurrence time of about 1 s seen in two different accreting neutron stars with magnetic fields of about 10^9 G (refs 6–8). As in MV Lyr, the recurrence time observed in these other accretors is similar to the viscous timescale of the inner disk. The identification of magnetically gated accretion bursts, together with the combination of accretion rate and rotation rate, suggests that the disk is truncated very close to the co-rotation radius at 0.014 R\odot (see Methods). By establishing the presence of dynamically important magnetic fields in ‘non-magnetic’ white dwarfs, our results open a new route for studying the strength and evolution of magnetic fields in white dwarfs. Furthermore, the observations of accretion bursts in MV Lyr fill the gap in the distribution of magnetic field strengths of systems displaying magnetic gating and thus underscore the universality of magnetospheric accretion across an enormous range of stellar parameters.

Online Content Methods, along with any additional Extended Data display items and Source Data, are available in the online version of the paper; references unique to these sections appear only in the online paper.

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Author Contributions S.S. analysed the Kepler data, identified the phenomenon, interpreted the results and was the primary author. T.J.M. first proposed that the phenomenon might be magnetically gated accretion and helped to work out the initial parameter space. C.D.A. contributed theoretical analysis of the bursts and created Fig. 4. C.K. carried out AAVSO-based calibration of the Kepler data, created Fig. 1a and estimated the accretion rate in the magnetic gating state. P.J.G. laid out Figs 1 and 2 and provided the literature on nova-likes. All authors shared ideas, interpreted the results, commented and edited the manuscript.

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METHODS

Data sources. The Kepler data for MV Lyr were obtained from MAST in reduced and calibrated format\textsuperscript{1,2}. The Kepler telescope/detector combination is sensitive to light across a wide range of wavelengths (400 nm to 900 nm). This maximizes the signal-to-noise and gives robust relative brightnesses over time for the sources, but also makes it difficult to calibrate Kepler photometry, either in absolute terms or against other observations obtained in standard (narrower) passbands. In the case of MV Lyr, we are fortunate to have access to the extensive historical data set on this system from amateur observers (in particular, courtesy of the AAVSO (see Fig. 1c)). This data set includes V-band observations spanning nearly 50 years, including the entire period over which Kepler observed the source. We have used this overlap to establish an approximate transformation of Kepler’s count rates for MV Lyr into standard V-band magnitudes. To achieve this, we first excluded outliers from the AAVSO data set and removed all observations separated by more than 2 minutes in time from the nearest Kepler data point. We then linearly interpolated the Kepler light curve onto the timestamps of the remaining AAVSO data and fitted a sixth-order polynomial to the relationship \[ m = f(m_{\text{AAVSO}}), \] where \[ m_{\text{AAVSO}} = -2.5 \log_{10}(\text{count rate}) + 12 \] and \( f(x) = 13.34 + 1.097x + 0.0585x^2 - 0.0826x^3 + 0.01745x^4 - 0.003327x^5. \] By allowing for a higher-order polynomial transformation, we are implicitly correcting for colour terms arising from the difference between the two bandpasses, under the assumption that the colour of the system primarily tracks its luminosity. The root-mean-square scatter about our transformation is 0.07 magnitudes across the entire dynamic range, which spans \( 12 < m < 18. \) Owing to the increase in noise at the faint end of this range \( (m_{\text{V}} > 15.5), \) the scatter is slightly higher in this limit \( (0.14 \text{ magnitudes}). \)

Power spectrum. We visually identified the deep low state of MV Lyr in the Kepler light curve to fall between days 930 and 944 (BJD = 2454833). During this interval, a data gap of about 20 hours is present in the Kepler data. We therefore fit the low state into two 6.2-day uninterrupted segments (thus avoiding the data gap) and interpolate both on the same 58.8-s time grid. We then perform a discrete Fourier transform (DFT) on each independently. For comparison, we applied the same segmentation and analysis to Kepler data of MV Lyr just after the deep low state, selecting the segment between 955 and 969 (BJD = 2454833). Figure 2a shows the result of averaging the individual deep-low-state DFTs (black line) and the comparison DFTs (red line). We point out that no coherent periodicity is observed in any DFT, with the exception of a known recurrent artefact at about 390 cycles per day, present in many other Kepler targets, and particularly strong during Campaign 10 when MV Lyr entered the deep low state\textsuperscript{3}. The fact that no coherent periodicity has been found in nearly 4 years of Kepler observation of MV Lyr is also ascertained by numerous other analyses\textsuperscript{20–22,34}. Additional constraints. We can set independent limits on the spin period of the white dwarf, the accretion rate and the magnetic field strength by setting the magnetospheric radius (where the disk is truncated) equal to the co-rotation radius. When the disk is truncated close to co-rotation, the mass accretion rate can be expressed as

