JOURNAL OF THE KOREAN ASTRONOMICAL SOCIETY
28: 45 ~ 59, 1995

THE LUMINOSITY FUNCTION AND INITIAL MASS FUNCTION FOR THE PLEIADES CLUSTER *

LEE, SEE WOO AND SUNG, HWANKYUNG
Department of Astronomy, Seoul National University
(Received Mar. 7, 1995; Accepted Mar. 22, 1995)

ABSTRACT

In the best observed Pleiades cluster, the luminosity function(LF) and mass function(MF) for main sequence(MS) stars extended to $M_V \approx 15.5 (V \approx 21)$ are very similar to the initial luminosity function(ILF) and initial mass function(IMF) for field stars in the solar neighborhood showing a bump at $log\ m \simeq -0.05$ and a dip at $log\ m \simeq -0.12$. This dip is equivalent to the Wielen dip appearing in the LF for the field stars. The occurence of these bump and dip is independent of adopted mass-luminosity relation(MLR) and their characteristics could be explained by a time-dependent bimodal IMF. The model with this IMF gives a total cluster mass of $\sim 700 M_\odot$, ~ 25 brown dwarfs and ~ 3 white dwarfs if the upper mass limit of progenitor of white dwarf is greater than $4.5 M_\odot$. The cluster age on the basis of LF for brightest stars is given by $\sim 8 \times 10^7 yr$ and all stars in the cluster lie along the single age sequence in the C-M diagram without showing a large dispersion from the sequence.

Key Words : open cluster, cluster:luminosity function, mass function

I. INTRODUCTION

In the LF for the solar neighborhood field stars, the Wielen dip(Wielen 1974) appears at $M_V \approx 7$, and its intrinsic existance has been confirmed by the completeness test by Upgren and Armandroff(1981). The dip has been also observed by star counts in other sky regions(Reid 1982; Pritchet 1983; Bahcall and Soneira 1984; Yoshii *et al.*1987). From 25 well observed open clusters and associations, Lee and Chun(1988) derived an averaged LF of these clusters in which a dip like the Wielen dip appears at $M_V \simeq 7$. This result suggests the same mechanism for the formation for field stars and clusters on average even though present mass function(PDMF) for MS stars in individual clusters are somewhat different from that for the field stars. Recently Phelps and Janes(1994) also showed that the similar grandient of the averaged LF for 8 young open clusters to that for the field stars in the range of $m = 1.4 \sim 7.9 M_\odot$.

In the Pleiades cluster, Hambly *et al.*(1993:HHJ) measured very faint stars down to $V \sim 21$, using the UK Schmidt plates and Stauffer *et al.*(1991) observed faint stars in the outer region of the cluster. The addition of these faint stars to the data of bright stars(Hertzsprung 1947; van Leeuwen 1983; van Leeuwen *et al.*1986), flare stars(Jones 1981; Stauffer 1984) and pre-MS(PMS) stars (Stauffer 1980,1982) make it possible to determine the detailed LF for the Pleiades cluster down to the near end of MS in the C-M diagram.

In the present study, it is attempted to derive LF and MF for the Pleiades cluster by using the published data. For this, the observed data are examined and summarized in section II, and from the data, the LF and MF are derived in sections III and IV, respectively, stressing the appearance of a bump at $M_V = 5^m \sim 6^m$ and a dip at $M_V \simeq 7^m$. Some possible mechanisms for the occurrence of the bump, dip and the characteristics of the cluster are examined discussing time-dependent bimodal IMF in section V. The conclusion is presented in the last section, suggesting some physical properties of the cluster.

---

* This work was supported by Seoul National University DAEWOO Research Fund and in part by the Basic Science Research Institute Program, Ministry of Education, BSRI-94-5411.

II. DATA

The most of stars brighter than $V \approx 15.^m5$ in the Pleiades cluster are within the $\sim 3^\circ \times 3^\circ$ area around the cluster center, and they were observed by Hertzsprung(1947). Their magnitude and colors were measured by photoelectric observations(Mermilliod 1988), and their membership were determined from the proper motion survey by Jones(1970, 1973, 1981). van Leeuwen *et al.*(1986) measured about 400 Pel stars($6 < V < 15$) within the $\sim 8^\circ \times 8^\circ$ area by the Walraven system, and 136 stars among them are classfied as member stars on the basis of dispersion of stars from the mean line in the C-M diagram. We converted $(V - B)_{VBLUW}$ to the Johnson $(B - V)$ color by the following transformation equation given by Thé *et al.*(1980);

$$(B - V) = -4.5581 - [20.8221 + 23.2558(V - B)_{VBLUW}]^{1/2} : -0.02 < (B - V) < 1.15. \quad (1)$$

