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# A MODEL FOR THE SPACE DENSITY OF DWARF CARBON STARS

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## ABSTRACT

Recent studies of faint high-latitude carbon stars have shown that a significant fraction of them are not distant asymptotic giant branch (AGB) stars but rather belong to the local population of spheroid dwarfs. In this paper we attempt a theoretical prediction of the local space density of such dwarf carbon stars (dCs), based on the assumption that they are ordinary main-sequence stars that were able to accrete enough carbon-enriched material from a binary companion on the AGB to make their C/O ratio larger than unity.

A simulated population of dCs is constructed by following the evolution of a large number of binaries using simple analytic fits to detailed evolutionary calculations and determining which ones would presently contain a dC. The zero-age parameters of the sample are chosen randomly from distributions derived from the observed properties of unevolved binaries.

The space density of halo dCs that we predict ($\sim 2$–$4 \times 10^{-7}$ pc$^{-3}$) is in agreement with current observational constraints. The predicted local space density of disk dCs ($\sim 1 \times 10^{-6}$ pc$^{-3}$) may be somewhat higher than observed. The fraction of binaries that produces dCs depends strongly on initial metallicity, and virtually no dCs are formed in systems with an initial metallicity of more than half solar. Thus, all disk dCs are predicted to be in binaries that formed in the very early phases of disk star formation, and their number depends strongly on assumptions about the age–metallicity relation during this epoch. The predictions for the halo are much less model-dependent.

The simulated orbital period distributions are bimodal, with one peak between $10^3$ and $10^5$ days and another peak between $10^2$ and $10^3$ days. The shorter period component is caused by systems that have gone through a common envelope phase. The simulated period distributions bear a strong resemblance to the observed orbital period distribution of barium and CH giants, which may be the evolved descendants of the disk and halo dC populations we have modeled.

*Subject headings:* accretion, accretion disks — binaries: general — stars: carbon — stars: evolution — stars: statistics

## 1. INTRODUCTION

Main-sequence stars do not produce carbon, so it has been widely assumed that faint carbon (C) stars are simply distant examples of the classical, bright C giants. The first exception, G77-61, was discovered on the main sequence by Dahn et al. (1977). This $V = 13.9$ star has a classical C spectrum but a high proper motion and thus most certainly main-sequence luminosity. G77-61 was found to be a spectroscopic binary with an orbital period of 245 days and a measurable trigonometric parallax (yielding a distance of 58 pc; Dearborn et al. 1986). These authors argued that the most reasonable explanation of the prominent carbon bands in the dwarf's spectrum is mass transfer from a now unseen companion during the companion's thermally pulsing asymptotic giant branch (TP-AGB) phase. More recently, four further dwarf carbon stars (dCs) were recognized by their high proper motions (Green, Margon, & MacConnell 1991; Green et al. 1992). At least two more dCs were soon discovered by similar means (Warren et al. 1993). In addition, Heber et al. (1993) found that PG 0824+289, a hot DA white dwarf, is in a double-line spectroscopic binary with a dC companion of absolute magnitude very similar to G77-61 ($M_V \approx +10$). Another DA/dC composite system, CBS 311, was recently discovered by Liebert et al. (1994). Both these hot DA/dC systems appear to have low proper motions (Deutsch 1994).

The three dCs currently proven to be in binary systems (G77-61, a radial velocity binary, and PG 0824+289 and CBS 311, with composite spectra) provide strong experimental confirmation for the theoretical inference that dCs must be binaries and that the post-AGB binary companions must be white dwarfs. Furthermore, the *IUE* upper limit of 6000 K for the companion to G77-61 (Dearborn et al. 1986), along with a temperature near 60,000 K for the EUV-emitting DA companion to PG 0824+289 (Heber et al. 1993), shows that white dwarf (WD) companions to dCs exhibit an exceptionally wide range of temperatures. The observed wide temperature range of these WDs in turn suggests a wide range of times since mass transfer in the dC/WD systems. Since dCs are innocent bystanders to AGB mass transfer, they should be found in both the spheroid and the disk. Most of the known dCs were originally recognized as dwarfs because of their high proper motion, and these have the large space velocities characteristic of the old halo population (Green et al. 1991). For instance, G77-61 has a large proper motion and space velocity, with a cool companion. In contrast, both of the confirmed dC/DA systems have

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low proper motions, implying that they may belong to the disk population, and very *hot* companions, indicating that the mass transfer phase occurred only recently. The high proper motion/cool WD and low proper motion/hot WD binary systems may thus represent examples of spheroid and disk dCs, respectively.

## 2. OBSERVATIONAL LIMITS ON THE SPACE DENSITY OF CARBON DWARFS

From large-area (objective-prism and CCD) surveys, Green et al. (1994) provide a crude estimate for the surface density of faint high-latitude carbon (FHLC) stars of about 0.02 $\deg^{-2}$. From their proper-motion survey of 39 FHLC stars, Green et al. (1992) have estimated that at least $\approx 13\%$ of FHLC stars are spheroid dwarfs. Their proper-motion survey thus provides a lower limit to the surface density of dCs of $A_{\rm dC}^{\rm spher} = 0.0026$ $\deg^{-2}$. The best estimates available (Dearborn et al. 1986; Heber et al. 1993; Liebert et al. 1994) are consistent with the assumption that most dCs have luminosity similar to G77-61 ($M_V \approx 10.2$). For purposes of illustration, we conservatively take the surveys to be complete to $V = 18$, corresponding to a distance of $\approx 400$ pc for dCs. The resulting local space density of high proper motion (i.e., spheroid) dCs is thus estimated to be at least $N_{\rm dC}^{\rm spher} \approx 4 \times 10^{-7}$ $\rm pc^{-3}$.

It is more difficult to estimate the dC space density due to the disk population, since disk dCs are much less likely to have large proper motions. Bahcall & Soneira (1984) estimate the ratio of local space densities of disk and spheroid stars to be $N^{\rm disk}/N^{\rm spher} \approx 500$. We assume for a first estimate that the distribution of both disk and spheroid stars is homogeneous out to 400 pc. If evolution of dCs were identical in disk and spheroid, by comparison to our estimate of $A_{\rm dC}^{\rm spher}$ above, this would imply a surface density of disk dCs to $V = 18$ of $A_{\rm dC}^{\rm disk} \approx 1.3$ $\deg^{-2}$. Since this is more than a factor of 50 larger than the *total* FHLC surface density, we can say with some confidence that the fraction of dwarfs that are dCs ($f_{\rm dC}$) must be much smaller in the disk than in the spheroid.

Based on unavoidably heterogeneous compilations from the literature, Green et al. (1992) conclude that the local space density of dCs probably surpasses that of all other types of C stars combined. Their conclusion is probably conservative for two reasons: (1) magnitude limits typical of most surveys resulting in C star discoveries are too shallow to identify and sample even the closer of the very faint C dwarfs, and (2) only high proper motion objects were included in their dC sample. These considerations suggest that, contrary to the formerly prevailing paradigm, *dwarf C stars may be the numerically dominant type of carbon star in the Galaxy*. In this paper, we show that this conclusion is supported by the results of our theoretical study of the evolutionary scenario proposed for dCs.

