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THE MASS OF PROGENITORS OF WHITE DWARFTS IN OPEN CLUSTERS *

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ABSTRACT

31 white dwarfs in 10 open clusters are examined, and their maximum mass and the upper mass limit of their progenitors are obtained as $1.22 \pm 0.02 M_{\odot}$ and $7.2 \pm 0.4 M_{\odot}$,respectively, suggesting that the upper mass limit of white dwarfs is less than $8 M_{\odot}$. The final mass of white dwarfs shows no clear correlation with the initial mass of their progenitors, and it is found that a deficient gap of initial mass exists between ~ 4 and ~ $5.2 M_{\odot}$. This gap seems to correspond to the mass range for carbon detonation or deflagration. The total expected numbers of white dwarfs are 11 ~ 22 in Hyades with 7 known white dwarfs and 17 in Praesepe with 8 known white dwarfs. These known white dwrfs are all younger than the others in both clusters. But one known white dwarf in Pleiades is older one among 2 ~ 3 expected white dwarfs.

Keywords: stars:white dwarfs, evolution, cluster:open cluster, initial mass function

I. INTRODUCTION

The luminosity and age of white dwarfs in star clusters can be well determined since the distance and age of the clusters are accurately known. More than 10 open clusters had been surveyed for search of white dwarfs by using deep *U* & *V*-plates, and more thant 30 white dwarf candidates in clusters have been reported, deriving the final mass, initial mass and cooling time of white dwarfs(Weidemann 1990). The radius, mass and cooling time of white dwarfs are indirectly derived by using various theoretical models(Koester 1972; Sweeny 1976; Wood 1990; Koester *et al.*1979; Shipman 1979; Strittmatter & Wickramasinghe 1971) and observed parameters such as magnitude, colors, surface gravity and effective temperature. Therefore, the above physical parameters are model-dependent. In the present sturdy, we use various relations for the deviration of radius and cooling time in order to avoid some systematic effects in their derivation. Also we condiser a possible range of cluster age instead of a single age for 9 clusters. The physical parameters are derived in section II and the final mass and initial mass are discussed in section III. Total expected numbers of white dwarfs in well observed three clusters such as Hyades, Praesepe and Pleiades are estimated by using their luminosity function and initial mass function in section IV. The conclusion is presented in the last section.

II. DERIVATION OF PHYSICAL PARAMETERS

(a) Data

The apparent distance modulus, reddening and age of 10 open clusters with known white dwarfs are listed in Table 1 where the references for white dwarfs are given in the last column and the number in

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Table 1. Open Clusters and White Dwarfs

Cluster	$(m-M)$	$E(B-V)$	$age(10^7 yr)$	N	reference
NGC2451	7.4	0.05	$6 \sim 8$	1(3)	1
NGC2422	8.8	0.09	$7.5 \sim 8$	1	2
NGC2168(M35)	10.54	0.27	$7 \sim 10$	2	3
Pleiades	5.63	0.04	$8 \sim 10$	1	4
NGC2516	8.35*	0.12	$10 \sim 14.1$	3	5
NGC1039(M34)	8.65*	0.10	$20 \sim 25$	3(5)	6
NGC2287	8.7**	0.01	31.6	2	7
NGC3532	8.35*	0.04	$30 \sim 35$	3	8
Praesepe	6.04	0.00	$65 \sim 75$	8(11)	9
Hyades	3.35	0.00	$70 \sim 80$	7	10

*: Meynet, Mermilliod, Maeder 1993, A&AS, 98, 477 **: Strobel, Skaba, Proga 1992, A&AS, 93, 271
reference 1: Koester & Reimers 1985, A&A, 153, 260 2: Koester & Reimers 1981, A&A, 99, L8
3: Reimers & Koester 1988, A&A, 202, 77 4: Eggen & Greenstein 1965, ApJ, 141, 83
5: Reimers & Koester 1982, A&A, 116, 341 6: Anthony-Twarog 1982, AJ, 255, 245
7: Koester & Reimers 1981, A&A, 99, L8 8: Reimers & Koester 1981, A&A, 218, 118
9: Anthony-Twarog 1984, AJ, 89, 267 10: Eggen & Greenstein 1965, ApJ, 141, 83

parenthesis is the number of candidates given in the reference. The observed parameters for each white dwarf are listed in Table 2. Some colors were estimated from the effective temperature for given surface gravity. By using the basic observational parameters, we derived radius, final mass, cooling time of white dwarfs and initial mass of their progenitors. The of white dwarfs luminosity was obtained by applying the bolometric corrections given by Strittmatter & Wickramasinghe(1971).

