CLASICAL NOVAE AS A PROBE OF THE CATACLYSMIC VARIABLE POPULATION

DEAN M. TOWNSLEY
Department of Physics,
Broida Hall, University of California, Santa Barbara, CA 93106

AND

LARS BILDSTEN
Kavli Institute for Theoretical Physics and Department of Physics,
Kohn Hall, University of California, Santa Barbara, CA 93106; bildsten@kitp.ucsb.edu

Abstract to the ApJ

ABSTRACT

Classical Novae (CNe) are the brightest manifestation of mass transfer onto a white dwarf in a cataclysmic variable (CV). As such, they are probes of the mass transfer rate, \( M \), and WD mass, \( M_{\text{WD}} \), in these interacting binaries. Our calculations of the dependence of the CN ignition mass, \( M_{\text{ign}} \), on \( M \) and \( M_{\text{WD}} \) yields the recurrence times of these explosions. We show that the observed CNe orbital period distribution is consistent with the interrupted magnetic braking evolutionary scenario, where at orbital periods \( P_{\text{orb}} > 3 \) hr mass transfer is driven by angular momentum loss via a wind from the companion star and at \( P_{\text{orb}} < 3 \) hr by gravitational radiation. About 50\% of CNe occur in binaries accreting at \( M \approx 10^{-9} M_\odot \text{ yr}^{-1} \) with \( P_{\text{orb}} = 3-4 \) hr, with the remaining 50\% split evenly between \( P_{\text{orb}} \) longer (higher \( M \)) and shorter (lower \( M \)) than this. This resolution of the relative contribution to the CN rate from different CVs tells us that \( 3(9) \times 10^5 \) CVs with WD mass \( 1.0(0.6) M_\odot \) are needed to produce one CN per year. In addition, one CN per year requires a CV birthrate of \( 1(2) \times 10^{-4} \text{ yr}^{-1} \), and likely ejects mass into the ISM at a rate \( M = 3(9) \times 10^{-5} M_\odot \text{ yr}^{-1} \). Using the K-band specific CN rate measured in external galaxies, we find a CV birthrate of \( 2(4) \times 10^{-4} \text{ yr}^{-1} \) per \( 10^{10} L_{\odot, K} \), very similar to the luminosity specific Type Ia supernova rate in elliptical galaxies. Likewise, we predict that there should be \( 60-180 \) CVs for every \( 10^{10} L_{\odot, K} \) in an old stellar population. The population of X-ray identified CVs in the globular cluster 47 Tuc is similar to this number, showing no overabundance relative to the field.

The observed CN \( P_{\text{orb}} \) distribution also contains evidence for a CV population which has no period gap. These are likely systems with a strongly magnetic WD (Polars) in which it has been suggested that the field interferes with the wind of the companion, limiting angular momentum losses to those of gravitational radiation and eliminating the period gap. With this reduced \( M \), Polars evolve more slowly than systems which undergo magnetic braking. Using a two-component steady state model of CV evolution we show that the fraction of CVs which are magnetic (22\%) implies a birthrate of 8\% relative to non-magnetic CVs, similar to the fraction of strongly magnetic field WDs.

Subject headings: binaries: close—novae, cataclysmic variables—stars: statistics—white dwarfs

1. INTRODUCTION

A Classical Nova (CN) outburst is the result of a thermonuclear runaway in the hydrogen-rich accreted layers on a white dwarf (WD) in a mass transferring cataclysmic variable (CV) binary (see [Shara 1985] for a review). The number of CNe with measured orbital periods, \( P_{\text{orb}} \), has been increasing; [Diaz & Bruch 1997] made a first comparison to the CN period distribution with 30 objects, and recently [Warnier 2002] listed \( P_{\text{orb}} \) for 50 CNe. These range from 1.4 hours to more than 16 hours, with most below 5 hours. Cataclysmic variables (CVs; [Warnier 1995]) consist of a WD primary accreting mass from a normal low-mass star that is filling its Roche lobe, and spend most of their life accreting at rates \( M \approx 10^{-9} - 10^{-11} M_\odot \text{ yr}^{-1} \) (e.g. [Howell, Nelson, & Rappaport 2001] hereafter HNR). CVs are formed when the companion (of mass \( M_2 \)) to a WD (made during a common envelope event) comes into contact with its Roche lobe as a result of angular momentum losses. The CV evolves toward shorter orbital periods as the binary loses angular momentum at a rate \( J \) and the companion transfers mass to the WD at a rate \( M \). The orbital period distribution of CN, a direct reflection of the CN frequency, provides a diagnostic of \( M \) in CVs over the time to accumulate an unstable layer, \( 10^{3-7} \) years.

