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MASS TRANSFER IN CATACLYSMIC VARIABLES: CLUES FROM THE DWARF NOVA PERIOD DISTRIBUTION

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ABSTRACT

Evidence is presented in support of the hypothesis that the mean mass-transfer rate at a given orbital period, $\langle \dot{M}(P) \rangle$, is not continuous across the 2–3 hr gap in the orbital period distribution for cataclysmic variables. We point out that although dwarf novae comprise nearly half (48%) of all disk systems with orbital periods less than 10 hr, only three systems out of the 22 with periods between 3 and 4 hr appear to be dwarf novae. We use the overall orbital period distribution for dwarf novae in conjunction with the predictions from current theories of dwarf nova eruptions to argue that mass-transfer rates must be generally higher for systems with orbital periods greater than 3 hr relative to systems with periods less than 2 hr. We further argue that $\langle \dot{M}(P) \rangle$ cannot increase more steeply than $P^{1.7}$ unless the white dwarf mass is positively correlated with orbital period.

Subject headings: stars: accretion — stars: binaries — stars: dwarf novae

I. INTRODUCTION

Cataclysmic variables are close binary systems consisting of a red dwarf (the secondary) which fills its Roche lobe and transfers material to a white dwarf companion (the primary) (for reviews of these systems see Robinson 1976; Warner 1976; Cordova and Mason 1983; Wade and Ward 1985). In order to conserve angular momentum, the transferred material usually forms an accretion disk surrounding the white dwarf component. A shock front or "hot spot" is formed where the interstar mass-transfer stream impacts the disk. If the white dwarf has a sufficiently strong magnetic field ($B \approx 10^8$ G), then an accretion disk cannot form and the material is forced to follow the field lines onto one or both of the white dwarf's magnetic poles. These magnetized systems are referred to as the AM Her stars (for a review see Chiapetti, Tanzi, and Treves 1980 and Liebert and Stockman 1985).

The secular evolution of cataclysmic variables is not well understood. However, it is clear that there cannot be conservation of total mass and angular momentum in the binary (Patterson 1984). Conservative mass transfer from a less massive to a more massive star will increase the binary separation and, as a consequence, the size of the mass-losing star's Roche lobe. Thus, the very action of mass transfer in such a system would result in the cessation of further mass transfer. As discussed by Patterson (1984), the most promising solution to this dilemma is to require the Roche lobe of the secondary to shrink in response to the loss of angular momentum from the binary. Several studies have shown that gravitational radiation can remove a sufficient amount of angular momentum to drive modest mass transfer ($\dot{M} \approx 10^{-10}\ M_{\odot}\ \mathrm{yr}^{-1}$) in the ultrashort period ($P \lesssim 2$ hr) systems (Paczyński 1967; Faulkner 1971; Tutukov and Yungelson 1979; Paczyński and Sienkiewicz 1981; Rappaport, Joss, and Webbink 1982). Among the longer period systems, gravitational radiation appears to be inadequate to drive the mass-transfer rates which are expected to be present (Kieboom and Verbunt 1981; Verbunt 1984). Magnetic braking of the secondary's rotation by its own stellar wind, in conjunction with the requirement that it remain in synchronous rotation (because of tidal friction), appear to be dominating the evolution of these relatively long period systems (Verbunt and Zwaan 1981; Mochnacki 1981; Patterson 1984; Verbunt 1984).

In order to evaluate evolutionary theory and, in particular, to understand the orbital period distribution of cataclysmic variables (including the now-famous period gap between 2 and 3 hr), it is obviously desirable to have reliable estimates for the mass-transfer rates (or time-averaged accretion rates) as derived from observation. Unfortunately, a direct determination of the mass-transfer rate is difficult to achieve (Verbunt and Wade 1984). Early attempts to derive $\dot{M}$ from orbital period changes proved to be unsuccessful for reasons discussed earlier; namely, because the total system mass and angular momentum do not remain constant during the secular evolution of a cataclysmic variable. Attempts to estimate $\dot{M}$ from the hot spot or disk luminosity have also proved disappointing because the bolometric corrections and distances are poorly known. Despite these difficulties, Patterson (1984) has attempted to estimate the mass-transfer rates for a large sample of cataclysmic variables using a variety of techniques. Although the accuracy of the mass-transfer rates for individual systems may be quite poor, Patterson has presented compelling evidence that the mass-transfer rate is correlated with the orbital period of the binary.