(b) Radius

The radius of white dwarfs can be derived from three different methods. The first one is to use the correlation between luminosity and effective temperature of a black-body:

$$\log R(R_\odot) = -0.2M_{bol} - 2\log T_{eff} + 8.4724,$$

where the absolute bolometric magnitude M_{bol} and effective temperature of the sun were taken as $M_{bol}^{\odot} = 4.75$ and $T_{eff}^{\odot} = 5770K$(Allen 1973). The second method is to use visual magnitude V corrected for interstellar reddening and atmospheric extinction and model magnitude V_o which is related to the relation of $\log \int_0^\infty F_\lambda S_\lambda d\lambda$. Here F_λ is the flux of a model star for given effective temperature and surface gravity and S_λ is the total response function of V-filter system.

$$\log R(R_\odot) = 4.914 + 0.2(V_0 - V) - \log \pi,$$

where π is a stellar parallax. The value of V_0 is given in Table 1 of Koester *et al.*(1979) for different effective temperature(or colors) and surface gravity. The third method is to use the computed Eddington flux H_ν whose values are given in Table 2 of Shipman(1979) for given effective temperature and colors:

$$\log R(R_\odot) = -2.631 - 0.2V - 0.5\log H_\nu - \log \pi.$$

In the last case, we used color $(U-V)$ and effective temperature for the derivation of two different radii. Then by using the above three relations, the four different radii are derived for each white dwarf and their mean values are listed in Table 2. The range of radius for all the white dwarfs is shown in Table 3.

(c) Final Mass

For degenerate white dwarfs, the unique mass-radius relation is obtained. Hamada & Salpeter(1961) derived this relation for the assumption of zero temperature, and Wood(1990) derived for the finite