It is generally thought that the paucity of CVs with 2 hr \( \lesssim P_{\text{orb}} \lesssim 3 \) hr (e.g. [Shafter 1992]), the so-called period gap, is due to switching between a high \( J \) state above 3 hours to a comparatively low \( J \) state below 3 hours (e.g. HNR). Upon such a sudden reduction in \( J \), the requisite reduction in \( M \) causes the companion, which has been slightly out of thermal equilibrium due to the high mass loss rate, to contract and fall inside the Roche lobe, halting mass transfer. Eventually as \( P_{\text{orb}} \) continues to decrease due to angular momentum loss, Roche lobe contact is reestablished. The simplest paradigm of CV evolution holds that \( J \) is determined by the WD mass \( M_{\text{WD}} \), \( M_2 \) and \( P_{\text{orb}} \). Interrupted magnetic braking (IMB) has arisen as a good candidate for \( J \) prescriptions (e.g. [Paczynski & Sienkiewicz 1983; Rappaport et al. 1983; Spruit & Ritter 1983; Hameury et al. 1988; Kolb 1992] HNR). In the IMB scenario, \( J \) is initially driven by angular momentum lost in the stellar wind of the secondary star (Verbunt & Zwaan 1984) for \( P_{\text{orb}} \gtrsim \).
3 hours. The magnetic braking is interrupted (potentially by the loss of the radiative core), and \( J \) falls to that carried away by gravitational radiation. For \( T_{\text{orb}} \leq 3 \text{ hours} \), IMB predicts that typical accretion rates near \( P_{\text{orb}} \leq 3 \text{ hours} \) are \( \dot{M} \approx 10^{-4} \dot{M}_\odot \text{ yr}^{-1} \), and decrease to \( \dot{M} \approx 5 \times 10^{-11} \dot{M}_\odot \text{ yr}^{-1} \) below 2 hours. This factor of 20 drop in \( \dot{M} \) across the period gap requires that the \( \dot{M} \) dependence of the CN frequency on \( P_{\text{orb}} \) be taken into account when explaining the orbital period distribution of CN. These two \( \dot{M} \) values are self-consistent and independent of assumptions about the WD thermal state. This is in contrast to all prior \( M_{\text{ign}} \) calculations (see e.g. [Fujimoto 1982, MacDonald 1984, Prialnik & Kovetz 1995]), which the WD will approach under prolonged accretion. For \( P_{\text{orb}} \gtrsim 3 \text{ hours} \), the magnetic braking phase, the WD has only marginally enough time, \( \sim 10^7 \) years, to reach \( T_{c,\text{eq}} \). However, at these accretion rates, \( M_{\text{ign}} \) is insensitive to \( T_c \) because the ignition occurs in a layer which is not conductively coupled to the core. Hence the temperature is set by the response of the envelope to the energy being released by compression (TB04). At lower \( \dot{M} \), \( T_c \) determines \( M_{\text{ign}} \), but the lower \( \dot{M} \) state for CVs is long-lived (> 10^9 years), allowing the WD core to reach \( T_{c,\text{eq}} \). Thus, for CV evolution, use of \( T_{c,\text{eq}} \) provides \( M_{\text{ign}} \)'s which are self-consistent and independent of assumptions about the WD thermal state. We are most interested in CN rates for \( P_{\text{orb}} \leq 4 \text{ hours} \), so we include a fraction \( X_{\text{He}} = 0.001 \) in our ignition models.

