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CONTRIBUTION OF WHITE DWARFS TO CLUSTER MASSES

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ABSTRACT

I have undertaken a literature search through 1997 July 31 of white dwarfs (WDs) in open and globular clusters. I have tried to make a careful evaluation in each case of the likelihood that the object is a WD and that it is a cluster member. The results are presented for 13 open clusters and 11 globular clusters. Currently there are 36 single WDs and five WDs in binaries known among the open clusters, and 340 single WDs and 11 WDs in binaries known among the globular clusters. From these data, I have calculated WD mass fractions for four open clusters (the Pleiades, NGC 2168, NGC 3532, and the Hyades) and one globular cluster (NGC 6121). I develop a simple model of cluster evolution that incorporates stellar evolution but not dynamical evolution to interpret the WD mass fractions. I augment the results of my simple model by turning to sophisticated *N*-body simulations incorporating stellar evolution. I find that even though these clusters undergo a range of degrees of kinematic evolution, from moderate (the Pleiades, NGC 2168, and NGC 3532) to strong (the Hyades and NGC 6121), the WD mass fraction is relatively insensitive to kinematic evolution and little changed from a model incorporating only stellar evolution with a Salpeter-like initial mass function. By comparing the cluster mass functions with that of the Galactic disk, and incorporating plausibility arguments for the mass function of the Galactic halo, I estimate the WD mass fraction in these two field populations. I assume the Galactic disk is ~ 10 Gyr old and that the Galactic halo is ~ 12 Gyr old, although the WD mass fraction is insensitive to age within this regime. I find that the Galactic halo should contain from 8%–9% ($\alpha = -2.35$) to perhaps as much as 15%–17% ($\alpha = -2.0$) of its stellar mass in the form of WDs. The Galactic disk WD mass fraction should be 6% to 7% (for a median stellar age of 5 to 7 Gyr and $\alpha = -2.35$), consistent with the empirical estimates of 3% to 7%.

Key words: Galaxy: stellar content — globular clusters: general — open clusters and associations: general — stars: luminosity function, mass function — white dwarfs

1. INTRODUCTION

Since white dwarfs (WDs) are faint for most of their evolutionary lifetime, their mass fraction in clusters and in the field is difficult to measure. Yet the WD mass fraction is important both for the dynamical evolution of star clusters and potentially for the mass of the Galactic disk and halo. Even in the immediate solar neighborhood, the range of the WD mass density estimates vary by more than a factor of 2, from $2.0 \times 10^{-3}\ M_\odot\ \mathrm{pc}^{-3}$ (Liebert, Dahn, & Monet 1988) to $4.6^{+2.2}_{-0.4} \times 10^{-3}\ M_\odot\ \mathrm{pc}^{-3}$ (Oswalt et al. 1996). While the solar neighborhood stellar density itself is poorly constrained, for a value of $\sim 6.4 \times 10^{-2}\ M_\odot\ \mathrm{pc}^{-3}$ (Mihalas & Binney 1981, p. 229; and consistent with Kuijken & Gilmore 1989, after subtracting the interstellar gas mass) the WD mass fraction ranges from 3% to 7%. In the Galactic halo the situation is even more poorly constrained, and the WD mass fraction is effectively observationally unknown. Indeed, studies of gravitational lensing in the Milky Way (e.g., Alcock et al. 1997) led to a flurry of papers during 1997 examining whether $\sim 50\%$ of the Galactic dark matter could be in the form of halo WDs. The bulk of these studies concluded that such a high halo WD mass fraction can be ruled out (see Gibson & Mould 1997 and references therein), but the mere fact that the mass fraction of WDs is so poorly known drives speculation about its importance. For the clusters, the presumed source of the field WDs, the WD mass fraction must depend on the cluster age and kinematic evolution (see, e.g., Vesperini & Heggie 1997). In the last 3 years a number of studies have identified and measured the properties of WDs in open and globular clusters. Most of these new cluster WD measurements have been made possible by the ability of the *Hubble Space Telescope* (*HST*) to detect very faint point sources and separate them from the many faint resolved background galaxies. These studies have been motivated by the independent information available from cluster WDs on cluster distances (Renzini et al. 1996), cluster ages (von Hippel, Gilmore, & Jones 1995), and constraints on stellar evolution (Richer et al. 1997). An important by-product of these studies is the number and mass contribution of WDs to their parent clusters. To the best of my knowledge no one has yet extracted this important information. In this paper, I first tabulate the known cluster WDs and estimate their fraction by mass in a handful of clusters. I then use a simple interpretive model supplemented by cluster dynamical studies in the literature to argue that the observed numbers of cluster WDs are about what one would expect based on stellar evolutionary theory alone, and are insensitive to the cluster dynamical history. Finally, I discuss the relevance of the cluster WD mass fractions to the disk and halo field star WD mass fractions.

