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Research Note

Outburst activity of the intermediate polar DO Draconis (3A 1148+719)*

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Abstract. An analysis of the long-term light curve of the intermediate polar DO Dra is presented. The courses of the outbursts were resolved and their light curves are analyzed. The decays of the respective outbursts are faster than exponential. The decay rate $\tau_{\rm D} = 0.92$ days mag$_{\rm vis}^{-1}$ in comparison with 1.68 days mag$_{\rm vis}^{-1}$ for non-magnetic systems and suggests that the magnetosphere is not fully compressed during the outburst of DO Dra. The typical recurrence time $T_{\rm C}$ of outbursts over the last 63 years is found to be 870 days, the standard deviation of most outbursts being 100 days. The quiescent level displays fluctuations on the time scale of tens and hundreds of days without any apparent trend between the neighbouring outbursts.

Key words: stars: activity – stars: binaries: close – stars: binaries: general – stars: magnetic fields – stars: novae, cataclysmic variables – stars: individual: DO Dra

1. Introduction

The hard X-ray source 3A 1148+719 was identified with a faint (≈ 16 mag) cataclysmic variable (CV) by Patterson et al. (1982). They claimed that this object is identical to the variable star reported by Tsesevich (1934) and catalogued as YY Dra (Kukarkin et al. 1969). However, the co-ordinates of Tsesevich's star do not accurately agree with those of 3A 1148+719 and the types of variability are largely discordant. Arguments both for (Patterson & Eisenman 1987) and against this identification were brought (Kholopov & Samus 1988). The optical counterpart of 3A 1148+719 was given a new name, DO Dra (Kholopov et al. 1987). However, both names, YY Dra and DO Dra, are still used for 3A 1148+719 by various authors. We will use DO Dra, following GCVS.

DO Dra is an intermediate polar (IP) because besides the orbital period $P_{\rm orb} = 3.96$ hours (Mateo et al. 1991) it also displays a stable periodicity at 275 seconds (Patterson et al. 1992), the white dwarf (WD) spin period being 529.31 sec (Haswell et al. 1997). The ratio of the X-ray to the optical luminosity $F_{\rm X}/F_{\rm V} \approx 10$ is the highest of any known CV. The accretion disk is supposed to be quite faint because the absorption lines of the M secondary can be seen down to $\lambda \approx 500$ nm (Patterson et al. 1992). Norton et al. (1999) argued that DO Dra is a disk-fed accretor with a weak magnetic field of the WD, so the radius at which material is captured by the field lines is relatively small. The inclination angle is moderate, $i = 45° \pm 4°$ (Haswell et al. 1997).

Several episodes of quite a short brightening by about 5 mag were revealed on the archival plates by Wenzel (1983a,b) and Hazen (1986). They pointed to a very long recurrence time, of the order of 1000 days.

2. The sources of the data and the analysis

Monitoring of many cataclysmic variables is almost entirely the domain of the associations of amateur observers due to the character of the long-term activity of these objects (unpredictable episodes of the low states in nova-like variables and, on the other hand, often relatively short outbursts separated by long intervals of quiescence in dwarf novae). The observations are mostly visual but they are quite numerous and come from a large number of observers; the objectivity of the features in the light curve can therefore be assessed. Visual data, if treated carefully, can be very useful for the analysis of long-term activity (Percy et al. 1985, Richman et al. 1994). Accuracy even better than 0.1 mag can be achieved by averaging the data. This is quite sufficient for analyses of these large-amplitude variable stars.

DO Dra has been extensively monitored by several associations of observers especially in the recent years. The presented analysis is based on the data from the AFOEV database, operated at CDS (France), VSNET database (Japan) and VSOLJ database (Japan). The combined data set was corrected for the observations repeated in several databases. The number of positive observations from the respective databases then amounts 346 (AFOEV), 419 (VSNET) and 211 (VSOLJ), respectively. The density of the coverage (including 4226 negative observations which yield the upper limits), important for detection of the rare outbursts in DO Dra, is unprecedented for this star.

* This research has made use of the AFOEV database, operated at CDS (France), VSNET database (Japan) and VSOLJ database (Japan).

