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# Spectroscopy of the enigmatic short-period cataclysmic variable IR Com in an extended low state

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## ABSTRACT

We report the occurrence of a deep low state in the eclipsing short-period cataclysmic variable (CV) IR Com, lasting more than two years. Spectroscopy obtained in this state shows the system as a detached white dwarf plus low-mass companion, indicating that accretion has practically ceased. The spectral type of the companion derived from the SDSS spectrum is M6–7, somewhat later than expected for the orbital period of IR Com. Its radial velocity amplitude, $K_2 = 419.6 \pm 3.4$ km s$^{-1}$, together with the inclination of 75°–90° implies $0.8 < M_{\rm wd} < 1.0\,{\rm M}_{\odot}$. We estimate the white dwarf temperature to be $\simeq$15 000 K, and the absence of Zeeman splitting in the Balmer lines rules out magnetic fields in excess of $\simeq$5 MG. IR Com still defies an unambiguous classification, in particular the occurrence of a deep, long low state is so far unique among short-period CVs that are not strongly magnetic.

**Key words:** stars: dwarf novae – stars: individual: IR Com – novae, cataclysmic variables – white dwarfs.

## 1 INTRODUCTION

Cataclysmic variables (CVs) are binary systems in which a white dwarf accretes matter from a low-mass main-sequence star via Roche lobe overflow (see Warner 1995 for a comprehensive overview). The observational appearance of a CV, and therefore its classification depends only on relatively few fundamental properties, primarily the mass transfer rate from the companion, the magnetic field of the white dwarf, the mass ratio, and the orbital period. A small number of CVs defy a definitive classification, probably straddling the boundary of one or more of the defining physical properties. Such systems provide an excellent challenge to test our understanding of the accretion processes in CVs as well as the evolution of compact binaries (e.g. Patterson et al. 2013).

IR Com is an eclipsing CV with an orbital period of 2.09 h, just at the lower boundary of the period gap (Richter et al. 1997), where gravitational wave radiation is the dominating angular momentum loss agent (Tutukov et al. 1985). The long-term light curve of Richter et al. (1997) is very atypical for CVs below the period gap, displaying erratic variations between 16 and 17 mag, punctuated very rarely by short bright states reaching 14 mag, and occasional fainter states near 18 mag. As such, it does not resemble the dominant class of short-period CVs, i.e. dwarf novae which exhibit quasi-periodic outbursts of their thermally unstable accretion disc (Meyer & Meyer-Hofmeister 1981). However, it also does not share the characteristics of polars, discless CVs containing a strongly magnetic white dwarf, that show irregular long-term brightness variations related to changes in the mass-loss rate of the companion star (e.g. Kafka & Honeycutt 2005). Both Richter et al. (1997) and Kato, Baba & Nogami (2002) discuss the possibility of IR Com being an intermediate polar (IP), i.e. a CV with a weakly magnetic white dwarf, but argued against that hypothesis because of the non-detection of a spin period in the optical photometry, and of the long duration of one of the well-sampled outburst-like events. This leaves IR Com being one of the few CVs falling in-between the well-established classes, and strongly suggests that at least one of its fundamental physical properties must be close to the limiting value that defines the observational threshold between the different CV classes.

We report the first spectroscopic observation on IR Com obtained during the longest lasting low state recorded so far, constrain the stellar parameters, and discuss the possible nature of the system.

## 2 OBSERVATIONS

Spectroscopy of IR Com was obtained by SDSS on two occasions, once using the original SDSS spectrograph on 2008 January 15 (Abazajian et al. 2009), and again on 2012 June 11, this time with the BOSS spectrograph (Ahn et al. 2014). The first spectrum (Fig. 1), even though partially corrupted, is typical of a short-period CV, characterized by a blue continuum superimposed by strong, double-peaked Balmer and He emission lines, and a noticeable flux contribution from the low-mass companion star at the longest wavelengths. In contrast, the BOSS spectrum is entirely dominated by the two stellar components, with practically no evidence for ongoing accretion – in fact, it resembles the plethora of detached white dwarf/M-dwarf binaries identified by SDSS (Silvestri et al. 2006; Rebassa-Mansergas et al. 2007, 2010, 2012). The normalized Hα