Assuming that all dCs are the result of mass transfer in a binary system, the fraction of dwarfs that become dCs will depend on the complicated interaction of a large number of parameters describing the populations at hand. These may include the fraction of stars in binaries, the binary mass ratio distribution, distribution of binary orbital period, and semi-major axis, as well as the metallicity and age of the population. These latter two parameters clearly differ between the disk and spheroid populations. Since low metallicity facilitates driving C/O past unity, this difference may be responsible for the anti-correlation between metallicity and C/M AGB star ratios observed in the Galaxy (see, e.g., the bulge; Blanco & Terndrup 1989) and in Local Group galaxies (see, e.g., Aaronson, Olszewski, & Hodge 1983). Age and metallicity differences thus provide a likely explanation for the larger fraction of dwarfs that are dCs in the spheroid compared to the disk. Other effects such as the means of accretion (e.g., Roche Lobe overflow or wind) and mixing efficiency and depth in the accreting star currently preclude simple analytic predictions. In this work we have constructed simulated samples of dCs to determine whether reasonable assumptions lead to dC space densities that are compatible with observations and to investigate how these assumptions affect the expected properties of dCs.

## 3. METHOD

To construct the simulated samples, we use the following method. First, a zero-age binary is created by randomly choosing parameters from observationally determined distributions: primary mass, secondary mass, orbital separation, and time of formation (equivalent to metallicity). The evolution of the binary is then followed to determine whether this system could presently be observed as a binary containing a dwarf carbon star. By repeating this process for many choices of zero-age parameters, a simulated sample is constructed. The details of the simplified description of binary evolution that we have used are described in the subsections below.

### 3.1. *The Zero-Age Binary Parameters and Star-Formation Rate*

The first step in constructing our simulated samples is to assume some shape for the distribution of primary mass, orbital separation, mass ratio, and metallicity in zero-age binaries. The first two of these are not very controversial, and we use a primary mass ($M_1$) distribution according to Miller & Scalo (1979). For the orbital separation $a$ we take a distribution that is flat in log $a$ ($dN \propto d \log a$). The most likely shape of the mass ratio distribution $q$ ($0 < q < 1$) is still uncertain. The latest determinations (Mazeh & Goldberg 1992) seem to favor a flat distribution in $q$ ($dN \propto dq$). Earlier work (e.g., Duquennoy & Mayor 1991) found that the observed distribution is compatible with the assumption that the masses of stars in binaries are drawn independently from the same IMF, i.e., they are not correlated. We have calculated models using both of these prescriptions.

The age and metallicity distributions are described by a two-component model (Truran 1994). The disk population is modeled by an exponentially decaying star-formation rate (SFR) starting 12 Gyr ago, with a decay timescale of 5 Gyr. In this period, the metallicity increases from $Z_{D,i} = 2 \times 10^{-3}$ to $Z = 4 \times 10^{-2}$, at a rate proportional to the SFR. The formation of the halo is assumed to occur between 15 and 12 Gyr ago, with a constant SFR and a metallicity increasing from $Z = 10^{-4}$ to $Z_{D,i} = 2 \times 10^{-3}$.

The normalization of the formation rate of disk binaries with currently evolved primary stars has been derived from a comparison of the results of similar binary simulations with the observed white dwarf luminosity function (see de Kool & Ritter 1993, but with some modification as described below). The number of binaries formed in the halo-formation phase was chosen to reproduce the estimated local ratio of disk to halo stars of 500 to 1 (e.g., Bahcall & Soneira 1984). More recent estimates of this ratio (e.g., Morrison 1993 finds $850 \pm 300$ to 1) would lower the predicted number of halo binaries proportionately. Such ratios based on star counts themselves depend on the detailed modeling of Galaxy populations. Since we find below that disk dCs are likely to be old,

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the lower normalization of Bahcall & Soneira (1984) may be more consistent, since it is closer to the (smaller) old or thick disk space densities.

### 3.2. *The Evolution of the Primary Star*

Once the zero-age parameters of a binary are chosen as described above, we follow the evolution of the primary star to determine if it will be able to transfer a significant amount of C-enriched material to the secondary. Thus, we need to know the evolution of stellar radius, wind mass-loss rate, and chemical composition of the envelope, for a large range of initial mass and metallicity. These properties must be simple to calculate since we want to simulate a large enough population. Such a prescription for the later stages of stellar evolution is presented in a paper by Groenewegen & de Jong (1993, hereafter GdJ) on the properties of carbon stars on the AGB. A short outline is given here; for more details we refer the reader to GdJ. After a binary is created, we first calculate the core mass the primary will have at the first thermal pulse (GdJ; Lattanzio & Malaney 1989; Becker & Iben 1980). Using the core mass–luminosity and luminosity–effective temperature relations for AGB stars (GdJ; Boothroyd & Sackmann 1988; Iben 1977; Wood 1990), the radius of the primary at the first TP is then derived. If the orbital separation is such that the primary fills its Roche lobe before the first TP, the binary is discarded as a potential dC candidate, since the evolution will be cut short before C-enriched material can reach the surface of the primary. If the binary is wide enough for the primary to start the TP phase and begin dredging up processed material containing a high C abundance, the mass accretion onto the secondary is followed. First, the envelope mass and chemical composition at the first TP is derived (GdJ). Typically, 0.2 $M_\odot$ is lost in a wind before the first TP, and the chemical composition is slightly different from that at zero age as a result of a first and possibly a second dredge-up.

The TP phase is approximated as a continuous burning process. During this phase, a fraction $1 - \lambda$ of the material that goes through hydrogen and helium burning is added to the core, and a fraction $\lambda$ is assumed to be dredged up, changing the composition of the envelope. The composition of the burned material is 22% carbon, 2% oxygen, and 76% helium by mass. GdJ find a good fit to the observed C-AGB luminosity function in the LMC by taking $\lambda = 0.5$. If the core mass is less than a certain value, dredge-up is not supposed to occur. The critical core mass is assumed to be $M_{c,\mathrm{crit}} = 0.56 + 0.7\,(Y - 0.2)$, where $Y$ is the zero-age helium abundance. As the primary evolves, its envelope loses mass by a wind, at a rate given by a Reimers's law: $\dot{M}_1 = \eta(4 \times 10^{-13} LR/M)\ M_\odot\ \mathrm{yr}^{-1}$. We have used either $\eta = 3$ or $\eta = 1$, the first choice being the value preferred by GdJ. Using the SFR from the previous section and the stellar evolution model for the primary described here (with $\eta = 3$), our model predicts a current local space density of carbon AGB stars *in binaries* of $1.1 \times 10^{-7}$ $\mathrm{pc}^{-3}$, in very good agreement with the *total* space density of C-AGB stars derived observationally of $1.85 \times 10^{-7}$ $\mathrm{pc}^{-3}$ (from Table 1 of Jura 1991). Using $\eta = 1$ leads to an overproduction of C-AGB stars by a factor of 15.