As a result of the uncertainties involved in reliably estimating $\dot{M}$ and because systematic errors with orbital period may be present, the correlation found by Patterson has not been universally accepted (e.g., see Verbunt and Wade 1984; Verbunt 1984). The purpose of this paper is to provide additional support in favor of the hypothesis that the mass-transfer rates are, in general, high for cataclysmics with orbital periods longward of the 2–3 hr period gap relative to systems with periods below the gap (the ultrashort period systems). We argue that this hypothesis offers a natural explanation for the observed dwarf nova period distribution. Our purpose is *not* to argue for the existence of a direct correlation between the mass-transfer rate and orbital period, nor is it to estimate absolute mass-transfer rates for individual systems. Specifically, we propose to use the eruptive characteristics of cataclysmic variables within a given period range as an indicator of the mean mass-transfer rate within that range.

II. DISCUSSION

a) Predictions from Disk Instability Models

The cataclysmic variables have been segregated into several classes in order to distinguish their eruptive behavior. The principal classes include classical novae, recurrent novae, novalike variables, and dwarf novae. For the purposes of our discussion we will only consider two groups: (1) dwarf novae—systems which show quasi-periodic outbursts of typically 3–5 mag and (2) systems thought to contain accretion disks that do *not* display eruptions (i.e., AM Her systems are excluded). It is generally accepted that dwarf novae eruptions are caused by a quasi-periodic modulation of the mass-accretion rate onto the white dwarf. This modulation may take place as a result of variations in the mass-transfer rate from the secondary star (Bath *et al.* 1974; Bath 1985) or as a result of an instability in the accretion disk which is fed by material from the secondary star at a constant rate (Meyer and Meyer-Hofmeister 1983 [MM]; Faulkner, Lin, and Papaloizou 1983 [FLP]; Cannizzo, Ghosh, and Wheeler 1982; Cannizzo and Wheeler 1984 [CW]; Smak 1984; Mineshige and Osaki 1984 [MO]). The latter explanation for dwarf nova eruptions appears to be the most promising primarily because it is able to predict the correct order of magnitude for the eruption amplitudes and frequencies with a minimum of assumptions. The discussion presented here is based on the assumption that dwarf nova eruptions are the result of disk instabilities.

It is beyond the scope of this paper to discuss the disk instability theories in detail; however, the predictions are summarized below. According to the dwarf nova models, the material transferred from the secondary star is initially stored in a disk with low viscosity. When the stored material reaches a critical temperature and surface density, a thermal instability ensues, heating the material, raising its viscosity, and causing it to be accreted onto the white dwarf. A general feature of these models is that the instabilities which result in dwarf nova eruptions do not occur if the mass-transfer rate rises above some critical level, $\dot{M}_{\rm crit}$.

Although the exact value of $\dot{M}_{\rm crit}$ is model dependent, the various theories of disk instability predict similar values. Expressions for $\dot{M}_{\rm crit}$ are reproduced below:

$$\text{MM:} \quad \dot{M}_{\rm crit} \approx 10^{16} r_{10}^{2.6} \text{ g s}^{-1} ,$$

$$\text{CW:} \quad \dot{M}_{\rm crit} = 1.38 \times 10^{16} r_{10}^{2.6} M_1^{-0.87} \text{ g s}^{-1} ,$$

$$\text{FLP:} \quad \dot{M}_{\rm crit} = 1.02 \times 10^{16} \alpha^{3/10} r_{10}^{21/8} M_1^{-7/8} \text{ g s}^{-1} ,$$

$$\text{Smak:} \quad \dot{M}_{\rm crit} = 1.2 \times 10^{16} r_{10}^{2.7} \text{ g s}^{-1} ,$$

$$\text{MO:} \quad \dot{M}_{\rm crit} = 1.1 \times 10^{16} r_{10}^{2.7} \text{ g s}^{-1} ,$$

where r_{10} is the radius in the disk in units of 10^{10} cm, M_1 is the mass of the white dwarf in solar units, and α is the parameter relating the gas pressure to the vertically averaged stress in the disk. For the purposes of our discussion we will take $\alpha = 1$. It appears that all five models are in remarkable agreement on the form of $\dot{M}_{\rm crit}$. We will adopt:

$$\dot{M}_{\rm crit} = 10^{16} r_{10}^{2.6} M_1^{-0.87} \text{ g s}^{-1} . \tag{1}$$