2. SURVEY OF OBSERVATIONS

Starting with the NASA ADS Abstract Service, I performed a literature search on WDs in open and globular clusters through 1997 July 31. I included cataclysmic vari-

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TABLE 1

WHITE DWARFS IN OPEN CLUSTERS

Cluster (1)	Alias (2)	N_s (3)	Reference (4)	N_b (5)	Reference (6)	N_c (7)	Mass (8)	Reference (9)	Age (10)	Reference (11)
Hyades..........		7	1, 2	3	9, 14	[a]	410–480	16	0.63	21
Pleiades.........	M45	1	3, 4, 5	...		1–2	1000–2000	17, 18	0.07	22
NGC 2168......	M35	2	3, 6	...		...	≥1600–3200	19	0.09	3, 6
NGC 2287......	M41	2	4	...		...	...		0.18	4
NGC 2420......		4	7	...		...	≥4000	20	2.4	23
NGC 2451......		1	3, 8	...		...	...		0.07	8
NGC 2477......		4	7	...		...	...		1.2	7
NGC 2516......		4	9	...		...	...		0.14	24
NGC 2632......	M44	4	10	...		...	...		0.7	25
NGC 2682......	M67	1	11	2	11, 15	...	...		4.0	24
NGC 3532......		6	3, 12, 13	...		...	≥600	13	0.17	13
Total		36		5		...				

NOTE.—NGC 2632 = Praesepe.

[a] See discussion in § 4.1.

REFERENCES.—(1) Wegner, Reid, & McMahan 1989; (2) I. N. Reid 1997, private communication; (3) Reimers & Koester 1988a; (4) Koester & Reimers 1981; (5) Weidemann 1977; (6) Reimers & Koester 1988b; (7) von Hippel et al. 1995; (8) Koester & Reimers 1985; (9) Koester & Reimers 1996; (10) Wagner et al. 1986; (11) Pasquini, Belloni, & Abbott 1994; (12) Koester & Reimers 1993; (13) Reimers & Koester 1989; (14) Böhm-Vitense 1993; (15) Landsman et al. 1997; (16) Reid 1992; (17) Meusinger et al. 1996; (18) van Leeuwen 1980; (19) Leonard & Merritt 1989; (20) Leonard 1988; (21) Perryman et al. 1998; (22) Stauffer et al. 1994; (23) Demarque, Sarajedini, & Guo 1994; (24) Meynet, Mermilliod, & Maeder 1993; (25) Mermilliod 1981.

ables and other types of binary systems where the authors specifically discussed the WD nature of one of the binary components. My literature search covered 49 open cluster references and 82 globular cluster references. In assessing whether an object was a cluster WD, I examined the likelihood of cluster membership as well as the likelihood that the object is a WD. For the globular clusters, I required that the authors give a high likelihood of the object's being a cluster member and being a WD, although most of the globular cluster WDs were identified purely on the basis of multicolor photometry. For the globular cluster photometric candidates, I checked that they had the appropriate colors and magnitudes for the cluster distances and that there were few, or no, field stars with the same colors and magnitudes. Nonetheless, especially near the limit of the photometry, it is difficult to judge the number of genuine WDs identified. For the open clusters, where field contamination is much more problematic, I was stricter about membership probabilities and required that the authors used proper motions or some other criteria to evaluate membership and that the resulting membership probability was "probable" or better.

The results of the literature search for open and globular clusters are presented in Tables 1 and 2, respectively. In both tables columns (1) and (2) list the names of the clusters, column (3) lists the numbers of known single WDs, column (5) lists the numbers of known WDs in binaries, column (7) lists the numbers of WD members calculated to exist, and column (8) lists the total cluster masses in solar masses. Columns (4) and (6) provide references to the previous columns, whereas column (9) provides references to the previous two columns. Table 1 has two more columns than Table 2, and its column (10) lists the cluster ages in Gyr, with references in column (11). The cluster masses are often lower limits and generally apply to cluster stars within some luminosity or mass range and/or within some central area of the cluster. For the open cluster ages, there were often multiple references and I have chosen recent and representative values. Nonetheless, I represent the age range with the error bars in Figure 2, below. I assume that all globular

TABLE 2

WHITE DWARFS IN GLOBULAR CLUSTERS

Cluster (1)	Alias (2)	N_s (3)	Reference (4)	N_b (5)	Reference (6)	N_c (7)	Mass (8)	Reference (9)
NGC 104.......	47 Tuc	9	1	2	1, 6	...	1,300,000	14
NGC 5272......	M3	...		1	7	...	...	
NGC 6121......	M4	258	2	...		20,000	70,000	15, 16, 17
NGC 6397......		40	3	3	8	...	...	
NGC 6402......	M14	...		1	9	...	...	
NGC 6539......		...		1	10	...	...	
NGC 6624......		...		1	11	...	...	
NGC 6752......		21	4	...		...	...	
NGC 6838......	M71	12	5	...		...	...	
NGC 7078......	M15	...		1	12	...	...	
Terzan 5........		...		1	13	...	...	
Total		340		11				