The \( M_{\text{ign}} \) results of TB04 are shown in Figure 1. Compared to previous ignition mass calculations, TB04 found larger \( M_{\text{ign}} \) at \( M_\odot \gtrsim 10^{-10} M_\odot \text{ yr}^{-1} \) due to the lower \( T_c \), and similar \( M_{\text{ign}} \) at \( M_\odot \gtrsim 10^{-4} M_\odot \text{ yr}^{-1} \) due to offsetting effects of the lower \( T_c \) and the inclusion of \( ^3\text{He} \) leading to an earlier trigger. TB04 found that for the few systems which have a known ejected mass and \( P_{\text{orb}} \) (giving some indication of \( \dot{M} \)), the ejected masses are similar to \( M_{\text{ign}} \), implying that each CN event ejects approximately the amount of material accreted since the last event. TB04's results do not show the trivial \( M_{\text{ign}} \propto R^4/M_{\text{WD}} \) scaling assumed for a unique ignition pressure (see their discussion). An ignition pressure of \( p = 2 \times 10^{19} \text{ dyne} \)
cm$^{-2}$ would have $10^{-5}$, $10^{-4}$ and $10^{-3} M_{\odot}$ contours which are vertical lines at $M_{\text{WD}} = 1.3$, 1.0 and 0.58 $M_{\odot}$. (This ignition pressure is used by Gehrz et al. (1998) in their discussion of the nucleosynthetic impact of nova ejections.) As we will see, most CNe have $M \sim 10^{-3} M_{\odot}$ yr$^{-1}$, and thus lower $M_{\text{ign}}$ than this prescription implies.

Also shown in Figure 1 is the region (hatched) where steady burning is expected. For $0.52 \leq M_{\text{WD}}/M_{\odot} \leq 0.68$, the calculations of Pierantoni et al. (2003) are shown. For $M_{\text{WD}} \geq 0.6 M_{\odot}$, the upper bound is found from the core mass-luminosity relation of Paczynski (1970), and the lower bound is taken to be 0.4 of this (Nomoto 1982). At higher $M$, envelope buildup and expansion into a giant is expected.

3. THE CLASSICAL NOVAE ORBITAL PERIOD DISTRIBUTION

The observed distribution of CN orbital periods (Warnet 2002) is shown in Figure 2 by the thin solid line. These data differ only very slightly from the collection in Ritter & Kolb (2003). We have neglected any selection effects, as they have not been satisfactorily quantified to date. These are complex, so we will not attempt a conclusive discussion, only mention two important ones, CN outburst brightness and remnant brightness. The tables in Prialnik & Kovetz (1995), for the coldest $T_{c}$ and $M_{\text{WD}} = 1 M_{\odot}$, imply that CN outbursts for systems with $M \sim 10^{-10} M_{\odot}$ yr$^{-1}$ are 3-4 times as bright as those for systems with $M \sim 10^{-8} M_{\odot}$ yr$^{-1}$. However, the spatial distribution in the Galaxy and the effects of absorption must be considered in order to judge how the observed population reflects this brightness variation. (See Ritter et al. [1999] for some discussion.) It is likely that remnant brightness depends on $M_{\text{f}}$ and thus $P_{\text{orb}}$, introducing additional selection effects in remnant recovery and characterization.

3.1. Using Previous Population Synthesis Calculations

In order to calculate the CN frequency we must first use the IMB prescriptions to obtain $M_{\text{f}}$ from $P_{\text{orb}}$. Since the secondary fills its Roche Lobe, $P_{\text{orb}}$ is directly related to $M_{\text{f}}$ by its mass-radius relation. We enforce $R_{2} = 0.46 a(M_{2}/M_{\text{WD}} + M_{3})^{1/3}$, so that $P_{\text{orb}} = 9$ hr $(M_{2}/M_{\odot})^{-1/2} (R_{2}/R_{\odot})^{3/2}$. To reproduce IMB for $P_{\text{orb}} > 3$ hours we use the magnetic braking law from HNR (see also Rappaport, Verbunt, & Joss 1983)

$$J_{\text{mb}} = -9.4 \times 10^{38} \left( \frac{M_{2}}{M_{\odot}} \right) \left( \frac{R_{2}}{R_{\odot}} \right)^{3} \left( \frac{P_{\text{orb}}}{\text{hr}} \right)^{-3}.$$  