Table 2. White Dwarfs in Open Clusters

CLUSTER	NAME	V	B-V	U-B	M_V	M_{bol}	log L	log T_e	log g	$< \frac{100R}{R_\odot} >$	$< \frac{M_f}{M_\odot} >$	$< log\ \tau >$	$< \frac{M_i}{M_\odot} > \ddagger$	
HYADES	EG 26	14.47	0.15	-0.67	11.12	10.04	-2.116	4.170	8.08	1.37±.04	0.51±.06	8.18±.11	2.78±.08	2.73±.11
	EG 36	14.23	-0.03	-0.84	10.88	9.03	-1.712	4.291	8.10	1.24±.03	0.59±.04	7.86±.07	2.63±.04	2.59±.07
	EG 37	14.00	-0.10	-0.97	10.65	8.08	-1.333	4.397	8.12	1.15±.02	0.65±.01	7.53±.02	2.57±.04	2.54±.06
	EG 38	13.98	0.29	-0.69	10.63	10.02	-2.108	4.199	8.00	1.21:	0.60±.03	8.21±.12	2.80±.09	2.76±.11
	EG 39	14.21	-0.09	-0.89	10.86	8.82	-1.629	4.323	8.12	1.10±.12	0.64±.04	7.81±.06	2.62±.04	2.58±.07
	EG 42	13.83	-0.15	-1.04	10.48	7.75	-1.199	4.451	8.23	1.09±.05	0.70±.04	7.41±.08	2.56±.05	2.52±.06
	EG316	14.93	-0.07		11.58	10.22	-1.820	4.215	8.30	1.04±.04	0.75±.02	8.01±.12	2.69±.07	2.65±.09
PRAESEPE	EG 61	17.68	0.15	-0.74	11.64	10.66	-2.365	4.147	8.10	1.11±.07	0.69±.05	8.43±.12	3.13±.27	3.06±.23
	EG 59	17.91	0.16	-0.68	11.87	10.79	-2.416	4.133	8.15	1.06±.06	0.68±.02	8.46±.14	3.25±.38	3.00±.15
	EG 60	18.35	0.19	-0.69	12.31	11.52	-2.709	4.106	8.40	0.88±.06	0.85±.02	8.68±.13	3.50±.20	3.40±.14
	LB5893	17.57	-0.01	-0.92	11.53	9.66	-1.965	4.305	8.50	0.91±.07	0.91±.03	8.22±.13	2.86±.13	2.81±.10
	LB1839	18.83	0.23	-0.77	12.79	12.14	-2.957	3.949	8.12	1.22±.15	0.61±.10	8.82±.15	3.67±.16	3.57±.10
	LB1876	17.69	0.15	-0.50	11.65	11.02	-2.509	4.080	7.96	1.33±.07	0.53±.03	8.46±.17	3.27±.38	3.19±.34
	LB6072	18.73	0.24	-0.78	12.69	12.16	-2.965	3.986	8.00	1.13±.03	0.64±.05	8.80±.17	3.45±.17	3.35±.11
	LB6037	18.98	0.37	-0.40	12.94	12.56	-3.125	3.940	8.00	1.24±.08	0.57±.05	8.83±.13	4.08±.31	3.87±.10
	LB5934	19.82	0.08	-0.90	13.78	12.18	-1.973	4.219	9.20	0.41±.06	1.31±.03	>9	—	—
	LB5962	19.22	0.33	-0.58	17.18	12.74	-3.197	3.904	8.04	1.22±.08	0.57±.03	8.96±.09	—	—
	LB6042	18.82	0.14	-0.47	12.78	12.15	-2.960	4.041	8.57	0.87±.03	0.92±.03	>9	—	—
PLEIADES	EG 25	16.52	-0.20	-1.10	11.01	8.16	-1.276	4.456	8.43	0.89±.02	0.88±.02	7.67±.12	7.22±.38	6.94±.50
N2516	1	19.61	$-0.16^\dagger$	$-1.13^\dagger$	11.26	8.34	-1.437	4.477	8.60	0.72±.01	1.05±.05	7.80±.10	6.45±.83	—
	2	19.55	$-0.19^\dagger$	$-1.18^\dagger$	11.20	7.82	-1.240	4.556	8.90	0.63±.02	1.14±.02	7.63±.18	6.52±.10	—
	5	20.09	$-0.17^\dagger$	$-1.17^\dagger$	11.74	8.55	-1.521	4.525	9.00	0.52±.01	1.22±.02	7.96±.18	6.78±.55	—
N2287	2	20.1	$-0.10^\dagger$	$-1.02^\dagger$	11.4	8.95	-1.680	4.398	8.31	0.97±.04	0.79±.03	7.93±.12	3.85±.09	—
	5	20.1	$-0.10^\dagger$	$-1.02^\dagger$	11.4	8.95	-1.680	4.398	8.31	0.97±.04	0.79±.03	7.93±.12	3.85±.09	—
N3532	1	19.55	$-0.14^\dagger$	$-1.08^\dagger$	11.20	8.46	-1.483	4.447	8.45	0.78±.04	0.96±.07	7.83±.10	3.74±.12	—
	5	19.19	$-0.14^\dagger$	$-1.09^\dagger$	10.84	8.05	-1.320	4.455	8.42	0.91±.02	0.86±.02	7.55±.05	3.60±.10	—
	6	19.89	$-0.14^\dagger$	$-1.10^\dagger$	11.54	8.75	-1.601	4.455	8.5	0.65±.03	1.12±.02	7.96±.10	3.86±.18	—
N2422	1	19.1	$-0.26^\dagger$	$-1.25^\dagger$	10.70	5.99	-0.496	4.778	8.9	0.59±.05	1.14±.01	6.94±.16	6.07±.17	—
N1039	34147	19.80	0.22	-0.27	11.15	10.49	-2.295	4.068^*	7.5	1.72±.02	0.32±.01	8.30±.11	6.08±.70	—
(M34)	48096	20.17	0.19	-0.41	11.52	10.60	-2.338	4.127^*	8.0	1.26±.06	0.56±.04	8.36±.13	6.04±.86	—
	43084	19.23	0.26	-0.41	10.58	10.00	-2.098	4.084^*	7.6	2.30±.20	0.29:	8.15±.08	5.50±.60	—
	35149	21.06	0.29	-0.17	12.41	11.77	-2.807	4.033^*	8.25	1.09±.05	0.71±.04	8.74±.11	—	—
	38034	21.22	-0.10	-0.68	12.57	11.08	-2.534	4.237^*	8.82	0.63±.09	1.13±.07	8.74±.09	—	—
N2451	1	19.60	$0.12^\dagger$		12.20	10.91	-2.462	4.204	8.6	0.79±.02	0.99±.03	8.54:	—	—
	5	18.90	$0.14^\dagger$		11.50	10.36	-2.244	4.176	8.13	1.14±.03	0.66±.02	8.4:	—	—
	6	16.90	$-0.12^\dagger$		9.50	6.45	-0.682	4.491	7.63	1.58±.05	0.37±.04	8.29:	6.90±.49	—
N2168	3	20.24	$0.06^\dagger$		9.70	6.19	-0.575	4.574	8.16	1.16±.13	0.65±.10	7.02±.09	5.90±.39	—
(M35)	4	20.05	$0.06^\dagger$		9.51	5.59	-0.336	4.644	8.29	1.08±.07	0.72±.06	6.78:	5.82±.37	—

Note: Hyades - Shipman(1979) & Koester *et al.*(1979) for $log\ T_e$ and $log\ g$

Praesepe - Eggen & Greenstein(1965) for $(B-V)$ & $(U-B)$ of EG 61

Pleiades - Koester *et al.*(1979) for $log\ T_e$ and the mean of Sweeney's(1976) & Koestar *et al.*(1979) values of $log\ g$

$< \frac{100R}{R_\odot} >, < \frac{M_f}{M_\odot} >, < \frac{M_i}{M_\odot} >$: mean values

$\dagger$: colors derived from $log\ g$ & $log\ T_e$

$*$: $log\ T_e$ derived from colors

$\ddagger$: Hyades - 1^{st} one for age of $7 \sim 7.5 \times 10^8 yr$ and $2^n d$ one for age of $7 \sim 8 \times 10^8 yr$