REFERENCES.—(1) Paresce, De Marchi, & Jedrzejewski 1995; (2) Richer et al. 1997; (3) Cool et al. 1996; (4) Renzini et al. 1996; (5) Richer & Fahlman 1988; (6) Ables et al. 1989; (7) Hertz, Grindlay, & Bailyn 1993; (8) Grindlay et al. 1995; (9) Côté et al. 1997; (10) D'Amico et al. 1993; (11) Stella, White, & Priedhorsky 1987; (12) Anderson et al. 1990; (13) Ergma & Fedorova 1991; (14) Meylan & Mayor 1986; (15) Richer et al. 1995; (16) Sigurdsson 1993; (17) Peterson et al. 1995.

clusters listed in Table 2 are 12 ± 2.3 Gyr old based on recent *Hipparcos* subdwarf studies (Reid 1997; Gratton et al. 1997; Chaboyer et al. 1998). This topic is discussed further below, although precise ages are not critical to the results of this paper.

Using the values listed in Tables 1 and 2, I was able to estimate WD mass fractions for four open clusters (the Pleiades, NGC 2168, NGC 3532, and the Hyades) and one globular cluster (NGC 6121). Following is a brief discussion of how I arrived at each of the cluster WD mass fractions. The discussion is ordered by increasing cluster age.

2.1. *Open Clusters*

Pleiades.—There is one known WD cluster member, with a mass of 0.98 $M_\odot$ (Bergeron, Saffer, & Liebert 1992). It is unlikely that there are any undiscovered Pleiades WDs, since the proximity and youth of the Pleiades make any cluster WD relatively bright and easy to detect. It is still possible, however, that one or two Pleiades WDs exist as close companions to one of the brightest cluster stars. The total cluster mass is 1000–2000 $M_\odot$ (van Leeuwen 1980; Meusinger, Schilbach, & Souchay 1996). Assuming the single known WD is the only cluster WD, the Pleiades WD mass fraction is $(7.4 \pm 2.5) \times 10^{-4}$. The Pleiades are 70 Myr old (Stauffer, Hamilton, & Probst 1994) with a main-sequence turnoff mass of 5.3 $M_\odot$ (Weidemann 1977).

NGC 2168 (=M35).—There are two known WD members, each with masses of 0.7 ± 0.1 $M_\odot$ (Reimers & Koester 1988a,1988b). There are unlikely to be other single cluster WDs, but the constraints on members of multiple systems are weak. The total cluster mass is at least 1600–3200 $M_\odot$ (Leonard & Merritt 1989). Since both the WD count and cluster mass are lower limits, and both are unlikely to be more than a factor of 2 too low, I will assume that the ratio of the two is roughly correct. The WD mass fraction for this cluster is then $(6.6 \pm 3.3) \times 10^{-4}$, where I have increased the error estimate by 50% to reflect the uncertainties inherent in the two lower limits. NGC 2168 is 85 ± 15 Myr old with a main-sequence turnoff mass of ~ 5 $M_\odot$ (Reimers & Koester 1988a, 1988b).

NGC 3532.—There are six known cluster WDs, with a total mass of ~ 4.6 $M_\odot$ (Reimers & Koester 1988a, 1989; Koester & Reimers 1993). As is the case for NGC 2168, this is a lower limit because of possible WDs in multiple systems. It is also a lower limit in that only the central $30' \times 30'$ of the cluster have been surveyed for WDs. Regardless, the total WD count is unlikely to more than double. The total cluster mass in the same central region is ≥ 600 $M_\odot$ (Reimers & Koester 1989). I believe this is a weaker constraint than the WD count, and therefore the WD mass fraction is an upper limit of $\leq 7.7 \times 10^{-3}$. NGC 3532 is 165 ± 35 Myr old (Reimers & Koester 1989) with a main-sequence turnoff mass of 3.8 ± 0.6 $M_\odot$ (Reimers & Koester 1988a, 1989; Koester & Reimers 1993).

Hyades.—Despite the size of the Hyades on the sky, it is near enough and its population has been well enough studied that it is likely that all of its WDs have been found. This includes seven single WDs and three WDs in binaries (HD 27483 consists of two F6 V stars and one WD, Böhm-Vitense 1993; HZ 9 consists of an M4.5e V star and a WD, and V471 Tau consists of a K2 V star and a WD, White, Jackson, & Kundu 1993). The total mass in these 10 Hyades WDs is 6.4 $M_\odot$. The expected error in the total mass is smaller than the errors in the individual masses, which are generally less than 5%. There are currently three more candidate cluster WDs, but they are unlikely to be members (I. N. Reid 1997, private communication). The total mass of the Hyades was estimated by Reid (1992) to be 410–480 $M_\odot$. The Hyades WD mass fraction is $(1.45 \pm 0.15) \times 10^{-2}$. The Hyades are 625 ± 50 Myr old (Perryman et al. 1998) with a main-sequence turnoff mass of 2.3 $M_\odot$ (Böhm-Vitense 1993).