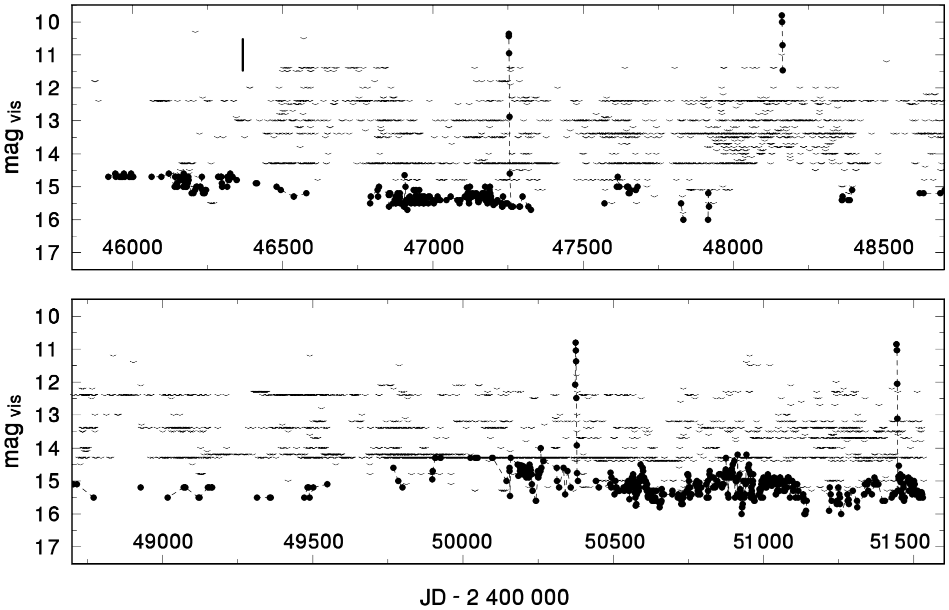

Fig. 1. The light curve of DO Dra over the years 1984–1999. The points denote the one-day means of the positive observations and are connected by line for the densely covered intervals. The ∨ symbols mark the upper limits of brightness and can be used to constrain the possibly missed outbursts. The outburst reported by Hurst et al. (1985) is marked by a vertical bar. See text for details.

The light curve was plotted and submitted to a visual inspection. The observations already marked as unreliable in the original files were rejected in most cases. Further, several observations, largely deviating from the neighbouring points in the light curve, were rejected. The curve was then smoothed by binning the positive observations (976) into one-day means (728). The resulting light curve, covering the years 1984–1999 (Fig. 1), was used for a large part of this study. *Four outbursts, defined by multiple observations from several nights, are clearly visible*. The two last outbursts also were partly covered by the CCD observations (Ouda station – Kyoto University, VSNET) which proved to be in good agreement with the visual data. It can be seen that although DO Dra is faint for most of the time (about 14.5 –16 $\mathrm{mag_{vis}}$) and therefore beyond the reach of some amateur telescopes, the coverage by the negative observations (4226) is often quite dense, especially after JD≈ 2 450 000. The outburst reported by Hurst et al. (1985), marked by a vertical bar in Fig. 1, falls into a weakly covered interval of the light curve.

2.1. Light curves of the outbursts

The light curves of four covered outbursts are displayed in detail in Fig. 2a-d. Due to the short duration of the outbursts and their rapid decline we preferred to plot the individual observations rather than the one-day means here to improve the coverage. It can be seen that the rise to the maximum is so fast that in three cases it is not covered by observations and in one case only the upper half is covered. However, the negative observations still enable us to put the upper limits on the duration of the respective events.

