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On the Properties of Galactic Novae and Their Orbital Period Distribution

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ABSTRACT

Using population synthesis techniques, we analyze the orbital period distribution and other ensemble properties of galactic novae. We find that the frequency of nova outbursts in the galactic disk should be about 30 events per year (to within a factor of ~ 5). This frequency is in agreement with previous theoretical estimates and the observationally inferred rates (but we caution that there are many uncertainties inherent in the calculations). We also find that the frequency-averaged mass of degenerate dwarfs in nova systems is in the range of $0.95 \pm 0.15 M_{\odot}$ which is in good agreement with the observational estimate of $0.90 M_{\odot}$.

If period-dependent observational selection effects are not substantial, we show that any theoretical model (and/or region of parameter space) pertaining to the formation and evolution of galactic novae can be constrained by comparing the predicted ratio of novae above the period gap to that below the gap (i.e., ν_{above}/ν_{below}) with the observed one. Using the observationally inferred lower limit and given that the temperature of the accreting degenerate dwarfs has a significant effect on the estimated nova frequencies for CV's in the orbital period range of 1 to 2 hours (i.e., below the period gap), we conclude that (on average) the degenerate dwarfs in systems below the gap are relatively cold ($< 3 \times 10^7$K), and that they may be significantly cooler than the dwarfs found in the high-period systems. We note that this result is in accord with recent observations and underscores the need for theoretical calculations of the thermal evolution of degenerate dwarfs in nova systems.

Subject headings: binaries: close – novae, cataclysmic variables – stars: statistics

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1. Introduction

Our understanding of novae has benefitted enormously from recent advances in the modeling of thermonuclear runaways (TNR's) combined with population synthesis techniques that allow us to quantify (statistically) the properties of the progenitor population. For classical novae (CNe), the parent population is thought to consist of Cataclysmic Variables (CV's). CV's are close, interacting binary systems in which a low-mass star ($< 2M_{\odot}$) transfers mass to its degenerate dwarf (DD) companion via Roche lobe overflow. Once a critical mass (m_{crit}) of hydrogen-rich material has been deposited on the degenerate dwarf's surface, a thermonuclear runaway ensues often causing most of the transferred matter and some of the DD's envelope to be ejected from the binary system (see, e.g., Livio 1994, and references therein). TNR's are 'periodic' and can recur on cycles of the order of years to more than 10^6 years depending on the DD's mass (M_{dd}), its internal temperature (T_{dd}), and on the mass-accretion rate ($\dot{m}$).

Theoretical investigations of the properties of TNR's have been carried out by a number of groups including Starrfield et al. (1972), Paczyński and Żytkow (1978), Prialnik, Shara, and Shaviv (1978,1979), Iben (1982), Sion and Starrfield (1986), and Prialnik and Kovetz (1995; hereafter, PK), Kato (1997), and Starrfield et al. (2000). While there are still some important theoretical issues yet to be resolved (e.g., the amount of envelope mass that needs to be accreted to trigger a TNR, the change in the mass of the DD after a TNR, and the heavy element enrichment of the ejecta), these calculations have conclusively established that for a fixed $\dot{m}$, the more massive the DD, the higher the frequency of TNR's (they also tend to be faster and brighter).

Using population synthesis techniques, the statistics and properties of CV's in our galaxy are generally well established. Much of the initial work concentrated on determining the birth rates of the Zero-Age CV's (ZACV's) and deriving their present-day properties (see, e.g., Politano 1988, 1996; de Kool 1992; Kolb 1993; and, Tutukov and Yungelson 1995). Later work focused more on the study of a particular set of properties or phenomena associated with CV's and related systems (see, e.g., Di Stefano and Rappaport 1994; Yungelson et al. 1996; Howell, Rappaport, and Politano 1997; Kolb and Politano 1997 (hereafter, KP); and, Howell, Nelson, and Rappaport 2001, hereafter HNR). With respect to the statistical properties of novae, Ritter et al. (1991) calculated the mass spectrum of degenerate dwarfs and concluded that the mean DD mass in CV's (by nova frequency) was between 1.04 - 1.24 $M_{\odot}$ (compared with an observationally inferred value of $0.90M_{\odot}$). Kolb (1995) investigated the orbital period distribution of galactic novae and showed that many of the properties of the synthetic distribution were in reasonable agreement with the observations. Subsequently, Yungelson, Livio, and Tutukov (1997) considered different (non-constant) rates of star formation and suggested that the present-day nova frequency in a given galaxy is probably strongly correlated with the star formation history for that particular type of galaxy (e.g., ellipticals versus spirals). They further suggested that differences in the disk and bulge populations of galactic novae is related to the difference in the ages of the respective progenitor populations.

The 'ensemble properties' of the observed novae cannot be understood without first having a detailed knowledge of the evolution of the underlying CV's. The secular evolution of CV's has been studied extensively (see, e.g., Paczyński and Sienkiewicz 1981, Rappaport, Joss, and Webbink 1982; Rappaport, Verbunt, and Joss 1983, hereafter RVJ; Spruit and Ritter 1983; Nelson, Chau, and Rosenblum 1985; Hameury et al. 1988; Beuermann et al. 1998; HNR). According to the generally accepted model, a low-mass star overflows its Roche lobe and matter is accreted by the degenerate dwarf companion. After a short phase of Kelvin timescale mass transfer, the orbital period (P_{orb}) of the system decreases and mass transfer is driven by angular momentum losses. The unique distinguishing features of the CV orbital period distribution are: (i) the existence of a so-called 'period gap' between approximately 2.2 to 2.8 hours (periods between which relatively few CV's have been observed); and, (ii) a minimum orbital period ($\sim$ 80 minutes) at which point CV's presumably evolve from lower to higher P_{orb}'s (see HNR for more details). During a CV's evolution, long-term-average mass transfer rates decrease (see, e.g., Patterson 1984) causing a corresponding decrease in the frequency with which TNR's occur.

In this paper, we investigate the synthetic orbital period distribution of galactic (disk) novae over a substantial region of parameter space under the assumption of a constant birthrate. This study was initially motivated by the fact that although almost an order of magnitude more novae have been observed for systems with high orbital periods (i.e., above the period gap), there are approximately two orders of magnitude more CV's with orbital periods below the period gap (based on the analysis of HNR). We show that this seemingly incongruous result is in accord with our theoretical understanding of the properties of the galactic CV population and the conditions leading to TNR's themselves. We also investigate the dependence of the synthetic nova frequencies on the temperature of the DD's and conclude that most DD companions in CV's below the period gap are likely to be relatively 'cold' whereas the ones above the gap may be considerably hotter. However, several important caveats apply and will be discussed in more detail.

In §2 we give a detailed description of our population synthesis calculations (including the assumptions concerning the IMF and component mass correlations) and describe the binary evolution codes that were used to carry out the computations. We also discuss how the nova frequencies are calculated. In §3 we present the results from our population synthesis study and explore the sensitivity of our results to uncertainties in the input physics. Finally, in §4 we summarize our results and propose future work from both an observational and theoretical perspective.

2. Population Synthesis

In order to determine the ensemble properties of galactic (disk) novae, a population of ZACV's was generated. Since this investigation is designed to complement the work of HNR who analyzed the present-day properties of CV's, the techniques used to carry out the binary population synthesis (BPS) are very similar and are largely based on the work of Politano (1996) but with the incorporation of a stellar wind from the primary component of the primordial binary. A Monte Carlo simulation is used to generate the primordial population and then the evolution of individual binaries is followed to see which ones undergo a common envelope (CE) phase of evolution. During this short-lived phase, the envelope of the giant star engulfs the secondary, leading to a spiral-in episode which leaves the secondary in a close orbit with the cooling core of the giant (i.e., the newly-born DD companion). Once the properties of the individual ZACV's are determined, a detailed secular evolution of each of these systems is calculated in order to compute the nova frequency, ν.