The actual value may be subject to uncertainties due to the injection stream or reheating by hard radiation from inner parts of the disk which have yet to be thoroughly explored. The important point for the purposes of this discussion is that, for a given value of r (or, alternatively, for a given orbital period), dwarf novae should generally have mass-transfer rates which are lower than their noneruptive counterparts. Smak (1982) has shown this prediction to be satisfied for a selected sample of cataclysmics where both $\dot{M}$ and r_{10} have been estimated. Assuming that the disk instability theories outlined above are qualitatively correct, we propose to show that the observed orbital period distribution of dwarf novae is a natural consequence of mass-transfer rates being generally higher above of the 2–3 hr period gap.

b) The Dwarf Nova Period Distribution

Figure 1 shows the orbital period distribution for all cataclysmics with orbital periods less than 10 hr and which are thought to contain accretion disks. The data have been taken primarily from Patterson (1984). The confirmed dwarf novae are indicated by the solid black and shaded regions. It is clear that the dwarf nova period distribution is different from the overall period distribution. Nearly all of the ultrashort period systems are dwarf novae, while the majority of the longer period systems have not been observed to exhibit dwarf novae eruptions.

It is remarkable that although nearly half (48%) of the 74 systems considered are dwarf novae, *only three*—AB Dra ($P = 3.65$ hr; Thorstensen and Freed 1985), IP Peg ($P = 3.8$ hr; Goranskij *et al.* 1985), and CN Ori ($P = 3.9$ hr; Schoembs 1982)—are found with orbital periods between 3 and 4 hr, even though this period range contains more cataclysmics (22) than any other bin of comparable width. Specifically, 86% of the cataclysmic variables in this period range do not exhibit dwarf novae eruptions. If we were to assume that the dwarf nova distribution samples the overall distribution, then the probability of finding only three dwarf novae out of 22 cataclysmics in the 3–4 hr range is $\sim 10^{-3}$. Perhaps the 3–4 hour range should be referred to as the "dwarf nova gap." It is hard to imagine how selection effects could substantially alter this result. Dwarf novae are identified by observing their outbursts which should favor their discovery over noneruptive cataclysmic variables. There does not appear to be a strong correlation between the mean time between eruptions or the eruption amplitude and the orbital period of the binary (Cannizzo, Shafter, and Wheeler 1986).

If, as we argue, the mass-transfer rates are generally higher for cataclysmic variables with periods greater than 3 hr, compared with systems with periods less than 2 hr, then how can we explain the existence of several dwarf novae with periods longer than ~ 4 hr? There are two possibilities. (1) The average mass-transfer rate could decline somewhat for orbital periods longer than ~ 4 hr. This is not a particularly satisfying explanation since it now requires us to argue that the mass-transfer rates are high only in the 3–4 hr range. (2) A much simpler explanation follows naturally from the dwarf nova instability models. The system dimensions become larger as the orbital period increases; the larger system dimensions allow the formation of larger accretion disks. As we have just seen, the value