When the binary is evolving under the influence of magnetic braking, the $M_{2}$ is large enough that the secondary is out of thermal equilibrium and therefore has a larger radius than a main sequence star of the same mass (the effect that leads to the period gap). In order to account for this we use the $M_{2}-R_{2}$ relation found by HNR using a bipolype model for the secondary and evolving under equation 1, $R_{2}/R_{\odot} = 0.81 (M_{2}/M_{\odot})^{0.67}$. For $P_{\text{orb}} < 3$ hours, we apply gravitational radiation losses given by

$$J_{g} = \frac{32 G Q a^{5}}{5 c^{5}} \left( \frac{a}{R_{\odot}} \right)^{4} \left( \frac{M_{\text{WD}} M_{3}}{M_{\odot} M_{\odot}} \right)^{2} \left( \frac{P_{\text{orb}}}{\text{hr}} \right)^{-5},$$  

where $Q$ is the moment of the binary about the orbital center, $\omega = 2\pi/P_{\text{orb}}$, $a$ is the orbital separation and $M_{s} = M_{\text{WD}} + M_{3}$. We use $R_{2}/R_{\odot} = 0.71 (M_{2}/M_{\odot})^{0.77}$ for a star in thermal equilibrium also from HNR. These $M_{2}-R_{2}$ relations give a period gap (transition from the former to the latter) at 2-3 hours when the donor is 0.21 $M_{\odot}$, as found for this “standard model” (Model A) in HNR.

In addition to $M_{\text{ign}}$ and the IMB prescriptions we also require a CV population model to construct the CN orbital period distribution. Detailed Monte Carlo CV population models are explored by HNR and by Nelson et al. (2004), in the same context as here, but without the TB04 predictions of $T_{c}$ from $M_{\text{f}}$. HNR calculated the number of CVs per period interval, which we denote $n_{P}$ so that $n_{P} dP$ is the number with orbital periods between $P$ and $P + dP$. We use a single characteristic mass in lieu of a detailed $M_{\text{WD}}$ distribution. For the HNR population we use $M_{\text{WD}} = 0.72 M_{\odot}$, the average CN $M_{\text{WD}}$ for their populations, and $X_{\text{He}} = 0.001$.

Using the above relationships to obtain $M_{s}$, $n_{P}$ from HNR, and the $M_{\text{ign}}$ from TB04, the resulting CN distribution is shown by the dashed line in Figure 2 and is normalized to match at $P_{\text{orb}} = 3.5$ hours. The most noticeable difference between this and our steady-state model presented below (thick solid line) is how the CV population based on HNR drops off at long $P_{\text{orb}}$ due to the CVs being born throughout the 3.5-6 hour range. The exact form of this turnover depends on the common envelope phase (Nelson et al. 2004) through the orbital period distribution of the common envelope products. By construction, the HNR distribution lacks systems in the
period gap. Every system which comes into contact with a companion that has a radiative core \((P_{\text{orb}} \gtrsim 2.4 \text{ hours})\) goes through a MB phase. This distribution matches quite well in both the 1-2 hour and 3-4 hour regions, keeping in mind the \(\sqrt{N}\) noise present in the observed distribution. The HNR population extends down to 1 hour due to the famous discrepancy in the period minimum between observation and theory (Kolb & Baraffe 1999).

### 3.2. Simpler Population Calculations

In order to understand how the \(P_{\text{orb}}\) distribution depends separately on the distribution of \(M\) and the CV birth distribution, we also construct a steady-state population with a specified birth distribution. CVs are born (i.e. come into contact and initiate mass transfer for the first time) at a variety of orbital periods determined by the distribution of \(M_{\text{WD}}\) and \(M_2\) after the common envelope event. For a population of \(n_p\) CVs per period interval with characteristic mass \(M_{\text{WD,}n}\), conservation implies

\[
\frac{\partial n_p}{\partial t} = \frac{\partial (n_p P_{\text{orb}})}{\partial P_{\text{orb}}} + b_P,
\]