We typically start with 10^8 primordial binaries in each dataset (a dataset being defined by a unique set of physical parameters such as the IMF and degree of correlation between the components). Datasets of this size are needed in order to obtain good statistics for the relatively rare high-mass DD's. We do not compute all of the evolutions for systems containing low-mass DD's (but at least 3% of all of the primordial systems in the original dataset are evolved). This prescription typically gives us on the order of 10^5 pre-CV's to evolve.

2.1. Determination of the ZACV's

The chemical composition of the primordial binaries from which the ZACV's formed is assumed to be solar. We adopt a constant birthrate function (BRF) such that 0.6 stars with masses $\geq 0.95 M_\odot$ are born in the Galaxy per year. The mass of the primary is picked using Eggleton's (1993) representation of the Miller and Scalo (1979) IMF. To determine the mass of the secondary (M_2), we consider three representative probability distributions describing the correlation between the masses of the primordial binary. Our preferred distribution (which is identical to the one used by HNR) has a probability distribution given by $f(q) =$

5/4 $q^{1/4}$, where $q \equiv M_2/M_1$ (see, e.g., Abt and Levy 1978). This distribution function has the property that the mass of the secondary is weakly coupled to the mass of the primary. We also examine the case for which M_2 is completely independent of M_1, and thirdly one for which the correlation is quite strong (i.e., $f(q) = 2\,q^1$). Although we have chosen distribution functions that correspond to a reasonable range of possible correlations, we emphasize that the physics of binary formation is poorly understood and thus the probability distribution represents a major source of uncertainty. We adopt a lower limit for the mass of the secondary to be 0.09 $M_\odot$ thereby ensuring that all of our secondaries had attained approximate thermal equilibrium (i.e., were close to the main sequence) before the onset of mass transfer. The initial orbital period is chosen from a distribution that is uniform in $\log(P_{orb})$ over the period range of 1 day to 10^6 years (see, e.g., Abt & Levy 1978; Duquennoy & Mayor 1991). We also investigate a similar type of distribution in which the orbital separation (A) is chosen randomly (in terms of log (A)) from a range of values between 10 and $3 \times 10^6 R_\odot$. We find that the new results are similar to the original ones and that none of our conclusions need to be revised.

If the radius of the Roche lobe of the primary is larger than the radius of the primary at the base of the giant branch, mass transfer can occur on a dynamical timescale, thereby leading to a common envelope phase. The final spiral-in separation is based on simple energetic considerations (see, e.g., Taam, Bodenheimer, & Ostriker 1978; Meyer & Meyer-Hofmeister 1979; Livio & Soker 1988; Webbink 1992). The expression that we use in determining A_f, the final orbital separation after spiral-in, is given by:

$$\epsilon\,\frac{GM_2}{2}\left(\frac{M_c}{A_f} - \frac{M_1}{A_o}\right) = \frac{GM_{env}(M_{env} + 3M_c)}{R_1} \tag{1}$$

where M_c ($\equiv M_{dd}$) and M_{env} are the core and envelope masses of the primary, respectively, R_1 is the radius of the primary, A_o is the initial orbital separation, and ϵ is the energy efficiency factor for ejecting the envelope (see Rappaport, Di Stefano, & Smith [1994] for a detailed explanation of the derivation). The effects of varying CE efficiencies are explored by considering a plausible range of values for ϵ ($0.3 \leq \epsilon \leq 1.0$).

Dewi and Taurus (2000) have analyzed the energetics of CE evolution by explicitly taking into account the binding energy of the envelope of the primary to its core. Their parameterization of this ratio is expressed in terms of λ. The effects of the envelope binding energy have been approximated in Equation (1) and it does an adequate job of approximating those effects for higher mass giants ($\gtrsim 4\ M_\odot$) that are not too close to the tip of the AGB. We have used their formulation of the energetics and our giant models to test the effects of λ on the CE evolution. We find that the inclusion of λ is ignorable for our $\epsilon = 1$ models but has the tendency to increase the 'effective magnitude' of ϵ for smaller values (e.g., $\epsilon = 0.3$).

2.2. Evolution of the ZACV's

After the spiral-in episode, the two detached components are given the opportunity to come into contact, via magnetic braking, within the age of the Galaxy (minus the time taken for the primary to evolve to the point when a CE phase occurs). For those systems that do come into contact (i.e., a ZACV), the secular evolution of these systems is then computed thereby allowing us to determine the distribution of mass-transfer rates. For secondary (donor) stars with masses $\leq 0.95 M_\odot$, the evolutionary tracks of CV systems were calculated using a version of a bi-polytrope code that was first developed by RVJ to explore the effects of the parameterized Verbunt & Zwaan (1981; hereafter VZ) magnetic braking law. According to their algorithm, the mass losing donor (i.e., secondary) is approximated by a bi-polytrope wherein the convective envelope is modeled by an $n = 3/2$ polytrope and the radiative core by an $n = 3$ polytrope. The original version of the code has been modified substantially to allow for improvements to the input physics (the details of the latest changes are discussed in HNR).

This bi-polytrope code is used in conjunction with a simplified stellar evolution code that can evolve higher mass donors ($> 0.95\ M_\odot$; see Di Stefano et al. [1995] for details). This latter code was developed so as to reproduce the salient features of the evolution of CV-type systems containing a high-mass and/or evolved donors (e.g., thermal-timescale mass transfer). Although it is a fast code (designed to evolve large numbers of systems for population syntheses), it yields a good facsimile of the mass-transfer and orbital period evolution of systems for which $P_{orb} \gtrsim 4$ hours. For the present study, the simplified code is used to calculate the evolution of donors until their masses are reduced to $0.9 M_\odot$, at which point the bi-polytrope code is then used to calculate the subsequent evolution.

Orbital angular momentum losses are driven by gravitational radiation, magnetic braking via a magnetic stellar wind (VZ law), and systemic mass loss. The magnetic braking parameters are chosen so as to best reproduce the observed period gap (see HNR). Specifically, we take $\gamma = 3$ and allow for possible variations in the strength of the braking by introducing a multiplicative constant (defined here as C_{MB}) which normally is assigned a value of unity. We also "interrupt" the braking when the radiative core is reduced to less than 15% of the mass of the donor. This procedure leads to a period gap that spans the range of 2.1 hr $\lesssim P_{orb} \lesssim$ 2.85 hr; this reproduces the observed gap of approximately 2.2 to 2.8 hours (Warner 1995). For the present calculation, we assume that all of the mass that is transferred from the donor is lost as a result of nova explosions on the surface of the DD accretor and that this mass carries away the specific angular momentum of the DD (i.e., a fast, isotropic wind; see, e.g., Schenker, Kolb and Ritter 1998). If we define $\beta = \Delta M_{dd}/|\Delta M_2|$ where β is the ratio of the change in the mass of the DD to the mass transferred, this assumption is equivalent to setting $\beta = 0$. According to the PK models, β is approximately zero during the evolution of typical CV's but may be a small as -0.5 during the late phases of the evolution. In §3.2 we examine the effects of setting $\beta = -1$ on the nova frequencies.