In order to assess the common properties of the respective outbursts, it is instructive to superpose them into a common plot. We applied the method of alignment according to the decay branches, similar to that used for CH UMa in Šimon (2000, hereafter Paper I). The outburst having the maximum in JD = 2 451 443 was chosen as the template. The remaining outbursts were shifted along the time axis to match this template. The level of brightness 12.0 $\mathrm{mag_{vis}}$ was chosen as the reference level in the vicinity of which the match was attempted. The result is shown in Fig. 3. The decay branches of the respective outbursts were then merged into a common file and smoothed by the program HEC13 (author Dr. P. Harmanec), based on the method of Vondrák (1969 and 1977). The input parameters of the fit $\epsilon \ = 10^{-2}$ and the length of the bin $\Delta T \ = 0.5$ day satisfy the course of the decay. In our case the input ϵ parameter was chosen so that the fit reproduces just the main course of the decay. The standard deviation of the residuals of this fit is 0.29 $\mathrm{mag_{vis}}$. The smoothed decay light curve is plotted as the thick solid line in Fig. 3.

Fig. 3 clearly shows that the decay branches of the respective outbursts are remarkably similar to each other. The smoothed course reveals that the decay is curved downwards, it means that

Table 1. Outbursts in DO Dra. $T_{\max}$ refers to the moment of the maximum brightness in JD–2 400 000. The epoch number and $O-C$ (days) are calculated according to Eq. (1). The last column gives the reference.

$T_{\max}$JD	Epoch	$O-C$	Ref.
28267	−21	128	Hazen (1986)
31505	−17	−106	Hazen (1986)
33242	−15	−105	Hazen (1986)
37764	−10	77	Wenzel (1983b)
40171	−7	−120	Wenzel (1983a)
42740	−4	−155	Wenzel (1983a)
46367	0	0	Hurst et al. (1985)
47252	1	17	this paper
48160	2	57	this paper
50374	4	535	this paper
51443	5	736	this paper

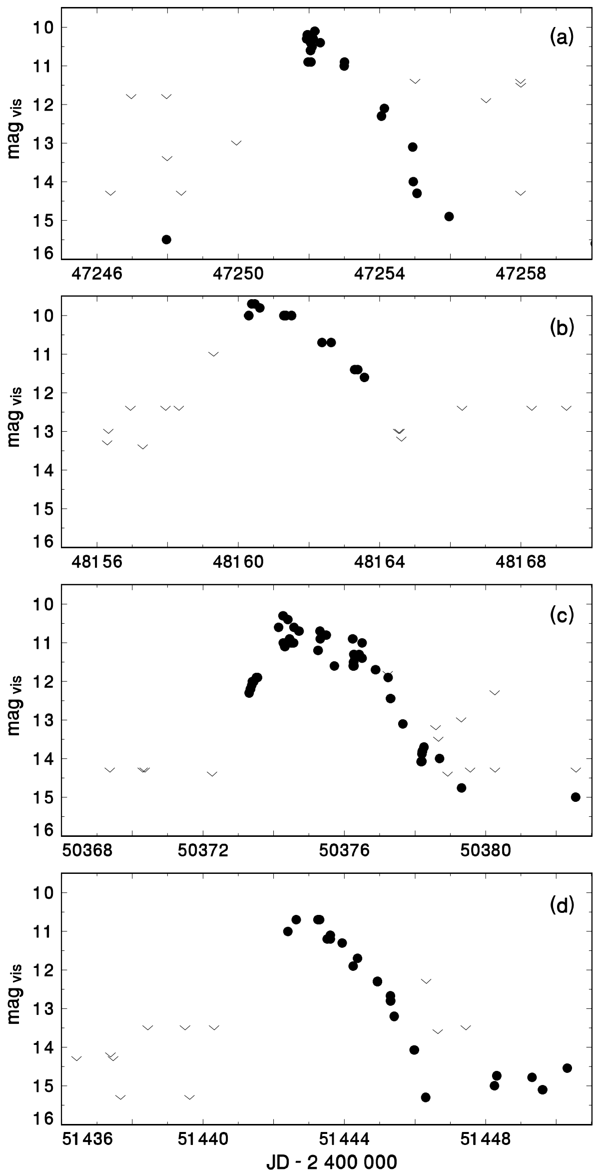

Fig. 2a–d. The appearance of four outbursts in DO Dra. The individual (unbinned) observations are plotted to improve the coverage because the rises and decays are quite rapid. The scale of both axes in each plot is identical and allows one to compare the light curves of the respective events. See Sect. 2.1 for details.

it is faster than exponential. If a linear approximation is made, we obtain the decay rate $\tau_{\rm D} = 0.92$ days $\mathrm{mag}_{\rm vis}^{-1}$.