We now have all the ingredients to follow the evolution of the binary through the AGB phase of the primary. Using typically a few hundred time steps, we follow the radius of the primary, the accretion rate on to the secondary (see below), the chemical composition of the wind material, and the evolution of the orbit due to wind mass loss and accretion either until the envelope is exhausted or until the primary fills its Roche lobe, leading to a common envelope (CE) phase.

### 3.3. *Orbital Evolution, Accretion, and Mixing*

The orbital evolution during the wind accretion phase is calculated using angular momentum conservation, with the assumption that the part of the primary's wind that is not accreted by the secondary leaves the system with the specific angular momentum of the primary. The accretion rate onto the secondary from the primary's stellar wind is treated in the Bondi-Hoyle approximation:

$$\dot{M}_2 = \dot{M}_1 \frac{R_A^2}{4a^2}, \quad R_A = \frac{GM_2}{v_{\mathrm{rel}}^2}.$$

Here $v_{\mathrm{rel}}$, the speed of the secondary relative to the wind, is taken as the sum of the orbital and wind velocities. Because winds from AGB stars are known to accelerate slowly, the secondary will usually be in the wind acceleration zone if significant accretion takes place. We use a fit to a wind acceleration model by Sedlmayr, Gail, & Dominik (1987),

$$v_{\mathrm{wind}} = 15[1 - e^{[(a-r)/2R]^2}]\ \mathrm{km\ s}^{-1},$$

where $R$ is the primary's radius.

If the primary fills its Roche lobe during the evolution, the system almost always enters a common envelope phase. The only exceptions are those cases in which either the giant envelope mass has become smaller than the core mass or the mass ratio $(M_2/M_1)$ has become larger than $\sim 1.2$, in which case stable mass transfer is possible (see, e.g., Webbink 1985; Hjellming & Webbink 1987). The outcome of the common envelope phase is predicted with the standard "$\alpha$-prescription" (see, e.g., de Kool & Ritter 1993), which assumes that a fraction $\alpha$ of the orbital binding energy liberated during the spiraling together of the secondary and the giant core is used for the expulsion of the envelope. A careful study (e.g., Iben & Tutukov 1989) of the evolution of several observed post-CE binaries leads to the conclusion that $\alpha \sim 1$, and we have used this value in our simulations. It is still an open question how much accretion onto the secondary can occur during a CE phase. In most models we will just assume that a fixed fraction $f_{\mathrm{CE}}$ of the primary's envelope is accreted. However, from the rather normal appearance of the secondary star in many post-CE binaries, we know that the amount of accreted mass is not likely to be very large.

From the accretion rate and the composition of the accreted material, we can calculate the abundances at the surface of the secondary if we make a further assumption about how the accreted material mixes into the star. It is certain that mixing will occur in the convective surface layers of the secondary, but it is not yet known to what extent mixing into the underlying radiative layers occurs. Proffitt (1989) and Proffitt & Michaud (1989) argued that the higher mean molecular weight of the accreted material leads to instability and rapid mixing even into radiative layers. On the other hand, the assumption of mixing into convective layers only is often used. We shall present results for both assumptions. (A minimum amount of mixing with a fraction $10^{-3}$ of the secondary mass is used if the mass in the convective envelope becomes very small.)

## 4. RESULTS

### 4.1. *The Standard Model*

We first present the results of our simulations for one "standard" set of assumptions (referred to as model A) and

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then investigate how these assumptions influence the outcome. These standard assumptions were based on what we considered to be the best a priori choice, i.e., without any attempt to fit observed distributions. They are the following:

1. A flat initial mass ratio distribution (IMRD) $dN \propto dq$;
2. A wind mass-loss rate $\eta = 3$;
3. The fraction of the primary's envelope accreted during a common envelope phase, $f_{CE} = 0.1$;
4. Complete mixing of accreted material into secondary;
5. Transition metallicity between halo and disk at $Z_{D,i} = 0.002$.

Other parameters enter the calculations, mainly describing the evolution of the primary star (see § 3.2). Since these have already been calibrated by detailed comparison with an observed sample of C-AGB stars in the LMC by GdJ, and since they predict the observed local space density of C-AGB stars rather well (§ 3.2), we will not vary them here. Table 1 summarizes the total space density of dCs that is predicted by the different models.

Figures 1*a*–1*c* show the expected space density of the current population of dCs in the standard model as a function of orbital period, mass, and C/O ratio. Note that these do not necessarily represent the distribution expected from observations, since selection effects can change these distributions significantly.

The orbital period distribution (Fig. 1*a*) is bimodal, with a large peak between $10^3$ and $10^5$ days and a smaller one below $10^3$ days. The smaller peak consists of those binaries that went through a CE phase near the end of the evolution of the primary. Since a significant overabundance of carbon only occurs when the primary envelope mass is already significantly reduced because of extensive mass loss, this CE phase does not result in extreme loss of orbital angular momentum—typically the separation is reduced by less than a factor of 10. The long-period peak is significantly broader for the halo component. The short-period end is shifted compared to the disk dCs because the lower initial metallicity in the halo causes the primary AGB radius to be smaller, allowing the systems to remain detached at shorter periods. The low initial metallicity also makes it easier to push C/O past unity, so that less accretion is necessary to produce a dC, allowing dCs to form in longer period binaries.

TABLE 1

PREDICTED LOCAL SPACE DENSITY OF DWARF CARBON STARS

| Model | $N_{spher}$[a] | $N_{disk}$[a] | Model Description |
|---|---|---|---|
| A..... | 1.9 | 8.0 | Standard |
| B..... | 3.9 | 21 | Uncorrelated masses |
| C..... | 3.6 | 37 | $\eta = 1$ |
| D..... | 1.7 | 5.5 | Zero accretion in CE phase |
| E..... | 3.6 | 95 | Mixing only in convective zone |
| F..... | 1.1 | 2.3 | Disk $Z_{D,i} = 0.004$ |

[a] Units of $10^{-7}$ pc$^{-3}$.

The carbon dwarf mass distribution is shown in Figure 1*b*. It is strongly peaked toward 1 $M_\odot$. This is mainly due to the