2.3. Nova Rates

The frequency of nova events depends on the 'critical mass', m_{crit} (i.e., the amount of mass that must be accreted on the DD's surface before a TNR can occur). This mass is determined from a fit to the grid of models of Prialnik & Kovetz (1995; hereafter PK) for DD's with three representative (interior) temperatures: (i) $T_6 = 50$ [hot]; (ii) $T_6 = 30$; (iii) $T_6 = 10$ [cold], where $T_6 \equiv T_{dd}/10^6$K. The PK models were used primarily because they form a self-consistent grid that covers most of the temperature range of interest. They tend to have smaller m_{crit}'s compared to other models. This represents a major source of uncertainty in the determination of the integrated nova frequency (ν_{tot}). The nova frequency is obtained by evaluating $m_{crit}/\dot{m}$ over each timestep in the evolutionary sequence and then we use the method described in HNR (see equation [12]) to derive the present-day frequency (ν). M_{crit} *can* be very dependent on the temperature of the DD and that this dimension of parameter space must be included in the analysis. Even though m_{crit} is normally weakly dependent on $\dot{m}$, the inclusion of $\dot{m}$ into the calculation is very important since the magnitude of $\dot{m}$ can vary by more than four orders of magnitude during the entire evolution of a CV. If the mass-transfer rate ever became so high that TNR's gave way to weak cyclic or stable burning on the surface of the DD (i.e., a supersoft X-ray source; see, e.g., Di Stefano et al. [1995], or Kahabka and van den Heuvel [1997] for more details), then the value of ν is set equal to zero.

We tested a variety of numerical fits to the PK grid of models and have listed 4$^{\text{th}}$ order approximations for the values of m_{crit} (see Appendix A). For the results that will be reported in §3, we use the 4$^{\text{th}}$ order fits but also investigate the results of 3$^{\text{rd}}$ order fits which tend to be better behaved near the grid boundaries (it was sometimes necessary to extrapolate to lower values of both $M_{\rm dd}$ and $\dot{m}$ than had been calculated by PK). This is especially important when calculating the contribution to ν by helium DD's (see §3 for a discussion). Overall, the use of 3$^{\text{rd}}$ order fits for m_{crit} changed our predicted nova frequency distribution very little.

3. Results

The synthetic galactic (disk) nova frequencies (ν_{tot}) for a representative sample of parameter space is shown in Table 1 (see §2 for a discussion of the parameterizations). The temperature of the accreting dwarf companions is an important factor and we list ν_{tot} for hot ($T_6 = 50$) and cold ($T_6 \equiv T/10^6\mathrm{K} = 10$) degenerate dwarfs; the geometric average of (ν_{tot}) for all three temperatures is also listed. The frequency-averaged mass of the DD's (corresponding to the geometric mean for all three DD temperatures) is also given.

Based on our normalization for the BRF and for the regions of parameter space that we explored, we expect on the order of ~ 30 nova explosions per year from (disk) sources in our galaxy (to within a factor of 5). This rate is in concordance with previous observational estimates that span the range of between 11 - 97 events/year (see Ciardullo et al. 1990; and, Liller and Mayer 1987). Similar theoretical estimates have been obtained by Yungelson, Livio, & Tutukov (1997) for a constant birthrate function (17 - 90 events/year). They used the PK grid of nova models but employed different input physics and normalizations for the progenitor population. In their investigation of the contribution of ONeMg DD's to the galactic production of ^{26}Al, KP calculated the integrated nova frequency to be between $\sim 1 - 20$ events/yr. Their ν's are systematically lower than ours due primarily to different prescriptions for the calculation of m_{crit} (but partially due to differing treatments of the CE phase of the binary evolution and different normalizations for the formation of CV's).

The tabulated data shows several trends that merit explanation: (1) For most cases, hot DD's are likely to experience more than twice the rate of TNR's than cold DD's. The conditions leading to the triggering of a TNR can be very sensitive to temperature and consequently, under certain conditions such as low $\dot{m}$'s, considerably less mass needs to be accreted on the surfaces of hot DD's before they experience a nova event. (2) There is a clear trend for ν_{tot} to decrease as the correlation between primary and secondary masses of the primordial binary becomes stronger. For the range of $f(q)$'s that we investigate (i.e., from uncorrelated to 'strongly' correlated), we see a decrease in ν_{tot} of nearly an order of magnitude for all cases. This trend is to be expected; for example, had we assumed a perfect correlation (i.e., $M_{1,o} = M_{2,0}$), the nova frequency would drop to virtually zero due to dynamical instabilities that result when high-mass donors [$\gtrsim 1 M_\odot$] are paired with low-mass [$\lesssim 0.6 M_\odot$] DD accretors. (3) We see that small values of CE efficiency (e.g., $\epsilon = 0.3$) can lead to values of ν_{tot} that are a factor of ~ 2 to 3 times larger than those for $\epsilon = 1$. This result is only weakly dependent on the assumed DD temperature and primordial component mass correlation. Since the orbital separation of the binary after the CE phase of evolution is approximately proportional to the value of ϵ, a large value can lead to systems (pre-CV's) that never achieve Roche lobe contact and thus do not produce novae. This is especially true for binaries containing massive DD's ($\gtrsim 1.05\ M_\odot$) since A_f is steeply dependent on the core mass of the primary. Thus the vast majority of pre-CV's ($\epsilon = 1$) that can attain a semi-detached state in a Hubble time are those for which $M_{dd} \lesssim 1 M_\odot$. Since massive DD's undergo TNR's much more frequently than less massive ones (for a fixed $\dot{m}$), it follows that ν_{tot} will be substantially larger for the $\epsilon = 0.3$ cases.

This latter result is also reflected in the frequency-averaged value of the DD's mass (i.e., $\langle M_{dd} \rangle$ in Table 1). We see that $\langle M_{dd} \rangle$ is substantially larger for the $\epsilon = 0.3$ systems ($\sim 1.1 M_\odot$) than for the $\epsilon = 1$ systems ($\sim 0.8 M_\odot$). These results are in accord with the observational estimate of $0.90 M_\odot$ (Ritter et al. 1991). The distribution of nova frequency with respect to M_{dd} is illustrated in Figure 1. A histogram of the predicted nova frequencies as a function of M_{dd} binned in widths of 0.02 $M_\odot$ for two different values of ϵ (= 0.3, 1) is presented. Only CV's with $M_{dd} \lesssim 1.05 M_\odot$ contribute significantly to the integrated frequency for $\epsilon = 1$. Our calculations also show that the dependence of $\langle M_{dd} \rangle$ on the temperatures of the DD's is small (varying by $\lesssim 0.04 M_\odot$). Thus we claim that $\langle M_{dd} \rangle$ is relatively insensitive to T_{dd} (for the range of temperatures covered by the PK grid) in comparison to the other uncertainties discussed above.

Even though a substantial fraction of CV's are thought to contain helium DD's (Politano 1996), their contribution to ν_{tot} is proportionally very small and ranges between $\sim 0.5\%$ to slightly more than 5% for all of the cases that we calculated. This claim is illustrated by Figure 1 where it can be seen that HeDD's ($M_{dd} \lesssim 0.46 M_\odot$) make a relatively small contribution to ν_{tot}. The relative unimportance of helium dwarfs has previously been noted by Ritter et al. (1991) and by Yungelson, Livio, and Tutukov (1997). Unfortunately, the grid of PK models does not extend to masses as small as those needed to consider helium degenerate dwarfs. Nonetheless, we were able to use our fourth-order fits to extrapolate their models. As a further check on these extrapolations, we also employ a simple analytic formula that was applied beyond the edges of their grid. This formula is expressed in terms of the radius (R_{dd}) and mass (M_{dd}) of the DD, and the mass-accretion rate $\dot{m}$ as follows:

$$m_{crit} \propto {M_{dd}}^{-0.5}\, {R_{dd}}^{3.2}\, \dot{m}^{-0.1} \qquad (2)$$

This equation is similar to the power-law fit used by Livio (1994) but the exponents are somewhat different (see Nelson 2003 for more details). The analytic approach yields a slightly higher contribution ($\sim 50\%$) to ν_{tot} from HeDD's than does the fourth order extrapolation, but overall it is still relatively minor.

