

# General Properties of Quiescent Novae

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## **Abstract.**

The observed properties of novae before and after eruption are discussed. The distribution of orbital periods of novae shows a concentration near 3.2 h, which resembles that of magnetic cataclysmic variables, and there is some evidence that many of the novae themselves are magnetic near that orbital period. Desynchronisation of polars by nova eruptions can lead to an estimate ( $\sim 2 \times 10^3$  y) for the time between eruptions for the strongly magnetic systems; this is much shorter than that found from other methods. The similarity of pre- and post-nova luminosities, at high rates of mass transfer, is ascribed to irradiation of the secondary producing a self-sustained high  $\dot{M}$  state. This slows cooling of the white dwarf after eruption, delays the onset of full scale dwarf nova outbursts in most systems, and delays any descent into a hibernation state of low rate of mass transfer.

## **INTRODUCTION**

This conference is mostly about the high luminosity state, and the transitions into and out of it, but full understanding of the nova process must include the nature of the low luminosity white dwarf and its accretion environment, in which it spends most of its life.

## **CYCLIC EVOLUTION AND HIBERNATION**

As is well known, the mechanisms of orbital angular momentum loss generally invoked to drive CV evolution are magnetic braking (MB) for orbital periods longer than about 2 h and gravitational radiation (GR) for shorter periods (Note that it has long been pointed out that GR alone is not sufficient to account for the observed luminosities of many of the short period systems (Warner 1987), though these may not be representative of the long-term mean brightness). Basic models of MB (e.g. Verbunt & Zwaan 1981) are single valued, giving a unique relationship between mass transfer rate ( $\dot{M}$ ) and orbital period  $P_{orb}$ . The large range (factors of 1000 or more) of  $\dot{M}$  that is observed at most values of  $P_{orb}$  (Patterson 1984; Warner 1987, 1995a) shows that at least one other parameter is determining the instantaneous  $\dot{M}$ . Whether standard MB and GR set the long-term average, or whether additional mechanisms are required, is not yet certain. Large temporary excursions of  $\dot{M}$  above the average set by MB can be generated by the effect of irradiation of the secondary by the primary and inner disc, which increases the scale height of the atmosphere of the secondary. If the response of the entire secondary to irradiative heating at the surface is calculated, cyclical evolution is found which alternates between a high  $\dot{M}$  state in which the secondary expands and a low  $\dot{M}$  state

in which it contracts (King et al. 1995). Time scales for the transitions are  $\sim 10^4 - 10^5$  y, and durations in the high states are  $\sim 10^7$  y. Such cycles do not develop for secondary masses below  $\sim 0.65 M_{\odot}$  because of the large thermal inertia in the convective envelope (King et al. 1996).

In addition, the observed high  $\dot{M}$  after nova eruption, and the subsequent steady reduction, which is in quantitative agreement (e.g., for V1500 Cyg: Somers & Naylor 1999) with the prediction (Prialnik 1986) of the effects of irradiation of the disc and the secondary by post-nova cooling of the white dwarf (Schreiber & Gänsicke 2001), show that variation about the mean certainly occurs through the intervention of novae. The additional mass transfer caused by heating of the secondary during (and for a century or more after) a nova eruption is, in theory, followed by a phase of lowered accretion rate (Kovetz, Prialnik & Shara 1988) which is needed to maintain the secular average (but allowing for the fact that the eruption itself alters the orbital separation and therefore changes the radius of the Roche lobe of the secondary).

The question remains as to whether this is sufficient to send CVs into deep and sustained hibernation. Some evidence that this does not happen for at least 200 y has been given by Somers, Mukai & Naylor (1996) and Somers, Ringwald & Naylor (1997) for WY Sge (Nova Sagittae 1783), which is the oldest definitely recovered nova and still shows enhanced  $\dot{M}$ . But T Sco, the nova of 1860 that occurred in the globular cluster M 80, has been recovered and appears about a factor of ten fainter than normal nova remnants and does not appear (from absence of orbital modulation) to be a high inclination system (Shara & Drissen 1995). In addition, not all novae that occurred early in the twentieth century have been recovered, and until they are it cannot be claimed that there is no evidence for hibernation within the first century or so of nova eruption. The most important fact continues to be that no stellar remnants of the bright novae noted in Oriental records of one to two millennia ago are observable today (Shara 1989) – instead of being the nova-like systems at magnitudes 12 – 15 that modern bright naked eye novae become, they have faded beyond easy identification. This is the most persuasive case for eventual extended very low  $\dot{M}$  states for post novae.

Another case, and certainly easier to observe (at  $V \sim 12$ ), is AE Aqr, with its magnetic primary rotating at  $P_{rot} = 33$  s, which must have been established as an equilibrium rotation period at high  $\dot{M}$ , but which has currently a low  $\dot{M}$  suggestive of quite deep hibernation. Systems like AE Aqr would be quite difficult to discover at great distances (AE Aqr is one of the closest of CVs, at a distance of 86 pc), so they may be more common than realised.