2.2. *Globular Clusters*

NGC 6121 (=M4).—Because of the distance and age of NGC 6121, current observations sample only the brighter portion of the WD cooling sequence, with the faintest WDs expected at $V \geq 31$. In addition, to reach even the brighter WDs in NGC 6121 requires the *Hubble Space Telescope*, and so observations cover only a small part of the cluster field. Although the WD mass fraction cannot be estimated directly, as done above (§ 2.1) for open clusters, it can still be derived by counting the number of horizontal-branch stars and knowing their evolutionary lifetime in comparison with the lifetime of the cluster WDs (essentially the lifetime of the cluster). Richer et al. (1995) used this technique and estimated that the number of WDs expected in NGC 6121 is 2×10^4. No error estimates were given, so I assume an error of $\pm 1 \times 10^4$. Among the more than 200 WDs that Richer et al. (1997) find in NGC 6121, they estimate a mean mass of 0.51 ± 0.03 $M_\odot$. Since the observable (i.e., brighter) WDs are strongly weighted to those that have evolved off the main sequence in the last ~ 5 Gyr, I make the small correction to 0.55 $M_\odot$ as the mean cluster WD mass. Modern mass estimates for NGC 6121 based on dynamical models range from 4.3×10^4 $M_\odot$ (Peterson, Rees, & Cudworth 1995) to $\sim 10^5$ $M_\odot$ (Sigurdsson 1993). I take the mean of these two estimates and use the range as the error estimate: $M_{\rm cluster} = (7.2 \pm 2.9) \times 10^4$ $M_\odot$. The NGC 6121 WD mass fraction is 0.15 ± 0.10. For NGC 6121, as well as the rest of the globular clusters listed in Table 2, I assume ages of 12 ± 2.3 Gyr (Reid 1997; Gratton et al. 1997; Chaboyer et al. 1998). Although these ages are still a topic of debate, Figures 2 and 3 (below) demonstrate that the WD mass fraction loses age sensitivity well before 12 Gyr. The main-sequence turnoff mass in globular clusters is ~ 0.85 $M_\odot$.

3. A SIMPLE INTERPRETIVE MODEL

The WD mass fractions for the four open clusters and one globular cluster support a general picture of an increasing WD mass fraction from less than 1% at an age of approximately 100 Myr (Pleiades, NGC 2168, NGC 3532) to ~ 1% by 1 Gyr (Hyades) to ~ 15% by ~ 10 Gyr (NGC 6121). How reasonable is such an interpretation? To fully address this question would require a comparison of the data with detailed cluster models that fully incorporate stellar evolution and cluster dynamics. Vesperini & Heggie (1997) have created just such model globular clusters using a sophisticated N-body treatment incorporating stellar evolution, and they even explicitly followed the cluster WD mass fractions. Terlevich (1987) and de la Fuente Marcos (1996) used similar theoretical treatments to investigate the general evolution of open clusters, though they did not specifically investigate the evolution of the WD mass fraction. Since the currently available theoretical results do not cover the entire range of cluster ages and physical parameters, I will tie together the open cluster and globular cluster data with a simple interpretive model that incorporates only the effects of stellar evolution and not dynamical evolution. To correct for the effects of dynamical evolution, I will, where possible, use the results of the aforementioned theoretical studies.

I assume all open and globular clusters were created in a single-burst star formation event and that their initial mass functions (IMFs) can be characterized by a single or a double power law of the form

$$N \sim M^{\alpha} \quad (1)$$

over the mass range $0.1\ M_{\odot} \leq M \leq 80\ M_{\odot}$. Current *HST* work on globular clusters (G. Piotto 1997, private communication) that are thought to have suffered little stellar evaporation is consistent with a single power law mass function (MF) up to the present-day turnoff mass, $\sim 0.85\ M_{\odot}$, at least at the precision necessary for calculating WD numbers. I consider a range of single power law IMF slopes, $\alpha = 0, -1, -2, -2.35$, and -3, and one double power law IMF slope, $\alpha = -2$ for $M \geq 0.6\ M_{\odot}$ and $\alpha = -1$ otherwise. The double power law IMF is essentially the Galactic disk MF given by Gould, Bahcall, & Flynn (1997). On this system, the slope of -2.35 is the Salpeter (1955) value. Stars evolve from the zero-age main sequence through the asymptotic giant branch on timescales given by the stellar evolution parameterizations of Eggleton, Fitchett, & Tout (1989) and Tout et al. (1997).[2] While the parameterizations used here are all for solar-metallicity stars, the differential effect on the WD mass fractions is slight, with only a small difference in the turnoff mass as a function of metallicity affecting the overall mass in main-sequence stars. WDs are produced from post–asymptotic giant branch stars via the initial-final mass relation. I have tried two different initial-final mass relations; one given by von Hippel, Bothun, & Schommer (1997) based on the data compiled by Weidemann & Koester (1983),