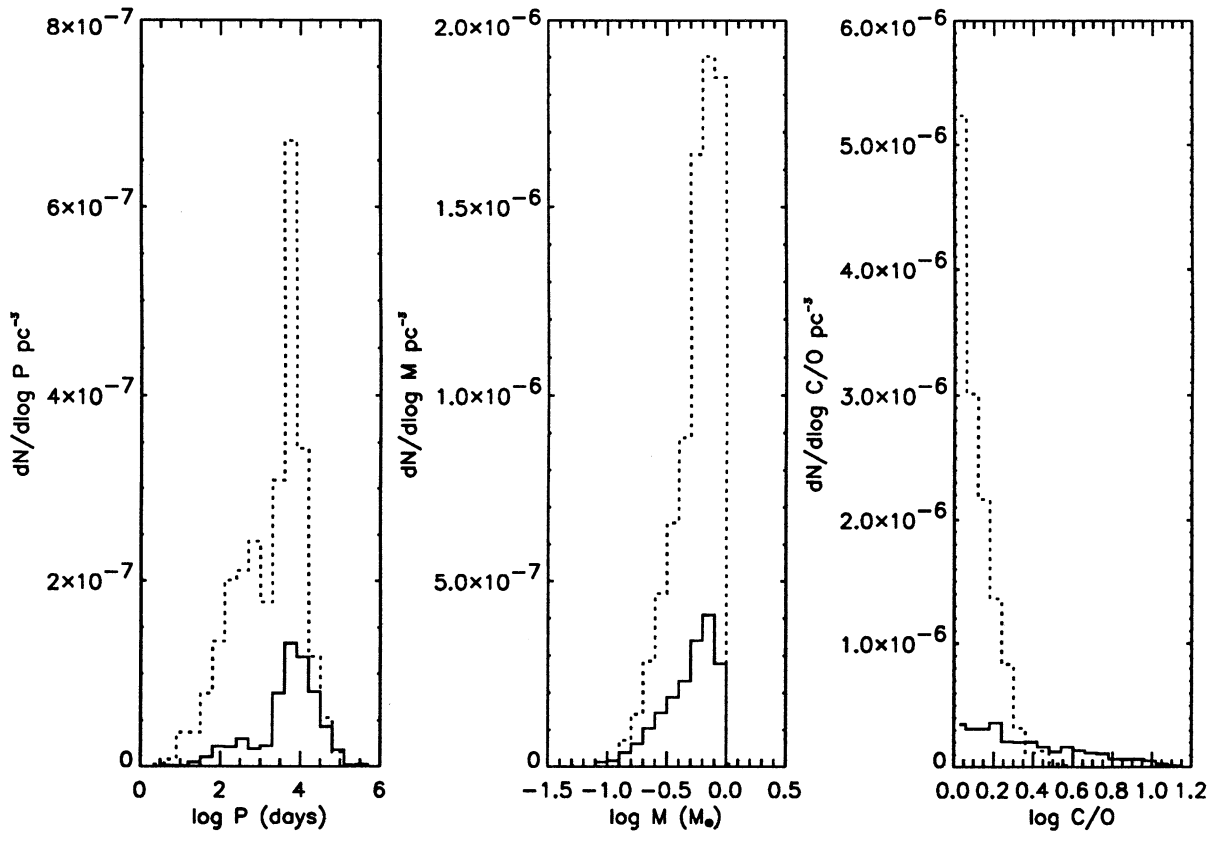


FIG. 1*a* FIG. 1*b* FIG. 1*c*

FIG. 1.—Distributions for model A: the standard model. (*a*) Orbital period distribution; (*b*) dC mass distribution; (*c*) C/O ratio distribution. The solid line shows the spheroid population; the dotted line shows the disk population.

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assumed IMRD (see below). The steep cutoff at $\sim 1\ M_\odot$ comes from the requirement that the dC is still on the main sequence. With the standard age–metallicity relation, almost all binaries that are observed to contain dCs were formed between 12 and 10 Gyr ago, with 10 Gyr roughly corresponding to $Z = 0.01$. Binaries formed with an initial $Z$ above this value cannot produce any secondaries with C/O > 1, and all dCs formed in the first 2 Gyr of disk star formation that were more massive than $\sim 1\ M_\odot$ have evolved from the main sequence by now. Note that the limit on the secondary mass does not lie at the mass where the evolutionary time is exactly 10 Gyr because a dC at the high-mass limit of the distribution has typically accreted a few tenths $M_\odot$ at some time *after* it was formed, amounting to 10%–20% of their original mass. Larger accreted fractions are rare and only occur when the original mass was not too small (greater than 0.3 $M_\odot$). Thus, it is not likely that many secondaries that were originally brown dwarfs were able to start nuclear burning after the mass accretion phase.

The old age of present disk dCs implies that they will have a larger scale height than the average disk population that was used to normalize the formation rate. We have assumed that kinematical evolution has increased this scale height by 50% compared to the average, thus diluting the disk dC population. Our predictions for the present space density have thus been reduced by a factor of $\frac{2}{3}$ over the results that would have been obtained with a straight application of the normalization of de Kool & Ritter (1993).

The distribution of C/O ratios is shown in Figure 1*c*. It is seen that very high C/O ratios can only be expected from halo dCs, which started with a very low initial metallicity. The disk dCs rarely have C/O > 3.

In Figure 2 we have plotted the expected correlations between the properties of 1000 halo dC binaries simulated in the standard model: log $P$ vs. log C/O, log $P$ vs. log $M$, and log $M$ vs. log C/O diagrams. It is clear that no tight correlations between any of these observable quantities are predicted. There seems to exist a very broad correlation between C/O and orbital period for the systems that did not experience a CE, in the sense that the mean C/O increases with decreasing period. To show this more clearly, we also plot the mean relation in Figure 2*a*, obtained by averaging the orbital period and C/O over 100 points after sorting them by increasing orbital period. This correlation, expected as a result of increased accretion for smaller separations, is present in all models, although it is generally less strong for the disk systems.

In the following sections we will change some of the assumptions made in the standard model and discuss how the results for these different assumptions compare with the results for model A.

### 4.2. *Changing the Initial Mass Ratio Distribution*

In Figures 3*a*–3*c* we show the properties of the dC sample if we do not take a flat distribution in the mass ratio of zero-age binaries but instead assume that the masses in binaries are uncorrelated, i.e., each star is picked independently from the same initial mass function (model B). This results in a much larger fraction of binaries with low-mass secondaries. The effect of this is an increase in the number of dCs by a factor of about 2.5 for the disk and 1.5 for the halo population.

In the disk population, the fraction of systems at short periods increases because low-mass stars accrete a larger fraction of their initial mass during the CE phase. The effect is not so strong for the halo population since in that case even higher mass stars will change their C/O ratio during a CE phase.

Figure 3*b* shows that, in this model, we do not expect the dC mass distribution to be peaked toward 1 $M_\odot$, which seems to be in better agreement with the low masses ($M \sim 0.4\ M_\odot$) inferred from the observed dC absolute magnitudes. On the other hand, weaker molecular bands may simply make dCs with higher effective temperatures more difficult to find.

### 4.3. *Changing the Wind Mass-Loss Rate*

As shown in Figures 4*a*–4*c*, decreasing the wind mass-loss parameter $\eta$ from 3 to 1 (model C) increases the number of expected dCs by a factor of 5 for the disk systems and a factor of 2 for the halo systems. The main reason for this is that the lower wind mass-loss rate gives the primary a longer lifetime while it is on the TP-AGB, thus allowing it to generate more carbon, which is subsequently accreted by the secondary.