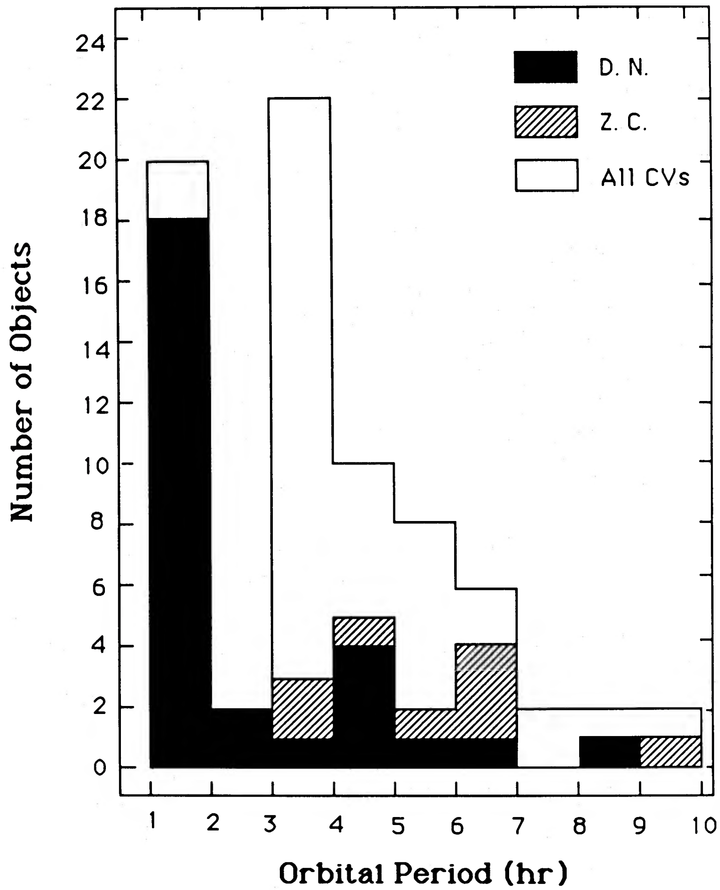

FIG. 1.—Orbital period distribution for all cataclysmic variables (excluding AM Her systems) having periods less than 10 hr. Z Cam systems are represented by the shaded regions, while all other dwarf novae are indicated in solid black. It is remarkable that over half of the dwarf novae have periods between 1 and 2 hr, while only three dwarf novae out of 22 systems are found in the 3–4 hr range (two of which are Z Cam systems). Note the famous "period gap" between 2 and 3 hr.

of $\dot{M}_{\rm crit}$ increases strongly as the outer radius of the accretion disk gets larger. Consequently, for a given mass-transfer rate and white dwarf mass, it seems reasonable to assume that instabilities (dwarf nova eruptions) will become more common at longer orbital periods.

In order to explore this possibility further, we must express $\dot{M}_{\rm crit}$ as a function of orbital period. Kepler's third law can be written as

$$P({\rm hr}) = 0.151[M_1(1+q)]^{-1/2}a_{10}^{3/2} , \quad (2)$$

where M_1 is the mass of the white dwarf in solar units, a_{10} is the stellar separation in units of 10^{10} cm, and $q = M_2/M_1$. In order to proceed further, we must make an assumption about the relationship between the outer radius of the disk and the orbital separation, a. We will begin by assuming that the transferred material is inviscid and that it orbits the white dwarf in a thin ring (we will modify this assumption shortly). If angular momentum is conserved, then we require that the material orbiting in the ring have the same specific angular momentum as the material spilling over at the inner Lagrangian point. In this case we may write

$$v_d r_d \approx [2\pi f(q)^2 a^2]/P , \quad (3)$$

where v_d and r_d are the velocity and radius of material in the ring and $f(q)$ is the distance from the center of the white dwarf to the inner Lagrangian point in units of the stellar separation, a, and is only a function of the mass ratio. A convenient formula for f, accurate to $\sim 1\%$, as deduced from the tables of Plavec and Kratochvil (1964), is

$$f(q) = 0.5 - 0.227 \log(q) , \qquad 0.1 < q < 10 . \quad (4)$$

with the aid of Kepler's third law, equation (3) can be rewritten as

$$r_d/a = f(q)^4(1+q) . \quad (5)$$

In this simple picture we find that the radus of the ring is a function only of the mass ratio. Of course, real disks are not inviscid. In a viscous disk the angular momentum lost by material spiraling in toward the white dwarf is transferred to other disk material, forcing it to move out to larger radii. Consequently, we expect that a viscous disk will be somewhat larger than r_d. This has been confirmed observationally by a number of eclipse observations which indicate that the disks extend out to ~ 2–3 times the zero viscosity radius (Sulkanen, Brasure, and Patterson 1981).