$$M_{\rm WD} = 0.48 - 0.016 M_{\rm ZAMS} + 0.016 M_{\rm ZAMS}^2\ , \quad (2)$$

and the other the "standard model" parameterization of Wood (1992),

$$M_{\rm WD} = 0.49462 \exp\,(0.09468 M_{\rm ZAMS})\ , \quad (3)$$

where $M_{\rm ZAMS}$ is the zero-age main-sequence mass and $M_{\rm WD}$ is the mass of the resulting WD, both in solar masses. Although these two parameterizations are different, with the Wood standard model parameterization being nearly linear, they yield essentially the same results, since the IMF and stellar evolutionary lifetimes are the main determinants of the WD mass fractions. This is encouraging since even if the initial-final mass relation is different at globular cluster metallicities, it is unlikely to significantly alter the WD mass fractions.

The highest mass main-sequence star that forms a WD is most likely $\sim 8\ M_{\odot}$ (Koester & Reimers 1996). There is some question, however, whether this upper mass limit varies, depending perhaps on stellar abundances or rotation (Weidemann 1977), and it may be as low as $\sim 5\ M_{\odot}$ in some clusters. Both these upper mass limits are used in this model. All gas ejected from evolving stars and all neutron stars and black hole remnants are assumed to leave the cluster. Globular cluster gas masses have been shown to be negligible (see Krockenberger & Grindlay 1995 and references therein), and the number of detected neutron stars is small enough (see, e.g., Manchester et al. 1991) and neutron star kicks are expected to be high enough (see, e.g., Helfand, Taylor, & Manchester 1977), that most neutron stars should leave the cluster. The model does not include binary stars. Open clusters are known to have a large number of binaries, while globular clusters have binary fractions of typically $\leq 5\%$ (see, e.g., Richer et al. 1997). The challenge in comparing this simple model with the clusters is to observationally correct for binaries in the open clusters. It does not matter, for instance, that this model would not predict cluster cataclysmic variables. The key point is to predict the expected mass fraction of WDs as a function of stellar population age. Finally, as discussed above, cluster kinematic evolution is not incorporated.

Figure 1 shows the fraction of mass lost from the model clusters as a function of age, up to 15 Gyr, for IMFs characterized by slopes $\alpha = 0, -1, -2, -2.35$ (Salpeter 1955), and -3. A double power law slope case is also plotted, with $\alpha = -2$ above $0.6\ M_{\odot}$ and $\alpha = -1$ otherwise (as advocated Gould et al. 1997 for the Galactic disk field stars). The dashed lines are for model runs with $M_{\rm up} = 5\ M_{\odot}$, and the solid lines are for model runs with $M_{\rm up} = 8\ M_{\odot}$. In this figure, the two different initial-final mass relations (eqs. [2] and [3]) would be indistinguishable, and so only model runs based on the quadratic initial-final mass relation (eq. [2]) are plotted. Clearly, IMF slopes as flat as 0 or -1 would cause the cluster to evaporate (see also Terlevich 1987). Even with slopes near the Salpeter value, much of the initial cluster mass is lost, and it is essential to keep track of mass loss, since it is significant enough to affect the total cluster mass and, hence, any calculated WD mass fractions.

Figure 2 shows the WD mass fraction for the model clusters as a function of the IMF slope, for $M_{\rm up} = 5$ and $8\ M_{\odot}$. Again, the model runs show only the results from the quadratic initial-final mass relation as the results for the exponential initial-final mass relation differed by only 0% to 3%,

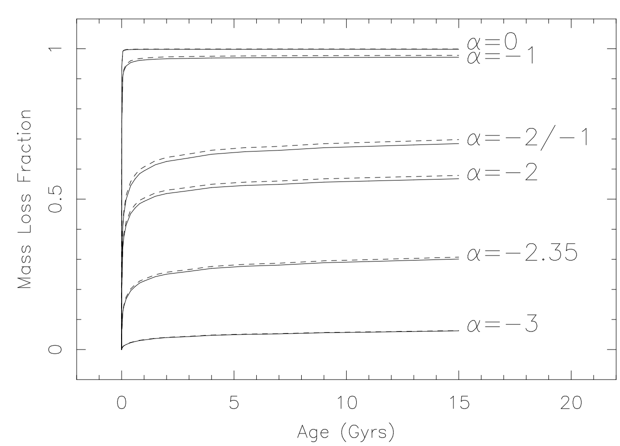

FIG. 1.—Fraction of mass lost from the model clusters as a function of age, up to 15 Gyr, for IMFs characterized by slopes $\alpha = 0, -1, -2, -2.35$, and -3, and a double power law slope with $\alpha = -2$ above $0.6\ M_{\odot}$ and $\alpha = -1$ otherwise (as advocated Gould et al. 1997 for the Galactic disk field stars). On this system, the slope of -2.35 is the Salpeter (1955) value. Dashed lines are for model runs with $M_{\rm up} = 5\ M_{\odot}$, and solid lines are for $M_{\rm up} = 8\ M_{\odot}$.