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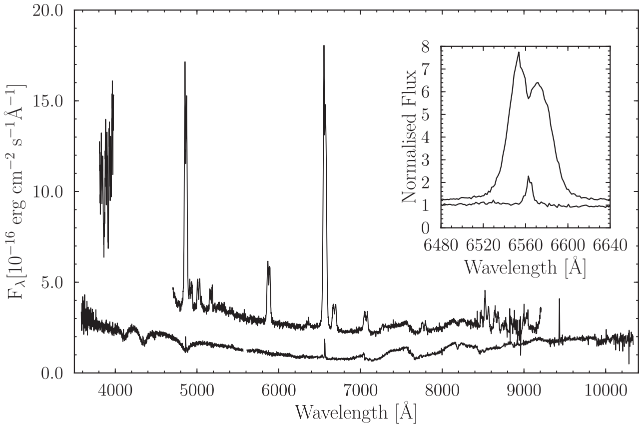


**Figure 1.** Comparison of the two spectra of IR Com obtained by the SDSS in 2008 January (top) and 2012 June (bottom, no offset has been applied to the two spectra). The 2008 spectrum is typical of a short-period non-magnetic CV, with strong double-peaked Balmer and He lines from the accretion disc, and some contribution from the companion at $\lambda > 7000$ Å. In contrast, the 2012 spectrum is entirely dominated by the white dwarf and its M-dwarf companion. The inset shows the H$\alpha$ emission line normalized to the continuum flux, with the 2008 emission line offset by +0.2. For the low-state H$\alpha$ profile, the three sub-spectra obtained in 2012 were averaged in the rest frame of the companion star to avoid orbital smearing.

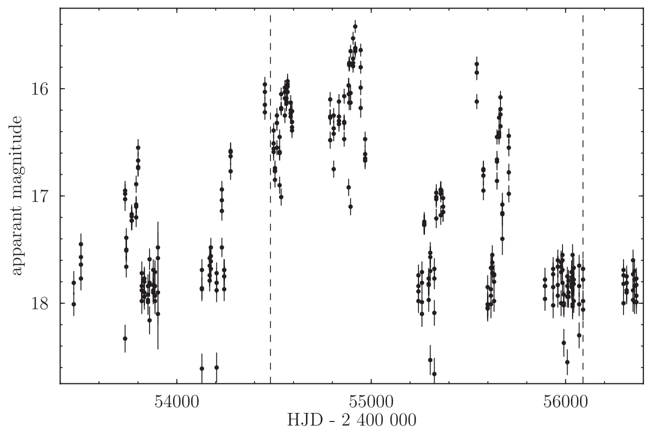


**Figure 2.** CRTS light curve of IR Com, obtained between 2005 April and 2013 March. The dashed lines mark the times at which SDSS spectra were taken (2008 January and 2012 June).

line profile in Fig. 1 illustrates the dramatic change in the strength and shape of the emission line.

In addition to the morphological change in the spectral appearance, IR Com was fainter during the 2012 observations. The light curve of IR Com obtained by the Catalina Real-Time Transient Survey (CRTS; Drake et al. 2009) between 2005 April and 2013 March (Fig. 2) shows that the system was actively accreting until ~2011 May. From 2011 November to 2013 March, IR Com was persistently faint in 72 CRTS observations, which is to our knowledge the longest and best recorded deep low state of this system. Eliminating a few individual data points where IR Com was unusually faint (which were taken during eclipse, see below), we find an apparent low-state magnitude of 17.8 in the unfiltered CRTS photometry.

**Table 1.** Radial velocities of the companion star in IR Com measured from the Na I 8183.27, 8194.81 Å doublet.

| HJD | RV (km s$^{-1}$) | $\sigma$RV (km s$^{-1}$) |
|---|---|---|
| 245 4480.995 852 | −413.6 | 20.5 |
| 245 6089.652 378 | −334.8 | 19.3 |
| 245 6089.663 743 | −52.8 | 23.6 |
| 245 6089.675 108 | 272.6 | 26.5 |

## 3 ANALYSIS

Several CRTS observations show IR Com fainter than the average low-state magnitude, $\simeq$17.8 (Fig. 2). Adopting the ephemeris of Feline et al. (2005), they all fall within the phase interval of the eclipse, $\phi \simeq -0.04$ to $\phi \simeq +0.04$ (see fig. 1 of Feline et al. 2005).