### 4.4. *Changing the Accretion during the Common Envelope Phase*

Figures 5*a*–5*c* show the effects of turning off the accretion during the CE phase ($f_{CE} = 0$, model D). As expected, there result considerably fewer systems with orbital periods below $10^3$ days, and virtually none below $10^2$ days. These distribu-

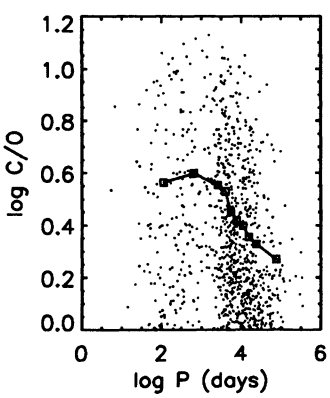


FIG. 2*a*

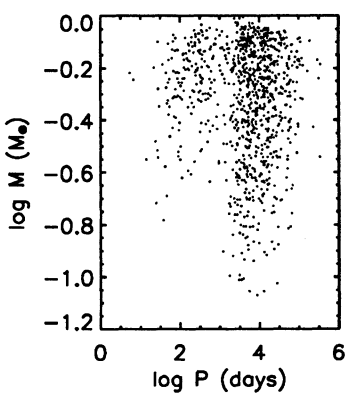


FIG. 2*b*

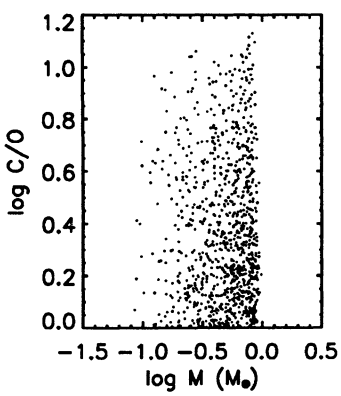


FIG. 2*c*

FIG. 2.—Correlations for the spheroid population in model A: the standard model. (*a*) log $P$ vs. log C/O; (*b*) log $P$ vs. log $M$; (*c*) log $M$ vs. log C/O. The connected points in Fig. 2*a* show the mean relation, derived as described in the text.

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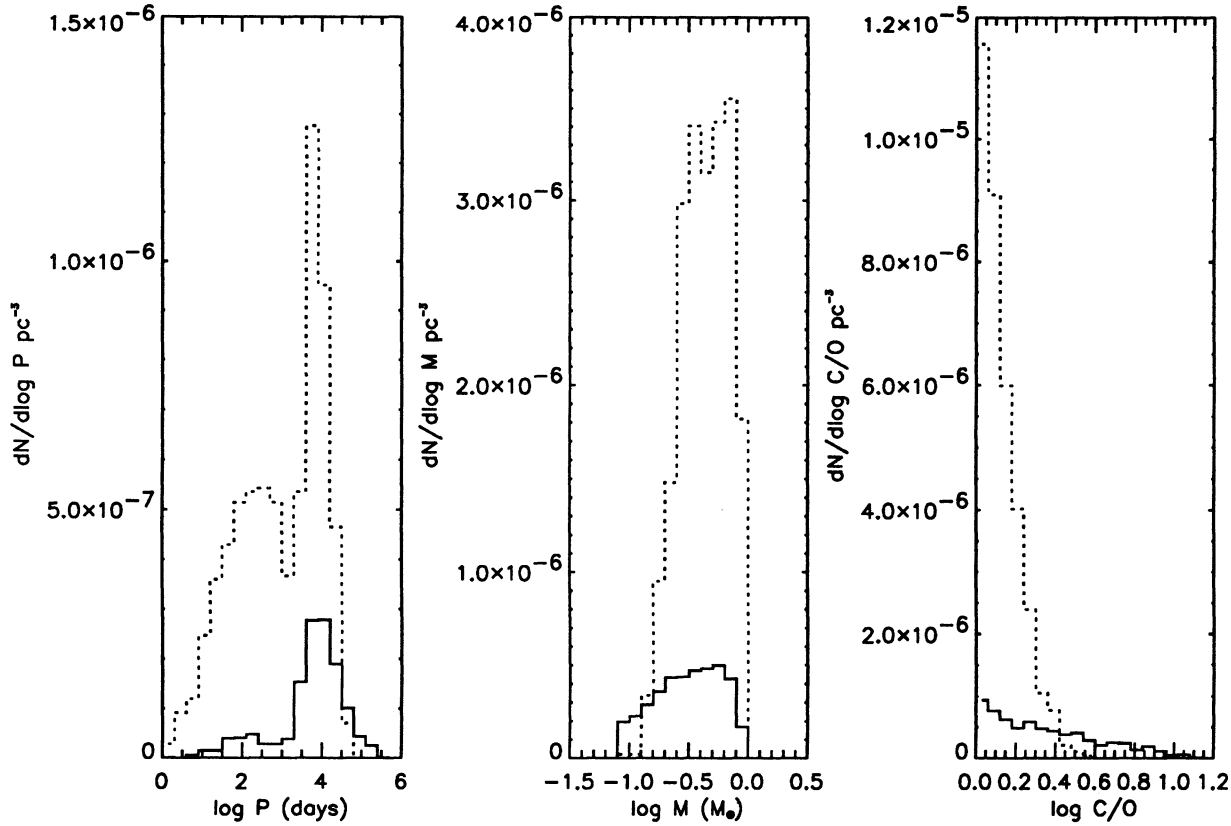


FIG. 3*a* FIG. 3*b* FIG. 3*c*

FIG. 3.—Distributions for model B: uncorrelated primary and secondary masses. (*a*) Orbital period distribution; (*b*) dC mass distribution; (*c*) C/O ratio distribution. The solid line shows the spheroid population; the dotted line shows the disk population.