[2] Specifically, the main-sequence, subgiant, and red giant lifetimes are given by eqs. (A3), (A11), and (A19), respectively, of Eggleton et al. (1989). The core He-burning lifetime is given by eqs. (6), (A1), and (A17) of Tout et al. (1997).

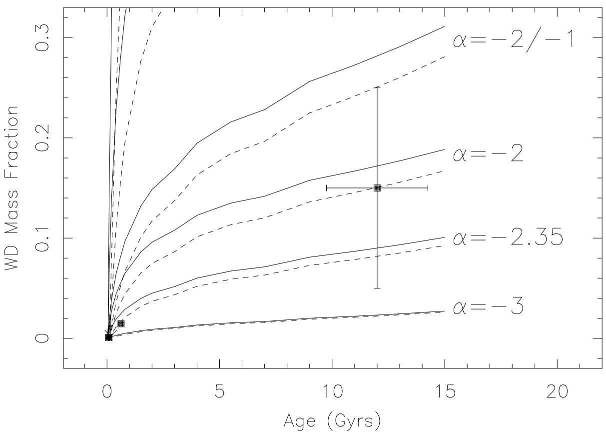

FIG. 2.—WD mass fraction for the model clusters as a function of the IMF slope, for $M_{up} = 5\ M_\odot$ (*dashed lines*) and $8\ M_\odot$ (*solid lines*). Also plotted are the four open cluster and one globular cluster values, along with their 1 σ uncertainties. The arrow near log (age) = −0.8 Gyr is the upper limit value for NGC 3532. On this scale the open cluster values are difficult to separate from the model lines near the origin.

depending on the IMF slope, M_{up}, and age (the difference is always $\leq 1.2\%$ for a Salpeter IMF slope). Also plotted are the four open cluster and one globular cluster WD mass fractions, along with their 1 σ uncertainties. In order to make the Hyades and NGC 6121 data points visible, the $\alpha = 0$ and -1 model runs are not plotted in their entirety. Figure 3 is similar to Figure 2, except that both axes are plotted as logarithms. The model IMF slopes are the same as in Figure 2. The onset of WD creation for $M_{up} = 8$ near log (age) = −1.3 Gyr and for $M_{up} = 5$ near log (age) = −0.7 Gyr can be simply understood as the stellar evolutionary lifetimes for 8 and 5 $M_\odot$ stars. The arrow near log (age) = −0.8 Gyr is the upper limit value for NGC 3532. It is clear from Figures 2 and 3 that the WD mass fractions for the four open clusters and one globular cluster are roughly consistent with an IMF with a Salpeter-like slope. For the two youngest open clusters (i.e., those with ages less than 100 Myr), the WD mass fractions display perhaps more sensitivity to the exact value of M_{up} than to the IMF slope. In addition, even if clusters IMFs can be fitted by power laws, the number of high-mass stars is likely to be small and should stochastically vary.

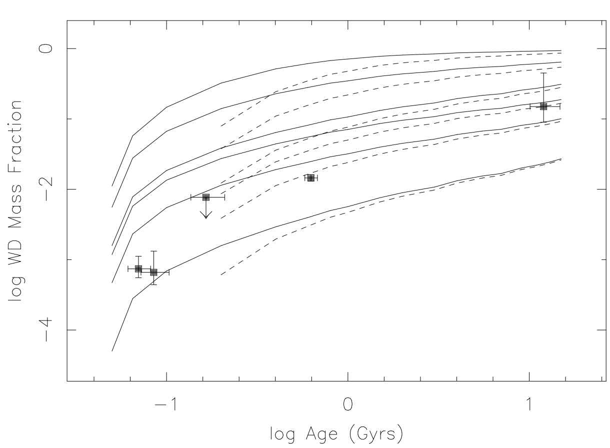

FIG. 3.—Same as Fig. 2, except that both axes are plotted as logarithms. Model runs are not labeled with the IMF slope for clarity of presentation, but are, from top to bottom, $\alpha = 0, -1, -2/-1, -2, -2.35$, and -3.

TABLE 3

WHITE DWARF MASS FRACTIONS

AGE (Gyr)	$M_{up} = 5\ M_\odot$		$M_{up} = 8\ M_\odot$	
	$\alpha = -2$	$\alpha = -2.35$	$\alpha = -2$	$\alpha = -2.35$
5	0.1094	0.0566	0.1309	0.0648
7	0.1203	0.0631	0.1418	0.0713
10	0.1408	0.0757	0.1623	0.0839
12	0.1506	0.0818	0.1720	0.0900

The WD mass fractions for a few representative old stellar populations are listed in Table 3. The first column lists the population age in Gyr, and the remaining columns list the WD mass fractions for four different IMF slope and M_{up} combinations, as labeled. The WD mass fractions range from 6% to 17% and are relatively insensitive to M_{up} and age. The primary sensitivity at these ages is to the IMF slope.