where \(b_P\) is the CV birth rate per period interval, i.e. the number of CVs per year which commence accretion for the first time between \(P\) and \(P + dP\). We assume that all matter accreted from the companion is ejected in the CN, consistent with current observations (TB04), so that \(M_{\text{WD}}\) is constant. We also assume that the CV birthrate has been constant over the last 4 Gyrs, the time it takes a CV to reach the period minimum at \(P_{\text{orb}} \approx 80\) minutes (HNR). Beyond this point the companion becomes essentially fixed in radius, so that the binary expands and \(M\) drops quickly. These assumptions give a steady-state \((\partial n_p/\partial t = 0)\) CV population whose number density per period interval from equation (3) is

\[
n_p = \frac{1}{P_{\text{orb}}} \int_{P_{\text{orb}}}^{\infty} b_P dP,
\]

where we assume no systems at large \(P_{\text{orb}}\).

As noted above, the secondary’s mass-radius relation is well characterized by a power law, and so for Roche Lobe filling systems \(\alpha = d \ln P_{\text{orb}} / d \ln M_2\) is approximately a constant, typically between 0.5 and 1. Thus 
\(P_{\text{orb}} = -M_0 P_{\text{orb}} / M_2\) and the CN frequency per period interval is

\[
\nu_P \equiv \frac{M}{M_{\text{ign}}} n_p \propto \frac{M_2 / P_{\text{orb}}}{M_{\text{ign}}}.
\]

The direct dependence on \(M\) cancels for this observable. By far the most important part of the remaining \(M\) dependence is in \(M_{\text{ign}}\). Evaluating across the period gap, \(M_2\) is constant, while \(P_{\text{orb}}\) changes by 50% due to bloating of the companion above the gap. On the other hand \(M\) is expected to change from \(10^{-3} M_\odot\) yr\(^{-1}\) to \(5 \times 10^{-11} M_\odot\) yr\(^{-1}\), causing \(M_{\text{ign}}\) (from Figure 1) to increase from \(\approx 10^{-5} M_\odot\) to \(\gtrsim 10^{-4} M_\odot\), a factor of \(> 10\). Thus the CN orbital period distribution directly reflects \(M\) through its effect on \(M_{\text{ign}}\). With the consistent calculation of \(M_{\text{ign}}\) from \(M_{\text{WD}}\) provided by TB04, we can probe the \(M-P_{\text{orb}}\) relation directly by comparing the steady state population to observations. Evidence for evolution across the gap is then contained in the degree to which a single steady state distribution can reproduce the observations.

We use a binary with \(M_{\text{WD}} = 1.0 M_\odot\) as representative, since the actual mass distribution is very sensitive to the common envelope prescription (Nelson et al. 2004). Also, we set \(X_{\text{He}} = 0.001\) because this is the approximate level expected in the accreted matter (See section 2). In order to account for the possibility of systems which do not undergo magnetic braking, we use three populations. The first follows the IMB scenario (the IMB population), while the others only have \(J_{\nu}\) applied (the NMB [No Magnetic Braking] populations). In the NMB case the secondary mass-radius relation is that of an equilibrium main sequence star from HNR.

Though the detailed form of the birth distribution above the gap is sensitive to the CE prescription (HNR: Nelson et al. 2004), we employ a constant \(b_P\) between 3 and 5.5 hours for the IMB population. This captures the contrast in classical nova rate across the gap without depending explicitly on a particular CE prescription. CVs born with \(P_{\text{orb}} \lesssim 2.5\) hours do not undergo magnetic braking in the IMB scenario. We call this population the NMBb (NMB below gap) population, and it has \(b_P\) constant between 1.3 and 2.5 hours. A second NMBa (NMB all periods) population represents systems which do not undergo magnetic braking regardless of their birth \(P_{\text{orb}}\) (see discussion of magnetic systems below). This population has a constant birth function between 1.3 and 5.5 hours. Note that, unlike the HNR population, we directly specify the minimum \(P_{\text{orb}}\). These birthrates can then be used in equation (4) and (5), and the relative birth fractions for each population are given by \(b_P (P_{\text{max}} - P_{\text{min}})\).