2.2. The outburst recurrence time and its variations

The searches of the archival plates covering several decades (Wenzel 1983a,b, Hazen 1986) already lead to the conclusion that the recurrence time $T_{\rm C}$ of the outbursts in DO Dra must be quite long, of the order of 1000 days. The densely covered light curve along with the upper limits in Fig. 1 confirms this conclusion. In total, we managed to accomplish timings of 11 outbursts, summarized in Table 1. They spread over 63 years. Of course, due to the very short duration of outbursts in DO Dra it

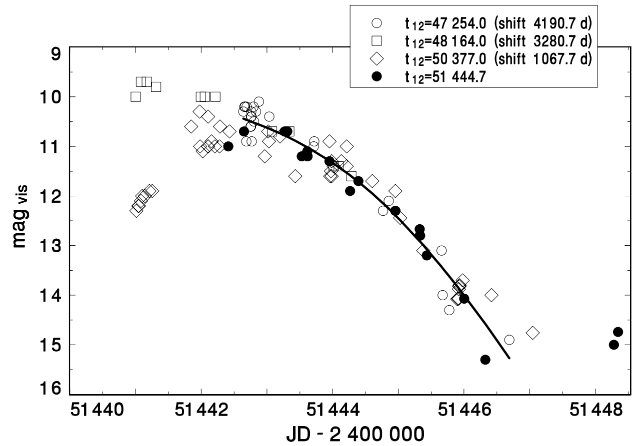

Fig. 3. The outbursts in DO Dra from Fig. 2, superposed into a common plot. The respective outbursts were shifted along the time axis to match the decay branch of the template – the time of crossing 12.0 $\mathrm{mag}_{\rm vis}$ and the shifts with respect to the template are listed in the figure. The thick line represents the smoothed decay curve. See Sect. 2.1 for details.

is quite likely that some outbursts were missed. Determination of a reasonable value of $T_{\rm C}$ is then difficult. Using the residuals of some reference period can help to overcome this problem, assuming that the process is cyclic. In Sect. 3 it will be argued that the outbursts in DO Dra can be explained by the same mechanisms as those in dwarf novae. It is true that outbursts in dwarf novae are not strictly periodic but $T_{\rm C}$ often does not vary considerably between the neighbouring outbursts. The $O-C$ diagram can then be constructed for some reference mean $T_{\rm C}$.

The method of determination of the recurrence time $T_{\rm C}$ of outbursts in dwarf novae using the $O-C$ residuals from some reference period (e.g. Vogt 1980) removes the drawbacks of the widely used approach based on the measurements of separation of the neighbouring outbursts. The method of the $O-C$ residuals is not sensitive to the exact length of the reference period and the $O-C$ diagram can be constructed even if there are gaps in the data. A more detailed discussion of this method was given in Paper I.

A set of the $O-C$ curves for slightly different reference periods was generated to obtain the mean slope of the $O-C$ values as small as possible. The final $O-C$ diagram is displayed in Fig. 4. The reference period of 868 days (Eq. (1)) keeps a large part of the $O-C$ curve at a very small slope and shows the course of the $O-C$ values of the outbursts with the best clarity. In most cases the error bars in Fig. 4 would be smaller than the symbols used. *The overall course of the $O-C$ values within the epochs $E=-21$ to 2 can be approximated by a straight line (i.e. the mean $T_{\rm C}$ is constant)* with a standard deviation of 101 days. Only the last two outbursts have largely deviating $O-C$ values and may suggest an increase of $T_{\rm C}$. In conclusion, it can be seen from Fig. 4 that the method of residuals enabled us to determine the mean $T_{\rm C}$ in spite of several missing outbursts. It can also be inferred from Fig. 4 that an outburst might pass unobserved around JD = 2 449 250; an examination of the light curve in Fig. 1 revealed that the segment of the light curve around this