It should also be kept in mind that at the shortest orbital periods there are dwarf novae like WZ Sge for which the estimated values of  $\dot{M}$  are an order of magnitude or more below that set by GR, and so these systems are in at least partial hibernation. WZ Sge's spin period of  $\sim 28$  s (Warner & Woudt 2002) also indicates a high  $\dot{M}$  in the past.

## PRE- AND POST-ERUPTION BEHAVIOUR

The survey of pre-eruptive behaviour of novae, made by Robinson (1975), disclosed only one (V446 Her) that could be thought to have had dwarf nova (DN)-like outbursts,

with a range of nearly 4 mag. The variations were largely irregular, but the ‘flares’ or ‘outbursts’ had such slow rises to maxima ( $\sim 10$  d) that they are incompatible with a CV having  $P_{orb} = 4.97$  h and (as concluded by Robinson on other grounds) are probably not normal DN outbursts. A similar remark may be made about the pre-outburst 1.6 mag variations in V3890 Sgr (Nova Sgr 1962: Dinerstein 1973). There is therefore no authenticated case of a nova eruption having taken place in a normal DN.

Robinson also found that pre- and post-eruptive magnitudes are very similar (an apparent exception, BT Mon, was later found to conform: Schaefer (1983)). This in general continues to be true, with definite exceptions of the three very fast novae GQ Mus (N 1983), CP Pup (N 1942) and V1500 Cyg (N 1975), all of which rose from exceptionally faint magnitudes (to which they have not returned), though V1500 Cyg was in a brighter state for a week before eruption. Their pre-eruptive luminosities were so low that they were certainly in states of low  $\dot{M}$  at those times.

The identity of pre- and post-eruptive luminosities is commonly used as evidence that a nova eruption does not seriously change the state of a CV. Yet the mass and angular momentum ejected in a nova eruption will certainly perturb the long-term orbital evolution – the question is: How long will it take for the effects to show themselves? This is relevant to the evidence or otherwise for hibernation, discussed above. Here I want to examine the implications of pre- and post-novae being, both spectroscopically and in luminosity, indistinguishable from nova-like variables (e.g. Chapter 4 of Warner 1995a).

The interrelationships between nova-likes, VY Scl stars and DN, as functions of  $P_{orb}$ , can be summarised as follows:

- The VY Scl stars (which are nova-likes showing randomly distributed states of low  $\dot{M}$ ), all lie roughly in the  $P_{orb}$  range 3.0 – 4.0 h.
- There are very few DN in the  $P_{orb}$  range 3.0 – 4.0 h.
- The values of  $\dot{M}$  that appear among the nova-likes in the region of  $P_{orb} = 3 - 4$  h are more than an order of magnitude greater than that predicted by the theory of magnetic braking (Warner 1987).

These strong correlations have been quantitatively explained by Wu, Wickramasinghe & Warner (1995a,b, hereafter WWW; see also Warner 1995a) in the following way: For  $P_{orb} < 4$  h the separation between the secondary and primary is small enough to produce significant irradiative heating of the secondary by the hot central regions of the disc and the primary which results in greatly enhanced  $\dot{M}$ . The surface temperature  $T_{eff}$  of the primary is largely governed by  $\dot{M}$  – in particular, the large values of  $T_{eff}$  found in nova-likes (up to 50 000 K, Sion 1999) are what are expected for accretion at  $\dot{M} \sim 10^{-8} M_{\odot} \text{ y}^{-1}$  (Section 9.4.4 of Warner 1995a). WWW found that, as the thickness of the accretion disc increases with  $\dot{M}$  and shields the secondary, this negative feedback automatically leads to an upper limit of  $\dot{M} \sim \text{few} \times 10^{-8} M_{\odot} \text{ y}^{-1}$ , and that the non-linearity of the situation leads to short lived high/low  $\dot{M}$  states as observed in the VY Scl stars (in which the important time scales are the response time of the outer envelope of the secondary, and the cooling time of the outer parts of the primary) and/or to long-lived ( $10^4 - 10^6$  y) high and low  $\dot{M}$  excursions. The upper limit on  $\dot{M}$  corresponds to  $M_V \sim 3.3$  in the  $3.0 < P_{orb} < 4.0$  h region, only slightly brighter than what is actually observed (Warner 1987).

To summarise: the predominance of nova-likes, and in particular the VY Scl stars, in the  $P_{orb} = 3 - 4$  h range is probably due to irradiation-enhanced  $\dot{M}$ ; the near absence of

DN is due to the relative rapidity of passage through states of intermediate  $\dot{M}$ . Below  $P_{orb} \sim 3$  h the mechanism causing the orbital period gap dominates.