The smoothed nova frequency distribution (with respect to P_{orb}) is shown in Figure 2. We contrast the temperature dependence of the nova density ($d\nu/dP_{orb}$) for several representative cases[2]. The fact that hot DD's can more easily trigger novae (on average) than cold ones is clearly demonstrated. This statement is true for all orbital periods except for those above $\sim$ 6 hours where we see almost identical contributions to ν. The high-period systems have much larger mass-transfer rates and m_{crit} tends to approach very similar values for both hot and cold DD's (see the PK models).

There is a distinct drop in ν for orbital periods between $\sim$ 2 and 3 hours. The reduction in nova frequency at $\sim$ 3 hours is a direct consequence of our assumption that magnetic braking is interrupted (or at least drastically reduced) at the point when the donor star develops an almost completely convective internal structure (see, for example, RVJ). Thus mass transfer stops (resulting in the cessation of nova events) and only resumes when gravitational radiation can shrink the orbital separation sufficiently so that the donor is forced back into contact with its Roche lobe ($P_{orb} \approx 2$ hours). When this occurs, mass transfer recommences and nova events are triggered. There is a slight enhancement in the nova frequency at orbital periods of approximately 2 hours due to the enhanced mass transfer ('Kelvin spike') that occurs at the onset of mass transfer. A larger spike is noticeable near the so-called 'minimum orbital period' (about 80 minutes). Near this orbital period, $|dP_{orb}/dt|$ becomes very small causing a buildup of systems. A similar finding was obtained by Kolb (1995).

Figure 2(a) also demonstrates that choosing a q^1 correlation (compared with an independent one) leads to smaller nova frequencies at shorter orbital periods and greater ones for very large P_{orb}'s. This can be understood given the fact that P_{orb} is roughly proportional to M_2 (for $P_{orb} \gtrsim 4$ hours), and that the $q^{1/4}$ dependence forces ZACV's to have higher mass donors (and thus larger P_{orb}'s) than for the uncorrelated case. When the secondary (donor) masses are chosen independently, the Miller-Scalo IMF strongly favors the formation of lower mass stars and thus it is possible to have many more CV's (and novae) at lower orbital periods. Consequently our uncorrelated models show a much sharper decline in novae for systems located above the period gap.

With respect to the CE efficiency factor, we have already seen that a value of $\epsilon = 1$ (as opposed to 0.3) can significantly reduce the number of novae (see Figure 2[b]). It can also have a profound impact on the shape of the frequency distribution for systems located above the gap. Although the detailed explanation is more complex, ZACV's for which $\epsilon = 1$ tend to have (on average) lower mass donors than ZACV's for which $\epsilon = 0.3$. Thus we should expect fewer high-period CV's and a smaller nova frequency.

The effects of changing the magnitude of the magnetic braking torque by varying C_{MB} was also examined. For enhanced magnetic braking (with $C_{MB} = 3$), the increase in $\dot{m}$

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[2]In Figure 2, $d\nu/dP_{orb}$ has been approximated by averaging over 0.1 hour intervals in P_{orb}.

causes the value of P_{orb} at the upper limit of the gap to increase to ~ 4 hours (a value very much in disagreement with the observed distribution of CV's). For models with $f(q) \propto q^{1/4}$ and $\epsilon = 0.3$, the ratio of ν_{above}/ν_{below} does not change significantly (for all values of T_{dd}). When we set $C_{MB} = 0$ (i.e., only gravitational radiation), the gap disappears and ν_{tot} is greatly diminished simply because fewer systems can come into contact during the lifetime of the Galaxy.

3.1. Ratio of Frequencies Above and Below the Gap

Inspection of Figure 2 reveals that the temperature of the DD accretor is a very important factor in determining the orbital period distribution of novae. While the difference is not so noticeable above the period gap, it is very dramatic below the gap (more than an order of magnitude difference). As stated previously, this is due to the fact that m_{crit} is very temperature dependent for *low* mass-transfer rates. This issue is central to the determination of the relative numbers of novae above and below the period gap. Prialnik and Kovetz (1995) noted that "the recurrence period is almost unaffected by the temperature" of the DD. This statement is certainly valid for much of the ($\dot{m}$, M_{dd}) plane that they investigated but the recurrence periods can vary by nearly a factor of 10 for low $\dot{m}$'s ($\lesssim 10^{-10} M_{\odot}$ yr^{-1}). This range of $\dot{m}$'s is believed to apply to all CV's observed below the period gap and thus the ratio of nova frequencies above the period gap compared to that below the gap (i.e., ν_{above}/ν_{below}) is very temperature dependent.

In Figure 3 we contrast the observed P_{orb} histogram of galactic novae with the predicted orbital period distributions for two different correlations both corresponding to $\epsilon = 0.3$, and for both hot and cold DD's. The observed CNe data is taken from a table of CV observations compiled by Ritter and Kolb (1998)[3]. The predicted distribution has been arbitrarily normalized in such a way that the integrated number of novae for systems containing cold DD's below the period gap approximates the observed number. Because of the limited number of observations and inherent Poisson noise (and for other reasons discussed in §3.2), it is difficult to formulate any robust conclusions concerning the validity of the overall shape of the synthetic P_{orb} distribution based on the observed one. If selection effects are small, the data suggests that in order to fit the relative number of events above and below the gap, the DD's below the gap should be relatively cold while the ones in systems above the gap could

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[3]We have included a few cases from their table where the association between a nova event and a particular orbital period has been called into question. The exclusion of these cases does not change the subsequent conclusions.

(on average) be significantly hotter. This supposition is supported in part by the fact that DD's in systems above the gap experience a significantly higher frequency of nova events that will undoubtedly slow the cooling of the DD's and also experience greater compressional heating due to the higher $\dot{m}$'s. Moreover, once mass transfer starts, it takes a CV with a donor star of $\sim 1M_{\odot}$ only about 0.1 Gyr to evolve from high orbital periods to the upper limit of the period gap. However, *assuming* that the interrupted mass-transfer scenario is correct, the DD's will cool for ~ 1 Gyr before coming back into contact and then may spend up to another 10 Gyr evolving to the minimum orbital period and back through the gap (see HNR). Thus the low period systems would tend to be very much older and the DD's in these systems should (on average) be colder. The actual temperature of DD's depends on factors such as: (i) their masses (this affects the cooling timescales); (ii) the amount of time that they can cool after the CE phase; and, (iii) the masses of the donors (this directly affects $\dot{m}$ and thus the cooling timescales). In order to make an accurate assessment of the temperature distribution of the underlying DD population, we need a self-consistent calculation of the evolution of the internal properties of DD's as CV's evolve through millions of nova cycles that takes into account various amounts of mass erosion from the primary and compressional heating. We are presently working on this problem.