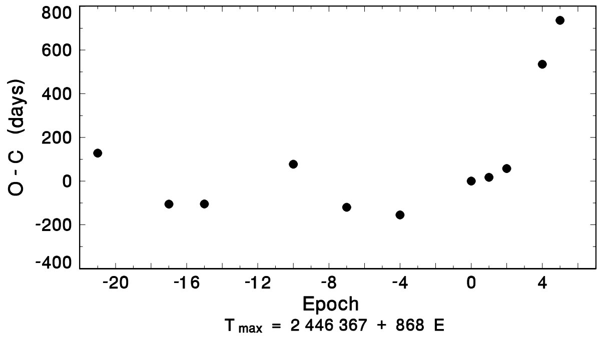

Fig. 4. The $O-C$ diagram for the outbursts in DO Dra. The $O-C$ values were calculated according to Eq. (1). The vertical dotted lines at each epoch enable a better assessment of the missing outbursts. See Sect. 2.2 for details.

date is not very densely covered and also contains several gaps in the coverage by the upper limits.

$$T_{\max} = 2\,446\,367 + 868\,E. \qquad (1)$$

2.3. Variations of the quiescent level

The light curve in Fig. 1 displays the well visible fluctuations of the quiescent level. The inspection of the densely covered part within JD = 2 450 100 – 2 451 500 revealed that these fluctuations cannot be ascribed to the observational noise and that they display trends on the time scale of tens of days and longer. In order to diminish the noise of the quiescent light curve in this segment, only the data of four observers who covered long intervals of the curve were used. The light curves of the respective observers were interactively shifted to match each other. This procedure removed slight systematic shifts of some observers, not exceeding 0.2 $\mathrm{mag_{vis}}$. In the last step, the observations were binned into the means, mostly of 7 observations. We preferred to preserve the number of observations instead of the length of the bin to keep the noise as low as possible. This approach emphasized the *slow* component of variations whose full amplitude reaches almost 1 $\mathrm{mag_{vis}}$ (Fig. 5).

3. Discussion

We have presented an analysis of the long-term activity of the intermediate polar DO Dra with emphasis on its outburst behaviour. The densely covered light curves enabled one to determine the course of the outbursts in this system for the first time and gave a rare opportunity to study outbursts in an intermediate polar.

A test whether the outbursts of DO Dra can be caused by the thermal instability, operating in dwarf novae (e.g. Smak 1984) can be made using the $P_{\rm orb} - M_{\rm V}$ diagram (Fig. 6). This diagram, based on the data from Hellier (1996), Patterson (1994), Warner (1997), Ritter & Kolb (1998) and VSNET (www.kusastro. kyoto-u.ac.jp/ vsnet/), also enables a comparison of DO Dra with other IPs (Fig. 6). $M_{\rm V}$ refers to the absolute visual magnitude. The relations between $P_{\rm orb}$ and the maximum brightness of outbursts in dwarf novae and their quiescent level are plotted, too, according to Warner's (1987) Eq. (13) and Eq. (18), respectively. It can be seen that most IPs lie between these two lines. They are fainter than nova-like systems which have $M_{\rm V}$ comparable to dwarf novae in outburst (Warner 1995). $M_{\rm V}$ depends on the inclination angle i but since most IPs plotted here do not show eclipses, their i is not larger than about 70°. It can readily be seen that DO Dra is the less luminous IP among those plotted in Fig. 6 and even lies below the level of quiescent dwarf novae. Along with the weak magnetic field of the WD in DO Dra (Norton et al. 1999) and moderate i (Haswell et al. 1997) it supports the idea that the low $M_{\rm V}$ of this system is caused by quite a low mass transfer rate and not by a largely truncated disk. DO Dra therefore lies in the region which fulfils the conditions for occurrence of dwarf nova outbursts.