The Na I 8183.27, 8194.81 Å absorption doublet of the M-dwarf is detected in all three 2012 low-state SDSS sub-spectra, and in one 2008 sub-spectrum. We fitted the Na I doublet with a double-Gaussian profile of fixed separation (see Rebassa-Mansergas et al. 2007 for details) to measure the radial velocity variation of the companion star. These radial velocities (Table 1) were then fitted with a sine function, keeping the period fixed to the value of Feline et al. (2005). We find a radial velocity amplitude of $K_2 = 419.6 \pm 3.4$ km s$^{-1}$ and a systemic velocity of $\gamma = 6.9 \pm 4.4$ km s$^{-1}$. The phase of the radial velocity curve agrees within 2 per cent with the expected blue-to-red crossing at $\phi = 0.0$ (Fig. 3).

The H$\alpha$ emission line in the bright state is strongly double peaked (inset in Fig. 1), as expected for the origin from the Keplerian motion in an accretion disc (Horne & Marsh 1986). During the low state, the H$\alpha$ emission is much weaker and narrower, and its radial velocity varies as expected for an origin on the inner hemisphere of the companion star. However, there is clear evidence for an asymmetry in the line profile, suggesting that emission from another location within the system contributes. Such additional H$\alpha$ components have been seen in a number of detached white dwarf/M-dwarf binaries, and CVs in low states, where they originate either on (or very close to) the white dwarf (e.g. Tappert et al. 2007, 2011; Parsons et al. 2012, 2013) or from material located between the two stars (e.g.

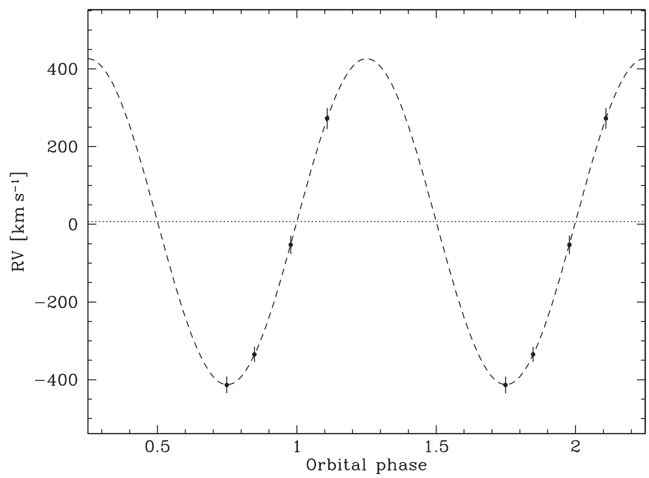


**Figure 3.** The radial velocity of the M-dwarf in IR Com was measured using the Na I 8183.27, 8194.81 Å absorption doublet from three BOSS sub-spectra and one SDSS sub-spectrum (Table 1). Fitting those velocities with a sinusoid of fixed period results in a radial velocity amplitude of $K_2 = 419.6 \pm 3.4$ km s$^{-1}$.

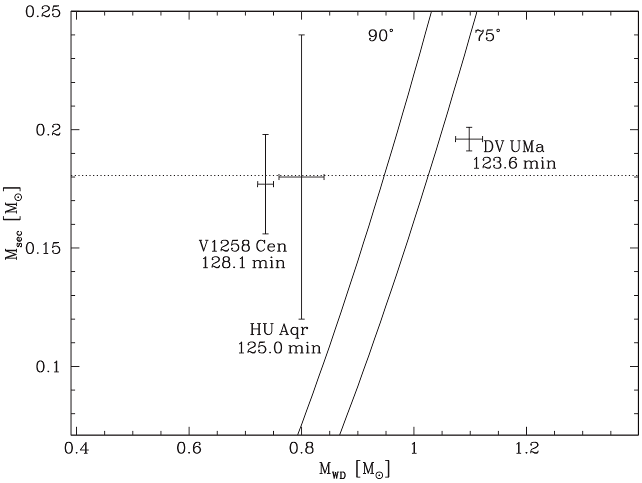


**Figure 4.** The detection of white dwarf eclipses (Feline et al. 2005) implies $i > 75°$. Together with the radial velocity amplitude of the companion star, $K_2 = 419.6 \pm 3.4$ km s$^{-1}$, this limits the range of possible white dwarf masses. The dashed line shows the donor mass for $P_{\rm orb} = 2.09$ h, according to the empirical CV evolution track of Knigge et al. (2011), and we show the component masses of three eclipsing CVs with very similar orbital periods to IR Com (Savoury et al. 2011; Schwope et al. 2011).