This steady state population is shown as the thick solid line in Figure 2, arbitrarily normalized to match the observed distribution (thin solid line) at 3.5 hours. The relative birth fractions for the curve shown are NMBa: 8%, IMB: 46%, NMBb: 46%. This model reproduces the major features of the observed population below 4 hours, including the slope in the cumulative distribution between 3 and 4 hours. The dependence on the common envelope prescription and binary population parameters is essentially contained in the average \(M_{\text{WD}}\) to which the shape of the curve is insensitive. The effect of a 30% change in \(M_{\text{WD}}\) is small compared to the > 20 times difference in \(M\) across the period gap.

The contrast in CN rate across the period gap does have some dependence on \(X_{\text{He}}\). Under gravitational braking only, as is the case below the period gap, \(M\) is low enough that \(M_{\text{ign}}\) is insensitive to \(X_{\text{He}}\). However, the CN rate above the period gap, where magnetic braking enhances \(M\), does depend on \(X_{\text{He}}\). The dependence can be estimated by using the ionization density, \(\rho_{\text{ign}} \propto T^{-3.2} X_{\text{He}}^{-1/2}\) from TB04, and combining with an ideal gas EOS, \(M_{\text{ign}} \propto \rho_{\text{ign}} T_{\text{ign}}\), and the power-law form of a free-free radiative envelope \(T \propto P^{2/8.5}\) to obtain 
\(\nu_P \propto 1 / M_{\text{ign}} \propto X_{\text{He}}^{0.33}\). This scaling is confirmed by numerical calculations. Thus the expected maximum value of \(X_{\text{He}} = 0.003\) (see Section 2) leads to a 50% enhancement of the CN rate above the period gap over \(X_{\text{He}} = 0.001\). Matching this new normal distribution to the observations at 3.5 hours, the rate below the gap is 2/3 of that shown in figure 2, still consistent with the observations. Thus the value we have adopted, \(X_{\text{He}} = 0.001\) is expected from donor evolution and provides the best fit to the data when birthrates above and below the period gap are assumed to be approximately equal.

The observed orbital period distribution of CN is consistent with CVs evolving across the period gap, and magnetic braking between 3 and 4 hours governed by a law like equation 1. As shown by the thick (model) and thin (data) solid lines in figure 2 the contrast between the 1-2 and the 3-4 hour ranges is of the appropriate size for a population in which \(J\) above 3 hours is enhanced by magnetic braking. This contrast in CN
rate is entirely due to the dependence of $M_{\text{ign}}$ on $M$.

3.3. Magnetic Accretors with No Magnetic Braking

The two components included in the model population, IMB and NMB, are also shown separately as the dot-dashed and dotted lines. These demonstrate the significant enhancement that magnetic braking implies in the CN rate over gravitational radiation alone. The prediction of a NMB model with $b_p = 0$ (all systems being born at long periods) falls weakly to shorter orbital period in the normal distribution, as for the IMB curve below 2 hours. With a constant $b_p$, a NMB model monotonically increases to shorter orbital periods as seen for the dotted lines. Thus a NMB model alone is inconsistent with the observed orbital period distribution. The period distribution is also satisfactorily reproduced without the addition of the NMB population, making our confirmation of the IMB prescriptions and evolution across the gap robust with some evidence for additional systems in and below the gap. Measurement of this additional contribution is limited by the current quality of data.

There are two reasons a CV might not undergo the MB phase. For example, if MB cannot work when the companion is fully convective, then there is a minimum companion mass ($0.25M_\odot$) for having an MB phase. We have implemented this by placing all systems born with $P_{\text{orb}} < 2.5$ hours in a NMB population. This can also be seen in the the small number of systems between 2 and 2.5 hours in the HNR population. Additionally, motivated by the lack of a clear period gap for magnetic CVs (Verbunt 1997, Li et al. 1998) have conjectured that in Polars the WD magnetic field prevents MB. Recent $T_{\text{eff}}$ measurements of magnetic WDs (Araujo-Betancor et al. 2003, Gnäcke & Townsley 2005) show that above the period gap, magnetic CVs have a significantly lower $M$ than Dwarf Novae at the same orbital period, providing direct evidence that magnetic CV evolution is quite different from that of non-magnetic systems.