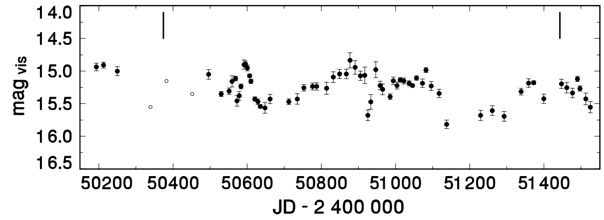

Fig. 5. Variations of the quiescent level of brightness in DO Dra. The points are bins mostly of seven observations, the bars represent their rms error. The empty circles denote the single observations in a weakly covered interval. Only the data for the quiescent level are plotted; the vertical lines denote the position of two outbursts, displayed in Fig. 2cd. See Sect. 2.3 for details.

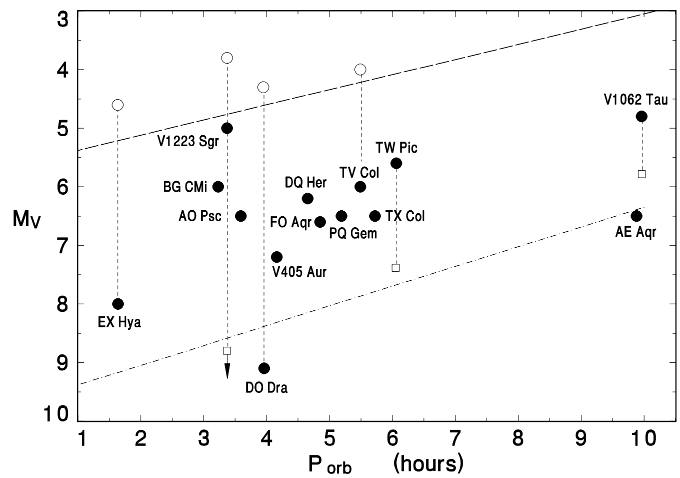

Fig. 6. Comparison of the position of DO Dra with other intermediate polars in the $P_{\rm orb} - M_{\rm V}$ diagram. The filled circles denote the typical brightness of the respective IPs. Outbursts and low states are marked by empty circles and squares, respectively. GK Per lies out of range. The relation between $P_{\rm orb}$ and the maximum brightness of outbursts of dwarf novae (dashed line) and their quiescent level (dot-dashed line) are plotted, too, according to Warner's (1987) Eq. (13) and Eq. (18), respectively. See Sect. 3 for details.

The decay branches remain remarkably similar for the individual outbursts of DO Dra. The properties of the cooling front which, in the framework of the thermal instability model always starts in the outer part of the disk and moves inwards, therefore remain stable for the respective events. The decay branch of the outbursts in DO Dra is faster than exponential. The observed decay rate $\tau_{\rm D} = 0.92$ days $\mathrm{mag}_{\rm vis}^{-1}$ is considerably faster than that for non-magnetic dwarf novae because Eq. (3.5) in Warner (1995) predicts $\tau_{\rm D} = 1.68$ days $\mathrm{mag}_{\rm vis}^{-1}$.

Width of the outbursts W in DO Dra can be compared with non-magnetic dwarf novae using the relation of van Paradijs (1983) where W is measured 2 mag below mag(max). The mean W for $P_{\rm orb} = 3.96$ hours is about 5.8 days (within 4.4–7.5 days). The rise of the outburst in Fig. 2c and the upper limits of the remaining three confirm that W in DO Dra is consistent with or slightly smaller than the lower limit for W of the narrow outbursts in non-magnetic CVs and by far smaller than W of the wide outbursts in these systems.

When explaining the features of the outbursts in DO Dra, it is natural to take into account the influence of the magnetized WD on the disk. Cannizzo (1994) presented models of the decay branches for various values of the inner disk radius $r_{\rm in}$, using the viscosity parameter α as a function of the disk radius in the form $\alpha = \alpha_0 (r/r_{\rm outer})^{0.325}$. Angelini & Verbunt (1989) used α independently of the radius but they modeled the full outburst light curve and $T_{\rm C}$ for two largely different values of $r_{\rm in}$. Both approaches confirm the decrease of $\tau_{\rm D}$ with increasing $r_{\rm in}$. Cannizzo's (1994) model further predicts that the decay branch ceases to be exponential with increasing $r_{\rm in}$.