The relevance of this theory to novae is clear: almost all novae are observed to erupt from CVs of the nova-like subtype, where  $\dot{M}$  is high (naturally high for  $P_{orb} > 4$  h, enhanced by irradiation to a high value for  $P_{orb} < 4$  h) and where a primary with  $T_{eff}$  up to  $\sim 50\,000$  K resides. After eruption, the primary has an even higher temperature, and  $\dot{M}$  is thereby even more enhanced (Priyalnik 1986), but both decrease as the primary cools. However, for  $P_{orb} \lesssim 4$  h, the primary is prevented from cooling below  $T_{eff} \sim 50\,000$  K because the irradiation-enhanced high  $\dot{M}$  equilibrium is re-established after eruption. It is this effect that results (at least for the shorter  $P_{orb}$  systems) in equality of luminosity before and after eruption. The equilibrium value of  $T_{eff}$  is sensitive to the mass of the primary (higher masses lead to more gravitational potential energy release but a smaller area to radiate it away); using equations 2.83b and 9.55 of Warner (1995a) we find  $T_{eff} \propto M^3$  for  $M > 1.0 M_{\odot}$ , where a large primary mass is adopted because there is higher probability for nova eruptions to be observed in high mass systems. As the selection for higher masses does not apply to nova-likes we should find that  $T_{eff}$ ,  $\dot{M}$  (and hence  $M_V$ ) in nova-likes is on average smaller (fainter) than in old post-novae. Comparison of Figures 4.16 and 4.20 of Warner (1995a) shows this is in fact the case.

For non-magnetic CVs with  $P_{orb} < 4$  h, therefore, the primary's cooling curve as computed by Priyalnik (1986) applies only until the irradiation-enhanced pre-nova equilibrium is regained. How long the latter phase will last is not yet known. Clearly, the effects of mass and angular momentum lost during eruption eventually must take their toll – in order to maintain the long-term average angular momentum drain from the orbit. For  $P_{orb} < 4$  h the irradiative equilibrium phase acts to delay the onset of the necessary low  $\dot{M}$  state – an example of deferred compensation.

These remarks are also relevant to the nature of the pre-eruption outbursts seen in V446 Her and V3890 Sgr, as mentioned above. The pre-eruption range of V446 Her was  $m_{pg} \sim 14.9 - 18.4$  (Robinson 1975) – and is larger than the range seen in its post-eruption variations, which are clearly standard DN outbursts (Honeycutt, Robertson & Turner 1995, Honeycutt et al. 1998). This and the slow rises appear more like VY Scl behaviour, but the large  $P_{orb}$  argues against this and it is likely that what is seen is a combination of normal DN outbursts (greatly under-sampled by the photographic archive plates) and some variations in  $\dot{M}$ , implying that  $\dot{M}$  was low enough before (as after) eruption for the accretion disc to be thermally unstable. We note that at  $P_{orb} \sim 5$  h the irradiation in V446 Her will not be sufficient to hold the system in a high  $\dot{M}$  nova-like state if its natural  $\dot{M}$  is below the critical value.

This last effect is seen as responsible for the non-appearance of DN outbursts in the majority of post-novae. The only systems for which authenticated standard DN outbursts have been seen are V446 Her ( $P_{orb} = 4.97$  h), GK Per ( $P_{orb} = 47.9$  h) and V1017 Sgr ( $P_{orb} = 137$  h), for all of which irradiation of the secondary is not important because of the large separations implied by the long orbital periods.

On the other hand, 'stunted' DN outbursts in nova-likes and old post-novae are commonly observed (Honeycutt, Robertson & Turner 1998). In these the time scales of typical DN outbursts are seen, but the amplitudes are only  $\sim 0.6$  mag. These can be understood as arising from outbursts in only the outer parts of the accretion discs, with

the inner parts kept permanently in a high temperature state through irradiation by the hot primary (Warner 1995b; Schreiber, Gänsicke & Cannizzo 2000).

It should be mentioned that, in addition to the variations in brightness on DN time scales (weeks or months), there are low amplitude (typically 0.1 – 0.2 mag) variations on time scales of years believed to be caused by  $\dot{M}$  variations resulting from magnetic cycling within the secondary (see Table 9.3 of Warner 1995a).

To return to pre-eruption light curves, Robinson (1975) found that 5 out of 11 well observed systems showed slow increases of brightness of 0.25 – 1.5 mag during 1 – 15 y before eruption. With the possible exception of the largest value (which is for V533 Her) the  $M_V$  increases are modest and may be the result of increases in  $\dot{M}$  from the secondaries as seen in the decadal cycles mentioned above. (Note, however, that an increase of only 0.33 mag in V for a high  $\dot{M}$  disc implies an increase in  $\dot{M}$  by a factor  $\sim 2$  (Smak 1989) – this may not apply to V533 Her, which is an intermediate polar (see below) and has a truncated disc). Such an increase in  $\dot{M}$ , with its concomitant increase of compressional heating in the surface layers of the primary, could well trigger a nova eruption. The observations imply that about half of nova-likes that have accreted almost a critical mass are triggered during a high part of a decadal cycle. Of course, this is what would be expected randomly anyway, so it is not evidence for such a triggering mechanism!

