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ALL QUIET IN GLOBULAR CLUSTERS

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ABSTRACT

Cataclysmic variables (CVs) should be present in large numbers in globular clusters (GCs). Numerous low-luminosity X-ray sources identified over the past few years as candidate CVs in GCs support this notion. Yet, very few "cataclysms," the characteristic feature of this class of objects in the field, have been observed in GCs. We address this discrepancy here, within the framework of the standard disk instability model for CV outbursts. We argue that the paucity of outbursts in GCs is probably not a direct consequence of the donors' low metallicities. We present diagnostics based on outburst properties allowing tests of the hypothesis that rare cataclysms are entirely due to lower mass transfer rates in GCs relative to the field, and we argue against this explanation. Instead, we propose that a combination of low mass transfer rates ($\gtrsim 10^{14}$–10^{15} g s^{-1}) and moderately strong white dwarf magnetic moments ($\gtrsim 10^{30}$ G cm^3) stabilize CV disks in GCs and thus prevent most of them from experiencing frequent outbursts. If it is so, rare cataclysms in GCs would signal important evolutionary differences between field and cluster CVs.

Subject headings: accretion, accretion disks — globular clusters: general — novae, cataclysmic variables — X-rays: binaries

1. INTRODUCTION

X-ray observations of globular clusters have uncovered many compact binaries (for a review, see Verbunt & Lewin 2004). Recent years brought considerable progress in our understanding of these sources, thanks to observations with the *Chandra X-Ray Observatory* and further identifications with the *Hubble Space Telescope* (Edmonds et al. 2003a, 2003b; Heinke et al. 2003; Haggard et al. 2004). Among the weak ($L_X \lesssim 10^{34}$ ergs s^{-1}) X-ray sources discovered, one identifies cataclysmic variable stars (CVs), quiescent low-mass X-ray binaries (qLMXBs), and binaries containing stars with active coronae. The presence of a large number of CVs in globular clusters is expected on theoretical grounds (e.g., Clark 1975; Katz 1975; Di Stefano & Rappaport 1994; Ivanova & Rasio 2005; Townsley & Bildsten 2005).

CVs are close binary systems in which a white dwarf accretes matter lost by a Roche lobe–filling low-mass stellar companion (see Warner 1995). In CVs of AM Her type (also called "polars"), the white dwarf's magnetic moment is sufficiently strong to synchronize its spin with the binary's orbital rotation and to preclude the formation of an accretion disk. Polars are soft X-ray emitters with luminosities $L_X \sim 10^{30}-10^{32}$ ergs s^{-1} (e.g., Verbunt et al. 1997). In intermediate polars (IPs),[1] magnetic moments are weaker and the white dwarf's rotation is not synchronous with the orbital motion. These systems may or may not possess an accretion disk depending on their specific parameters (see, e.g., King & Lasota 1991; Hellier 2002). When the disk is present, it is truncated by the white dwarf's magnetic field. IPs are the strongest X-ray emitters among CVs, with luminosities $L_X \sim 10^{31}-10^{33}$ ergs s^{-1} (Verbunt et al. 1997). In high optical luminosity persistent CVs of the nova-like type and in erupting dwarf nova systems, the presence of accretion disks is well established, but constraints on the weaker white dwarf magnetic moments are generally poor (see, e.g., Warner 2004). "Normal outbursts" in dwarf novae have amplitudes of 2–5 mag and last 2–20 days. Their recurrence times are typically from $\sim$10 days to months, and up to years in some cases. Some dwarf novae show "superoutbursts," which have brighter amplitudes by $\sim$0.7 mag, last $\sim$5 times longer and also have recurrence times longer than those of normal outbursts. Nova-like CVs and dwarf novae in outburst are rather weak X-ray emitters, but in their low state, quiescent dwarf novae have typical X-ray luminosities, $L_X \sim 10^{29}-10^{32}$ ergs s^{-1} (Patterson & Raymond 1985; Eracleous et al. 1991; Verbunt et al. 1997).

CVs identified in globular clusters have X-ray luminosities very similar to those of field CVs, even though some differences exist in the luminosity functions and one finds that cluster CVs have on average higher optical to X-ray luminosity ratios (Edmonds et al. 2003b). One is tempted to classify candidate CVs in GCs as quiescent dwarf novae, or perhaps IPs, on the basis of their X-ray luminosities. Since in the solar neighborhood, about half of the observed CVs show large-amplitude, recurrent outbursts, the same should be true of CVs in globular clusters if the two populations have similar characteristics. This expectation is not supported by observations. For instance, among the 22 confirmed CVs in 47 Tuc, only two showed variability that

[1] We shall restrict the use of the term "IP" to (nonsynchronous) systems that have detectable or directly inferable magnetic fields. The lowest detected field in an IP is 7×10^6 G (Wickramasinghe & Ferrario 2000).

could be interpreted as a dwarf nova outburst (Edmonds et al. 2003b). In the dense cluster M15, only one erupting dwarf nova was observed (Shara et al. 2004; Tuairisg et al. 2003). Other observational studies have consistently found that dwarf nova outbursts in GCs are rare (e.g., Bond et al. 2005; Kaluzny et al. 2005; Shara et al. 2005a).

This strange quietness of CVs in globular clusters has been noticed and commented on before (e.g., Shara et al. 1996; Grindlay 1999). One explanation offered is that most globular cluster CVs are strongly magnetic: the magnetic field of the white dwarf could suppress the instability at the origin of the dwarf nova outbursts by truncating otherwise unstable regions of the disk (see, e.g., Edmonds et al. 2003b). According to this proposal, the magnetic fields would be of the IP strength, i.e., $\gtrsim 10^6$ G. As it turns out, however, at least seven field IPs show dwarf nova outbursts (Hellier et al. 1997; Ishioka et al. 2002). Not all of these systems exhibit bona fide dwarf nova outbursts, but several have 3.5 mag outbursts lasting 5 days or longer. In addition, Shara et al. (2005b) observed in NGC 6397 two (unexpected) dwarf novae outbursts from CVs classified as magnetic on the basis of their He II 4686 emission lines. Even though most known IPs (more than 30 have been identified) do not indeed show dwarf nova outburst, it is clear that both in the field and in globular clusters, some magnetic CVs still undergo dwarf nova outbursts. This indicates that strong magnetic fields alone may not be able to explain the paucity of outbursts in GCs.

As an alternative, it has also been proposed that globular cluster CVs accrete at much lower rates than their counterparts in the field (e.g., Edmonds et al. 2003b). This would lead to less frequent outbursts and could in principle explain rare cataclysms in GCs. However, to this day there has been no detailed, quantitative investigation of this proposal. Implicitly, the low mass transfer rate hypothesis invokes the disk model instability (DIM) to describe (the lack of) dwarf nova outbursts (for a recent review of the model see Lasota 2001). Here we use the DIM to determine whether indeed low mass transfer rates alone could explain the very infrequent outbursts of candidate CVs in GCs. We argue that, given the observed X-ray luminosities of these systems, it is not a satisfactory explanation. Instead, we propose a solution to the rare cataclysm problem that invokes a combination of low mass transfer rates and moderately strong white dwarf magnetic moments to stabilize the disks of candidate CVs in GCs against outbursts. We determine quantitatively the conditions that must be satisfied by the mass transfer rates and the magnetic moments in these systems to allow globular clusters to be quiet systems of stars, rather than being the sites of incessant dwarf nova outbursts.

In § 2 we explain why, on the basis of DIM predictions and observed X-ray luminosities in GCs, one would naively expect candidate CVs in GCs to be subject to dwarf nova outbursts. In § 3 we argue that, even though the low metallicity of the gas accreted in GCs affects the ionization level of the disk, it is unlikely to be the explanation behind rare cataclysms in these systems. In § 4 we investigate whether it is possible for these candidate CVs to be subject to much less frequent outbursts than field CVs by having, on average, much lower mass transfer rates than field CVs. We conclude that it is not easily the case and explore in § 5 an alternative possibility involving a stabilization of the disks at low mass transfer rates by truncation due to moderately strong white dwarf magnetic fields. This appears to be the most satisfactory explanation for rare cataclysms in GCs. In § 5 we comment on additional consequences and possible extensions of our work.