Praesepe - 1^{st} one for age of $6.5 \sim 7.5 \times 10^8 yr$ and $2^n d$ one for age of $7 \sim 7.5 \times 10^8 yr$

Pleiades - 1^{st} one for age of $8 \sim 9 \times 10^7 yr$ and $2^n d$ one for age of $8 \sim 10 \times 10^7 yr$

NGC2516 - for age of $10 \sim 14.1 \times 10^7 yr$

NGC2287 - for age of $31.6 \times 10^7 yr$

NGC3532 - for age of $3 \sim 3.5 \times 10^8 yr$

NGC2422 - for age of $7.5 \sim 8 \times 10^7 yr$

NGC1039 - for age of $2 \sim 2.5 \times 10^8 yr$

NGC2451 - for age of $6 \sim 8 \times 10^7 yr$

NGC2168 - for age of $7 \sim 10 \times 10^7 yr$

temperature($T_{eff} = 20000K$) model. The differences of masses derived by these two relations were shown to be less than a few % for white dwarfs in Hyades by Weidemann *et al.*(1992). Therefore, in the present study we apply the zero-temperature M-R relation for the C-O core model to the four different radii. The mass of white dwarfs can also be estimated from the observation of gravitational redshift velocity. Weidemann *et al.*(1992) applied this method to the white dwarfs in Hyades. If we know surface gravity and radius, the mass can also be easily derived. For each white dwarf, we derived five different masses(M_f) and their mean values are listed in Table 2. The minimum final mass is $0.3M_{\odot}$ and the maximum final mass is $1.22 \pm 0.02M_{\odot}$ which is less than the Chandrasekhar mass limit $1.4M_{\odot}$ for white dwarfs. The considerable variation of final mass of white dwarfs is seen even in the same cluster as shown in Figure 1.

(d) Cooling Time

We used three different relations between luminosity and cooling time. The cooling time derived from the Koester's(1972) relation is in general smaller than the others derived from the Sweeney's(1976) and Wood's(1990) relations. The letter relation yields the largest cooling time. The difference of these three cooling times can be estimated from the standard deviation of their mean value in Table 2 where $< log\, \tau >$ is the mean value of logarithmic cooling times. The range of mean cooling time is given in Table 3 where the largest one is for the white dwarf, LB6037 in Praesepe. The cooling time of white dwarfs in a cluster should be less than the cluster age. According to this constraint, seven white dwarf candidates in Table 2 are rejected in Praesepe(Anthony-Twarog 1984), NGC1039(Anthony-Twarog 1982) and NGC2451(Koester & Reimers 1981).

(e) Initial Mass

We know the age of cluster and cooling time of white dwarf, and then the time of pre-white dwarf stage from the ZAMS phase is equal to the difference between cluster age and cooling time. From this time difference, we can find the initial mass(M_i) of progenitor of a white dwarf by using stellar evolutionary model. We adopted the model of Schaller *et al.*(1992) for $Z = 0.02$ in which stars with mass greater than $7M_{\odot}$ evolved up to the end of the carborn burning phase and stars with mass of $2 \sim 5M_{\odot}$ evolved up to the end of early asymtotic giant branch. This model includes semi-convection and overshooting. The different initial masses were derived for each of the three different cooling times and different ages of a cluster for each white dwarf. The initial mass increases as the cooling time increases and the cluster age decreases. These effects are revealed in the standard deviation of mean mass in Table 2. The derived initial masses range from $2.56 \pm 0.05M_{\odot}$ to $7.22 \pm 0.38M_{\odot}$, which agrees with that($\sim 7M_{\odot}$) estimated by Romanishin & Angel(1980) from white dwarfs in open clusters. Here the upper limit corresponds to the maximum mass limit of progenitor whose final fate become a white dwarf. The maximum initial mass is for the white dwarf EG25 in the Pleiades. The final mass of this white dwarf is $0.88M_{\odot}$ which is close to the value($0.9 \sim 0.95M_{\odot}$) estimated by Schulz & Wegner(1981). Therefore, a very large mass loss of $\sim$ 88% is required for this white dwarf. This may be achieved by the mass transfer to the companion in the binary system. Greenstein(1974), however, could not find any companion of this white dwarf by spectroscopic observation. It is noted that the initial masses of white dwarfs in NGC2516 ranges from $6.45M_{\odot}$ to $6.78M_{\odot}$. These masses are much smaller than the value ($8^{+3}_{-2}M_{\odot}$) derived by Reimers & Koester(1982, also see Weidemann & Koester 1983). This difference is due to the different distance moduli and different models adopted for the estimate of cooling time and initial mass. It is remarked that the initial mass of progenitors in Hyades and Praesepe are all less than $4M_{\odot}$ and the white dwarfs in Praesepe have on average larger progenitor mass than in Hyades. van de Heuvel(1975) pointed out that the stars with $M_i > 4M_{\odot}$ evolve through the C-detonation and consequently no white dwarfs were left as seen in Hyades.