A comparison of the predicted ratio of the number of novae above the gap to the number below the gap (i.e., ν_{above}/ν_{below}) with the observed one can be a potentially powerful diagnostic tool. By analyzing the ratio, we can virtually eliminate the need to make an absolute calibration of the frequency (in other words, we can eliminate many of the selection effects associated with galactic extinction and we do not need to know the precise magnitude of the [assumed] birthrate). Moreover, we can establish a statistically significant *lower* limit on this ratio even though the number of novae below the gap is small. In order to use this observational constraint to test the validity of any BPS model, we require: (i) that observational selection effects are not biased towards the discovery of novae in systems with $P_{orb} > 2.5$ hours (relative to low-period systems); and, (ii) that the observational designations are not flawed.

Comparing the results presented in Table 2 with the *lower* limit imposed by ν_{above}/ν_{below}, we see that the predicted range of ratios for the volume of parameter space that we consider cannot be explained if hot DD's populate systems above and below the gap. While it is possible to accommodate a scenario wherein all systems contain cold DD's (especially for strongly correlated components), the results imply that it is much more likely that there is it greater percentage of hotter DD's above the gap than below it.

3.2. Discussion of Uncertainties

3.2.1. Observational Selection Effects

Galactic extinction and the ability to properly classify/validate novae events are important considerations in determining the galactic nova frequency based on the novae that are observed (see, e.g., Della Valle et al. 1992 for a discussion). The effects of galactic absorption are so large that the estimated range for ν_{tot} spans approximately an order of magnitude. By analyzing the ratio of ν_{above}/ν_{below} (as opposed to ν_{tot}), the effects of absorption become relatively unimportant. However, selection effects that skew the likelihood of observing novae above the gap compared to below the gap need to be examined carefully.

The probability of detection of a nova is strongly correlated with the bolometric luminosity (L_{max}) at maximum amplitude (see Table 2 of PK). According to the models of PK, L_{max} depends on M_{dd} and $\dot{m}$. For low-mass DD's (0.65 $M_{\odot}$), L_{max} is $\sim 50\%$ greater for low $\dot{m}$'s ($\sim 10^{-10} M_{\odot}$/yr) compared to high ones ($\sim 10^{-8} M_{\odot}$/yr). The same effect can be seen in high-mass DD's (1.4 $M_{\odot}$) but the increase in L_{max} is reduced by $\sim 10-20\%$. This result implies that the discovery of short-P_{orb} systems (and concomitantly low-$\dot{m}$ systems) should be enhanced. If this analysis is correct, it would have the effect of increasing our lower limit on ν_{above}/ν_{below}, thus making the constraint more powerful. However, the PK models also indicate that for the medium-temperature case ($T_6 = 30$), low-mass, low-$\dot{m}$ novae can be 30% brighter than the high-mass, high-$\dot{m}$ ones. This latter result would favor the discovery of short-period systems below the gap (assuming that the DD's had a constant temperature of $T_6 = 30$). If we consider high-mass DD's only, then regardless of the temperature, the low-$\dot{m}$ outbursts (i.e., those below the gap) are more likely to be detected.

Another selection effect that could potentially be significant concerns the likelihood of being able to determine the orbital period of the underlying CV as a function of the value of P_{orb} itself. This problem is difficult to quantify because it depends on factors such as the mass ratio (q) of the binary (the probability of eclipses depends on the mass ratio). Since the periodicities of most novae are determined using time-resolved optical photometry, it is generally easier to detect short-period modulations. If this is the determining factor then this selection effect would *strengthen* our observational constraint. If period-based selection effects strongly favor the discovery of systems above the gap, then the conclusions of §3.1 could be invalidated.

3.2.2. Disk and Halo Populations

There is also the possibility that the observed novae in this sample originate from two distinct populations. Della Valle et al. (1992) have suggested that the novae may belong to either a disk or halo population based on their observed characteristics (i.e., speed class and height above the midplane). The disk population would more properly pertain to our model wherein we assume a constant BRF and adopt a solar metallicity. The halo population may have been formed as a result of a burst of star formation that occurred early in the Galaxy's history. The differences in the observed properties of novae may be due to differences in the ages of the progenitors. Yungelson, Livio, and Tutukov (1997) claim that the currently observed nova rate is mainly determined by the present rate of star formation in the disk and that the fraction of present-day novae belonging to an old population must be less than $\sim 10\%$. We expect that a halo population of novae (if it exists) would have an orbital period distribution that is not radically different from that of the disk population (although we find that the upper limit of the gap is lowered to ~ 2.5 hours while the lower limit is decreased to slightly less than 2 hours for $C_{MB} = 1$). However, the DD's in the older population may be much colder (on average) and this may contribute to an increased value of ν_{above}/ν_{below}. If this is the case, then the spatial distribution of the two populations must be taken into account. The observational lower limit on ν_{above}/ν_{below} would have to be re-examined to determine if the halo systems (at high galactic latitudes) have been preferentially selected and to see if this favors the (volume-averaged) discovery of high-period systems.

3.2.3. ONeMg Novae

Another source of uncertainty that we have not taken into account concerns the formation of ONeMg DD's. ONeMg CV's are thought to form from primordial binaries containing intermediate mass stars (see, e.g., Gil-Pons and Garcia Berro 2000). The best evidence for the existence of these ONeMg CV's comes from observations of "neon novae". Based on the observed abundances of intermediate-mass elements (particularly neon) in the ejecta, these novae are believed to erode the underlying ONeMg dwarf (however, see Livio and Truran 1994 for a discussion on the necessity of invoking an ONeMg model). While it is clear that a newborn ONeMg DD will have a high mass, its lower limit ($\sim 1.1 M_\odot$) is not well-established.

KP used BPS techniques to investigate the galactic production of ^{26}Al resulting from these neon novae. They employed a grid of models corresponding to various correlation functions, critical (ignition) masses and, parameterizations of the erosion. Under the assumption that β remained constant throughout the evolution, KP calculated ν_{tot}'s for values of β between $\beta = 0$ (i.e., the one assumed in this paper) and $\beta = -1$ (corresponding to a rate of erosion of the DD equal to the mass-loss rate from the secondary). Unfortunately β is not easily deduced and will not be constant during the evolution of the CV.

To test the effects of erosion on our conclusions, we carried out a BPS for an uncorrelated population (component masses chosen independently) and adopted a value of $\beta = -1$ (i.e., $\Delta M_{env} = 2\Delta M_{acc}$ at ignition). Similar to the results reported by KP, we found that the values of ν_{tot} were not substantially altered. For every DD temperature, we found that ν_{tot} decreased by $\lesssim 20\%$ for both values of ϵ (see Table 1). KP found that the changes in ν_{tot} ranged from a 10% increase (for one case) to a maximum of a 40% decrease for all other cases (their low-temperature DD case [which would most closely correspond to our own] exhibited a $\sim 15\%$ decrease). With respect to the ratio of ν_{above}/ν_{below}, the largest change occured for our cold DD case (and $\epsilon = 1$); the ratio increased from a value of 2.4 to a value of 4.4 ($\sim 60\%$ increase). All other cases resulted in less than a 10% increase in ν_{above}/ν_{below}. Another source of uncertainty concerns the period distribution with which ONeMg CV's are formed. If the integrated fraction of ν_{tot} due to ONeMg novae is equal to that estimated by KP (i.e., $\sim 30\%$) and given that all CV's evolve rapidly from high P_{orb}'s (above the period gap) to values of $\lesssim 2$ hours, the effects of properly including ONeMg novae on ν_{above}/ν_{below} may not be very significant. Nonetheless we cannot rule out the possibility that this effect is important.