For illustrative purposes only we will adopt $r_{\rm out} = 2.5 r_d$. Thus, we have

$$r_{\rm out,\,10} \approx 2.5 a_{10} f(q)^4(1+q) . \quad (6)$$

Substituting this expression into equation (2) we find that

$$r_{\rm out,\,10} \approx 8.8(1+q)^{4/3} f(q)^4 P({\rm hr})^{2/3} M_1^{1/3} . \quad (7)$$

For periods less than ~ 10 hr, the mass of the secondary star in

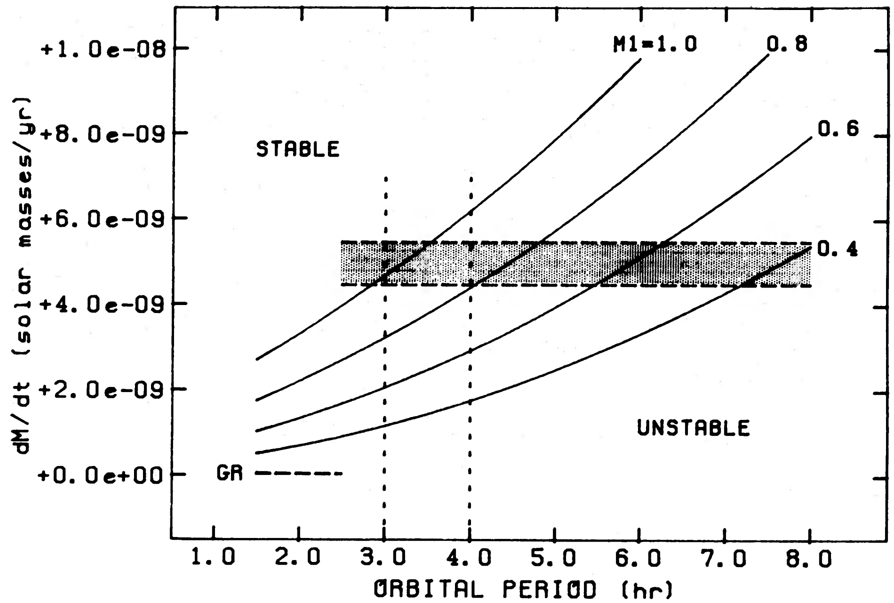

FIG. 2.—Critical mass-transfer rate dividing stable from unstable accretion is plotted as a function of orbital period for several representative values of the white dwarf mass. Stable accretion occurs for values of $\dot{M}$ and P which specify a point lying above the curve for a particular white dwarf mass. For example, we would predict that a system with $P = 5$ hr and $\dot{M} = 5 \times 10^{-9}\ M_\odot$ yr would have stable accretion if $M_1 \approx 0.4\ M_\odot$ and unstable accretion if $M_1 \approx 1\ M_\odot$. Dashed lines show an idealized case where the mass-transfer rate is represented by a simple step function. If $\langle \dot{M}(P) \rangle$ above the gap increases more slowly than the stability ($\dot{M}_{\rm crit}$) curves, and if $\langle \dot{M}(3\ {\rm hr}) \rangle$ is greater than $\dot{M}_{\rm crit}(3\ {\rm hr})$, then systems with periods near the upper boundary of the period gap will generally have stable accretion and dwarf novae will be rare. This region is indicated by the vertical dotted lines.

a cataclysmic variable is, to first order, a function only of the orbital period of the system. In particular, the mass of the secondary can be approximated by $M_2/M_\odot \approx 0.11P({\rm hr})$ (Whyte and Eggleton 1980). Consequently, by noting that $q = 0.11P/M_1$, the critical mass-transfer rate as given by equation (1) can be written in terms of P and M_1 only. Specifically,

$$\dot{M}_{\rm crit}(M_1, P) \approx 2.8 \times 10^{18}(1 + 0.11P/M_1)^{3.47} \times [0.5 - 0.227 \log (0.11P/M_1)]^{10.4} P^{1.73}\ {\rm g\ s^{-1}}\ . \quad (8)$$

Figure 2 shows $\dot{M}_{\rm crit}$ plotted as a function of P for several values of M_1. As expected, for a given value of the white dwarf mass, $\dot{M}_{\rm crit}$ increases with P. This allows dwarf novae to exist with relatively high mass-transfer rates if the period is sufficently long.