Finally, high  $\dot{M}$  discs in CVs with  $P_{orb} \lesssim 4$  h commonly show superhumps arising from precessing elliptical accretion discs (e.g. Patterson 1999), and post-novae are no exception. V603 Aql, V1974 Cyg, CP Pup and probably V4633 Sgr, V2214 Oph and GQ Mus are examples. Superhumps are a diagnostic for high  $\dot{M}$  discs, and as such can be used to identify high luminosity discs at short  $P_{orb}$  – where almost all CVs have very low  $\dot{M}$  (e.g. Fig. 9.8 of Warner 1995a). The only one so far found (that is not a known recent nova) is BK Lyn ( $P_{orb} = 0.075$  d; Skillman & Patterson 1993), which may possibly be the remnant of Nova Lyn 101 AD (Hertzog 1986). Such systems have very low amplitude photometric modulations and are difficult to find. The only known reason for high  $\dot{M}$  at such short  $P_{orb}$  is connected with eruption, and such systems therefore are strongly indicative of prehistoric novae. If the identification of BK Lyn with the nova of 101 AD could be proven, it would show that at very short  $P_{orb}$  a high  $\dot{M}$  might be (self-) sustained for at least a millennium.

## ORBITAL PERIODS OF NOVAE

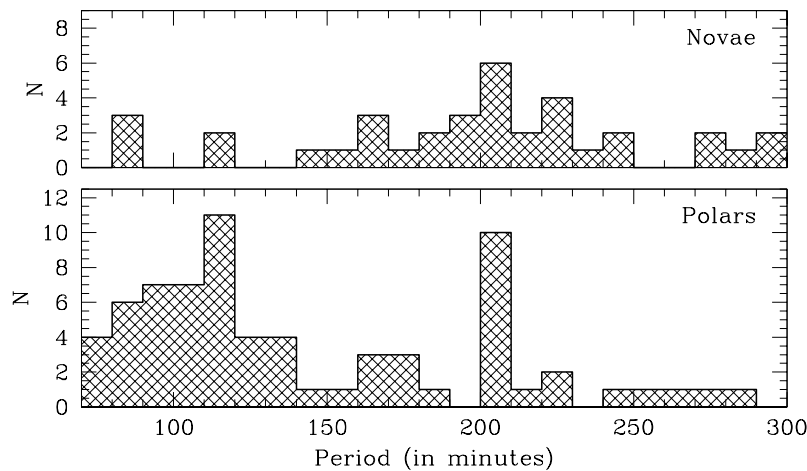
In their discussion five years ago of the orbital period distribution of novae, and their progenitor population, Diaz and Bruch (1997) listed 30 objects with known  $P_{orb} < 24$  h (six of which are considered by Downes et al. to be unreliable period determinations). The number of classical novae (omitting recurrent novae, all of which seem to be different from the ‘non-recurrent’ ones) with known periods  $< 24$  h is now the 50 listed in Table I (which also omits some uncertain determinations - and note that a few may be superhump periods, which are a few percent different from  $P_{orb}$ ), and demonstrates considerable observational progress in the past 5 years.

The frequency distribution of nova orbital periods is shown in Figure 1.

**TABLE 1.** Orbital Periods of Novae

Star	Date	Magn. range	$P_{orb}$	Star	Date	Magn. range	$P_{orb}$
RW UMi	1956	6 – 18.5	1.418	WY Sge	1783	5.4 – 20.7	3.687
GQ Mus	1983	7.2 – 18.3	1.425	OY Ara	1910	6.0 – 17.5	3.731
CP Pup	1942	0.5 – 15.2	1.474	V1493 Aql	1999	10.4 – >21	3.74
V1974 Cyg	1992	4.2 – 16.1	1.950	V4077 Sgr	1982	8.0 – 22	3.84
RS Car	1895	7.0 – 18.5	1.980	DO Aql	1925	8.7 – 16.5	4.026
DD Cir	1999	7.7 – 20.2	2.340*	V849 Oph	1919	7.3 – 17	4.146
V Per	1887	9.2 – 18.5	2.571	V697 Sco	1941	10.2 – 19.7	4.53*
QU Vul	1984	5.6 – 17.5	2.682	DQ Her	1934	1.3 – 14.6	4.647
V2214 Oph	1988	8.5 – 20.5	2.804	CT Ser	1948	7.9 – 16.6	4.68
V630 Sgr	1936	1.6 – 17.6	2.831	T Aur	1891	4.2 – 15.2	4.906
V351 Pup	1991	6.4 – 19.0	2.837	V446 Her	1960	3.0 – 17.8	4.97
V4633 Sgr	1998	7.4 – >20	3.014	V533 Her	1963	3.0 – 15.0	5.04
DN Gem	1912	3.5 – 16.0	3.068	HZ Pup	1963	7.7 – 17.0	5.11
V1494 Aql	1999	4.0 – >16	3.232	AP Cru	1936	10.7 – 18.0	5.12
V1668 Cyg	1978	6.7 – 19.8	3.322	HR Del	1967	3.5 – 12.3	5.140
V603 Aql	1918	-1.1 – 11.8	3.324	V1425 Aql	1995	7.5 – >19	5.419
DY Pup	1902	7.0 – 19.6	3.336	BY Cir	1995	7.2 – 17.9	6.76*
V1500 Cyg	1975	2.2 – 18.0	3.351	V838 Her	1991	5.4 – 15.4	7.143
V909 Sgr	1941	6.8 – 20	3.36	BT Mon	1939	8.5 – 16.1	8.012
RR Cha	1953	7.1 – 18.4	3.370	V368 Aql	1936	5.0 – 15.4	8.285
RR Pic	1925	1.0 – 12.1	3.481	QZ Aur	1964	6.0 – 17.5	8.580
V500 Aql	1943	6.6 – 17.8	3.485	CP Cru	1996	9.2 – 19.6	11.3*
V382 Vel	1999	2.7 – 16.6	3.508	DI Lac	1910	4.6 – 15.0	13.050
V533 Her	1963	3.0 – 14.8	3.53	V841 Oph	1848	4.2 – 13.5	14.50
V992 Sco	1992	8.3 – 17.2	3.683*	V723 Cas	1995	7.1 – >18	16.638