Using the Schmidt plate combined with V- and I-filters, Stauffer *et al.*(1991) measured magnitude and color and also estimated the probability of membership for SK stars($14 < V < 18$) and HCG stars($12 < V \leq 18$) within $4^\circ \times 4^\circ$ area around the cluster center. Among these, 169 SK stars and 72 HGC stars are classified as member stars whose membership probability is greater than 50%. The color $(V - I)_o$ is converted to the color $(B - V)_o$ by using the relation between reddening free colors $(V - I)_o$ and $(B - V)_o$ which was derived from the data of Stauffer(1982, 1984) and Stauffer and Hartmann(1987), taking the reddening relation of $E(V - I) = 1.6E(B - V) = 0.05$(Savage and Mathis 1979).

Recently Hambly and Jameson(1991) measured R and I Schmidt plates to determine photographic I magnitude and $(R - I)$ color for stars within the $\sim 3^\circ \times 3^\circ$ area around the cluster center. Hambly *et al.*(1993) reported 440 member stars($14.5 < V < 21$) which were chosen on the basis of positional membership criterion. The photographic magnitude I_N and color $(R_{59F} - I_N)$ are converted to the Cousins system, I and $(R - I)$ by using the relation given by Bessell(1986), and V and $(B - V)$ are derived by using the Bessell's(1991) relation of effective temperature and bolometric correction. In this procedure, some uncertainty could be involved in the derivation of V and $(B - V)$. The bolometric magnitude for the sun is taken as $M_{bol}^{\odot} = +4.72$.

The measured areas of the Pleiades cluster are different with different observers as mentioned above, and also the completeness of measured stars up to a certain magnitude is different with observed areas and observers. This ploblem has been discussed by Stauffer *et al.*(1991). According to their suggestion, the member stars brighter than $M_V = 4.5$ were taken from the Hertzsprung stars, Trumpler stars and Pel stars over the $4^\circ \times 4^\circ$ area, assuming that they are complete over the area. The member stars of $4.5 < M_V \leq 6.5$ were taken from the Hertzsprung stars and AK stars(Stauffer *et al.*1991) which were also measured by the Walraven system(van Leeuwen *et al.*1986), and stars of $6.5 < M_V \leq 9.5$ were taken from the data given by Stauffer *et al.*(1991). Stars fainter than $M_V = 9.5$ are mainly by the HHJ stars(Hambly *et al.*1993) within the $3^\circ \times 3^\circ$ area. The accuracy of the data for faint stars is estimated to be $\sigma_V \sim 0.2$, $\sigma_{B-V} \sim 0.05$ including the uncertainty arisen from the transformation between photographic and standard system.

III. C-M DIAGRAM AND LUMINOSITY FUNCTION

All observed member stars in the Pleiades cluster are plotted in the C-M diagram shown in Figure 1 where $E(B - V) = 0.033$(Breger 1986) and $(m - M_V)_o = 5.55$(Hambly *et al.*1991; Johnson 1957) were adopted. The solid line in Figure 1 denote the zero-age main sequence(ZAMS) of which bright part is a theoretical ZAMS taken from the evolutionary models of Schaller *et al.*(1992;$Z = 0.02, Y = 0.28$) for $M_V \leq 6.55$ and of D'Antona and Mazzitelli(1994;$Z = 0.019, Y = 0.28$) for $6.6 < M_V < 8.4$, and the the faint part ($M_V \geq 10.3$) is the emprical ZAMS given by Schmidt-Kaler(1982). Between $M_V = 8.4$ and 10.3, we took a ZAMS point at $M_V = 9.0$ and $(B - V) = 1.40$. The magnitudes and colors of the adopted ZAMS are given in Table 1.