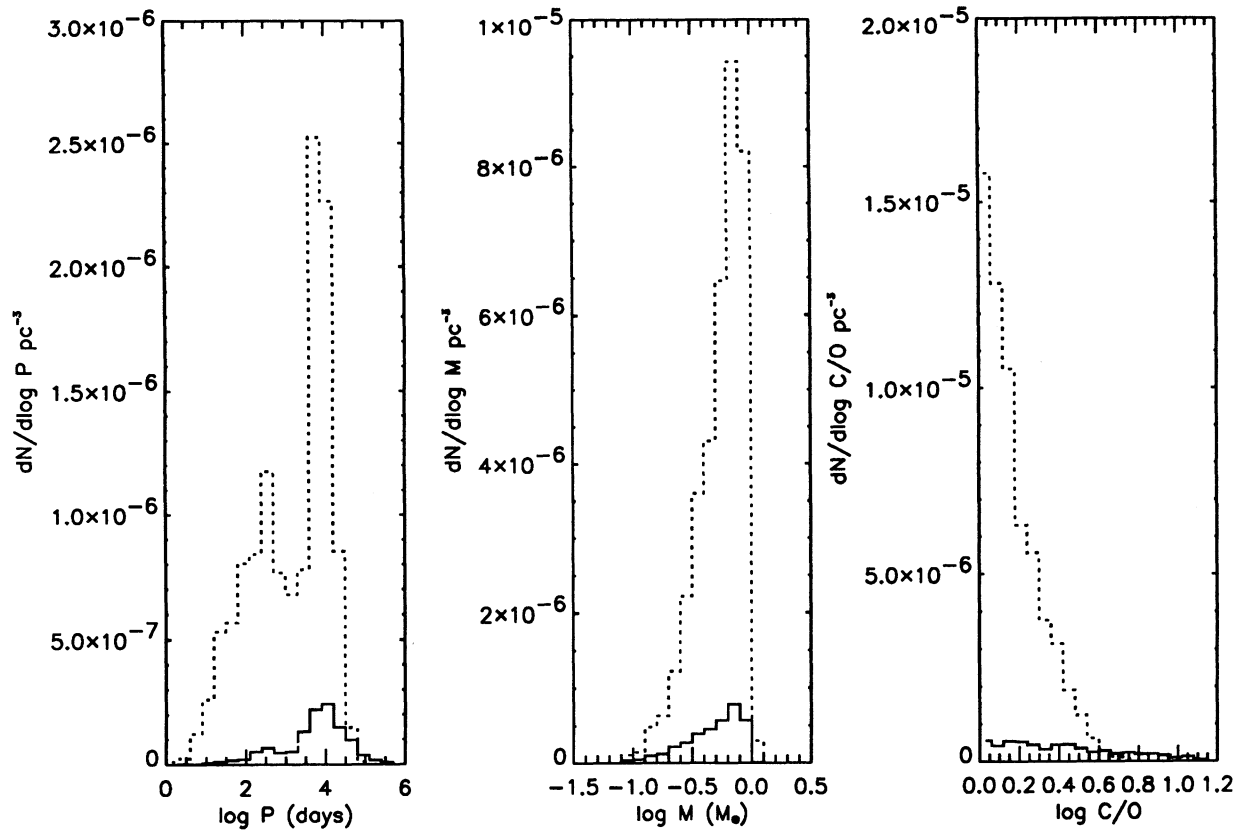


FIG. 4*a* FIG. 4*b* FIG. 4*c*

FIG. 4.—Distributions for model C: smaller wind loss parameter ($\eta = 1$). (*a*) Orbital period distribution; (*b*) dC mass distribution; (*c*) C/O ratio distribution. The solid line shows the spheroid population; the dotted line shows the disk population.

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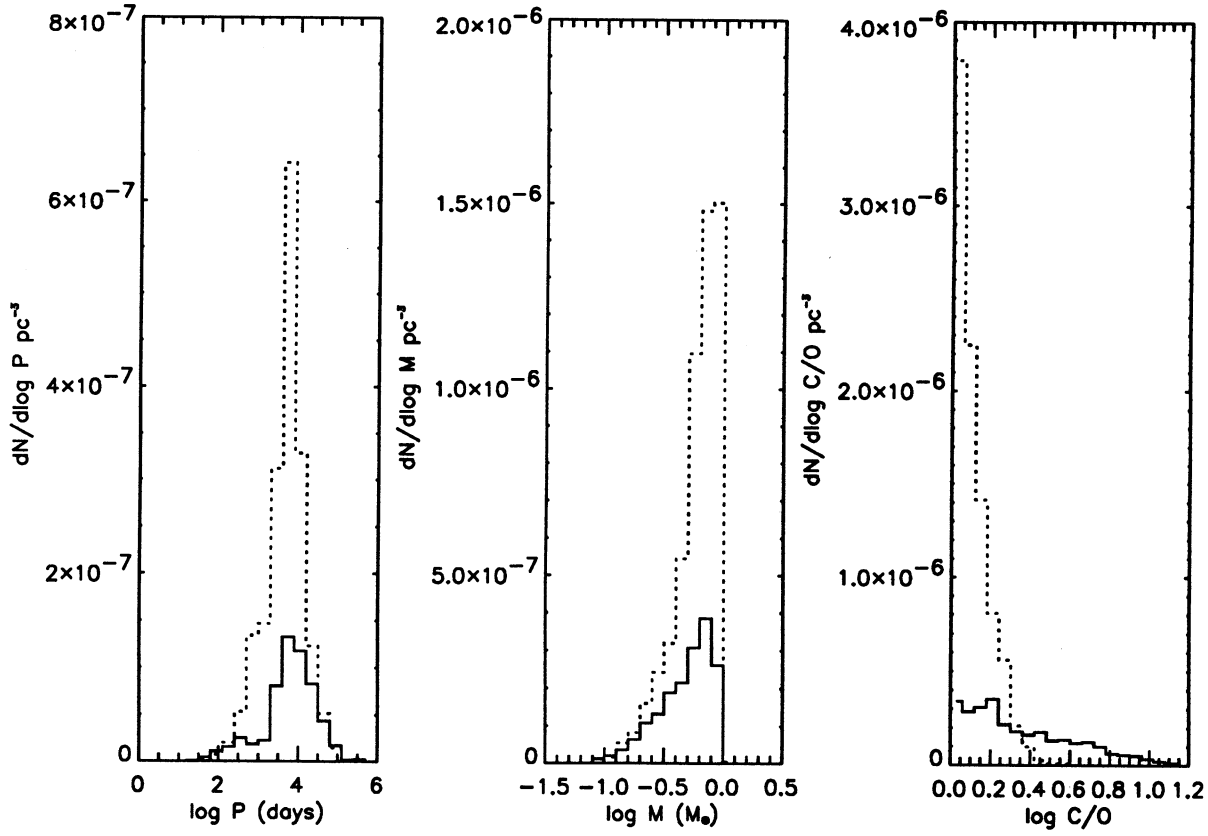


FIG. 5a FIG. 5b FIG. 5c

FIG. 5.—Distributions for model D: no accretion during CE phase ($f_{CE} = 0$). (*a*) Orbital period distribution; (*b*) dC mass distribution; (*c*) C/O ratio distribution. The solid line shows the spheroid population; the dotted line shows the disk population.

tions are not in contradiction with the observed dC properties, but considerations involving other types of post–wind mass transfer binaries may require that some accretion takes place during the CE (see § 5).

### 4.5. *Changing the Mixing Assumption*

Figures 6*a*–6*c* illustrate the effect of changing from complete mixing of material accreted by the secondary to mixing in the convective envelope only (model E). This increases the number of disk dCs by a factor of 10, the extra systems all having a high secondary mass and a low-mass convective envelope. Stars with $M > 1\ M_\odot$ have very small or no convective envelopes, so that the accreted matter does not mix into the secondary at all. This makes it very easy to produce an envelope with C/O > 1, so that only for model E can more recently formed binaries (with $Z > 0.01$) still produce dCs. This accounts for the dCs with $M > 1\ M_\odot$ in Figure 6.

The effect on the number of halo dCs is only marginal (an increase by a factor of 1.5) since the high-mass halo secondaries that would be more likely to become dCs have all evolved from the main sequence by now.

### 4.6. *Changing the Initial Metallicity of the Disk Population*

To illustrate how sensitive the results are to the assumed age–metallicity relation, Figures 7*a*–7*c* show the effect of increasing the metallicity at which the transition from halo to disk population occurs from $Z_{D,i} = 0.002$ to $Z_{D,i} = 0.004$ (model F), which still lies within the range of values allowed by observations (Truran 1994). This reduces the number of disk dCs by a factor of 2.5, and the number of halo dCs by a factor of 1.5, simply because the higher metallicities make it more difficult to produce secondaries with C/O > 1.