\* Woudt & Warner, unpublished



**FIGURE 1.** The frequency distribution of the orbital periods of Novae (upper panel) and Polars (lower panel).

To the list of novae that have been observed to erupt it should eventually be possible to add ones that are demonstrably novae that were overlooked in the relatively recent past. As a class, the desynchronised polars, discussed below, provide four probable examples with periods 1.85, 3.35, 3.35 and 3.37 h. The X-Ray source RX J1039.7-0507, with  $P_{orb} = 1.574$  h, is probably another (see poster by Woudt & Warner at this conference).

A FAQ (Frequently Asked Question) is whether the  $P_{orb}$  distribution for classical novae shows a gap (or, at least, a greatly lowered space density) in the range 2 – 3 h in the same way as dwarf novae (see, e.g., Warner 1995). Using the range  $2.11 < P_{orb}(\text{h}) < 3.20$  for the empirically determined period gap (for CVs of all types: Diaz & Bruch, 1997) there are eight novae in the ‘gap’, which does not support the presence of a gap – though a reduction of population relative to the number of novae immediately above 3.2 h is undeniable – but so is the rapid fall in numbers for  $P_{orb}$  below 3 h.

A FUQ (Frequently Unasked Question) is what we should learn from the answer to the above FAQ. A point to be considered is that all white dwarfs accreting at the rates commonly seen in CVs must eventually undergo nova explosions (we exclude here the highest accretion rates which lead to Ultra Soft X-Ray Sources steadily burning hydrogen near their surfaces). The population of novae is therefore drawn from all of those CV subtypes that have high enough accretion rates to produce novae. If there is a population of detached systems in the period gap, which is the conventional explanation for the ‘missing’ CVs in the gap, they obviously do not contribute to the census of novae. If there is in fact a lower space density of novae at the position of the traditional period gap, it may simply be representing the gap we already see in some other subtypes.

There are few known short orbital period novae, and the reason for this is not immediately obvious. The space density of CVs in the range  $P_{orb} - P_{orb} + dP_{orb}$  should be inversely proportional to  $dP_{orb}/dt$ , and therefore proportional to  $\langle \dot{M} \rangle^{-1}$ , and the frequency of nova eruptions should be proportional to  $\langle \dot{M} \rangle$  (where  $\langle \rangle$  denotes the long-term secular mean), so the fraction of CVs that become novae should be roughly independent of  $\langle \dot{M} \rangle$ . The observed large pile-up of CVs at short  $P_{orb}$  (which is even larger in distributions predicted by population syntheses) – is not represented by a similarly large number of novae. Furthermore, the novae are sampled from a larger volume of space than the other CVs, so the short  $P_{orb}$  novae have an even lower relative space density than expected.

Even if there is no obvious period gap, Table 1 and Fig. 1 do have one distinctive feature: there is a concentration of novae in the range 2.8 – 4.1 h (44% of all known orbits lie in this 1.3 h range). The remainder are spread widely: another 48% cover the 6.3 h of ranges 1.4 – 2.8 h and 4.1 – 9 h. In some respects this is a mirror image of what happens in the DN, where there is a large number with  $P_{orb} < 2$  h and very few in the range 3 – 4 h. We can partly understand this through the fact that the average mass transfer rate is very much lower below the period gap than above, which ensures that most CVs below the gap lie below the critical transfer rate for stable accretion discs, and at the same time they accrete mass so slowly that the frequency of nova eruption *per star* is low. But above the gap the anticorrelation of classical and dwarf novae populations must be more subtle. We shall see below that there is some evidence that many of the novae in the central part of the 3 – 4 h range have magnetic primaries; these would have to be subtracted from any comparison with the dwarf novae (which at most are weakly

magnetic), but this still leaves the 3 – 4 h range clearly favoured by novae.