2. DISK STABILITY AND X-RAY LUMINOSITIES

In the disk instability model (DIM), outbursts of a steadily fed, thin accretion disk are caused by a thermoviscous instability in regions of partial gas ionization (leading to large opacity variations). There exist a range of accretion rates for which the instability operates, determined by the existence of partial ionization regions. According to the model, there are three possible global regimes of accretion for a disk: a hot and stable regime at high accretion rates, an unstable regime at intermediate accretion rates, and a cold and stable regime at low accretion rates. The critical rates determining locally whether or not the disk is partially ionized and unstable are strong functions of radius:

$$\dot{M}_{\rm A} = 4.0\times10^{15}\,\alpha^{-0.004}\left(\frac{M_1}{M_\odot}\right)^{-0.88}\left(\frac{r}{10^{10}\ \rm cm}\right)^{2.65}\ {\rm g\ s^{-1}} \quad (1)$$

$$\dot{M}_{\rm B} = 9.5\times10^{15}\ \alpha^{0.01}\left(\frac{M_1}{M_\odot}\right)^{-0.89}\left(\frac{r}{10^{10}\ \rm cm}\right)^{2.68}\ {\rm g\ s^{-1}}, \quad (2)$$

where M_1 is the white dwarf's mass, α is the usual viscosity parameter, r is the radial distance from the center of mass, and these specific criteria refer to a disk with solar abundance material. At each radius r, $\dot{M}_{\rm A}$ is the critical accretion rate below which the disk is cold/neutral and stable and $\dot{M}_{\rm B}$ is the critical value above which the disk is hot/ionized and stable. Note that, in the DIM, it is necessary to postulate different values of α for the disk in the hot state and in the cold state ($\alpha_{\rm hot} \sim 0.1$; $\alpha_{\rm cold} \sim 0.01$) to successfully reproduce dwarf nova outbursts.

For a disk to be in a globally hot and stable regime, the accretion rate must be everywhere larger than the value of $\dot{M}_{\rm B}$ at the outer edge. Similarly, to be in a globally cold and stable state, the accretion rate must be everywhere smaller than the value of $\dot{M}_{\rm A}$ at the disk inner radius. If neither of these criteria is satisfied, then parts of the disk are partially ionized and subject to instability, which results in large amplitude outbursts.

The X-ray luminosities of candidate CVs in GCs are useful in that they provide constraints on the rate at which mass is being accreted onto the white dwarf in these systems. Boundary layers in CVs accreting at low rates ($\lesssim 10^{16}$ g s^{-1}) should be hot, optically thin, and emitting X-rays (Tylenda 1981; Narayan & Popham 1993; Medvedev & Menou 2002; Pringle & Savonije 1979). Using the standard virial argument for half of the energy being released in the boundary layer, the X-ray luminosity is roughly expected to be

$$L_{\rm X} = 1.33\times10^{32}\eta_{\rm X}\frac{\dot{M}_{\rm in}}{10^{15}\ {\rm g\ s^{-1}}}\frac{M_1}{M_\odot}\left(\frac{r_{\rm in}}{10^9\ \rm cm}\right)^{-1}\ {\rm ergs\ s^{-1}}, \quad (3)$$

where $\eta_{\rm X} \leq 1$ is the efficiency of conversion of the energy released into X-rays and $\dot{M}_{\rm in}$ is the accretion rate at the disk inner radius, $r_{\rm in}$ (assumed to extend all the way down to the white dwarf, for now). Given the uncertain efficiency η_X, observed X-ray luminosities provide only approximate lower limits on $\dot{M}_{\rm in}$. Still, it follows rather simply from the X-ray–inferred accretion rates and the DIM stability criteria that candidate CVs in GCs should typically be subject to dwarf nova outbursts if they contain extended disks reaching down to the white dwarf's surface (see § 5 for detailed criteria). This would also imply that, at any time, most of these candidate CVs should be in a quiescent phase of accretion, during which mass is being accumulated in the disk, until the next outburst is triggered. By comparison with the outburst properties of CVs in the field, however, one is forced to recognize that candidate CVs in GCs do indeed appear to be erupting very infrequently.

3. A METALLICITY EFFECT?

One of the well-known characteristics of stellar systems in GCs is their lower average metallicity compared to systems in the field: could this be the underlying cause of rare cataclysms in GCs? Following the conclusions of Gammie & Menou (1998; see also Menou 2000), it seems possible that dwarf nova outbursts are effectively triggered when a critical ionization rate is reached that is sufficient for MHD recoupling, turbulence, and transport to develop fully in the disk, in conditions approaching ideal MHD. This is likely to occur at much lower values of the ionization fraction (perhaps $\sim10^{-5}$; Gammie & Menou 1998) than the fraction ~0.5 at which ionization affects opacities: this low critical ionization value for MHD turbulence appears to be the relevant "master" trigger for the outbursts, which would then be followed by disk heating and then opacity changes (as postulated in the DIM) when the ionization fraction approaches ~0.5.

In the bulk of the quiescent disk, thermal first ionization of alkali metal is the dominant mechanism contributing to the low level of ionization required (Gammie & Menou 1998). Given the exponential dependence on temperature of the ionization fraction in the Saha equation, relative to the linear dependence on electron density, it appears very unlikely that a change by even 1 or 2 orders of magnitude in the metallicity of the gas can affect much the condition for outburst triggers, which will be entirely dominated by what sets the temperature conditions in the disk. This indicates that, in the unsteady evolving disk postulated to be present during quiescence in the DIM, metallicity is not expected to have much of an effect on the conditions triggering outbursts.

If the structure of quiescent dwarf nova disks were to be layered in quiescence, however, the situation could be quite different (Gammie 1996; Menou 2002). In the simplest version of the layered accretion scenario, the temperature of the isothermal dead zone is constant and determined by the level of activity of the MHD-turbulent surface layers. The only time-dependent component in the model is the gradual accumulation of mass in the dead zone. At a fixed temperature but increasing density, one can imagine how the metallicity of the gas being accreted in a given system can be important in determining the exact level of ionization present in the disk and thus when the next outburst will be triggered. As it turns out, however, mass accumulation alone cannot trigger an outburst through MHD recoupling. Using for simplicity the Saha equation for a first-ionized, single-species gas (e.g., the most easily ionized alkali metal), and fixing the temperature, we find that in the low ionization limit ($n_e/n_n \ll 1$), the ionization fraction n_e/n_n varies with density as $n_n^{-1/2}$, where n_e and n_n are the electron and neutral densities, respectively. The same scaling obtains for the magnetic Reynolds number, which goes down as a result of mass accumulation in the dead zone. The importance of Hall terms also goes down relative to the Ohmic terms at larger densities (e.g., Balbus & Terquem 2001). Therefore, even though the absolute value of the ionization fraction would depend linearly on metallicity in this simple fixed-temperature model for layered accretion, the ionization fraction would go down with time as mass accumulates in the dead zone and there would be no way of triggering an outburst on the basis of MHD recoupling at later times.

We also note that if one were to invoke the possibility of finite stresses and dissipation in the dead zone (Fleming & Stone 2003), this layer would then no longer be isothermal and at a fixed temperature as gas accumulates. The exponential dependence on temperature of the ionization fraction is then again very likely to overcome any linear metallicity dependence. We conclude from these various considerations that, according to existing models for quiescent dwarf nova disks, it does not appear that the low metallicity of donors in GCs is the underlying cause of their rare cataclysms.

One remaining possibility related to low metallicities is that the quality of magnetic coupling in the donor's atmosphere and thus the amount of magnetic flux being transferred to the disk are actually able to influence the disk evolution by modifying its MHD conditions, as proposed by Meyer & Meyer-Hofmeister (1999). If it were the case that, on average, the material being transferred in GCs carries less magnetic flux than in field CVs, it could in principle explain the reduced activity of candidate CVs in GCs. However, since the influence of metallicity on the magnetic properties of a stellar atmosphere or the resulting effect that this would have on the disk MHD behavior are not understood at a quantitative level, it is currently difficult to rule in favor or against this scenario.