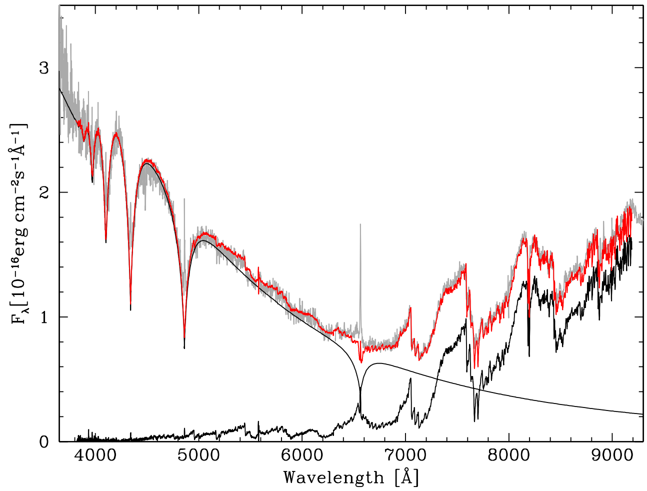


**Figure 5.** The low-state spectrum of IR Com (grey) obtained by SDSS can be modelled by the combination of an ∼15 000 K white dwarf and an M6–7 dwarf (both black, red is the sum of the two) at a distance of $d = 115$–165 pc.

Gänsicke et al. 1998; O'Donoghue et al. 2003; Kafka et al. 2005; Parsons et al. 2011). Disentangling the multiple H$\alpha$ components in IR Com and identification of their origin will require observations with higher spectral resolution than the available SDSS low-state spectroscopy.

## 4 RESULTS AND DISCUSSION

### 4.1 System parameters

The measured radial velocity amplitude of the companion star, $K_2 = 419.6 \pm 3.4$ km s$^{-1}$, can be used to compute the mass function of the white dwarf. Feline et al. (2005) obtained high-time resolution photometry of IR Com in quiescence, and showed that the morphology of their light curve is consistent with a deep eclipse of the white dwarf (as opposed to only the bright spot being eclipsed). This sets a conservative limit on the binary inclination, $75° < i < 90°$, and the corresponding mass functions (Fig. 4) imply $0.8 < M_{\rm wd} < 1.0\,{\rm M}_{\odot}$, which is fully consistent with the relatively high average CV white dwarf mass found by Zorotovic, Schreiber & Gänsicke (2011) and Savoury et al. (2011). The companion mass can currently not be constrained. For $P_{\rm orb} = 2.09$ h, the semiempirical CV evolution sequence of Knigge, Baraffe & Patterson (2011) suggests $M_2 = 0.186\,{\rm M}_{\odot}$ (see Fig. 4), which would further constrain the primary mass to $0.95 < M_{\rm wd} < 1.03\,{\rm M}_{\odot}$.

We used the spectral decomposition method developed by Rebassa-Mansergas et al. (2007) for the analysis of detached white dwarf/M-dwarf binaries to estimate the stellar parameters of IR Com from the low-state SDSS spectrum (Fig. 5). In brief, the composite SDSS spectrum is first fitted with two grids of white dwarf and M-dwarf templates derived from SDSS spectroscopy, which gives the spectral type and flux contribution of the companion. In a second step, the best-fitting M-dwarf template is subtracted from the composite spectrum, and the residual spectrum is fitted with pure-hydrogen (DA) white dwarf models from Koester (2010). We find that the companion in IR Com has a spectral type of M6–7, which is later than expected for its orbital period (Beuermann et al. 1998; Knigge et al. 2011). The model atmosphere fit to the residual white dwarf spectrum results in $T_{\rm wd} \simeq 17\,500$ K and $\log g = 9.5$, which is the highest gravity in the model grid, corresponding to a Chandrasekhar mass white dwarf. The white dwarf temperature, as well as the implied secular accretion rate, is typical for the orbital period range (Townsley & Bildsten 2003; Townsley & Gänsicke 2009). However, given that the mass function implies $0.8 < M_{\rm wd} < 1.0\,{\rm M}_{\odot}$, it appears that the fit to the Balmer lines substantially overestimates the surface gravity. One possibility is a magnetic field, too low to result in visible Zeeman splitting in the Balmer lines, but sufficiently strong to cause additional broadening of the lines, mimicking the higher pressure in a more massive white dwarf. We return to this in Section 4.3. Another possibility is that He in the atmosphere results in increased Stark broadening, as the He I $\lambda$ 4471 Å absorption line is visible in the BOSS spectrum. A more definitive atmosphere model will require better quality low-state spectroscopy to fit also for the He abundance.