4. Summary and Conclusions

Any model describing the formation and evolution of the ensemble properties of galactic novae must: (i) fit the observed nova distribution very well; and, (ii) yield good agreement with the observationally inferred values of ν_{tot} and $\langle M_{dd}\rangle$. The results of this type of analysis can, in principle, be used to invalidate (or tightly constrain) certain scenarios and/or regions of parameter space (the caveats having been noted in §3). We obtain the best agreement with the observational data for the most conservative set of assumptions; namely: (1) a correlation that is independent or weakly dependent on the masses of the components of the primordial binary; (2) a CE efficiency of $\sim 50\%$; (3) a constant birthrate; (4) the cooling of DD's as the CV evolves from high periods to low periods; and, (5) the standard magnetic braking scenario describing the evolution of CV systems.

A potentially powerful tool that can be used to constrain the models is the observed ratio ν_{above}/ν_{below}. By placing a statistically significant *lower limit* on ν_{above}/ν_{below} (and assuming that observational selection effects do not have the net effect of decreasing this lower limit), we can cast considerable doubt on any models that predict an even lower value. For the BRF, values of ϵ, and $f(q)$'s that we considered, this limit strongly suggests that

DD's in nova systems with $P_{orb} \lesssim 2$ hours cannot be hot and probably have temperatures (on average) that are significantly less than 3×10^7K. Moreover, it is very likely that the DD's found in the high-period systems are (on average) hotter than the ones found below the period gap.

The question as to whether there is a correlation between shorter P_{orb}'s and lower DD temperatures in CV's has already generated considerable interest. Gansicke (1997) has analyzed accreting DD for two subclasses of CV's (polars and DNe). His data was obtained by carrying out UV spectroscopy using the *International Ultraviolet Explorer* and HST. He concluded that for the seven magnetic CV's that he studied, the temperatures of the DD's decrease with decreasing P_{orb}. He contends that this relationship implies that short-P_{orb} CV's are necessarily older than the long-period ones. This conclusion is in general agreement with our understanding evolution of CV's[4].

Ideally, we need to observe DN systems in a state of prolonged quiescence while the accretion rate is sufficiently small that the accretion luminosity is unimportant. It would then be possible to measure the DD's intrinsic luminosity due to the cooling of its interior (and deduce its internal temperature). A multi-wavelength analysis of the spectrum of the boundary layers of DD's would prove invaluable towards inferring the temperature of the deep interior. This type of observational analysis has been carried out by Howell et al. (1999), and Szkody et al. 2002, amongst others. Further theoretical calculations need to be carried out in order to synthesize the broadband spectra that would be expected for various physical conditions in the envelope and interior of the DD. Thus a more accurate relationship between the boundary-layer temperature and the (deep) interior temperature of the DD could be determined. Observationally, the STIS dataset already consists of a large number of high-quality spectra of DD's in CV's. With the advent of new all-sky surveys (e.g., 2DF), many new binaries will be identified and some of them should make excellent candidates for multi-wavelength (quiescent) observations.

The results of this study have spawned several theoretical questions. For example, the evolution of the internal temperature of DD's undergoing various rates of accretion that incorporate the cooling and heating (due to TNR's and compression) of DD's needs to be computed. To date, nobody has followed the evolution of DD's over millions of TNR cycles. This a project that we are currently undertaking and ultimately plan to incorporate the secular changes in $\dot{m}$ as the CV evolves. We're also investigating the consequences of forming two distinct populations of galactic novae (disk and bulge). The DD's in the metal-poor halo

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[4]Although the DD's in TOAD's (post minimum-orbital-period systems) would be the oldest and presumably coldest (and may have P_{orb}'s exceeding 2 hours).

population could be considerably colder than the minimum temperatures considered in this analysis (i.e., $< 10^7$K) and may require the calculation of a new generation of nova models.

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A. Numerical Fits for the Critical Masses

Numerical fits to the critical masses m_{crit,T_6} triggering a TNR are carried out on the grid of nova models calculated by Prialnik and Kovetz (1995). The magnitude of this mass depends on the mass the degenerate dwarf, M_{dd}, its temperature, T_6 (expressed in units of 10^6 K), and on the mass-accretion rate, $\dot{m}$. Their models spanned the mass range of $0.65 - 1.4 M_\odot$ and included mass accretion rates from 10^{-6} to 10^{-11} $M_\odot$ yr^{-1}. The fits given by the equations below correspond to DD's whose temperatures are T_6 = 10, 30, and 50, respectively (i.e., from 'cold' to 'hot' degenerate dwarfs):

$$\begin{aligned}\log m_{crit,10} = & \quad 2.7786 + 3.934\, M_{dd} + 5.0537\, (\log \dot{m}) - 43.1301\, {M_{dd}}^2 \\ & + \; 0.96540\, (\log \dot{m})^2 - 4.2408\, M_{dd}(\log \dot{m}) + 41.1736\, {M_{dd}}^3 \\ & + \; 0.0675711\, (\log \dot{m})^3 - 0.57885\, {M_{dd}}^2(\log \dot{m}) - 0.601787\, M_{dd}(\log \dot{m})^2 \\ & - \; 13.6517\, {M_{dd}}^4 + 0.00149627\, (\log \dot{m})^4 + 0.196818\, {M_{dd}}^3(\log \dot{m}) \\ & - \; 0.0261981\, M_{dd}(\log \dot{m})^3 - 0.0081944\, {M_{dd}}^2(\log \dot{m})^2 \qquad \text{(A1)}\end{aligned}$$

$$\begin{aligned}\log m_{crit,30} = & \quad 68.5495 - 2.8677\, M_{dd} + 38.72477\, (\log \dot{m}) - 34.4884\, {M_{dd}}^2 \\ & + \; 7.371765\, (\log \dot{m})^2 - 5.41741\, M_{dd}(\log \dot{m}) + 35.88312\, {M_{dd}}^3 \\ & + \; 0.6018557\, (\log \dot{m})^3 + 0.250599\, {M_{dd}}^2(\log \dot{m}) - 0.666110\, M_{dd}(\log \dot{m})^2 \\ & - \; 12.78851\, {M_{dd}}^4 + 0.0179058\, (\log \dot{m})^4 - 0.17973\, {M_{dd}}^3(\log \dot{m}) \\ & - \; 0.0280407\, M_{dd}(\log \dot{m})^3 - 0.0098420\, {M_{dd}}^2(\log \dot{m})^2 \qquad \text{(A2)}\end{aligned}$$

$$\log m_{crit,50} = \quad 30.83777 + 9.4488\, M_{dd} + 20.84987\, (\log \dot{m}) - 35.62821\, {M_{dd}}^2$$

$$
\begin{aligned}
+ &\quad 4.254163\,(\log \dot{m})^2 - 0.84881\,M_{dd}(\log \dot{m}) + 35.98950\,{M_{dd}}^3 \\
+ &\quad 0.3638585\,(\log \dot{m})^3 + 0.029462\,{M_{dd}}^2(\log \dot{m}) - 0.103565\,(\log \dot{m})^2 M_{dd} \\
- &\quad 12.77111\,{M_{dd}}^4 + 0.01115254\,(\log \dot{m})^4 - 0.172654\,{M_{dd}}^3(\log \dot{m}) \\
- &\quad 0.0051944\,M_{dd}(\log \dot{m})^3 - 0.0220117\,{M_{dd}}^2(\log \dot{m})^2\,. \qquad \text{(A3)}
\end{aligned}
$$

The root mean-square (RMS) errors for the above three fits are 0.046, 0.034, and 0.049 dex, respectively. Even though we obtain the best fit for $\log m_{crit,30}$, we concentrate on the 'hot' and 'cold' results to obtain a realistic assessment of the sensitivity of the nova frequencies on the possible range of DD temperatures.