4. DISCUSSION

4.1. *Role of Kinematic Evolution*

Kinematic evolution causes mass segregation and stellar evaporation. Mass segregation alone is not expected to cause significant problems for my simple model, since observations of open clusters often cover the entire cluster and observations of globular clusters are generally made near a few core radii (e.g., De Marchi & Paresce 1995a, 1995b), where King models (see, e.g., Cool, Piotto, & King 1996) and *N*-body simulations (Vesperini & Heggie 1997) have consistently shown that the present-day mass functions (PDMFs) are very similar to the global MF. Generally, under a number of conditions relevant to the distant globular clusters, these global MFs are very similar to the IMF (Vesperini & Heggie 1997). For example, according to equation (16) of Vesperini & Heggie (1997), even for a globular cluster with $R_{peri} = 4$ kpc, $M_{initial} = 10^5\ M_\odot$, and age ≈ 12 Gyr, an IMF slope $\alpha = -2.5$ population should be very similar to the PDMF, which would have $\alpha = -2.2$. Globular clusters that orbit nearer the Galactic center were not modeled by Vesperini & Heggie, although the general trend for such clusters is preferential loss of low-mass stars because of disk shocking and tidal stripping. NGC 6121 has $R_{peri} \approx 1$ kpc (Peterson, Rees, & Cudworth 1995), and it is somewhat surprising that it still exists. Nonetheless, it does exist, and its low-mass stars exhibit an MF slope $\alpha \approx -2.3$ (H. B. Richer 1997, private communication). For this PDMF slope the WD mass fraction should be little affected by stellar evaporation. I conclude that despite the probably large amount of stellar evaporation this cluster has suffered, its kinematic evolution should not have significantly altered the WD mass fraction.

Although counterintuitive, stellar evaporation in open clusters may not preferentially eject low-mass stars, since mass segregation spares the low-mass members many encounters, particularly with the frequently produced central massive binary system (Terlevich 1987). It is not yet clear, however, what the relative evaporation of WDs versus the entire range of main-sequence stars is expected to be. Weidemann et al. (1992) tried to address this problem specifically for the Hyades. They argued that extrapolation of the Hyades PDMF up to 8 $M_\odot$ would predict at least 21 more cluster WDs than currently reside in the Hyades (seven single WDs and three in binaries). In addition, the coolest of the known Hyades WDs has a cooling age of 300 Myr, about half the cluster age. They argued that all the missing WDs were the older ones, which have had time to escape, and which perhaps had their velocities augmented by asymmetric mass loss during planetary nebulae ejection or dissolution of their precursor binary. To address how the Hyades might dissolve, they numerically integrated test particles in representative Galactic orbits. They concluded that evaporation of light stars in the Hyades has reduced the original population by a factor of perhaps 10. While Weidemann et al. did not specifically say how the Hyades WD mass fraction might evolve, their numbers indicate that despite a near-dissolution of the Hyades, the WD mass fraction should not have changed by more than a factor of 2. Even if 90% of the original Hyades stars have been lost, if they were preferentially low-mass members, less than 90% of the cluster mass would have been lost. This number compares closely with the $\geq 68\%$ fraction of WDs lost (currently 10, formerly more than 31).

Although the other three open clusters presented in Figures 2 and 3 have not been individually treated by theoretical studies, some guidance can be gained by the work of de la Fuente Marcos (1996). His N-body open cluster simulations disrupted after an average of ~ 115 Myr for $N = 250$ particles. The disruption time increased with the number of cluster members. All three of these open clusters are about 115 Myr old (the Pleiades is 70 Myr old, NGC 2168 is 85 Myr old, and NGC 3532 is 165 Myr old), yet all three were born with significantly more than 250 stars (see Table 1). These clusters not only still do exist, but they should still exist, and their stellar evaporation losses should not be catastrophic. Thus, by analogy with the Hyades, which seems to have approximately retained its WD mass fraction despite stellar evaporation, these three younger open clusters should be even less affected by stellar evaporation.

In summary, for the particular clusters studied here, kinematic evolution has been moderate (the Pleiades, NGC 2168, and NGC 3532) to strong (the Hyades and NGC 6121). Nevertheless, *kinematic evolution has little changed the WD mass fractions in these five clusters*. All five clusters have approximately the WD mass fraction that would be produced by stellar populations with a Salpeter-like IMF. The insensitivity of the WD mass fraction to the cluster dynamical history is a result of the fact that most WDs have masses intermediate between the top and bottom of the present main sequence in every cluster.