If the mean mass-transfer rate as a function of orbital period, $\langle \dot{M}(P) \rangle$, were known, we could compare the relationship directly with our solutions for $\dot{M}_{\rm crit}(M_1, P)$ and predict the period distribution for dwarf novae. Estimates of $\dot{M}$ for individual systems have been made (e.g., Patterson 1984) and can be used to estimate $\langle \dot{M}(P) \rangle$; however, for reasons outlined earlier, these estimates are uncertain and controversial. Nevertheless, we will discusss the impoications of an $\langle \dot{M}(P) \rangle$ relation derived by Patterson at the end of the next section. To begin with, however, we will turn the analysis around and use the observed period description of dwarf novae (which is well known) in order to provide general constraints on $\langle \dot{M}(P) \rangle$.

c) Constraints on $\langle \dot{M}(P) \rangle$

The $\dot{M}_{\rm crit}$ (M_1, P) curves derived in the previous section and plotted in Figure 2 indicate that the observed dwarf nova period distribution, in particular, the scarcity of dwarf novae with periods between 3 and 4 hr, can be qualitatively explained if the following constraints are placed on the $\langle \dot{M}(P) \rangle$ relation. (1) The mean mass-transfer rate must be higher above the period gap than it is below the gap. (2) The mean mass-transfer rate must, in general, increase more slowly than $P^{1.7}$ for periods above the gap (this constraint will be qualified below). (3) The mean mass-transfer rate just above the period gap ($P \approx 3$ hr) must be greater than $\dot{M}_{\rm crit}(3\ {\rm hr})$, for a given white dwarf mass.

The simplest functional form for $\langle \dot{M}(P) \rangle$ which fulfills these conditions is a step function across the 2–3 hr period gap. This form for $\langle \dot{M}(P) \rangle$ is not unexpected. A discontinuous change in the mean mass-transfer rate across the 2–3 hr period gap has been suggested on theoretical grounds by Spruit and Ritter (1983) and by Rappaport, Verbunt, and Joss (1983). These authors have argued that a sharp change in the mass-transfer rate of cataclysmic variables may be the result of a change in the structure of the core of the secondary star. A radiative core is necessary to anchor the secondary's magnetic field and prevent magnetic buoyancy in the convective envelope from expelling the magnetic field from the star. Consequently, a change from a radiative to a convective core will curtail angular momentum loss via magnetic braking. If the secondary is severely out of thermal equilibrium when this change occurs, then the mass transfer may stop completely until gravitational radiation reinitiates it at a later time. The transformation of the secondary to a fully convective state is expected to occur at a mass of ~ 0.2–$0.3\ M_\odot$. For a lobe-filling secondary this corresponds to an orbital period of ~ 3 hr.

For orbital periods less than 2.5 hr we assume that gravitational radiation is the predominant angular momentum loss mechanism which drives mass transfer. The mass-loss rate from the secondary star has been calculated by Patterson (1984). His equation (40) can be written as

$$-\dot{M}_2 = 5.11 \times 10^{-11}(\beta/\alpha)^{3.67} M_1^2 P^{-0.26} \times [(M_1 + 0.07P^{1.22})^{1/3}(M_1 - 0.055P^{1.22})]^{-1}\ M_\odot\ {\rm yr}^{-1}\ , \quad (9)$$

where α and β are parameters of order unity, P is the orbital period in hours, and for the ultrashort period systems we have followed Patterson (1984) and assumed that $M_2/M_\odot \approx 0.07\ P(\mathrm{hr})^{1.22}$. For the masses and periods considered here, the mass transfer driven by gravitational radiation never exceeds $10^{-10}\ M_\odot\ \mathrm{yr}^{-1}$.