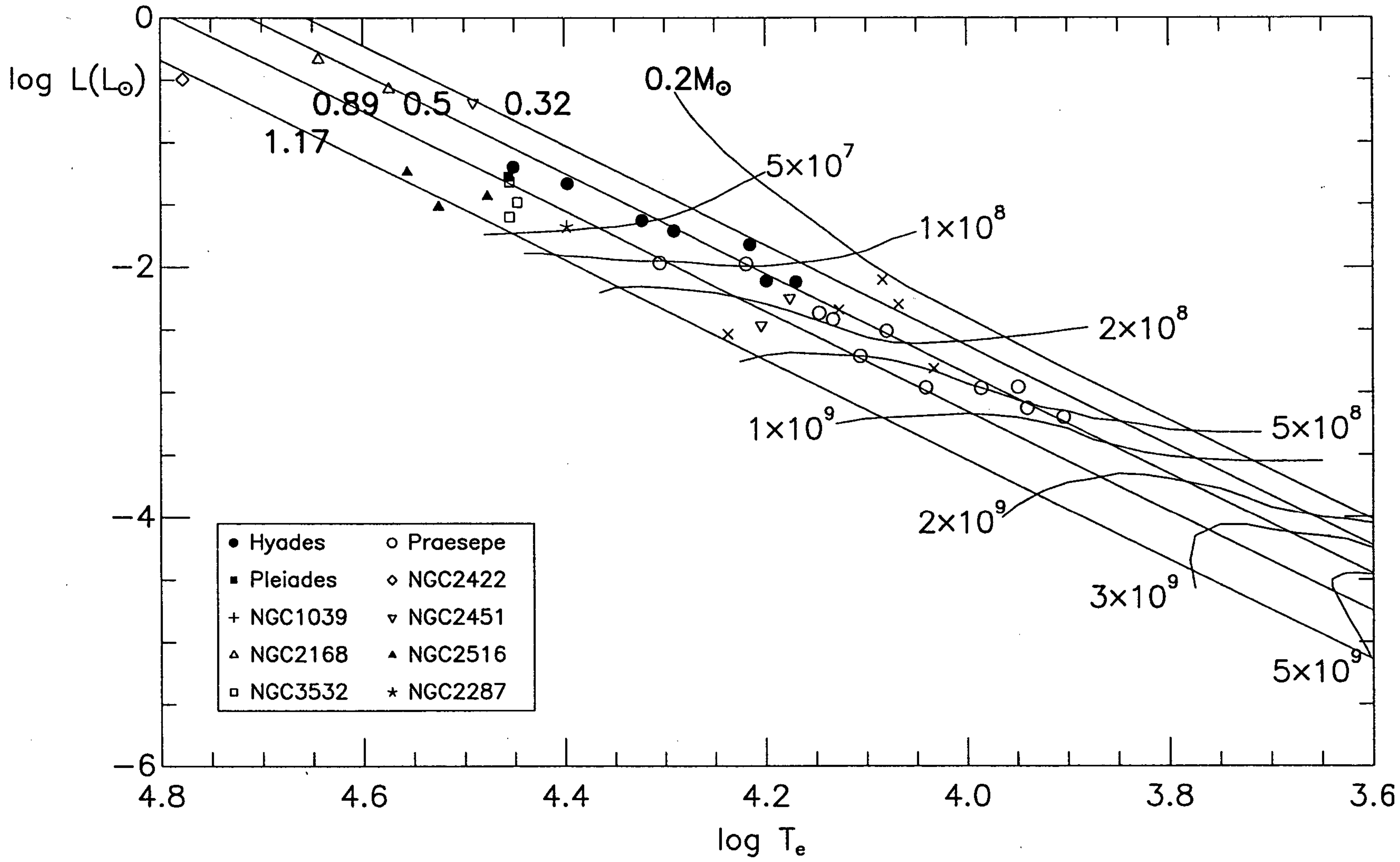

Fig. 1. Final masses of white dwarfs in open cluster in the H–R diagram. The relations of final masses with luminosity and effective temperature, and with cooling times are shown.