\[ \dot{M}_{\text{crit}} = \frac{\mu^2 \dot{P}_{\text{spin}}}{8 \pi R_{\text{WD}}^3}, \]

where \( \mu = B R_{\text{WD}}^3 \) is the magnetic moment of the white dwarf with radius \( R_{\text{WD}} \), \( \dot{P}_{\text{spin}} \) is the spin period of the white dwarf and \( R_{\text{WD}} \) is the inner disk truncation radius. The time-averaged strength of the toroidal field component, \( \eta = B_R R_{\text{WD}} \) (where \( B_R \) and \( B_t \) are azimuthal and poloidal magnetic field components respectively) is set to a constant \( 0.0585 \) of 0.1. Adopting the standard stellar parameters for MV Lyr, we infer \( 15 < \dot{P}_{\text{spin}} < 908 \text{ s}, \) \( 11.1 < \log_{10}(M/(M_\odot \text{ yr}^{-1})) < -9.7, 4.3 < \log_{10}(M/(\text{M}_\odot \text{ M}_\odot )) < 6.1 \) and \( \eta < R_{\text{WD}} < 0.189 R_{\odot}, \) displayed in Fig. 4 as the light-grey-shaded area. This includes the additional constraint on the outer disk circularization radius, the inner disk truncation radius at the white dwarf surface and the allowed maximum mass-transfer rate. We can further constrain these parameters through the observed white dwarf projected velocity\textsuperscript{29} of 150–250 km s\(^{-1}\) and the inferred system inclination of \( i = 10 \pm 3^\circ. \) This yields \( 19 < \dot{P}_{\text{spin}} < 98 \text{ s}, \) \( -10.9 < \log_{10}(M/(M_\odot \text{ yr}^{-1})) < -9.7, 4.3 < \log_{10}(B/\text{Gauss}) < 5.1 \) and \( \eta < R_{\text{WD}} < 0.043 R_{\odot}, \) displayed in Fig. 4 as the dark-grey-shaded area.

Burst recurrence timescales. In the magnetic gating model, the instability occurs in the inner regions of the accretion disk\textsuperscript{35,36} and the recurrence time is typically similar to the viscous timescale in this region (the time it takes to travel across \( R_{\text{WD}} / \Omega \), a characteristic evolution timescale)\textsuperscript{16} \( t_{\text{rec}} \approx R_{\text{WD}}^2 / \Omega \), where \( \Omega \) is the viscosity of a typical \( \alpha \)-disk\textsuperscript{4}, and can be estimated as \( \nu \approx \alpha (H/R)^3 (GM_{\text{WD}} R_{\text{WD}})^{1/2}. \) Assuming that the disk is truncated at the co-rotation radius, a white dwarf with \( M_{\text{WD}} = 0.73 \pm 0.1 M_\odot \) and a spin period \( 19 < \dot{P}_{\text{spin}} < 98 \text{ s} \) has a characteristic viscous accretion time in the range 0.8–4.4 h. This is consistent with the bursts recurrence timescale observed with Kepler, and possibly with other reports of bursts observed in previous low states\textsuperscript{41}. The viscous timescale is calculated assuming a viscosity parameter \( \alpha \approx 0.1 \) and disk aspect ratio \( H/R \approx 0.1 \), which is plausible if the inner regions of the disk are no longer geometrically thin as is seen at low accretion rates in neutron stars and black holes. Theoretical models of accretion disks around white dwarfs\textsuperscript{42} predict a much lower value for both \( H/R \) and \( \alpha \). However, several observational results\textsuperscript{20,43} suggest a much higher value of \( H/R \). The \( \alpha (H/R)^3 \) parameter is thus somewhat arbitrary, as long as it is not greater than 1.

Data availability. The data collected by the Kepler mission used in this study can be obtained from MAST in reduced and calibrated format (https://archive.stsci.edu/kepler/). The AAVSO V-band magnitudes can be obtained from AAVSO (https://www.aavso.org/).

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