Our assumed form of $\langle \dot{M}(P) \rangle$ for periods greater than 2.5 hr is indicated by the shaded region in Figure 2. The value of $\langle \dot{M} \rangle$ above the gap must be set arbitrarily because the $\dot{M}_{\mathrm{crit}}$ curves are uncalibrated and depend on uncertainties in the model—such as the ratio of the true outer radius of the disk to the zero viscosity radius and the effects of external heating. It is unlikely that the mass-transfer rate for a given system is uniquely determined by the orbital period. Certainly the mass ratio of the system (i.e., the white dwarf mass at a given period) will effect $\dot{M}$, as may other factors yet to be identified. Consequently, we have assumed an intrinsic dispersion in the $\langle \dot{M}(P) \rangle$ relation above the period gap. For a given white dwarf mass, the magnitude of the dispersion effectively determines the extent of the period range where both stable and unstable accretion may occur. It is primarily a combination of this effect in conjunction with variations in M_1 which can result in the presence of both dwarf novae and novalike variables in a given period range. For illustrative purposes, we have chosen a mean mass-transfer rate of $5 \times 10^{-9}\ M_\odot$ yr with a dispersion of 10% about this value.

From an inspection of Figure 2, it is clear that systems with the shortest orbital periods but which are still above the period gap [i.e., systems with $3 \lesssim P(\mathrm{hr}) \lesssim 4$] will be most prone to stable accretion, regardless of the magnitude of the intrinsic dispersion in the $\langle \dot{M}(P) \rangle$ relation. On the other hand, the ultrashort period systems should, for the most part, be unstable if gravitational radiation is the predominant angular momentum loss mechanism in that regime. Because we expect there to be a fair dispersion in $\dot{M}$ and M_1 at a given period, it is not terribly surprising that we find a few dwarf novae in the 3–4 hr regime, or that novalike variables exist with periods in excess of 4 hr.

The relatively steep dependence of $\langle \dot{M} \rangle$ on P described by Patterson (1984) is, however, more difficult to understand within the framework of our model. Patterson argued that $\langle \dot{M}(P) \rangle \propto P^{3.2}$ based on mass-transfer rates he estimated for a large number of cataclysmic variables, including the ultrashort period systems. Unless the white dwarf mass is correlated with orbital period, such a steep dependence of $\langle \dot{M} \rangle$ on P predicts that there should be no dwarf novae above the gap or that dwarf novae should be more prevalent between 3 and 4 hr than they are at longer periods—the opposite being true for the novalike variables. These predictions are inconsistent with the observed eruptive characteristics of cataclysmic variables.

We consider it quite likely that the mean mass-transfer rates do not increase as steeply as $P^{3.2}$ for $P \gtrsim 3$ hr. An inspection of Figure 7 from Patterson (1984) indicates that the data are at least consistent with the hypothesis that the mass-transfer rates are simply higher above the 2–3 hr gap than below it. There is enough scatter in the data that the distribution appears to be equally consistent with a step function as with the power law of index 3.2. If, however, we assume that the steep $\langle \dot{M}(P) \rangle$ relation estimated by Patterson is correct, then our model forces us to conclude that there must also be a positive correlation between the white dwarf mass and the orbital period of the system. In particular, any dependence of the mass-transfer rate on orbital period which increases more steeply than $\sim P^{1.7}$ requires that the novalike variables in the 3–4 hr regime contain lower mass white dwarfs than do the longer period dwarf novae. This behavior is simply a consequence of the fact that, for a given orbital period, the accretion disks are smaller in systems with low-mass white dwarfs. These smaller disks are more stable, for a given mass-transfer rate, than are larger disks. Figure 2 demonstrates this effect.

There exists some evidence in support of the hypothesis that the novalike variables in the 3–4 hr regime generally have lower mass white dwarfs than do the longer period dwarf novae. Although, typically, the masses of the white dwarfs in cataclysmic variables are not known very accurately, two of the more reliable masses have been estimated for relatively long period dwarf novae. Stover (1981) estimates the mass of the white dwarf in RU Peg ($P = 9$ hr) to be near the Chandrasekhar limit, while Hessman *et al.* (1984) conclude that the mass of the white dwarf in SS Cyg ($P = 6$ hr) is in excess of a solar mass. There are a few relatively long period dwarf novae which have less well-determined masses or eruption characteristics which are peculiar, or both. These include Z Cam ($P = 6.9$ hr; $M_1 \approx 1.17\ \dot{M}_\odot$; Robinson 1973), EM Cyg ($P = 7$ hr; $M_1 \approx 0.55\ M_\odot$; Stover, Robinson, and Nather 1981), and BV Cen ($P = 14.6$ hr; $M_1 \approx 0.83\ M_\odot$; Gilliland 1982). The only system which apparently has a low-mass white dwarf is EM Cyg. This is not terribly surprising, considering that EM Cyg has very weak eruptions and often resembles a novalike variable. Among the shorter period novalike systems mass estimates are available for the following eclipsing systems: RW Tri ($P = 5.5$ hr; $M_1 \approx 0.6\ M_\odot$; Kaitchuck, Honeycutt, and Schlegel 1983), UX UMa ($P = 4.7$ hr; $M_1 \approx 0.3\ M_\odot$; Frank *et al.* 1981; Shafter 1985), LX Ser ($P = 3.9$ hr; $M_1 \approx 0.4\ M_\odot$; Young, Schneider, and Shectman 1981), and PG 1012 − 029 ($P = 3.2$ hr; $M_1 \approx 0.58\ M_\odot$; Penning *et al.* 1984). All of these systems appear to have relatively low mass white dwarfs. Thus, it appears that the white dwarf masses may also be a contributing factor in shaping the dwarf nova period distribution.