4. LOW MASS TRANSFER RATES?

In this section, we want to determine whether it is possible for candidate CVs in GCs to be quiescent dwarf novae in which the donor star transfers mass at such a low rate that outbursts are much rarer than in field CVs. Although the direction of this effect is obvious, its magnitude is not. We have therefore decided to quantify how the outburst properties of a representative system depend on the mass transfer rate with a series of detailed time-dependent disk instability models. We have not explored scenarios in which differences between field and GC CVs are attributed to different values of the viscosity parameter α. If there is a "universal" saturation value for the turbulent transport driving accretion in these disks, it would presumably not differ between field and GC CVs.

It should be noted that, to the best of our knowledge, there has not been any systematic study of the observational statistics of dwarf nova outbursts in GCs. The quantity of most interest probably is the duty cycle of the outbursts. In principle, given a number of candidate CVs, a typical duty cycle, and the statistics of observations for a given cluster, one can predict the number of dwarf nova outbursts one ought to be observing at any time or through repeated observations (modulo the small number statistics). Additional outburst diagnostics may also be useful in determining the regime of accretion present in candidate CVs in GCs. We hope that the detailed study of outburst properties presented here will motivate a statistical study of observed duty cycles and perhaps new observational programs to obtain additional constraints.

4.1. *The Numerical Model*

In this section we use a standard version of the DIM, in which the disk extends all the way down to the white dwarf's surface, the mass transfer rate from the secondary star is constant and effects of disk irradiation are neglected. The numerical model, described in detail in Hameury et al. (1998), follows the thermoviscous evolution of a geometrically thin disk around the white dwarf. The equations of conservation of mass, angular momentum and energy for a Keplerian disk are solved on an adaptive grid that resolves narrow structures in the disk. A grid of disk vertical structures, which determine the local cooling rate of the disk as a function of its surface density, central temperature, and vertical gravity, is precalculated before running

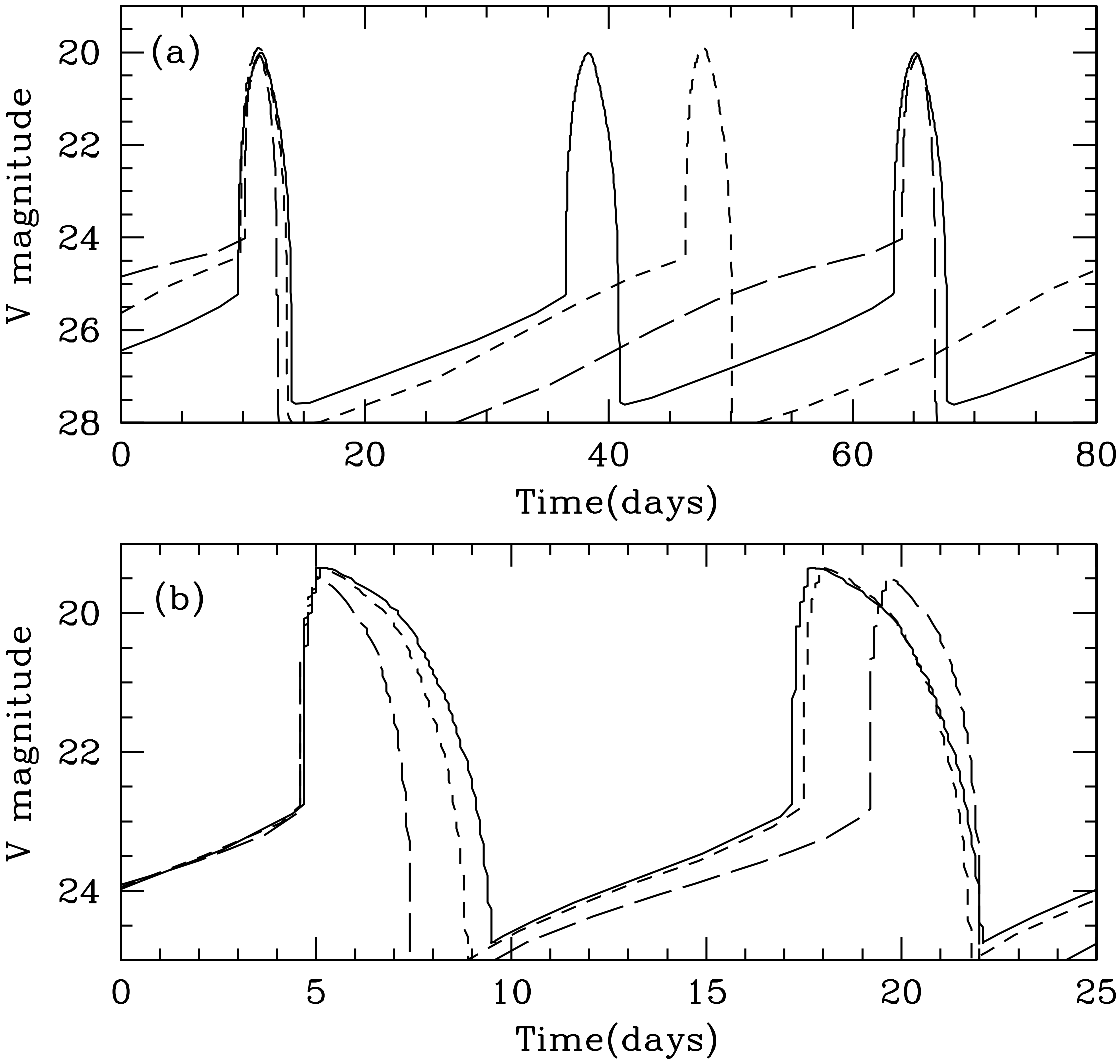

FIG. 1.—Outburst cycles predicted in a model with (*a*) $\dot{M}_T = 1\times10^{16}$ g s^{-1} and (*b*) 7.5×10^{16} g s^{-1}. In each panel, light curves for the following values of the disk inner radius are shown: $R_{\rm in} = 8.5\times10^8$ cm (*solid line*), $R_{\rm in} = 11.5\times10^8$ cm (*short-dashed line*), and $R_{\rm in} = 28\times10^8$ cm (*long-dashed line*). For clarity, light curves have been aligned on the first outburst peak.

the disk evolution. We only use models after they have converged to a periodic outburst pattern: the results shown are robust in the sense that memory of the initial conditions has been lost.

We show results for a specific model with parameters close to appropriate for the field dwarf nova VW Hyi ($P_{\rm orb} \simeq 1.8$ hr). The model has the following parameters: primary mass $M_1 = 0.6\ M_\odot$, time-averaged value of the disk outer radius $\langle R_{\rm out}\rangle = 2\times10^{10}$ cm, value of the disk inner radius $R_{\rm in} = 8.5\times10^8$ cm, and values of the viscosity parameters (unless otherwise specified) $\alpha_{\rm hot} = 0.2$ and $\alpha_{\rm cold} = 0.04$. The numerical resolution adopted is $N = 800$ radial grid points.

4.2. *Varying the Disk Inner Radius* $R_{\rm in}$

In the DIM, the value of the disk inner radius ($R_{\rm in}$, which is also the white dwarf stellar radius) does have some influence on the outburst properties of an unstable disk. Therefore, before launching into an extensive study of the dependence on the mass transfer rate, we have conducted a series of tests to determine the magnitude of the $R_{\rm in}$ dependence.

Figure 1 shows *V*-band light-curve predictions from models with different $R_{\rm in}$ values, at a given mass transfer rate, $\dot{M}_T$. Figure 1*a* shows models with $\dot{M}_T = 1\times10^{16}$ g s^{-1}, for which outbursts are triggered in the innermost regions of the disk ("inside-out outbursts"). Figure 1*b* shows models with $\dot{M}_T = 7.5\times10^{16}$ g s^{-1}, for which outbursts are triggered in the outermost regions of the disk ("outside-in outbursts"). In each panel, the solid line corresponds to a model with $R_{\rm in} = 8.5\times10^8$ cm, the short-dashed line to $R_{\rm in} = 11.5\times10^8$ cm, and the long-dashed line to $R_{\rm in} = 28\times10^8$ cm.