## 5. DISCUSSION

In view of the large number of uncertain parameters entering these simulations, the correspondence of our results with the space density inferred from observations is reasonable. In principle, our models make detailed predictions about the properties of dCs that can be compared to observations, especially the distribution of orbital periods. However, the present sample of dCs is not big enough to allow such a comparison. Orbits commonly require the availability of radial velocity data over several years' time, while nine of the 10 currently known dCs were discovered to be of interest as dwarfs only within the past few years.

A larger and better studied group of stars with peculiar abundances that presumably have also gone through a wind accretion phase are the barium (Ba) and CH stars. These are giants that show a strong overabundance of *s*-process elements, thought to be produced during shell burning on the AGB. The CH stars, with large Galactocentric (and *w*) velocities and low metallicities, are halo objects that probably represent the evolved, high-mass end of the population whose unevolved stars are the halo dCs. Similarly, the Ba stars, with old disk kinematics and near solar metallicities, are likely to represent the high-mass end of the population of disk stars that

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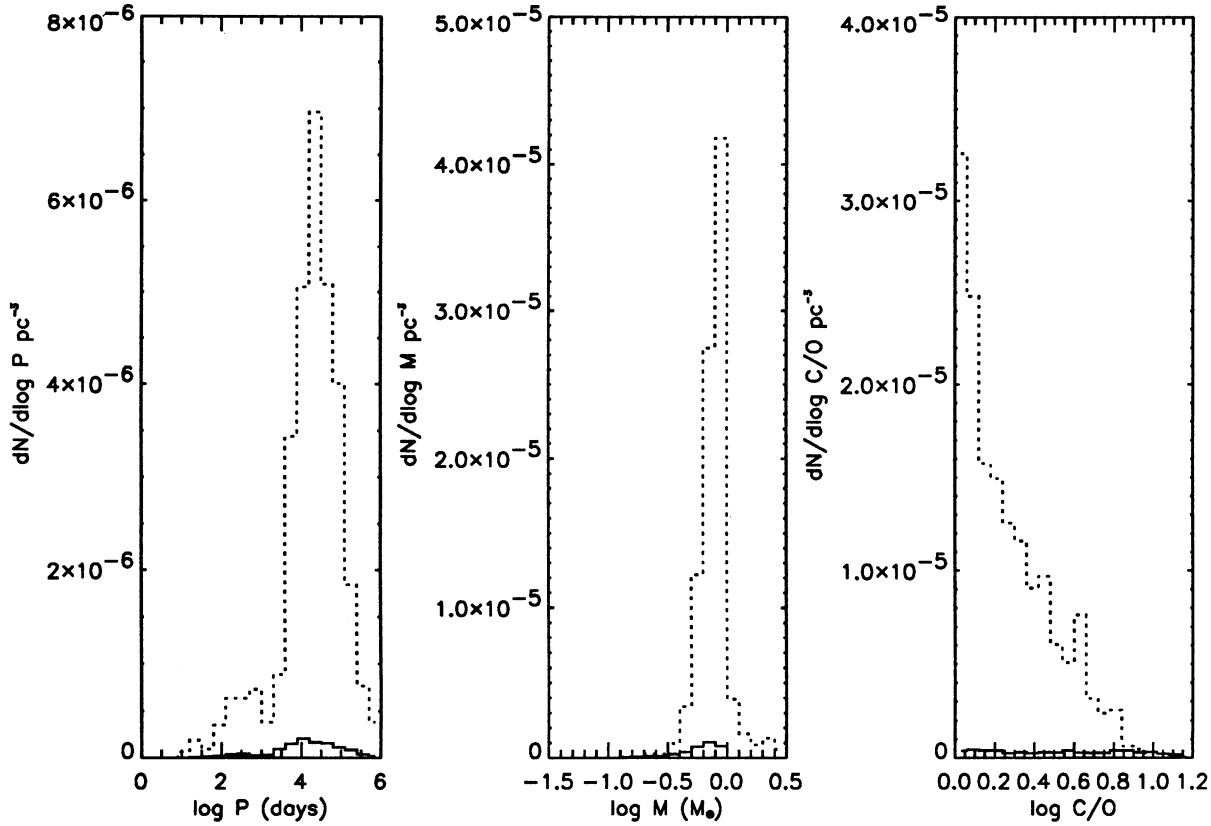


FIG. 6a FIG. 6b FIG. 6c

FIG. 6.—Distributions for model E: mixing into convective region only. (*a*) Orbital period distribution; (*b*) dC mass distribution; (*c*) C/O ratio distribution. The solid line shows the spheroid population; the dotted line shows the disk population.