Table 3. The Range of Physical Parameters

Parameter	Range	Parameter	Range
radius(R)	$0.005 \sim 0.023 R_\odot$	final mass(M_f)	$0.3 \sim 1.2 M_\odot$
initial mass(M_i)	$2.5 \sim 7.5 M_\odot$	cooling time(τ)	$6 \times 10^6 \sim 7 \times 10^8 yr$

III. RELATION BETWEEN FINAL MASS AND INITIAL MASS

The final mass(M_f) of white dwarfs in Table 2 are compared with the initial mass(M_i) of their progenitors in Figure 2 where bars represent uncertainties arisen from the use of different methods for final mass derivation and of different cooling times and adopted age range of each cluster for the initial mass derivation. When we consider mass loss by stellar wind and overshooting(Renzini 1984; Iben & Renzini 1983; Maeder & Meynet 1989; Chiosi 1986), the initial mass of progenitors increases with the increasing effect of mass loss and overshooting as demonstrated by Weidemann(1987), expecting a single correlation between M_f and M_i. However, as mentioned by Weidemann(1987), no single correlation exists and rather a very large variation($0.3 \sim 1.2 M_\odot$) of M_f is noticed particularly for $M_i > 5M_\odot$ in Figure 2. For instance, the white dwarfs in NGC2168, NGC1039(M34) and NGC2451 suggest the significant mass loss more than 85% of their initial mass. In Figure 2, it is clearly seen that there is a gap of initial mass where no white dwarfs are found between $M_i =\sim 4$ and $\sim 5.2 M_\odot$, and white dwarfs with $M_i > 5M_\odot$ show more dispersed distribution of final mass than those with $M_i < 4M_\odot$. According to the theory of stellar evolution(Iben & Renzini 1983; Renzini 1984), intermediate mass stars with $M_i < M_W$ become white dwarf through the quasi-stationary evolution. Here the critical mass M_W is given by

$$M_W \approx 1.0 + 9.33\eta^{0.35} - 3.53\eta^{0.27} + 0.8(b - 1.0),$$

where η and b are respectively, Reimers mass loss parameter and efficiency parameter of superwind loss. For a weak mass loss $\eta = \frac{1}{3}$ and $b = 0.1$, $M_W \approx 4M_\odot$, and for a very considerable mass loss, $\eta = 2$ and $b = 1$, $M_W \approx 8M_\odot$. The former case which corresponds to a stationary mass loss, may be applied to the stars with $M_i < 4M_\odot$ which become C-O white dwarfs in Figure 2. It is noted that the maximum initial mass of stars whose envelope mass is entirely losed by the Reimers steady mass loss mechanism before its core mass reaches $1.4M_\odot$ is $\sim 4M_\odot$(van de Heuvel 1975). On the other hand, Woolf(1975) pointed out that the progenitor mass of white dwarfs in the binary system can be as large as $4M_\odot$, and Paczynski(1970) suggested the maximum progenitor mass as $\sim 3.5M_\odot$ on the basis of dynamical instability of envelope in the course of the formation of a planetary nebula. In the classical evolutionary model without mass loss and overshooting, the upper mass limit of a star which develops an electron degenerate C-O core is $M_{up} = 8 \sim 9M_\odot$. This limit is lowered to $M_{up} \simeq 5.2M_\odot$ for significant mass loss and overshooting(Chiosi 1986) and hence stars with $M_i = 4 \sim 5.2M_\odot$ ignite carbon explosively under the degenerate condition, leading to the total disruption through carbon deflagration or detonation(Iben & Renzini 1983). This mechanism seems to produce the gap in Figure 2, suggesting the real existence of type $\mathrm{I}\frac{1}{2}$ supernova. The maximum initial mass of a star which can undergo the core collapse by electron capture, is $\sim 8M_\odot$ where the mass loss and overshooting are taken into account(Maeder & Meynet 1989). And the stars with $M_i = 5.2 \sim 8M_\odot$ have the maximum temperature at the position of off-center of the core because of significant neutrino loss at the core center and consequently the carbon ignition occurs at the position of off-center(Maeder & Meynet 1989). If a significant mass loss in envelope or a violent explosion occurs at the stage of off-center carbon ignition, we may expect the formation of very low mass C-O white dwarfs although their initial mass is greater than $\sim 5M_\odot$ as seen in Figure 2.