The recurrence times predicted in the model shown in Figure 1*a* depend on the value of $R_{\rm in}$ because inside-out outbursts are triggered close to the disk inner edge, and the value of the critical surface density, $\Sigma_{\rm max}$ ($\propto R^{1.1}$; see, e.g., Hameury et al. 1998), at which mass accumulation triggers the thermoviscous instability, increases with increasing $R_{\rm in}$ (the ignition radius $R_{\rm ignit}$ is $\simeq 1.5\times R_{\rm in}$ in each one of these models). On the contrary, the recurrence time is basically independent of $R_{\rm in}$ in the model with outbursts triggered in the outer regions of the disk (Fig. 1*a*; $R_{\rm ignit} \simeq 9\times10^9$ cm in all three cases).

Models in Figure 1*a*, with a mass transfer rate on the low side and inside-out outbursts, are probably the most relevant ones for candidate CVs in GCs. Even when multiplying the disk inner radius by a factor of 3, however, the effect is only a doubling of the outburst periodicity. Despite uncertainties associated with unknown white dwarf masses in GCs (which may be systematically larger than in the field because of mass segregation), the corresponding uncertainties for disk inner radii will remain small compared to the large factor of 3 variation shown in Figure 1*a*. Therefore, we conclude from these tests that fixing the disk inner radius to a reasonable value, $R_{\rm in} = 8.5\times10^8$ cm, is unlikely to affect much our conclusions on the effects of variations in the mass transfer rate.

4.3. *Varying the Mass Transfer Rate* $\dot{M}_T$

We have sampled a range of mass transfer rates from $\dot{M}_T = 10^{15}$ g s^{-1} to $\dot{M}_T \simeq 2\times10^{17}$ g s^{-1} with about 10 models. Above a few 10^{17} g s^{-1}, the disk becomes globally stable. For each model, three different $\alpha_{\rm hot}/\alpha_{\rm cold}$ viscosity prescriptions were investigated. Each model produces a light curve of the type shown in Figure 1. The morphology of these light curves changes with $\dot{M}_T$ and the α-values adopted. In order to quantify and better characterize the light-curve properties, we have defined nine useful attributes that we have systematically measured for all the calculated model light curves. As we elaborate further below, some of these attributes are direct observables, and as such, they could allow further observational tests of a given regime of accretion in CVs.

4.3.1. *Characterizing Outburst Cycles*

Peak V magnitude.—This is the *V*-band magnitude of the disk when it is most luminous (at the peak of an outburst). The *V*-band magnitude has been calculated by integrating the multitemperature blackbody emission from the disk (magnitude scale arbitrary).

$R_{\rm ignit}$.—This is the ignition radius, i.e., the radius of the disk annulus, which first becomes ionized and unstable and subsequently triggers a global outburst in the disk.

$T_{\rm cycle}$.—The recurrence (or cycle) time is computed as the time between two successive light-curve peaks.

$T_{\rm duration}$.—The outburst duration time is computed as the time during which the disk *V*-band magnitude is within 3 mag of its peak value. We have checked that this definition ensures that $T_{\rm duration}$ is estimated at a value very similar to what an eyeball estimate would give. Also, with this definition, we do not have to worry about defining properly a quiescence level, which would likely depend on contributions from a hot spot and the secondary star. $T_{\rm duration}$ is the sum of $T_{\rm rise} + T_{\rm decay}$ (defined below).

Duty cycle.—It is simply calculated here as the ratio $T_{\rm duration}/T_{\rm cycle}$. It basically captures the fraction of the time the dwarf nova is "on" (given our specific definition of $T_{\rm duration}$).

$T_{\rm quiescence}$.—It is calculated as the difference $T_{\rm cycle} - T_{\rm duration}$, where $T_{\rm duration}$ is taken for the outburst following the corresponding quiescence phase.

$T_{\rm rise}$.—The rise time is calculated as the time taken by the disk *V*-band magnitude to rise from its peak magnitude plus 3 to that peak magnitude.

$T_{\rm decay}$.—The decay time is calculated as the time taken by the disk *V*-band magnitude to decrease from its peak magnitude to that value plus 3. Note that this definition includes any "plateau" phases in the decay, which are found to exist at large values of the mass transfer rate, $\dot{M}_T$.

V fluence.—This is the fluence (time-integrated luminosity) of an outburst in the *V* band, calculated over the estimated outburst duration time $T_{\rm duration}$ (i.e., covering a range of 3 mag around the peak *V*-value). Here again, the absolute energy scale is arbitrary.

Note that, as is evident from their definitions, all these quantities are not independent from each other.

4.3.2. *Results*

Figure 2 shows how these nine outburst cycle attributes vary as a function of the mass transfer rate, $\dot{M}_T$. Solid, dashed, and dotted lines in each panel show results for three different viscosity prescriptions: $(\alpha_{\rm hot},\ \alpha_{\rm cold}) = (0.2, 0.04)$, $(0.2,\ 0.05)$, and $(0.3, 0.04)$, respectively. Changes in outburst attributes from one to the other of these prescriptions is only quantitative in nature. The qualitative trends with $\dot{M}_T$ shown in Figure 2 are therefore robust with respect to uncertain α prescriptions.

Note that we have not explored dependencies in our models related to the value of the disk outer radius, $R_{\rm out}$, which is itself determined by the binary's orbital period, $P_{\rm orb}$. Smak (1999) has argued in a related analysis that the dependence of the duration time, $T_{\rm duration}$, on the orbital period should scale as $P_{\rm orb}^{0.74}$. According to this scaling, even for a change by a factor 3 in orbital period, the corresponding change in $T_{\rm duration}$ (and possibly other outburst time attributes, such as the duty cycle) would only be about a factor of 2. This is comparable to uncertainties related to our poor knowledge of α, according to the results shown in Figure 2. For this reason, we have chosen to focus our numerical exploration on variations of $\dot{M}_T$ at a fixed disk size (i.e., same time-averaged value of $R_{\rm out}$). In the future, it may be interesting to explore further this dependence of model predictions on the binary's orbital period, especially if there were reasons to believe that candidate CVs in GCs have a different period distribution than CVs in the field.

As $\dot{M}_T$ is decreased, we find that the outburst fluence, its duration time $T_{\rm duration}$, its decay time $T_{\rm decay}$ and the duty cycle all decrease, while the quiescence time $T_{\rm quiescence}$, the recurrence time $T_{\rm cycle}$ and the outburst peak magnitude increase. The variations in the ignition radius, $R_{\rm ignit}$, and the rise time, $T_{\rm rise}$, both reflect the transition from outside-in to inside-out outbursts occurring at a mass transfer rate of a few 10^{16} g s^{-1} (see also Fig. 1). This transition is characterized by a significant increase in the rise time of the outburst (in the *V* band). At the highest accretion rates, the existence of extended plateau phases during outburst becomes obvious as the values of, e.g., $T_{\rm decay}$ and the *V*-band fluence, become large.

The trends with $\dot{M}_T$ shown in Figure 2 are strongly correlated with each other, and as such, they could be used to statistically test the notion that mass transfer rates are, on average, smaller in the population of CVs found in GCs, than in the field. As shown by Figure 2, this would require shorter duration and decay timescales for the outbursts, less luminous outbursts and reduced fluences (in the *V* band). Although it would be dangerous (and probably misleading) to do a comparison between individual systems, we believe that the trends shown in Figure 2 are rather robust and therefore meaningful in a global statistical sense. One would expect them to be followed by the few CVs showing dwarf nova outbursts in GCs, if it is true that their disks are fed, on average, at much lower rates than CVs in the field.