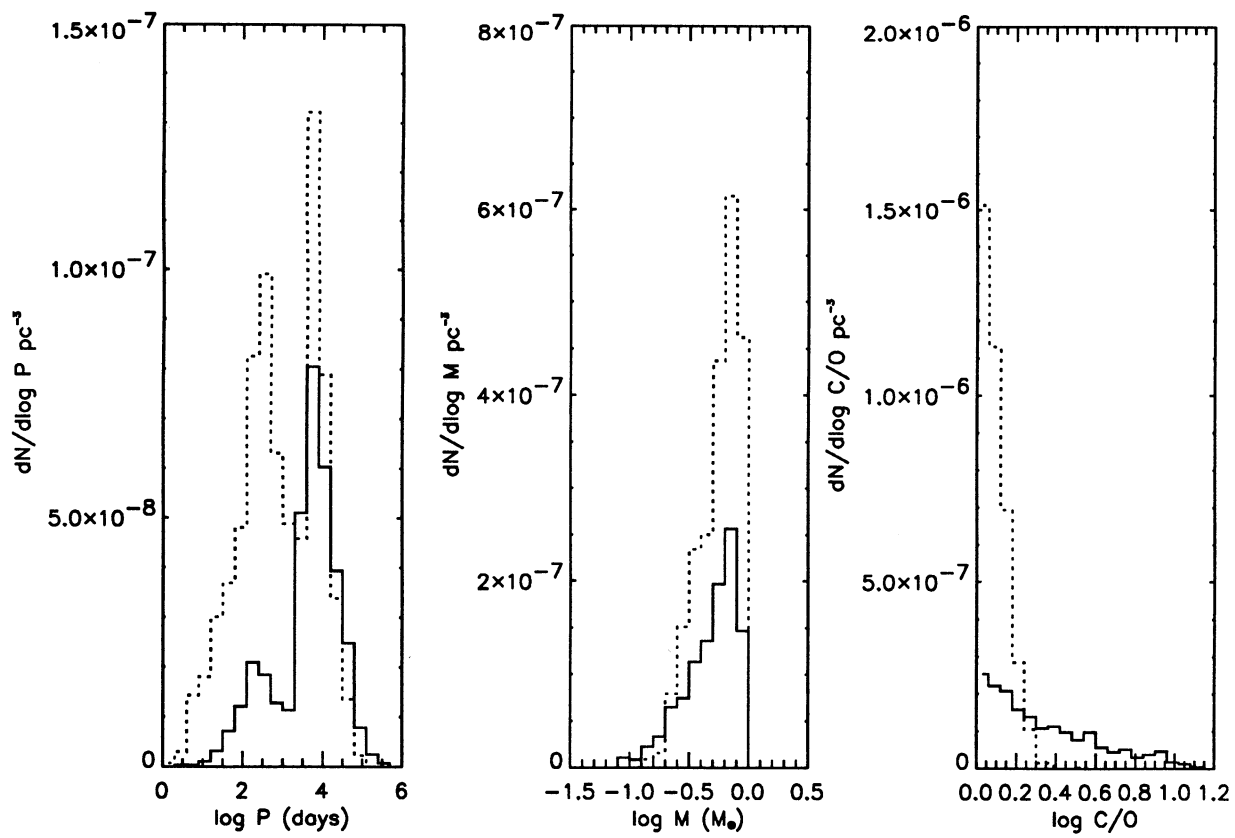


FIG. 7a FIG. 7b FIG. 7c

FIG. 7.—Distributions for model F: higher initial disk metallicity ($Z_{D,i} = 0.004$). (*a*) Orbital period distribution; (*b*) dC mass distribution; (*c*) C/O ratio distribution. The solid line shows the spheroid population; the dotted line shows the disk population.

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have experienced mass transfer from an AGB companion (including the CH subgiant stars; Smith, Coleman, & Lambert 1993). We might thus wish to compare our predictions for the current sample of dCs with the known orbital properties of the CH and Ba stars. McClure & Woodsworth (1990) present a sample of eight CH stars with orbital parameters, and Jorissen & Boffin (1992) have collected orbital periods and color indices indicating the degree of overabundance for 67 Ba stars. The observed orbital period distribution exhibits the same bimodal behavior that we find in our simulations. There is a small number of systems with periods below $10^3$ days followed by a very steep increase just above $10^3$ days with numbers dropping again at even longer periods. A large percentage of Ba stars have no detected period, which almost certainly means that it is very long. Although these main features are reproduced by our models, there is one significant difference: the steep rise in the number of observed systems occurs at shorter periods than we predict for dCs. The position of this rise is mainly determined by the radius of the thermally pulsing AGB star: just above this period the system can remain detached and thus avoid a CE phase. In our prescription, the only parameter influencing the AGB radius is the initial metallicity (smaller metallicity giving smaller radii), but no choice of parameters reproduces the rise at periods as low as $10^3$ days. A modification of the luminosity–radius relation from the one given by GdJ may be necessary to explain this observation. Another property of the Ba stars is that there is a small but significant correlation between *s*-process overabundance and orbital period, the overabundance on average increasing with decreasing orbital period. In our sample such a correlation is always present in the long-period systems. To produce a large overabundance in the short-period post-CE secondaries (as observed for Ba stars) it is necessary to assume that some accretion takes place during the CE phase. This result indicates how properties of a larger and better studied dC sample could help us understand general problems in binary evolution. Work to model the population of Ba stars in detail is currently in progress.

All our simulations here predict that *in the disk*, current samples of post–mass transfer dwarfs should have a C/O distribution peaking strongly toward unity. Among giants, this would correspond to the S stars. S giants have ZrO, LaO, and YO spectral features and C/O intermediate between normal giants and C giants. Two types of S stars are now known. The intrinsic S stars are part of an M–MS–S–SC–C evolutionary sequence on the AGB. The extrinsic S stars are post-MTB red giants with WD companions (e.g., Iben & Renzini 1983), analogous to the Ba giants, but of somewhat lower mass (Jorissen & Mayor 1992). As innocent bystanders to mass transfer, both extrinsic S dwarfs and Ba dwarfs are predicted to exist. Ba dwarfs have indeed been found (e.g., Proffitt & Michaud 1989; North & Lanz 1991), but no S dwarfs are yet known to exist. Although there may be strong selection effects working against the discovery of S dwarfs, they should cover at least as wide a mass/luminosity range as dCs (see Fig. 2*c*). Furthermore, the telltale molecular bands of S stars can be as strong as those of their M or C star counterparts. Finally, S giants are not confined to a range of C/O ratios so narrow as to sample only a small fraction of the stars near the peak of the C/O distribution (Smith & Lambert 1990). However, the accretion of sufficient mass to reach S-type envelope abundances may move the accretor so far up the main sequence that $T_{\rm eff}$ becomes too high for ZrO formation. What should a "dS" star look like? Model atmospheres are currently too poorly developed to predict in detail their spectral characteristics.

Despite the lack of a large sample of dCs with well-studied orbital characteristics, several results of our simulations of dC populations are encouraging. For those dCs with reasonable estimates to date (G77-61, PG 0824−289, and CBS 311), $M_V$ and $T_{\rm eff}$ correspond to an equivalent spectral type of about M0. This in turn corresponds to about half a solar mass, right where most of our models peak. Our results also clearly predict that a low initial metallicity greatly enhances the fraction of binaries that become dCs. We find that this fraction is typically 100 times larger in the halo population than in the disk population (Table 1). In addition, dCs will tend to be formed from systems with the lowest initial metallicities even *within* a given population. This seems consistent with the suggestion of an extremely low metallicity in G77-61 ([Fe/H] = −5.6; Gass, Liebert, & Wehrse 1988), raising the possibility that G77-61 or other dwarf C stars might be on the low-metallicity tails of their respective populations, or even members of the elusive Population III.

We are also encouraged that our derived space densities for the halo are within about a factor of 2 or less of estimates from observations. Because of unknown incompleteness of currently available samples of faint high-latitude carbon stars, these latter estimates are likely to be lower limits. We have not corrected for any selection effects here, which may be difficult to model. The objective-prism or photometric surveys that have yielded the majority of dC candidates are generally tuned to select stars by their strong $C_2$ or CN absorption in particular bands. These bands generally become harder to detect toward earlier spectral types since the molecules form preferentially at lower temperatures. At typical objective-prism resolutions, for example, serious incompleteness may set in for $T_{\rm eff} \geq 5500$ K. This must conspire with a competing effect, incompleteness toward fainter magnitudes, to narrow the range of spectral types represented in current samples of faint C stars. The recognition of the dCs in these samples has been mostly by proper motion, selecting against disk dCs: the only disk examples known to date were found serendipitously as companions to hot DA stars. Large-area, deep surveys for dCs might be accomplished via deep CCD objective-prism or grism observations, followed by *JHK* colors, which should distinguish dCs from C giants regardless of proper motion (see, e.g., Green et al. 1992).

The dCs can provide interesting information about stellar evolution because they retain the chemical imprint of their now extinct AGB companions. For example, they show indirectly that a very large fraction of stars formed in the halo must have gone through the C-AGB phase, in agreement with the observed correlation between the C/M AGB star ratio and metallicity. A large, well-quantified sample of dCs would go a long way toward a better understanding of how evolution in mass transfer binary systems is affected by age, metallicity, and other factors. The depth of most C star surveys to date was tuned to reach the most distant C giants in the galactic spheroid, but deeper surveys could still reveal more dCs locally.

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