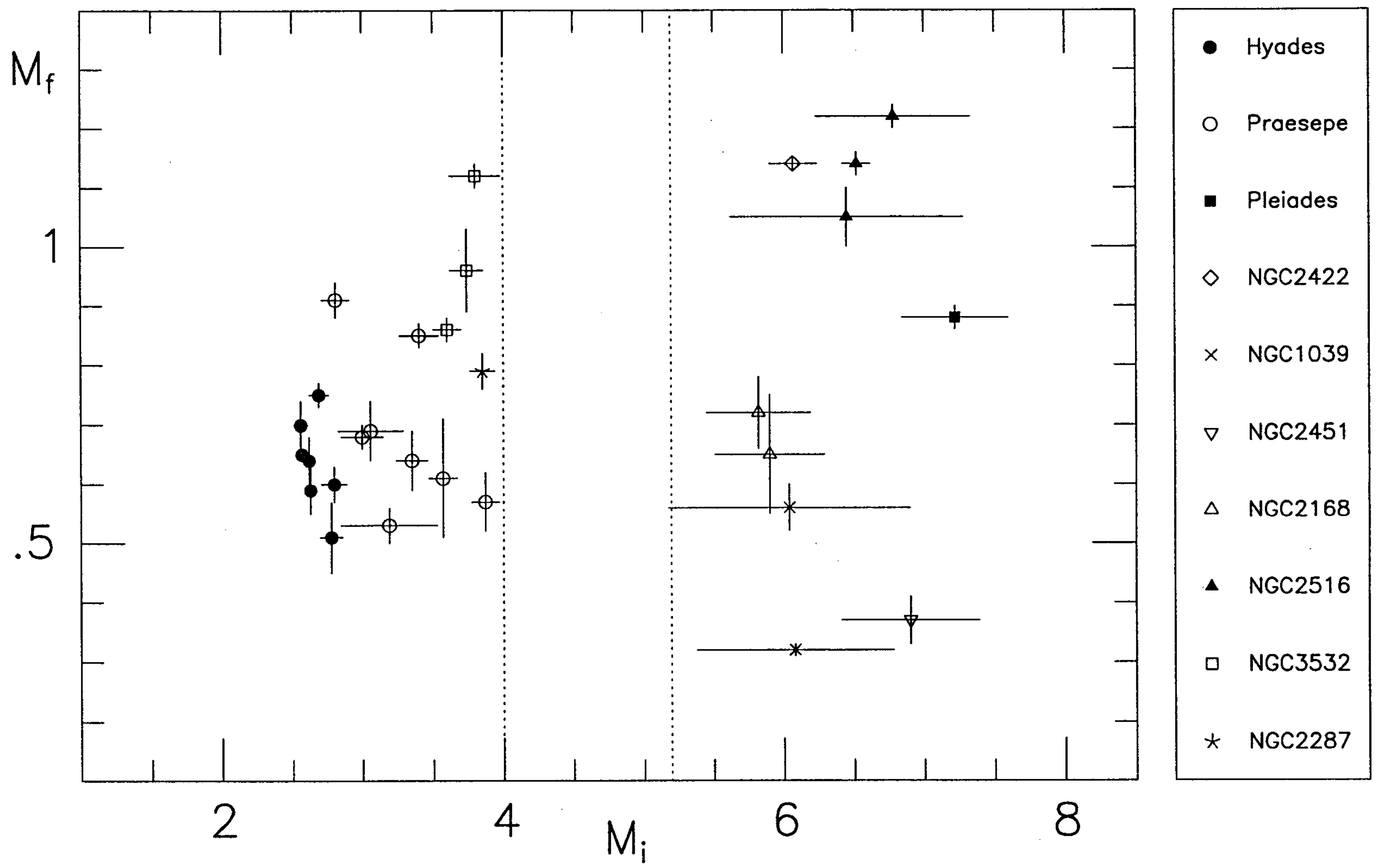

Fig. 2. Correlation between final masses of white dwarfs and their initial masses. The age of Hyades and Praesepe are taken as $7\sim7.5\times10^8$yr, $8\sim9\times10^7$yr is taken for the age of Pleiades(see section IV).

Table 4. Number of White Dwarfs

cluster	Hyades						Praesepe						Pleiades					
age(yr)	8×10^8		7.5×10^8		7×10^8		7.5×10^8		7.0×10^8		6.5×10^8		8.3×10^8		8.0×10^8		7.6×10^8	
M_i	N_{ex}	N_{ob}	N_{ex}	N_{ob}	N_{ex}	N_{ob}	N_{ex}	N_{ob}	N_{ex}	N_{ob}	N_{ex}	N_{ob}	N_{ex}	N_{ob}	N_{ex}	N_{ob}	N_{ex}	N_{ob}
2.4 ~ 2.5	2	4	0	0	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2.5 ~ 3.2	6~9	3	6~9	7	6~9	7	8	6	8	4	7	4	—	—	—	—	—	—
3.2 ~ 4.0	3~6	0	3~6	0	3~6	0	4	2	4	4	4	4	—	—	—	—	—	—
4.0 ~ 5.0	1~3	0	1~3	0	1~3	0	3	0	3	0	3	0	—	—	—	—	—	—
5.0 ~ 6.3	1~2	0	1~2	0	1~2	0	1	0	1	0	1	0	1	0	1	0	0	0
6.3 ~ 8.0	0~2	0	0~2	0	0~2	0	1	0	1	0	1	0	2	1	2	1	2	1
total	13~24	7	11~22	7	11~22	7	17	8	17	8	16	8	3	1	3	1	2	1