Perhaps the most easily used attribute that is shown in Figure 2 is the duty cycle of the outbursts. At mass transfer rates $\dot{M}_T \lesssim 3\times10^{15}$ g s^{-1}, a duty cycle $\sim$0.1–0.025 obtains, depending on the α-values adopted. It is already interesting to ask whether these values are consistent with the paucity of dwarf nova outbursts in a GC such as 47 Tuc. With 22 confirmed CVs and this type of values for the duty cycle, one would expect about 2–0.5 dwarf novae to be active (i.e., in outburst) at any time when 47 Tuc is observed! To do this comparison properly requires taking into account effects such as source crowding, the weaker

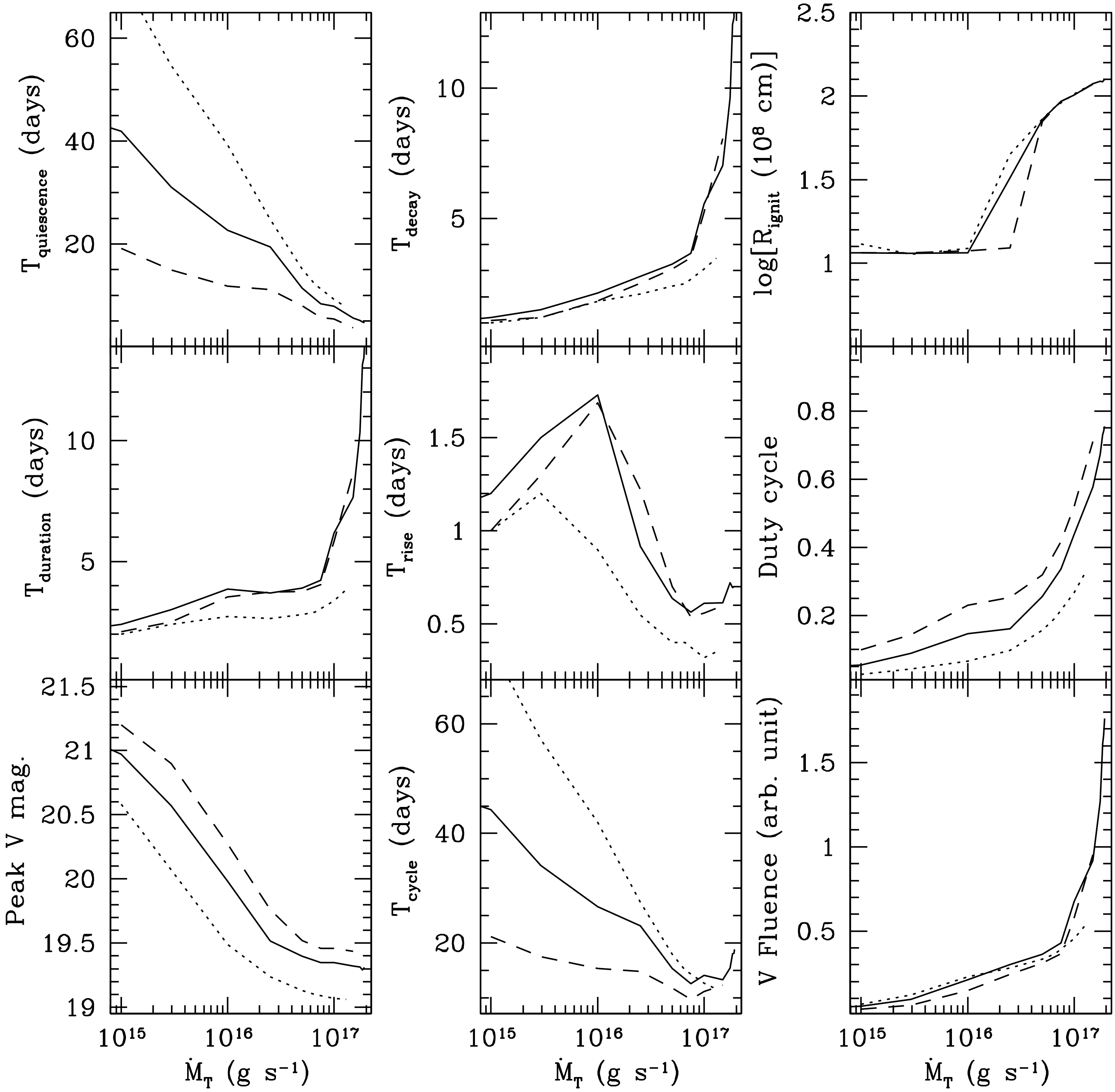

Fig. 2.—Predicted variations in outburst cycle properties as a function of the mass transfer rate, $\dot{M}_T$, from 10^{15} to 2×10^{17} g s^{-1}. In each panel, the solid line corresponds to the viscosity prescription $(\alpha_{\rm hot},\ \alpha_{\rm cold}) = (0.2,\ 0.04)$, the dotted line to $(\alpha_{\rm hot},\ \alpha_{\rm cold}) = (0.3,\ 0.04)$, and the dashed line to $(\alpha_{\rm hot},\ \alpha_{\rm cold}) = (0.2,\ 0.05)$. See text for details.

nature of the outburst expected (see values of peak V magnitudes in Fig. 2), etc., but this simple scaling already suggests that mass transfer rates $\dot{M}_T \lesssim 3\times10^{15}$ g s^{-1} may not necessarily easily explain the paucity of outbursts in at least one well-studied GC. The possibility that several tens of additional X-ray sources in 47 Tuc are in fact unconfirmed CVs (Townsley & Bildsten 2005; Heinke et al. 2005) would make this comparison even more meaningful.

In addition, it is important to note that one is not free to pick low values of $\dot{M}_T$ to justify a low frequency of outbursts in GCs and posit at the same time that the observed low-luminosity X-ray sources are the same systems, seen as dwarf novae in a quiescent phase. Indeed, the DIM requires the accretion rate in a quiescent disk not to be constant but rather fall with decreasing radius at least as steeply as the critical scalings given in equations (1) and (2). For the specific model we are considering here, if the disk is fed at a rate $\dot{M}_T = 10^{15}$ g s^{-1}, the implied accretion rate onto the white dwarf is $\dot{M}_{\rm in} \lesssim 10^{12}$ g s^{-1}, i.e., so low that it becomes essentially impossible to power the observed X-ray luminosities even with a 100% efficient X-ray conversion (see eq. [3]). This limitation is the main reason why we did not extend our detailed models below values of $\dot{M}_T = 10^{15}$ g s^{-1} in Figure 2.

By extension, given a distribution of X-ray luminosities for a population of candidate CVs in a GC such as 47 Tuc, one would have to pick a distribution of mass transfer rates that is compatible with these X-ray luminosities. Combining this constraint with the allowed values of the duty cycle shown in Figure 2 suggests that it would be rather difficult to explain the paucity of dwarf nova outbursts in GCs by invoking only very low mass transfer rates and stay consistent with the observed X-ray luminosities. Clearly, it would be interesting to derive in the future an improved, more quantitative version of this argument by using a better sampled statistics on the frequency (and perhaps additional attributes) of dwarf nova outbursts in a given GC.

4.4. *Very Long Recurrence Times?*

We have thus argued that it would be difficult for the population of candidate CVs in GCs, if they possess fully extended disks, to experience outbursts with recurrence times that would be much longer than those in the population of CVs in the field. We reached this conclusion using the DIM with standard parameters, in particular viscosity parameters $\alpha_{\rm hot} \gtrsim 0.2$ and $\alpha_{\rm cold} \gtrsim 0.04$. Although the value of $\alpha_{\rm hot}$ appears to be universal (Smak 1999), it may not be the case for $\alpha_{\rm cold}$. Indeed, there exist dwarf novae in the field with very long recurrence times, the best known example of which is WZ Sge (with a recurrence time $\sim$30 yr). This class of systems has been mentioned as a possible explanation for rare outbursts in GCs (Grindlay 1999). For these exceptionally long recurrence times (and the long outburst durations), the DIM requires a very low value of $\alpha_{\rm cold} \sim 3\times10^{-5}$ (Smak 1993; Osaki 1995). Such very low values of the efficiency of angular momentum transport in quiescent disks would require a physical explanation. Meyer & Meyer-Hofmeister (1999) have suggested that the viscosity in quiescent accretion disks is determined by the amount of magnetic flux transferred from the companion star together with the matter being accreted. According to this suggestion, when the companion leaves the main sequence to become degenerate, near the CV period minimum, its atmospheric temperature becomes so low that the amount of magnetic flux transferred is much reduced, resulting in much lower $\alpha_{\rm cold}$ values in quiescent disks. Since WZ Sge is very close to the CV minimum period, this could explain its extremely low viscosity in quiescence. To extend this interpretation to candidate CVs in GCs, however, would require most of them to have "brown dwarf" companions. At this point, observed CV periods in GCs do not support this expectation (see, e.g., Edmonds et al. 2003b).