4.2. *Implications for the Galactic Disk and Halo Field Populations*

How similar are the cluster WD mass fractions to those of the Galactic disk and halo? The essence of the question is how similar the field star IMF is to that of the observed clusters. For the open clusters and the Galactic disk, the expectation is that the IMFs should be essentially the same, since current work on star-forming complexes (Hillenbrand et al. 1993; Hillenbrand 1997), on open clusters (e.g., Reid 1992; von Hippel et al. 1996), and on the disk field population (e.g., Gould et al. 1997) all yield similar mass functions. While the disk field population includes stars of all ages, most studies of the Galactic star formation history (see, e.g., Twarog 1980; Pardi & Ferrini 1994) have concluded that the rate of star formation in the disk has been falling somewhat with time. Thus, the median stellar age of the disk is likely to be greater than half the disk age. Assuming a disk age of ~ 10 Gyr (Winget et al. 1987; Liebert et al. 1988; Oswalt et al. 1996), then for a median disk star age of 5 to 7 Gyr and $\alpha = -2.35$ (see Table 3), the Galactic disk WD mass fraction should be 6% to 7%. This number is consistent with the empirical estimate of 3% to 7% (Liebert et al. 1988; Oswalt et al. 1996).

For the globular clusters and the Galactic halo the situation is much less clear, even though a few globular cluster luminosity functions have now been measured to luminosities equivalent to nearly 0.1 $M_\odot$ (see, e.g., De Marchi & Paresce 1995a, 1995b; Elson et al. 1995; Cool et al. 1996). The greatest current difficulty is measuring the halo luminosity function, which is presently poorly known and controversial. Nontheless, the theoretical cluster simulations can again act as a guide. Consistently, larger clusters and clusters with steeper IMFs survive longer. Thus, the halo field star population was likely produced by clusters that were smaller and/or had a flatter IMF. The halo field IMF should not be too much flatter than the cluster IMFs, however, or it would violate a number of nucleosynthetic constraints (see Gibson & Mould 1997 and references therein). Assuming the Galactic halo is ~ 12 Gyr old (Reid 1997; Gratton et al. 1997; Chaboyer et al. 1998), it should contain from 8%–9% ($\alpha = -2.35$) to perhaps as much as 15%–17% ($\alpha = -2.0$) of its stellar mass in the form of WDs (see Fig. 2 and Table 3).

Continued observations of globular clusters and the next generation of combined N-body and stellar evolution models (Tout et al. 1997) should refine both our estimates of the WD mass fraction and the relationship between the cluster and the field star IMFs. It would be of particular interest to know if the disk and halo field star IMFs were in any way different from the open and globular cluster IMFs (as opposed to the PDMFs). This would indicate whether the types of star clusters that we find today are typical of the entire range of all star clusters ever formed. The WD mass fractions provide a particularly useful tool in this work, as they are less sensitive to cluster dynamics than the MFs.

5. CONCLUSION

I have undertaken a literature search through 1997 July 31 of white dwarfs (WDs) in open and globular clusters. I have tried to make a careful evaluation in each case of the likelihood that the object is a WD and that it is a cluster member. The results are presented for 13 open clusters and 11 globular clusters. Currently, there are 36 single WDs and five WDs in binaries known among the open clusters, and 340 single WDs and 11 WDs in binaries known among the globular clusters. From these data, I have calculated WD mass fractions for four open clusters (the Pleiades, NGC 2168, NGC 3532, and the Hyades) and one globular cluster (NGC 6121). I develop a simple model of cluster evolution that incorporates stellar evolution but not dynamical evolution to interpret the WD mass fractions. I augment the results of my simple model by turning to sophisticated N-body simulations incorporating stellar evolution (Terlevich 1987; de la Fuente Marcos 1996; Vesperini & Heggie 1997). I find that even though these clusters undergo a range of degrees of kinematic evolution from moderate (the Pleiades, NGC 2168, and NGC 3532) to strong (the Hyades, NGC 6121), the WD mass fraction is relatively insensitive to kinematic evolution and little changed from a model incorporating only stellar evolution with a Salpeter-like IMF. By comparing the cluster mass functions with that of the Galactic disk, and incorporating plausibility arguments for the mass function of the Galactic halo, I estimate the WD mass fraction in these two field populations. I assume the Galactic disk is ~ 10 Gyr old (Winget et al. 1987; Liebert et al. 1988; Oswalt et al. 1996) and that the Galactic halo is ~ 12 Gyr old (Reid 1997; Gratton et al. 1997; Chaboyer et al. 1998), although the WD mass fraction is insensitive to age within this regime. I find that the Galactic halo should contain from 8%–9% ($\alpha = -2.35$) to perhaps as much as 15%–17% ($\alpha = -2.0$) of its stellar mass in the form of WDs. The Galactic disk WD mass fraction should be 6% to 7% (for a median stellar age of 5 to 7 Gyr and $\alpha = -2.35$), consistent with the empirical estimates of 3% to 7% (Liebert et al. 1988; Oswalt et al. 1996). Ultimately, precise comparisons between the field and cluster MFs for both the disk and halo would be a means of determining if the clusters we see today are typical of those that built the field populations.

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