d) The Role of the Z Cam Systems

As a consequence of the general picture which we have presented, we expect that some fraction of the longer period dwarf novae should have mass-transfer rates near $\dot{M}_{\mathrm{crit}}$. Meyer and Meyer-Hofmeister (1983), Cannizzo, Ghosh, and Wheeler (1982), and FLP have argued that such systems can explain the behavior of the Z Cam stars. The Z Cam systems are dwarf novae which occasionally get stuck in a near outburst state and remain there for an unpredictable period of time. The behavior of the Z Cam systems can be nicely explained within the framework of the dwarf novae disk instability models. According to Meyer and Meyer-Hofmeister (1983), if the mass-transfer rate is near $\dot{M}_{\mathrm{crit}}$, then small fluctuations in $\dot{M}$ can cause the system to alternate between dwarf nova and novalike behavior. Assuming that the mass-transfer rates are higher for the longer period dwarf novae, it should come as no surprise that all known Z Cam systems have orbital periods above the gap. However, it is somewhat surprising that the known Z Cam stars seem to be quite uniformly distributed among the longer periods (see Fig. 1). In particular, for a given white dwarf mass we would predict that the Z Cam stars should be mainly concentrated in a relatively narrow range near the orbital period corresponding to the condition $\dot{M}_{\mathrm{crit}}(P) = \langle \dot{M}(P) \rangle$. A possible explanation for the lack of clumping of Z Cam systems is that the white dwarf masses may vary significantly from system to system. Another possibility is that the statistics are simply too poor to make any meaningful conclusions concerning the period distribution of these stars. The resolution of this problem may await the discovery of several more Z Cam systems. It is comforting to note that the two of the three dwarf novae with periods in the 3–4 hr range (CN Ori and AB Dra) are Z Cam systems.

III. CONCLUSION

The period distribution of dwarf novae is heavily concentrated toward orbital periods on the short side of the 2–3 hr period gap. In particular, more than half of all dwarf novae with periods less than 10 hr are ultrashort period systems. Furthermore, there are only three dwarf novae out of 22 cataclysmics known with orbital periods between 3 and 4 hr and two of the three are Z Cam systems! We have argued that the orbital period distribution for dwarf novae can naturally be explained in terms of present accretion disk theory if the average mass-transfer rates are generally higher for systems on the long side of the period gap in particular, for systems with orbital periods between 3 and 4 hr. Consistent with this hypothesis, all known Z Cam systems, which are believed to have the highest mass-transfer rates among dwarf novae, have orbital periods above the gap. The argument which we have presented does not depend on estimating mass-transfer rates for individual systems by using continuum slopes, emission-line equivalent widths, hot spot luminosities, or any of the traditional methods for inferring $\dot{M}$. Nevertheless, our conclusions are consistent with those presented by Patterson (1984), in the sense that we find that the mass-transfer rates are generally higher for systems above the period gap. For the most part our analysis is insensitive to the precise form of $\langle \dot{M}(P) \rangle$. However, it appears that the steep dependence of $\langle \dot{M} \rangle$ on P proposed by Patterson is inconsistent with our results unless the white dwarf mass is strongly correlated with orbital period.

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