An alternative solution to the WZ Sge long recurrence time puzzle, which does not involve any unusually low $\alpha_{\rm cold}$ value, has been proposed by Lasota et al. (1995; see also Hameury et al. 1997; Lasota et al. 1999). Noting that inner truncation can stabilize an otherwise unstable disk, these authors suggested that the quiescent disk in WZ Sge may be truncated by the magnetic field from the white dwarf or by "evaporation" of the innermost disk regions (see, e.g., Meyer & Meyer-Hofmeister 1994), sufficiently so that the disk becomes only marginally unstable. As a result of the truncation, one also expects an accretion rate at the inner edge of the (truncated) disk that is consistent with the observed X-ray luminosity. This model requires a rather strong enhancement of the mass transfer rate during outburst to reproduce observed outburst properties, however. This point is subject to theoretical controversy (Smak 2004 and references therein), but it seems to be supported by observations (Steeghs 2004). Whether this explanation for the very long recurrence times of WZ Sge is correct or not, the idea of disk stabilization by truncation is worth exploring for candidate CVs in GCs, as it seems to be a reasonable explanation for their resounding silence.

5. STABILIZED DISKS IN GLOBULAR CLUSTERS?

Most CVs in GCs could contain stable disks, which are not subject to the thermoviscous instability responsible for outbursts in field CVs, if regions of their disks that would normally be subject to the instability are systematically truncated. In this section, we first show that it is not possible to have such stable disks in candidate CVs in GCs unless truncation of the disk inner regions indeed happens. Then, we quantify the conditions under which the magnetic field from the accreting white dwarf is sufficiently strong to achieve stabilization of the disk by magnetospheric truncation. Given the unknown orbital period, nature of the donor star and composition of the material being transferred and accreted in these systems, we consider a number of possibilities successively below. In each case, we directly compare the values of the mass transfer rate, $\dot{M}_{\rm tr}$, required to satisfy the DIM global stability criteria (eqs. [1] and [2]), to the typical values of $\dot{M}_{\rm tr}$ necessary to power representative X-ray luminosities $L_{\rm X} \sim 10^{31}$ and $10^{32.5}$ ergs s^{-1} according to equation (3), for $\eta_{\rm X} = 0.5$. We adopt the white dwarf mass-radius relation ($M_{\rm WD}$-$R_{\rm WD}$) of Nauenberg (1972) for the accretor whenever it is necessary for our calculations.

5.1. *Full-Disk, Main-Sequence Secondary*

As mentioned in § 2, for the disk to be in a globally hot and stable state, the mass transfer rate must exceed the value of the accretion rate $\dot{M}_{\rm B}$ given by equation (2) at the disk outer radius. We adopt for simplicity a value of the disk outer radius $R_D = 0.9R_{L1}$, where R_{L1} is the primary's mean Roche lobe radius,

$$R_{L1} = 0.462\, a\left(\frac{M_1}{M_1 + M_2}\right)^{1/3}, \qquad (4)$$

where M_2 is the mass of the secondary and a is the binary orbital separation, determined by Kepler's law

$$a = 3.5\times10^{10}\left(\frac{M_1}{M_\odot}\right)^{1/3}(1+q)^{1/3}P_{\rm hr}^{2/3}\ {\rm cm}, \qquad (5)$$

with $q = M_2/M_1$ and $P_{\rm hr}$ is the orbital period in hours. For the main-sequence mass-period relation, we use $m_2 \simeq 0.11P_{\rm hr} \simeq R_2/R_\odot$ (see, e.g., King 1988), where $m_2 = M_2/M_\odot$. The condition $\dot{M}_{\rm tr} = \dot{M}_{\rm B}(R_D)$ for values of the mass ratio $q = 0.2, 0.5$, and 0.8 are shown as a function of the primary's mass, $M_{\rm WD}$, as the three upper solid lines in Figure 3. Above these lines, the disk is hot and stable.

For a disk to be in a globally cold and stable state, the mass transfer rate cannot exceed the value of the accretion rate given by $\dot{M}_{\rm A}$ in equation (1) at the disk inner edge, which is also the white dwarf radius in the case of a fully extended disk. The condition $\dot{M}_{\rm tr} = \dot{M}_{\rm A}(R_{\rm WD})$ is shown as a function of the primary's mass, $M_{\rm WD}$, as the lower solid line in Figure 3. Below this line, the disk is cold and stable. In addition, the two long-dashed lines in Figure 3 show, as a function of the primary's mass, the typical mass transfer rates required to power X-ray luminosities $L_{\rm X} \sim 10^{31}$ and $10^{32.5}$ ergs s^{-1} according to equation (3) for $\eta_{\rm X} = 0.5$.

As already emphasized by Shara et al. (1996) and Edmonds et al. (2003b), globally hot and stable disks would be too bright to explain the faint optical luminosities of candidate CVs in GCs. These candidate CVs also appear much too X-ray-bright to contain globally cold and stable disks extending all the way to the white dwarf's surface. From the comparison shown in

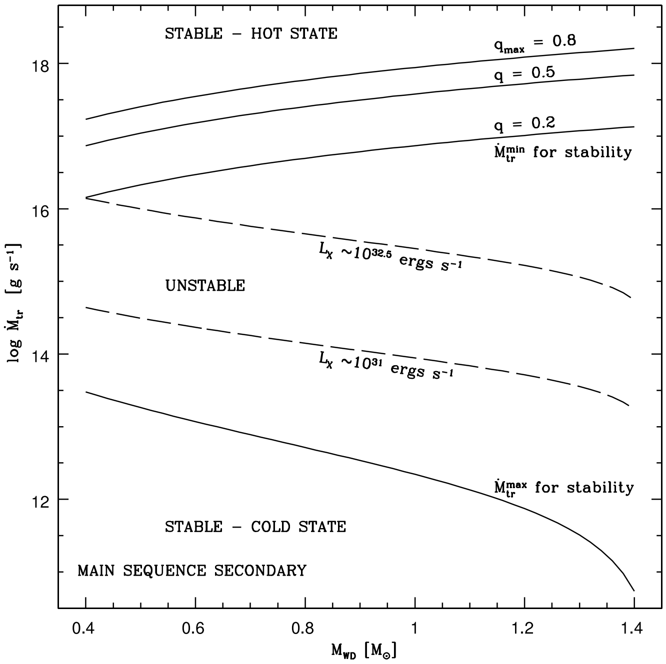

FIG. 3.—Comparison of the values of the mass transfer rate, $\dot{M}_{tr}$, required for a full CV disk to be globally hot and stable (*above the upper solid lines*) or globally cold and stable (*below the lower solid line*), with the values necessary to power X-ray luminosities $L_X \sim 10^{31}$ and $\sim 10^{32.5}$ ergs s^{-1} (*long-dashed lines*) according to eq. (3), for $\eta_X = 0.5$. White dwarf masses in the range $M_{WD} = 0.4$–$1.4\ M_\odot$ are considered. The donor is assumed to be a main-sequence star.