A possible explanation has already been given above in terms of the effects of irradiation of the secondary (WWW), which begin to be very important for  $P_{orb} < 4$  h. If mean values of  $\dot{M}$  over times of  $10^3 - 10^4$  y are either very high or very low in the 3 – 4 h range, with transitions between taking place relatively rapidly (hundreds of years), then dwarf novae (which would only exist in the transition region) will be rare. The only evidence for possible secular change in  $\dot{M}$  due to such transition is the difference in mean outburst intervals in U Gem ( $P_{orb} = 4.25$  h), which are 96.5 d for 1855–1905 and 107.6 d for 1905–1955 (Warner 1987).

## MAGNETIC NOVAE

At least a quarter of CVs have primaries with magnetic fields strong enough to affect the accretion flow. The strongest fields, in the polars, prevent the formation of accretion discs; the intermediate polars and DQ Her stars, which have progressively lower field strengths, have accretion discs truncated at their inner edge by the magnetosphere of the primary.

Eruptions on magnetic white dwarfs have occurred in RR Cha, GK Per, HZ Pup and V697 Sco, which are intermediate polars, and in DQ Her and V533 Her, but Nova Cygni 1975 (V1500 Cyg) remains unique as the only observed nova eruption that has been proven to have arisen on a strongly magnetic white dwarf, i.e. a polar. Photometry 12 years after the eruption showed it to have a light curve like that of a polar (Kaluzny & Semeniuk 1987) and subsequent polarimetric observations revealed the characteristics of a polar (Stockman, Schmidt & Lamb 1988) with a field  $\sim 25$  MG. An unexpected feature, however, was that the rotation period of the white dwarf is shorter by 1.8% than the orbital period – which is interpreted as being the result of coupling between the expanded atmosphere of the primary and secondary during eruption, with subsequent spin-up as the atmosphere collapsed back later. Observations have shown that the spin period  $P_{spin}$  is increasing at a rate that implies resynchronisation in  $\sim 185$  y (Schmidt, Liebert & Stockman 1995).

Nova Puppis 1991 (V351 Pup) has recently been found to have a light curve very similar to that observed for V1500 Cyg a decade after its eruption; although not yet detectably polarized, it may well turn out to be another example of eruption of a strongly magnetic system (Woudt & Warner 2001).

Indirect evidence for eruptions that occurred in magnetic systems in the past, but went unrecorded as novae, is given by the occurrence of three other desynchronised polars: BY Cam (Mason et al. 1998), V1432 Aql (RX J1940.1-1025) (Geckeler & Staubert 1997) and CD Ind (RX J2115-5840) (Ramsay et al. 2000). Their properties are listed in Table 2. The fact that  $P_{spin} > P_{orb}$  in V1432 Aql may be explained as coupling of the magnetic field of the primary with the dense wind during eruption (this is in competition with the purely dynamical transfer of angular momentum mentioned above for V1500 Cyg). The measured resynchronisation time scales, listed in Table 2, range over an order of magnitude:  $\sim 100 - 1000$  y, not correlated with the amount of asynchronism (as measured by the beat period  $P_{beat}$  between the orbital and white dwarf spin periods).



**TABLE 2.** Desynchronised Polars

Star	$P_{orb}$ (mins)	$P_{spin}$ (mins)	$P_{beat}$ (d)	$T_{syn}$ (y)
V1432 Aql	201.94	202.51	49.5	110
BY Cam	201.26	199.33	14.5	1107
V1500 Cyg	201.04	197.50	7.8	185
CD Ind	110.89	109.55	6.3	

V1432 Aql provides another form of indirect evidence for historical nova eruption. Schmidt & Stockman (2001) measure an effective temperature of 35 000 K for the primary, which is much greater than the typical 8000 – 20 000 K found for other polars (other than V1500 Cyg, which has 90 000 K from its recent eruption) and is out of equilibrium with the present rate of accretion heating. From the cooling calculations made by Prialnik (1986) this indicates a nova eruption in the past 75 – 150 y.

AE Aqr, already mentioned above, has an unknown  $T_{eff}$  because the dominant measurable UV flux comes from spots with  $T \sim 26000$  K produced by heating by the accretion columns (Eracleous et al. 1994). If the general non-heated surface temperature of the primary could be measured more accurately than the currently estimated 10 000 – 16 000 K this would provide a measure of how long ago the high  $\dot{M}$  phase (characteristic of the large  $P_{orb}$  of AE Aqr) was interrupted, probably by a nova eruption.

As has been pointed out before (Warner 1995a), the fraction  $f$  of polars that are desynchronised may provide a means of estimating observationally the otherwise inaccessible average time  $T_R$  between nova eruptions, at least for the magnetic systems. If  $\langle T_{syn} \rangle$  is the average resynchronisation time then  $T_R = \langle T_{syn} \rangle / f$ . There are about 68 known polars, so with 4 observed to be desynchronised and a mean  $\langle T_{syn} \rangle \sim 300$  y we have  $T_R \sim 5000$  y. This crude figure can be refined in several ways but, as we see below, it produces a serious conflict with what is known about  $T_R$  from other directions.