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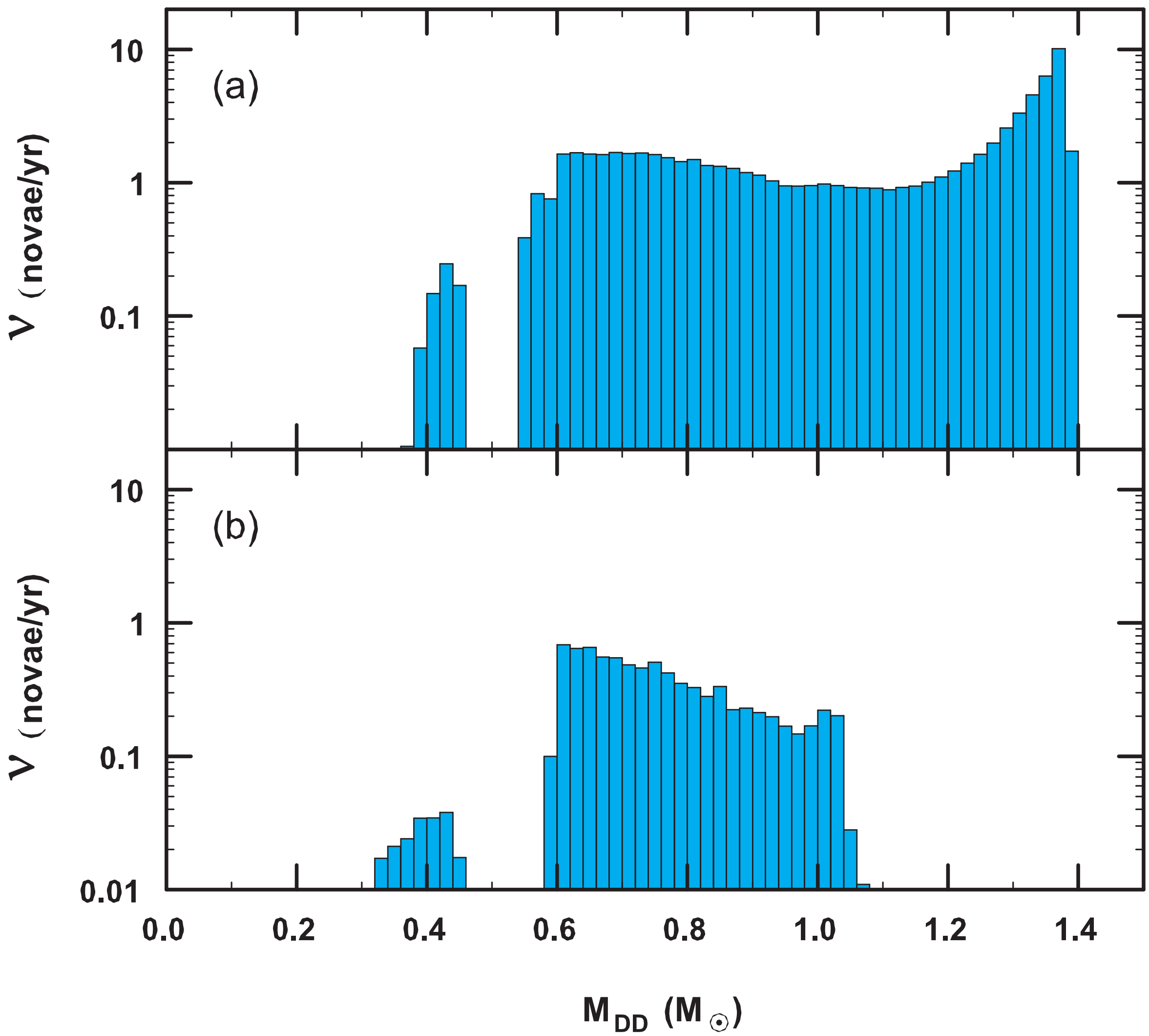

Fig. 1.— Histogram of the predicted nova frequencies (per 0.02 $M_{\odot}$ bin) as a function of the mass of the degenerate dwarf. Panel (a) corresponds to a dataset for which $\epsilon = 0.3$ and the component masses are uncorrelated. Panel (b) corresponds to q^1 correlation with $\epsilon = 1$. These results were calculated for the geometric average of the $T_6 = 50$, 30, and 10 models. The bars located at masses $\lesssim 0.46 M_{\odot}$ represent the contributions of helium DD's.