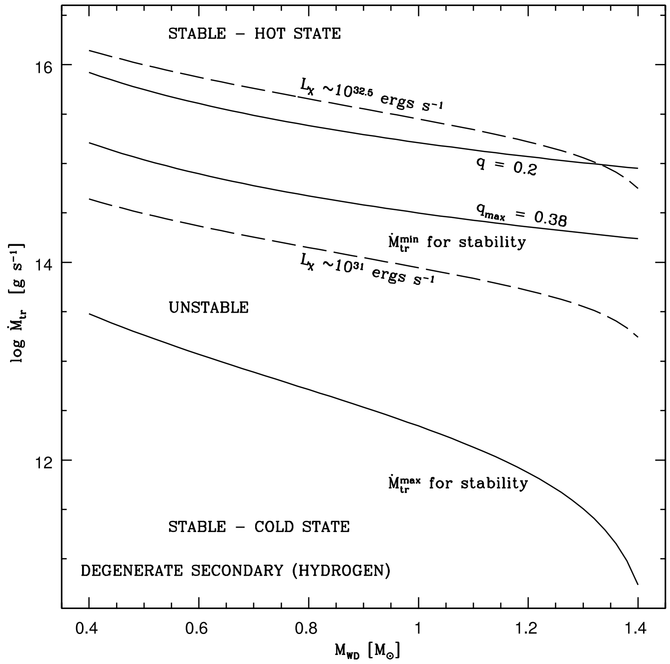

FIG. 4.—Same as Fig. 3, but for when the donor is assumed to be a hydrogen-rich degenerate star.

Figure 3, one would naively expect these candidate CVs in GCs to contain unstable disks and thus show dwarf nova outbursts much like their counterparts in the field.

5.2. *Full-Disk Degenerate Hydrogen-rich Secondaries*

Field CVs are supposed to evolve through a period minimum at $\lesssim 80$ minutes, at which point they become degenerate (see, e.g., King 1988). The mass transfer rates for such postminimum systems are very low, and if such systems were to exist in globular clusters, they would be interesting candidates for CVs containing cold and globally stable accretion disks. To test this hypothesis, we modify our analysis and assume the mass-radius relation for the secondary (King 1988)

$$R_2 = 10^9 (1 + X)^{5/3} m_2^{-1/3}\ \text{cm}, \quad (6)$$

which leads to a mass-period relation,

$$m_2 = 1.5 \times 10^{-2} (1 + X)^{5/2} P_h^{-1}. \quad (7)$$

The results are shown in Figure 4, where $X = 0.7$ was assumed. Although some of the candidate CVs in GCs with X-ray luminosities at the high end of the observed luminosity function could be described as systems containing hydrogen-rich degenerate donors and globally hot and stable disks, this could not be a solution for the entire population unless one is willing to consider extremely low values of the X-ray conversion efficiencies, η_X. In addition, the faint optical luminosities of candidate CVs in GCs appear to be inconsistent with globally hot and stable disks (Shara et al. 1996; Edmonds et al. 2003b).

5.3. *Full-Disk, Degenerate Helium Secondaries*

One should also consider the possibility that the donors in candidate CVs in GCs are helium-rich WDs, i.e., that these systems are members of the AM CVn class of double degenerate binaries (Warner 1995; Nelemans 2005).

For our purpose, we simply assume the mass-radius relation equation (6) with $X = 0$ and rederive the corresponding stability criteria. More realistically, the mass-radius relation for donors in AM CVn binaries would depend on their formation channel (Deloye et al. 2005), which could be rather complex in globular clusters (see, e.g., Ivanova & Rasio 2005).

One also has to modify the global stability criteria for disks that are now composed primarily of helium, with ionization properties that differ substantially from those of hydrogen. The criterion for a disk to be hot and stable becomes (Menou et al. 2002)

$$\dot{M}_B = 5.9 \times 10^{16} \left(\frac{\alpha}{0.1}\right)^{0.41} m_1^{-0.87} \left(\frac{r}{10^{10}\ \text{cm}}\right)^{2.62}\ \text{g s}^{-1}. \quad (8)$$

The value of $\dot{M}_A$ for a disk to be cold and stable was derived following the same algorithm as Smak (1983) or Tsugawa & Osaki (1997). The stability condition in this case is obtained by requiring that the maximal temperature in a cold and stable disk ($R_{max}^T = 49/46 R_{WD}$) be lower than the typical ionization temperature of helium [$\log T(\text{K}) \simeq 3.95$].

Figure 5 shows the results of our stability analysis for AM CVns in the usual format. Although some of the candidate CVs in GCs with X-ray luminosities at the low end of the observed luminosity function could be described as systems containing globally cold and stable disks (depending on M_{WD}), this does not appear to be a solution for the entire population. On the other hand, the faint optical luminosities of candidate CVs in GCs also appear to be inconsistent with globally hot and stable disks in these systems (Shara et al. 1996; Edmonds et al. 2003b).

5.4. *Truncated Disks*

A simple way of reconciling the observed X-ray luminosities of candidate CVs in GCs with the DIM and the rare occurrence of outbursts is to consider the possibility that disks in most of these systems are sufficiently truncated to be stabilized. There

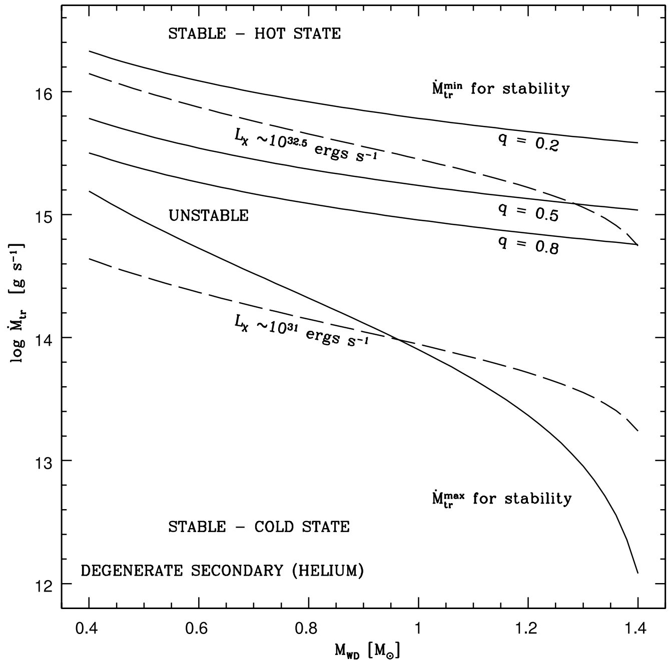

FIG. 5.—Same as Fig. 3, but for when the donor is assumed to be a helium-rich degenerate star.

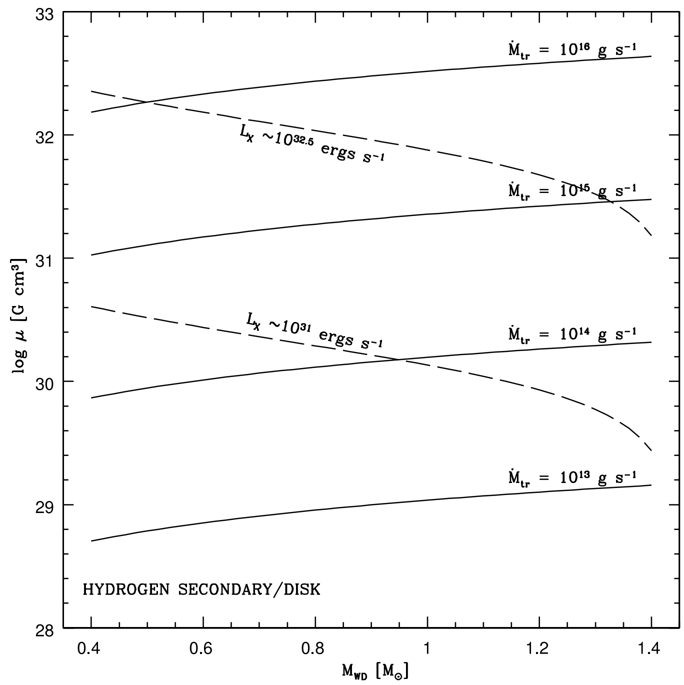

FIG. 6.—Minimum values of the magnetic moment μ of an accreting white dwarf required to truncate the unstable regions of a hydrogen-rich disk and stabilize it in the cold state, for four values of the mass transfer rate, $\dot{M}_{\rm tr}$ (*solid lines*). White dwarf masses in the range $M_{\rm WD} = 0.4-1.4\ M_\odot$ are considered. The mass transfer rate equivalents of $L_{\rm X} \sim 10^{31}$ and $10^{32.5}$ ergs s^{-1}, according to eq. (3) with $\eta_{\rm X} = 0.5$, are shown as long-dashed lines. Results for a helium-rich disk would be similar except for a reduction in all μ-values by a factor ~ 2.

is growing evidence that even the so-called nonmagnetic CVs posses magnetic moments sufficiently large ($\mu \gtrsim 10^{30}$ G cm^3) to partially truncate accretion disks in quiescent dwarf novae (see, e.g., Lasota 2004; Wheatley & West 2003; Warner 2004).