First,  $T_{syn}$  depends on a number of system parameters, including the mass of the white dwarf, the mass ejected and how well angular momentum was exchanged with it, the time since the eruption, etc. A global average of these effects could be obtained by appropriate theoretical modelling, but this may not be justified at present because of the small number of systems included in the statistics.

Second,  $f$  is undoubtedly underestimated because of insufficient observational coverage of many of the fainter polars. Perhaps not even all the polars with  $m_v < 16.0$  have been studied enough to detect asynchronism, but assuming that they have we note that V1432 Aql, BY Cam and CD Ind (we exclude V1500 Cyg as having been discovered in a non-standard way) constitute 3 out of about 20 systems with high state magnitudes brighter than 16. If this fraction applies also to the total population of polars, then there are another 7 de-synchronised systems among the fainter members (one of which is already known: V1500 Cyg, at  $m_v = 18.0$ ). This gives  $f \sim 0.15$  and reduces  $T_R$  to 2000 y.

Third, there are difficulties in detecting asynchronism for the older magnetic novae where synchronism has been nearly re-established. In essence, when the beat period  $P_{beat}$  becomes  $\sim$  months there is an observational bias against finding such systems. Superficially, it might be thought that, as the observed values of  $P_{beat}$  lie in the range 6 –

50 d, leaving the range 50 – ∞ d unexplored, there could be a large fraction of currently undetected desynchronised polars. However, the following reasoning suggests that the loss is not great.

The key aspect is that the synchronization torque is independent of the amount of de-synchronisation and is constant with time. The general form of the torque  $N_{syn}$  is  $N_{syn} \sim \mu_1 \mu_2 / a^3$ , where  $\mu$  is the magnetic moment (indigenous or induced in the case of the secondary) and  $a$  is the separation of stellar components (e.g. Hameury, King & Lasota 1987). The synchronisation time is  $T_{syn} = (P_{orb} - P_{spin}) / \dot{P}$ , where  $\dot{P} = dP_{spin}/dt$  is essentially constant with time because of the constant torque. At any time after the nova eruption we have the relationship

$$P_{beat} = \frac{P_{orb}^2}{|\dot{P}| T_{syn}}, \quad (1)$$

where  $T_{syn}$  is the time remaining until synchronisation. Suppose that the initial de-synchronisation produces a beat period  $P_{beat}(\text{init})$  (typically a few days) and that current observational techniques make it difficult to detect asynchronism for beat periods longer than some limit  $P_{beat}(\text{limit})$  (typically a few weeks). Then the fraction  $F$  of asynchronous systems that is detectable is

$$F = \frac{T_{syn}(\text{init}) - T_{syn}(\text{limit})}{T_{syn}(\text{init})} = 1 - \frac{P_{beat}(\text{init})}{P_{beat}(\text{limit})}. \quad (2)$$

The result is that with  $P_{beat}(\text{init}) \sim \text{week}$  and  $P_{beat}(\text{limit}) \sim \text{months}$ , very few of the desynchronised systems are overlooked, so the difficulty of detecting differences between  $P_{orb}$  and  $P_{spin}$  when they are very small has little effect on the estimate of  $f$ .

The deduced value of  $T_R \sim 2000$  y is distressingly incompatible with the estimated mass  $\sim 2 \times 10^{-4} M_{\odot}$  of ejecta in V1500 Cyg (Hjellming 1990) and the average mass transfer rate  $\sim 10^{-9} M_{\odot} \text{ y}^{-1}$  estimated for longer period polars (Beuermann & Burwitz 1995), which give  $T_R \sim 2 \times 10^5$  y. It could be that nova eruption is not the only mechanism that is capable of desynchronising polars, or that the ejecta masses of magnetic novae are grossly overestimated. Weakening of the synchronising torque with time does not help because it puts a larger fraction into systems with large  $P_{beat}$  that would currently be overlooked, necessitating an even larger correction to obtain the true number of desynchronised polars.

Another FAQ is whether polars show any period gap. The latter subject is one set about with controversy (Beuermann & Burwitz 1995; Wickramasinghe & Ferrario 2000). The list of polars shows that no absolutely empty gap is present. Beuermann & Burwitz note that comparing the number of systems in the period range of the gap with that just outside shows that gap polars are relatively twice as frequent as non-magnetic gap systems. They say that nevertheless the orbital distributions of magnetic and non-magnetic systems are not statistically different. Another point of view could be that the ‘period gap’ would probably not be noticed in polars if it were not so prominent in the non-magnetic CVs – and that it is probably equally true that the polar distribution is not statistically different from one that has no gap at all. However, here it is necessary to distinguish between two kinds of polars – several of the polars in the gap are strong cyclotron line emitters and are

interpreted as having extremely low accretion rates  $\sim 10^{-13} M_{\odot} \text{ y}^{-1}$  (Reimers & Hagen 2000). Such rates are  $< 10^{-3}$  of what is normally seen in polars and constitute systems in which accretion has nearly shut down, as predicted by some explanations of the period gap. For present purposes these systems should therefore be removed from the census of polars in the gap. These particular gap-filling polars are not going to contribute to the census of novae – they will take at least  $10^8$  y to accumulate sufficient mass to trigger a nova eruption.