A crude estimate of the distance to IR Com can be estimated following the prescription of Beuermann (2006), who made use of the fact that the surface brightness near 7500 Å and depth of the TiO band near 7165 Å are a strong function of the spectral type, and tabulated the relevant surface fluxes as a function of spectral type. Thus, measuring the mean observed fluxes in the bands 7450–7550 and 7140–7190 Å, and adopting $R_2 = 0.213\,{\rm R}_{\odot}$ (from Knigge's 2011 sequence) gives $d = 165$ and 115 pc for a companion spectral type of M6 and M7, respectively (a spectral type of M5–M4, as typically found near the lower edge of the period gap, would imply $d = 220$–285 pc).

### 4.2 A prolonged deep low state

The long-term light curve of Richter et al. (1997), spanning nearly 35 yr with rather sparse sampling, shows the system meandering between 16 and 17 mag, with occasional drops to 18 mag. So far, only four short, bright states reaching 14 mag have been reported (in 1959, 1988, 1996, and 2002; see Richter et al. 1997; Kato et al. 2002), which led to the classification of IR Com as a dwarf nova. However, while the eight years of CRTS data (Fig. 2) show copious amounts of accretion activity, no clearly defined dwarf nova-like outburst is obviously picked out, confirming that the outburst recurrence time is very long.

The most puzzling feature in the CRTS light curve is the extremely long low state, lasting over two years at the time of writing. Such extended low states have so far been well documented only among polars (e.g. Kafka & Honeycutt 2005), and among the VY Scl stars, a sub-group of the nova-like variables (e.g. Honeycutt & Kafka 2004). The fundamental cause for the occurrence of low states is not totally understood, but one hypothesis is that star spots on the companion star forming at or migrating into the inner Lagrangian point lead to a sufficient depression of the atmospheric scaleheight to reduce the mass-loss or stop it altogether (Livio & Pringle 1994; Hessman, Gänsicke & Mattei 2000). This effect should, in principle, be present in all CVs. In polars, the absence of an accretion disc implies that a drop in the mass-loss rate causes also an almost immediate drop in the system's brightness. VY Scl stars are normally in a state of high mass transfer, resulting in an ionized, highly viscous, hot and bright accretion disc that will rapidly drain on to the white dwarf once mass-loss from the companion ceases. The high temperature of the white dwarf (e.g. Gänsicke et al. 1999; Araujo-Betancor et al. 2003; Hoard et al. 2004) keeps any residual disc ionized, effectively suppressing disc outbursts during the low state (Leach et al. 1999).

Low states in dwarf novae are extremely rare. Schreiber, Gänsicke & Mattei (2002) detected a low state in the Z Cam-type dwarf nova RX And ($P_{\rm orb} = 5.04$ h, above the period gap), lasting $\simeq 200$ d.[1] Below the period gap, there is no published evidence for well-defined, long-lasting low states among dwarf novae, see the summary by Warner (1999). The best-documented system is HT Cas, which underwent an outburst-free period of ~4 yr, however, still exhibiting ~1.5 mag brightness fluctuations. The fundamental reason why dwarf novae, despite most likely undergoing similar mass transfer variations as polars or VY Scl stars, do not exhibit deep low states is that their accretion discs buffer substantial amounts of mass, and only a small fraction of mass is accreted on to the white dwarf during an individual outburst (e.g. Cannizzo 1993). Schreiber, Gänsicke & Hessman (2000) computed the outburst behaviour of a dwarf nova with a variable mass transfer rate (empirically determined from the polar AM Her), and found that outbursts never stop, even during prolonged states of zero mass-loss from the companion.