Using the magnetospheric radius,

$$R_{\rm m} = 9.8\times 10^8 \left(\frac{\dot{M}}{10^{15}{\rm g\ s^{-1}}}\right)^{-2/7} m_1^{-1/7} \left(\frac{\mu}{10^{30}\ {\rm G\ cm^3}}\right)^{4/7}\ {\rm cm}, \qquad (9)$$

and the stability criterion for a hydrogen disk in equation (1), one can deduce, for a given mass transfer rate, the minimum value of the magnetic moment required to truncate the unstable regions of the disk and thus effectively stabilize the rest of it in the cold state:

$$\mu \geq 2.3\times 10^{31} \left(\frac{\dot{M}}{10^{15}\ {\rm g\ s^{-1}}}\right)^{1.16} m_1^{0.831}\ {\rm G\ cm^3}. \qquad (10)$$

Figure 6 shows critical values of the magnetic moments, μ, required to stabilize the disks for four different values of the mass-transfer rate, $\dot{M}_{\rm tr}$ (*solid lines*). Representative X-ray luminosities, calculated from equation (3) with $\eta_{\rm X} = 0.5$, are also shown for comparison (*dotted lines*). Magnetic moments in the range 10^{29}–10^{32} G cm^3 are sufficient to stabilize disks and at the same time be consistent with the observed X-ray luminosities of candidate CVs in GCs. Redoing the same analysis for disks composed of helium, we find that the magnetic moments required to stabilize helium disks are only slightly lower, by a factor ~ 2.

The uppermost values of the magnetic moments shown in Figure 6 correspond to magnetic moments of the IP class, but they would be required only for the highest X-ray luminosities observed among candidate CVs in GCs. For the bulk of the population, values of $\mu \gtrsim 10^{30}$ G cm^3 are sufficient to stabilize disks. These values may in fact be relevant to some of the dwarf novae in the field. However, it is the combination of these moderately strong magnetic moments with mass transfer rates lower than in the field that is sufficient to stabilize the disks of candidate CVs in GCs and explain their rare cataclysms.

6. DISCUSSION AND CONCLUSION

Using a series of quantitative stability criteria and detailed time-dependent models, we have argued that it is not sufficient to invoke lower mass transfer rates relative to CVs in the field to explain the very infrequent outbursts of candidate CVs in GCs. The argument relies on observed X-ray luminosities to set lower limits on the rate of mass transfer in these systems. By contrast, we found that a combination of moderately strong white dwarf magnetic moments and low mass transfer rates can stabilize most disks in these systems and therefore explain rare cataclysms in GCs.

Our proposed explanation for the rare occurrence of cataclysms in GCs shares some similarities with a number of proposals previously made in the literature (e.g., Edmonds et al. 2003b; Grindlay 1999; Shara et al. 1996, 2004; Ivanova & Rasio 2005), but it is also specific in requiring that both magnetic truncation and low mass transfer rates be present in these systems. We have calculated limits on the mass transfer rates and magnetic moments that must be satisfied in candidate CVs in GCs for their disks to be stabilized. As a result of these specific requirements, one should be in a better position to put this theory to the observational test.

In that respect, we note that the comparatively low optical to X-ray luminosity ratios of candidate CVs in GCs may already be providing evidence in support of our scenario. At a given (low) mass transfer rate (thus fixing the amount of X-ray produced in the vicinity of the white dwarf), by truncating the inner, most optically luminous regions of a CV accretion disk, one may indeed reduce the optical to X-ray luminosity ratio of a system, relative to the untruncated case. Detailed models would be required to address this point more quantitatively.

Various properties of the few outbursts observed in GCs may also contain valuable information on the regime of accretion present in these systems, as we argued in § 4 for fully extended disks. Probably the most revealing observation for any candidate CV in a GC would be a period and/or mass transfer rate measurement, which may tell us right away whether or not outbursts are expected from this system, for a given value of the white dwarf magnetic moment. A measurement of the magnetic field strength itself would obviously be a most interesting test of our scenario, but this type of measurement is expected to be very challenging for any GC given the field strength values that we have been considering.

We have stressed throughout this work the need for, and the usefulness of, robust statistical studies of outbursts in GCs. Given that some outbursts may be missed by crowding effects in some clusters and that, for instance, a count of the total number of CVs in a GC as well studied as 47 Tuc is barely known at the order-of-magnitude level, it is a priori difficult to use existing reports on observed outbursts to constrain the models in a meaningful way. Shara et al. (2005a) have shown how completeness tests for a given cluster observational campaign can greatly help interpret outburst searches in GCs: more statistical studies of this sort, combined with long-term monitoring campaigns (e.g., Bond et al. 2005; Kaluzny et al. 2005), would clearly be useful.

If our interpretation for the origin of rare cataclysms in globular cluster CVs is correct, it points to lower average mass transfer rates and stronger white dwarf magnetic moments in these systems than in the field. This would indicate important and systematic evolutionary differences between field and cluster CV populations. Although such differences may be expected on the basis of distinct dynamical histories for CVs and their progenitors in GCs versus the field (e.g., Ivanova & Rasio 2005), our scenario is useful in making specific predictions for what these differences might be. Mass transfer rates $\dot{M}_T \gtrsim 10^{14}-10^{15}$ g s^{-1} are comparable to or lower than the already low value of $\sim 10^{15}$ g s^{-1} inferred for the very long recurrence time system WZ Sge (Smak 1993). These low $\dot{M}_T$ requirements could thus provide important constraints on the mechanism responsible for angular momentum loss in these binaries. For instance, using the same m_2-$P_{\rm orb}$ relations as in §§ 5.2 and 5.3, white dwarf masses in the range 0.4–1.4 $M_\odot$ and a standard formula for the rate of mass transfer driven by gravitational wave braking (Warner 1995), one finds that typical X-ray luminosities of candidate CVs in GCs can be explained by orbital periods ranging from a fraction of an hour to several hours.

We note that, based on a study of white dwarf compressional heating, Townsley & Bildsten (2002) concluded that GCs may possess a rather large population of CVs with very low mass transfer rates ($\lesssim 6\times10^{14}$ g s^{-1}), which could be post-turnaround binaries, i.e., CVs that have evolved past the minimum orbital period. Low mass transfer rates also imply long accumulation times for classical nova outbursts, which may thus be rarer in GCs than in the field. Finally, the low values of mass transfer rates in CVs may be related to the systematically low $\dot{M}_T$ values inferred by Heinke et al. (2003) for the population of quiescent LMXBs in GCs.

In the same vein, the typical values of white dwarf magnetic moments required in our scenario are below IP-class values, but they remain larger than the values implicitly assumed in standard models of erupting field dwarf novae (which are usually such that the disks are never truncated, not even in quiescence; but see also Lasota 2004). Systematically higher values of white dwarf magnetic moments in GCs relative to the field, as suggested by our interpretation of rare cataclysms, would then point to different stellar/dynamical evolutionary histories for the progenitors of these two CV populations (e.g., Ivanova & Rasio 2005).

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