Our observational facts for the outbursts in DO Dra (decay faster than exponential and faster than predicted for non-magnetic dwarf novae) are in good agreement with both above-mentioned models of outbursts in disks with the missing inner region. These facts further imply that despite the low field strength (Norton et al. 1999) the magnetosphere of the WD in DO Dra is not fully compressed during the outburst and the central region of the disk is still missing. Mass accretion during the outburst therefore is not large enough to diminish the Alfven radius down to the surface of WD and the matter is supposed to be still channelled onto its pole(s). Also the small W of the outbursts in DO Dra is in accordance with Angelini & Verbunt's (1989) model for outbursts in disk with large $r_{\rm in}$. These facts may suggest that the crude assumption made by Angelini & Verbunt (1989) that $r_{\rm in}$ remains the same in quiescence and during outburst is not far from true in the case of DO Dra.

We determined the mean $T_{\rm C}$ of the outbursts in DO Dra over the last 63 years to be about 870 days. The cycle-to-cycle variations of $T_{\rm C}$ are significantly smaller than the full amplitude of the $O-C$ variations, apart from the last two outbursts which may suggest an increase of $T_{\rm C}$. Position of DO Dra in the $P_{\rm orb} - T_{\rm C}$ diagram (Fig. 11 in Paper I) places this system well above the location of all dwarf novae having 3 hr$< P_{\rm orb} < 1$ day. The exceptionally long $T_{\rm C}$ along with the short duration of outbursts in DO Dra can be interpreted in terms of the thermal instability which starts in the inner region of the disk with missing central part (inside-out outburst), following the model of Angelini & Verbunt (1989). Their model showed that if the inner disk region is missing in quiescent IP, a higher critical density must be achieved to initiate the transition of the disk to the hot state in comparison with non-magnetic CV; longer $T_{\rm C}$ is therefore needed.

Mag(max) of DO Dra is consistent with Warner's (1987) relation for maxima of outbursts in non-magnetic dwarf novae (his Eq. (13)) (Fig. 6). The magnetic field of the WD in this system therefore does not lower much the visual luminosity at the outburst maximum. Again, following the models of Angelini & Verbunt (1989) it points to the inside-out type of outburst. The visual luminosity at maximum of outburst is supposed to come mostly from the middle region of the disk and is thus less dependent on the missing inner region.

There is no apparent trend in the variations of the quiescent level between the neighbouring outbursts of DO Dra. Instead, the slow component of these fluctuations, having quite a large amplitude (almost 1 $\mathrm{mag}_{\rm vis}$), can roughly be described as waves on the time scale of tens to hundreds days, that is much shorter than $T_{\rm C}$. It is not well known yet if these waves are tightly related to interaction of matter with the magnetic field of the WD but they are uncommon for most dwarf novae (WW Cet is a rare exception; Ringwald et al. 1996). On the other hand, they are similar to the dwarf nova HT Cas (Robertson & Honeycutt 1996) which is a suspected IP (Warner 1995).

Let us compare the outbursts of DO Dra with those reported for several other confirmed IPs. The outbursts in TV Col and V 1223 Sgr have a lower amplitude (about 2 mag), a much shorter duration (1 day or less) and much faster decay rate ($\tau_{\rm D} = 0.12$ and 0.21 days $\mathrm{mag}_{\rm vis}^{-1}$, respectively (Schwarz et al. 1988, van Amerongen & van Paradijs 1989). Both systems are significantly more luminous than DO Dra (Fig. 6). Outbursts of EX Hya ($T_{\rm C} \approx 600$ days) have $\tau_{\rm D}$ consistent with that of non-magnetic dwarf novae with the corresponding $P_{\rm orb}$ (Bailey 1975). Hellier & Buckley (1993) discussed these three IPs thoroughly (including their spectral changes over outburst) and concluded that their outbursts are caused by mass transfer bursts from the secondary instead of thermal instability.

In conclusion, our analysis has shown that the photometric parameters of outbursts of DO Dra, in conjunction with the deviating position in the $P_{\rm orb} - M_{\rm V}$ diagram and the weak magnetic field are consistent with the thermal instability in accretion disk with the missing inner region.

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