### 4.3 A low magnetic field?

Could the white dwarf in IR Com be magnetic? Kato et al. (2002) argued against an IP nature of IR Com, based on the fact that the outburst they observed was substantially longer (>4 d) compared to the very short ($\lesssim$1 d) outbursts seen among the handful of short-period IPs (e.g. EX Hya and HT Cam), and proposed IR Com to be a member of the SU UMa family.[2] Richter et al. (1997) also argued against an IP nature of IR Com, based on the non-detection of a coherent (white dwarf spin) period in their optical data. One might take the CRTS light curve (Fig. 2) as an additional argument against the IP nature of IR Com, as no deep long-lasting low states have been observed among IPs (Warner 1999).

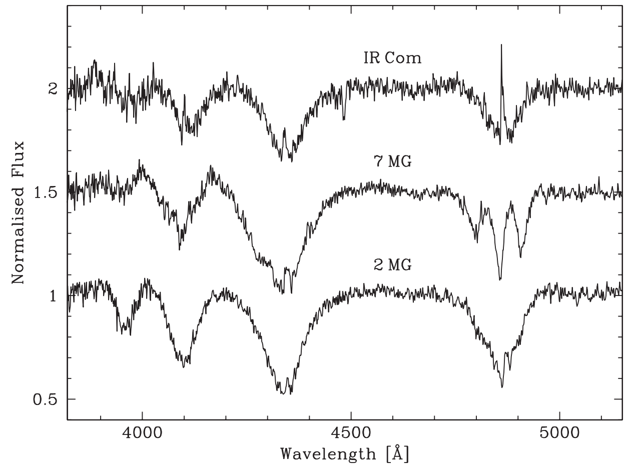


**Figure 6.** Normalized SDSS spectra of IR Com in the low state (top) and SDSS spectra of two DA white dwarfs from Kawka et al. (2007) with comparable temperatures and field strengths of 7 MG (SDSS J124851.31−022924.7, middle) and 2 MG (SDSS J164703.21+370910.4, bottom). The absence of Zeeman splitting in the Balmer lines of IR Com suggests that the magnetic field strength of its white dwarf is $B \lesssim 5$ MG.

The SDSS low-state spectrum of IR Com does not show any clear evidence for Zeeman splitting of the Balmer lines, and comparison to the SDSS spectra of magnetic DA white dwarfs from Kawka et al. (2007) rules out a magnetic field in excess of $\simeq 5$ MG (Fig. 6). This is less than the lowest field detected among polars, $B \simeq 7$ MG in V2301 Oph (Ferrario et al. 1995), but we cannot rule out a field in the range expected for IPs (a few 100 kG to a few MG; see Norton, Wynn & Somerscales 2004).

## 5 CONCLUSIONS

We detected a deep, long low-state in the short-period CV IR Com. Given that we can rule out a strong magnetic field on the white dwarf, the occurrence of such a low state is so far unique among the known population of short-period CVs, and we suspect that a weak magnetic field on the white dwarf may be the cause for this unusual behaviour. This possibility should be explored with higher resolution spectroscopy, or spectropolarimetry, capable of detecting sub-MG fields. We also encourage additional observations during a low state to refine the stellar masses and radii of the white dwarf and its low-mass companion.

Yet, (at least) one of the fundamental physical parameters in IR Com must differ from those of ordinary SU UMa-type dwarf novae below the gap to explain its unusual long-term variability. We have shown that the stellar masses and the accretion rate are normal for the orbital period of the system and, hence, despite those (somewhat circumstantial) arguments against IR Com being an IP, we believe that a weak magnetic field on the white dwarf is the most plausible cause for its observed behaviour.

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[1] Prior to the low state, RX And was in a standstill, which may explain the low state analogous to the VY Scl stars discussed above, i.e. the rapid draining of a hot, highly viscous disc.

[2] It is worth mentioning that no superhumps were detected during that outburst. If the true mass ratio of IR Com is close to the upper limit implied by our system parameters, $q < 0.22$, (Section 4.1), it may lie above the threshold where tidal instabilities are triggered in the accretion disc (Whitehurst 1988), even though superhumps have been detected in systems above the period gap having larger values of $q$ (Patterson et al. 2005).

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