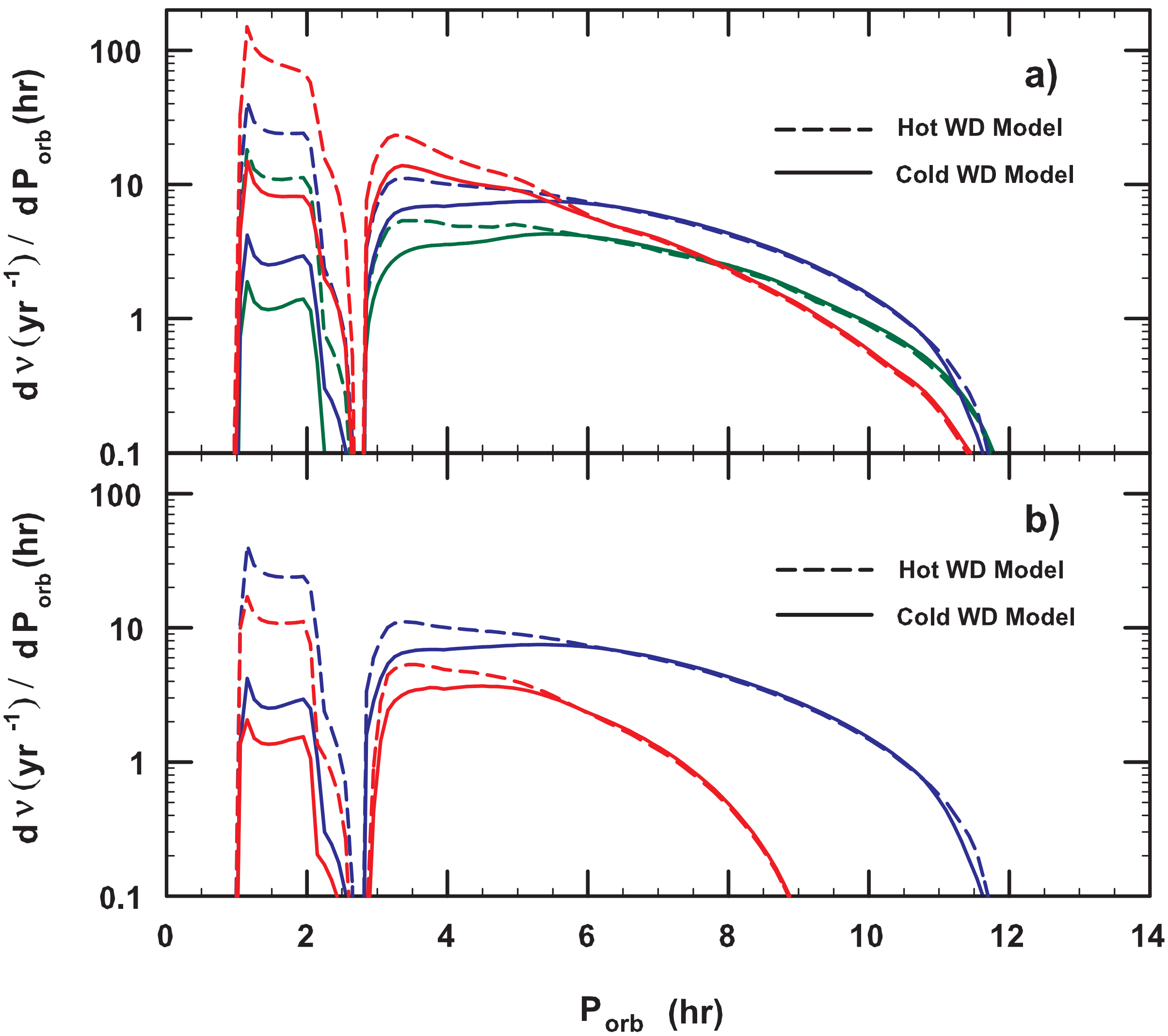

Fig. 2.— Theoretically predicted nova frequencies (densities expressed per hour of orbital period). For both panels, the solid (——) and dashed (— —) curves correspond to cold and hot DD's, respectively. Panel a): The red curves correspond to uncorrelated component masses, the blue to a $q^{1/4}$ correlation, and the green curves to a q^1 correlation ($\epsilon = 0.3$ for all three sets of curves). Panel b): The blue curves correspond to $\epsilon = 0.3$, and the red curves correspond to $\epsilon = 1.0$; $f(q) \propto q^{1/4}$ for both sets of curves.

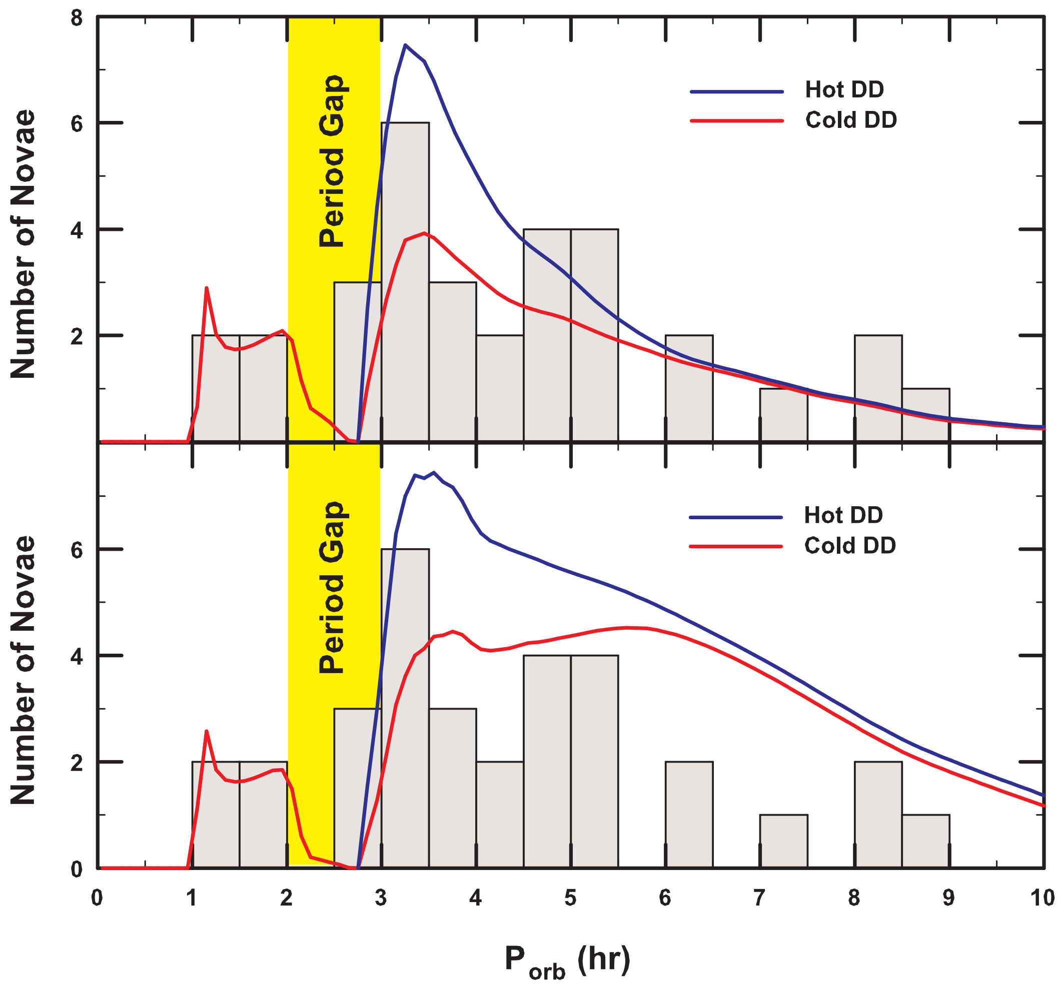

Fig. 3.— The orbital period distribution of observed novae is illustrated by the histogram (gray bars). The predicted distribution (arbitrarily normalized) is denoted by the solid curves (cold DD's) and dashed curves (hot DD's). The hot DD contribution for systems below the gap is not shown. Case (a) corresponds to a $q^{1/4}$ correlation, and (b) corresponds to uncorrelated primordial component masses ($\epsilon = 0.3$ for both cases). The approximate position of the observed 'period gap' is also shown.

Table 1. Galactic Nova Frequencies and Average DD Masses

$f(q)$	ϵ	Hot[a]	Cold[b]	Avg[c]	$< M_{dd} >$[d]
ind[e]	0.3	146	48	75	1.07
ind[e]	1.0	84	27	43	0.80
$q^{\frac{1}{4}}$	0.3	73	40	49	1.08
$q^{\frac{1}{4}}$	1.0	27	13	17	0.78
q^1	0.3	38	24	28	1.07
q^1	1.0	12	7	8	0.76
ind($\beta = -1$)[e,f]	0.3	143	42	69	0.85
ind($\beta = -1$)[e,f]	1.0	81	26	41	0.58

[a] ν_{tot}(novae/yr) for hot ($T_6 = 50$) DD models.

[b] ν_{tot}(novae/yr) for cold ($T_6 = 10$) DD models.

[c] ν_{tot}(novae/yr) for the geometric mean of $T_6 = 50, 30$, and 10 DD models.

[d] $< M_{dd} >$ is the frequency-averaged DD mass (in units of $M_\odot$) for the geometric mean of the three different temperature models.

[e] Masses of the primary and secondary in the primordial binary are chosen independently.

[f] The mass of the DD decreases at a rate equal to that lost by the secondary ($\beta = -1$; see the text for details).

Table 2. Ratio of integrated frequencies $(\nu_{above}/\nu_{below})$ [a]

$f(q)$	ϵ	Hot[b]	Cold[c]	Avg[d]	H/C[e]
ind[f]	0.3	0.52	3.6	1.3	4.8
ind[f]	1.0	0.46	2.8	1.1	3.8
$q^{\frac{1}{4}}$	0.3	1.54	11.7	4.0	13.9
$q^{\frac{1}{4}}$	1.0	1.13	7.1	2.7	8.7
q^{1}	0.3	1.95	15.1	5.2	16.2
q^{1}	1.0	1.38	8.8	3.4	8.8

[a] $(\nu_{above}/\nu_{below})$ is the ratio of galactic nova frequencies for CV's above the period gap to those below the gap.

[b] Hot ($T_6 = 50$) DD models.

[c] Cold ($T_6 = 10$) DD models.

[d] Geometric mean for $T_6 = 50, 30$, and 10.

[e] Ratio assuming Hot models above the gap and Cold below.

[f] Masses of the primary and secondary in the primordial binary are chosen independently.