IV. EXPECTED NUMBER OF WHITE DWARFS IN A CLUSTER

From the observational luminosity function, we can derive the present day mass function and initial mass function, IMF(Lee & Sung 1995). Then the total number of white dwarfs can be counted from the IMF. This method was applied to the well observed three open clusters Hyades, Praesepe and Pleiades(Lee & Sung 1996). The IMFs of these clusters are given in Table 4 in which stars with $M_i > 8M_\odot$ are excluded because the upper mass limit for white dwarfs is less than $8M_\odot$ as shown in Tables 2 and 3. N_{ex} and N_{ob} in Table 4 denote the expected number and observed number of white dwarfs, respectively. The expected initial masses of progenitors range from $M_i = 2.4$ to $2.8M_\odot$ for the age of $7 \sim 8 \times 10^8 yr$ in Hyades and from $M_i = 2.67$ to $3.97M_\odot$ for the age of $7 \sim 7.5 \times 10^8 yr$ in Praesepe. The initial mass of red giant stars, if exist, in Pleiades are $5.55M_\odot$, $5.65M_\odot$, $5.77M_\odot$, for the cluster age of $8.0 \times 10^7 yr$, $7.5 \times 10^7 yr$, and $7.0 \times 10^7 yr$, respectively. The observed number of white dwarfs in a given initial mass range should be equal to or smaller than the expected number of white dwarfs in a cluster. According to the above constraints and the initial mass function of white dwarfs, the age of Hyades should be younger than $8 \times 10^8 yr$, and the observed seven white dwarfs turn out to be the youngest ones among the total expected 11 ~ 22 white dwarfs. Weidemann *et al.*(1992) estimated 28 white dwarfs, considering the evaporation of low mass stars and taking the simple IMF($N \propto M^{-2.35}$). Recently Böhm-Vitense(1995) tried to find faint white dwarfs in the field of Hyades by the IUE observation, but no white dwarfs were detected. In Praesepe, about the half of the total expected 17 white dwarfs are observed, and the initial mass function of white dwarfs suggests that the age of Praesepe should be older than $6.5 \times 10^8 yrs$. Three white dwarfs are expected in Pleiades but only one white dwarf is known, and this is older than the other white dwarfs whose initial masses are expected to be $5.72M_\odot$ and $6.27M_\odot$. It is noted that a few white dwarfs with $M_i = 4 \sim 5M_\odot$ are expected according to the IMFs of Hyades and Praesepe but no such white dwarfs have been found yet.

V. CONCLUSION

The final masses of 31 white dwarfs in 10 open clusters show no clear correlation with the initial masses of their progenitors, and a large dispersion in final masses is seen particularly in the mass range of $M_i > 5M_\odot$. Some observational uncertainties should be responsible in part for this considerable dispersion. The maximum final mass is found to be $1.2M_\odot$ which is close to the Chandrasekhar limit, $1.4M_\odot$, and the maximum mass of their progenitors is found to be $7.2M_\odot$. This upper limit is close to the limit of $\sim 8M_\odot$ for white dwarfs which is expected in the classical evolutionary theory and also close to the lower limit for the star which can collapse by electron capture in the model with significant mass loss and overshooting(Maeder & Meynet 1989). A distinct gap of white dwarfs is found in the initial mass range of $M_i = 4 \sim 5.2M_\odot$, and this was also seen less distinctively in Figure 1 of Weidemann(1987).

The existence of this gap seems to be real although some observational uncertaintities are taken into account. It is noted that the initial mass is sensitive to the cluster age and we considered a possible range of age instead of a single age except for NGC2287 whose age seems to be correct. The gap suggests the real existence of carbon detonation or deflagration in the stars with mass between $\sim 4M_\odot$ to $\sim 5M_\odot$. Here $4M_\odot$ corresponds to the maximum mass limit for the stars whose envelope mass is losed entirely by the Reimers mass loss mechanism before the core mass reaches the Chandrasekhar limit(van de Heuvel 1975), and $\sim 5M_\odot$ corresponds to the lower mass limit for the off-center carbon ignition(Chiosi 1986; Maeder & Meynet 1989). Then the scenario for the formation of white dwarfs may be described as follows. Stars with $M_i < 4M_\odot$ becomes C-O white dwarfs through the quasi-stationary mass loss and stars with $5M_\odot < M_i < 8M_\odot$ become white dwarfs through a large mass loss at the off-center carbon-burning phase. The occurrence of considerable dispersion in final mass in the latter case may be related to violent mass loss and/or to the binarity of stars which can cause significant mass transfer to the other companion(Webbink 1979). The stars with mass between ~ 4 and $\sim 5M_\odot$ experience the C-detonation of deflagration when carbon ignites in the degenerate C-O core with Chandrasekhar limit mass, and hence they are entirely disrupted, becoming a type $\mathrm{I}\frac{1}{2}$ supernova(Iben & Renzini 1973).

Before deriving the firmer conclusion for the existence of the deficient gap in the initial mass of white dwarfs, however, more accurate observation and more extensive search for white dwarfs in open clusters are urgently needed to determine the accurate mass limit of the gap.

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