The absolute relative populations of magnetic and non-magnetic CVs is not well known because they are dominated by different and difficult to quantify selection effects. Approximately 22% of known CVs are magnetic (Araujo-Betancor et al. 2003). Using this steady state two component population model we find that, due to the slower evolution in the absence of MB, this requires that 8% of CVs born have strongly magnetic WDs, comparable to the fraction among field WDs (Jordan 1997, Wickramasinghe & Ferrario 2000). While giving tantalizing hints, the small number of observed systems makes it impossible to separate the prospective magnetic and non-magnetic contributions to the NMB population.

4. DISCUSSION AND CONCLUSION

We have shown that a very simple CV population model with the assumptions of IMB and the $M_{\text{ign}}$ calculated by TB04 reproduces the orbital period distribution of CN, supporting the idea that CVs evolve across the period gap. This agreement is independent of the outcome of the common envelope phase or properties of the primordial binary population. CN are one CV phenomena that is sensitive to $M$ averaged over the longest timescales, the CN recurrence time, $10^3 - 10^7$ years. The agreement with IMB provides additional evidence that the IMB prescriptions do indeed provide accurate long term average $M$’s for CVs. Townsley & Bildsten (2003) similarly found that the WD $T_{\text{eff}}$ in dwarf nova systems, which reflects $M$ due to compression of the envelope, matches the predictions of IMB. The existence of CN with $P_{\text{orb}}$ in the period gap implies that not all systems undergo IMB evolution, possibly due to inhibition of the secondary’s wind by a strong WD magnetic field (Li et al. 1994). This inhibition will lead to slower evolution of magnetic CVs, and thus increase their relative number in the CV population. We find that in order to obtain the 22% fraction of magnetic CVs observed (Araujo-Betancor et al. 2005), a relative birth fraction of magnetic CVs of 8% is required, comparable to the fraction among field WDs (Jordan 1997, Wickramasinghe & Ferrario 2000).

With a satisfactory $M$ distribution in hand, the total number of classical novae observed provides a measurement of the CV population. This conversion does not depend directly on CE parameters, because a relatively small number of both observed novae and CVs in general have $P_{\text{orb}} > 4$ hours, where the birth distribution is important. The conversion does, however, depend on the typical WD mass, due to its importance in setting $M_{\text{ign}}$. Note also that while most CV WDs have $M_{\text{WD}} \lesssim 0.7M_\odot$, including many helium WDs (HNR), the average CN mass is sensitive to the upper end of the mass distribution (Nelson et al. 2004). Knowledge of the $M$ distribution allows proper adjustment for the fact that while most CVs are below the period gap, most CN are in CVs above the period gap. This is a fairly short-lived period of the CV’s lifetime, lasting only $\sim 100$ Myr (HNR), which is preceded by the post common envelope inspiral and followed by accretion below the period gap during which the CN rate is much lower. We find that one CN per year implies $3 \times 10^3 (9 \times 10^3)$ CVs above the period minimum, $t \lesssim 3$ Gyr (4 Gyr) and a CV birthrate of $10^{-3} \text{yr}^{-1}$ ($2 \times 10^{-4} \text{yr}^{-1}$) if the average CN mass is $1.0M_\odot$ ($0.6M_\odot$).

Since pre-CVs finish the common envelope phase with a wide range of orbital periods, the total CV and pre-CV population, and thus the CN rate, should relate to the total amount of low-mass stars, which is well represented by the K-band light. The apparent dependence of nova rate on stellar population is still uncertain, but points to these older populations. Surveys of nova rates in external galaxies (Williams & Shafter 2004) continue to show that the K-band specific nova rate is about $2 \pm 1 \times 10^{-10} L_\odot^{-1} \text{yr}^{-1}$ and does not depend strongly on galaxy type in nearby galaxies, with the exception of the LMC and SMC. M31 shows evidence that the classical nova rates might be dominated by the bulge population (Shafter & Irby 2001). Our work allows us to convert the K-band specific Nova rate into the CV population and birthrate, giving $60-180$ CVs above the period minimum for every $10^6 L_\odot$, in an old stellar population and $2(4) \times 10^{-4}$ CVs born per year per $10^6 L_\odot$. The 24-133 CVs estimated from Chandra observations of 47 Tuc (Heinke et al. 2005) is consistent with the 60-180 predicted by our work for the cluster mass ($10^8 M_\odot$, Pryor & Meylan 1993), and agrees with the CN rate implied by the one or two CNe observed in the last $\sim 140$ yr in the Galactic GCs (Shara et al. 2004). Thus the GC CV population appears comparable to that in the field. The Type Ia supernova rate in elliptical galaxies is $3.5 \pm 1.3 \times 10^{-4}$ per year per $10^9 L_\odot$ (Mannucci et al. 2004), remarkably close to the CV birthrate. However, all indications are that the WD masses in CVs are not nearly large enough (TB03) to be Type Ia progenitors (Branch et al. 1998).