Novae are drawn from all those CV subtypes that have sufficiently high long-term average accretion rates. In the case of the magnetic systems we might look for similarities in the distributions of polars and novae. The frequency distribution of polars has spikes near 114 min (1.90 h) and 202 min (3.37 h) (Wickramasinghe & Ferrario 2001); it happens that all four of the desynchronised polars listed in Table 2 are members of these two groups.

Two novae (V1974 Cyg and RS Car) out of the five that have  $P_{orb} < 2.0$  h coincide with the 114 min peak. RS Car is strongly modulated in brightness but has not been observed well enough to detect any periods other than  $P_{orb}$  (or a superhump period), but V1974 Cyg could be a desynchronised polar – its multiple periodicities are interpreted as such by Semeniuk et al. (1995), but an explanation in terms of superhumps is preferred by Skillman et al. (1997) and Retter, Leibowitz & Ofek (1997). On the other hand, Shore et al. (1997) find that the flux distribution in V1974 Cyg can be accounted for entirely by a hot white dwarf, leaving no evidence for the presence of the disc required to generate superhumps, and thus indirectly supporting the desynchronised polar model.

This may be pure coincidence, but it is interesting that in addition to the 114 min peak, the concentration of novae around 3.3 h is centred roughly on 202 min and includes the magnetic nova type specimen V1500 Cyg. This suggests looking for possible evidence of magnetism in other novae within the 3.3 h cluster – the results are shown in Table 3.

Although partly indirect, this evidence for several magnetic systems within the 3.2 h cluster is strong, though most are not desynchronised polars.

A comparison between the  $P_{orb}$  distributions for polars and novae is shown in Figure 1. The clustering near 3.3 h is seen in both subclasses, but is much tighter and more pronounced in the polars. Adding the few intermediate polars to the polars does not change the distribution noticeably (especially as the former also have a weak preference for periods around 3.3 h, 5 of about 15 with  $P_{orb} < 5$  h being close to that value). There are selection effects, depending on period, that distort these period histograms (Diaz & Bruch 1997), but for comparisons between the subclasses these are probably not important.

Direct and indirect evidence for magnetic primaries also exists outside of the two period spikes. DQ Her and V533 Her are classic DQ Her stars. Confusion between the effects of asynchronism and those of superhumps leaves the statuses of V2214 Oph (Baptista et al. 1993) and GQ Mus (Diaz & Steiner 1989) uncertain. On the other hand, a high mass transfer disc with the centre missing is a characteristic of an intermediate polar, and such evidence exists for V Per (Shafter & Abbot 1989).

A possible prehistoric magnetic nova is the polar RXJ1313.2-3259 (Gänsicke et al 2000), which, with the relatively long orbital period of 4.19 h, would be expected to have a moderately high accretion rate and, from comparison with other CVs, a primary

**TABLE 3.** Properties of Novae with Orbital Periods near 3.3 hours

Star	Remarks
V351 Pup	Possibly magnetic like V1500 Cyg (Woudt & Warner 2001).
V4633 Sgr	Possible asynchronous polar (but also could simply be a superhump modulation) (Lipkin et al. 2001).
DN Gem	No evidence for magnetism.
V1494 Aql	41.7min X-Ray period attributed to pulsations (Starrfield & Drake 2001). No direct evidence for magnetism.
V1668 Cyg	Well observed but no magnetic signature at quiescence *.
V603 Aql	Possible intermediate polar, $P_{spin} = 62.9$ min (Schwarzenberg-Czerny, Udalski & Monier 1992).
DY Pup	Observations too sparse to check for magnetic signature.
V1500 Cyg	Polar.
V909 Sgr	Not well observed.
RR Cha	Intermediate polar with $P_{spin} = 32.50$ min (Woudt & Warner 2002).
RR Pic	At one time thought to be an intermediate polar but not confirmed by later observations (Haefner & Schoembs 1985).
V500 Aql	Well observed but no magnetic signature.

\* However, the apparently well-defined photometric modulation at a period of 10.54 h, seen during early decline (Campolonghi et al. 1980), could be a spin beat with the orbital period. A cycle of this modulation was detected by Di Paolantonio et al. (1981) but not by some other observers (Piccioni et al. 1984; Kaluzny 1990).

accretion-heated to about 30 000 K. In fact, RXJ1313 has a measured temperature of 15 000 K, which is compatible with heating at the estimated accretion rate of  $\sim 10^{-10} M_{\odot} \text{ y}^{-1}$ . To cool and reach equilibrium at 15 000 K after a nova eruption takes  $\sim 10^4$  y, so Gänsicke et al. suggest that the low accretion rate and temperature may be the result of an extended hibernation state that has lasted since a nova eruption  $\sim 10^4$  y ago.

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