The local galactic K-band luminosity density is $0.1-0.2 L_\odot \text{pc}^{-3}$ (Ohlhe & Merrifield 2001), giving a local CV space
density of approximately $9(27) \times 10^{-6}$ pc$^{-3}$ again for an average mass of $1.0 (0.6)$ $M_{\odot}$. This agrees well with the $2 \times 10^{-5}$ pc$^{-3}$ found by Politano (1996) from a theoretical calculation of the CV birthrate. This space density is only slightly higher than the $6 \times 10^{-6}$ pc$^{-3}$ inferred from the PG survey (Ringwald, 1996), but more than 10 times the $8 \times 10^{-7}$ pc$^{-3}$ obtained by Downes (1986). Both these survey numbers assume a scale height of CVs of 150 pc, whereas the above K-band luminosity density assumes a scale height of low mass stars of 300 pc. Although more modern color selected surveys exist, the lack of a broadly applicable, accurate CV distance measure hinders improved measurements of the space density.

In a similar manner, the total rate of matter injected into the ISM can be evaluated in terms of the CN outburst rate. Since we are assuming that all the matter transferred onto the WD is ejected in each CN outburst, this is just the average $M$ for the population times the total number of systems. We find that $3 \times 10^{-5} M_{\odot}$ yr$^{-1}$ (9 $\times 10^{-5} M_{\odot}$ yr$^{-1}$) is ejected into the ISM for each CN/yr if the average CN mass is 1.0 ($0.6 M_{\odot}$). The average initial mass of the donor contributes additional uncertainty, but generally less than that due to the unknown average WD mass. Though somewhat lower than the value of $2 \times 10^{-4} M_{\odot}$ per CN outburst found by Truran & Livio (1986), these values are similar to the $10^{-4} M_{\odot}$ per outburst used by Gehrz et al. (1998) to estimate the impact of nucleosynthesis in CN outbursts on both the ISM and primordial solar system material. An interesting effect of the contrast in $M$ across the gap is that while approximately 85% of CN outbursts occur above the period gap and only 2% of pre-period minimum systems are above the gap, approximately equal processed matter is contributed by objects above and below the period gap before the period minimum. This means that the type of CN which are observed most often are only half the story for ISM injection.

With proper calibration, classical novae provide a useful standard candle for extragalactic distance measurements (della Valle & Livio, 1993). The principle impediment to this usage is that the single measured parameter available for calibration, the rate of decline, depends on $M_{WD}$, $M$, and $T_c$. TB04 calculated $T_c$ consistently from $M$, eliminating it as a free parameter. Here we have demonstrated that IMB provides a satisfactory prediction of the $M$ distribution in the Galactic CV population, finding that CN outbursts occur predominantly when $M \sim 10^{-3} M_{\odot}$ yr$^{-1}$, with a significant tail at lower $M$. This leaves only $M_{WD}$ to be calibrated from the rate of decline. Thus, with the support of theory, a statistically complete measurement of nova magnitudes and decline rates may be sufficient to measure the distance to an external galaxy.

We thank Boris Gänsicke for discussion and early access to observational data. This work was supported by the National Science Foundation under grants PHY99-07949, and AST02-05956, and by NASA through grant AR-09517.01-A from STScI, which is operated by AURA, Inc., under NASA contract NAS5-26555. DMT is supported by the NSF Physics Frontier Centers’ Joint Institute for Nuclear Astrophysics under grant PHY 02-16783 and DOE under grant DE-FG02-91ER 40606.

REFERENCES

Gänsicke, B. T. & Townsley, D. M. in preparation
Paczynski, B. 1970, Acta Astronomica, 20, 47