Most of the stars above the ZAMS by $\Delta V \sim 0.^m4$ are probably binary stars of which fraction in the Pleiades cluster is 22 $\sim$ 26% according to Bettis(1975) and Stauffer(1984). Flare stars and the candidates of PMS stars (Landolt 1979; Stauffer 1980, 1984) mostly belong to the faint part($M_V > 8$) in Figure 1. The existence of PMS stars can be deduced from a large deviation above the ZAMS in the C-M diagram after applying correct interstellar extinction for these stars. In Figure 2, the emprical ZAMS of Schmidt-Kaler(1982) and theoretical ZAMS of Swenson

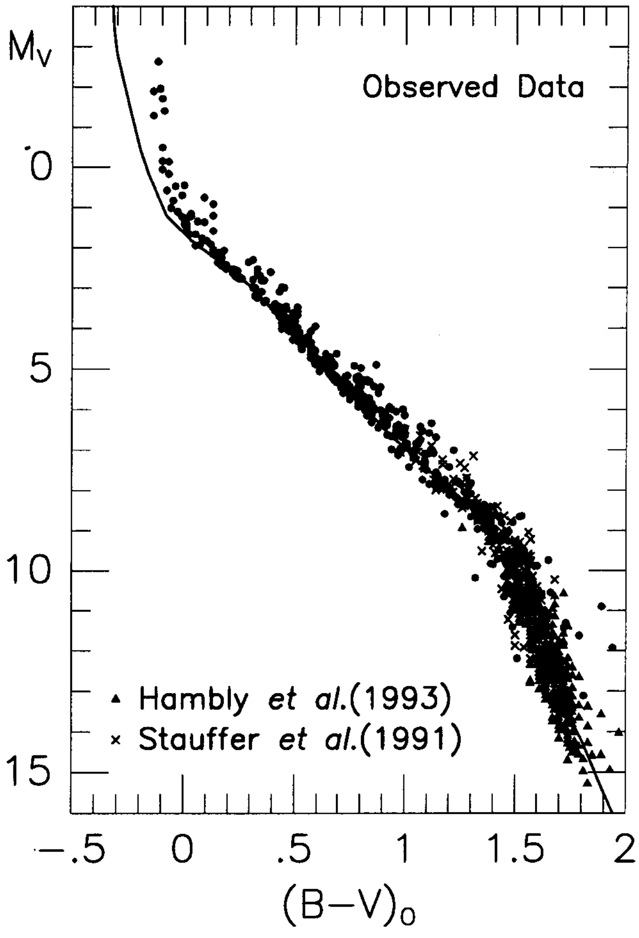

Fig. 1. C-M diagram for the Pleiades cluster. Solid line represents the adopted ZAMS.

Table 1. Adopted ZAMS

M_V	$B-V$	$U-B$	M_V	$B-V$	$U-B$	M_V	$B-V$	$U-B$
-6.11	-0.336	-1.222	-0.36	-0.193	-0.688	6.55	0.92	0.67
-5.66	-0.333	-1.213	0.14	-0.163	-0.570	7.42	1.09	0.97
-5.13	-0.330	-1.202	0.75	-0.116	-0.356	8.36	1.29	1.19
-4.69	-0.326	-1.185	1.19	-0.081	-0.232	9.00	1.40	1.22
-3.85	-0.318	-1.150	1.82	0.034	0.036	10.30	1.50	1.17
-3.43	-0.314	-1.130	2.44	0.184	0.099	12.00	1.60	1.20
-2.85	-0.302	-1.090	3.02	0.314	0.023	13.20	1.70	1.32
-2.40	-0.283	-1.020	3.95	0.462	-0.005	14.20	1.80	1.43
-1.77	-0.256	-0.926	5.25	0.716	0.262	15.50	1.90	1.53
-1.19	-0.231	-0.825	5.88	0.801	0.429	16.70	2.00	1.64

et al.(1994) pass roughly through the middle of the observed faint sequence, but the other theoretical ZAMSs of D'Antona and Mazzitelli(1985, 1994) and Burrows(1993) are located below the observed faint sequence, suggesting that the observed faint stars of $M_V > 9$ are mostly PMS stars. According to the PMS models, stars with mass smaller than $0.8M_\odot$ take the time longer than $8 \times 10^7 yr$ to reach the ZAMS, and hence many faint stars in the Pleiades cluster seem to be at the PMS stage although they were born much earlier than bright, upper MS stars.

When the observed ZAMS of Pop I stars which corresponds to the ZAMS of Hyades cluster, is applied to the Pleiades cluster in the C-M diagram, many MS stars between $(B - V) = 0.8$ and 1.45 lie below the ZAMS. This result has been considered as a UV excess due to lower metallicity of the Pleiades cluster($[Fe/H] = 0.05$) than the Hyades cluster($[Fe/H] = 0.15$)(VandenBerg and Poll 1989) or the decrease in brightness by circumstellar shell around faint stars(Stauffer 1980, 1982). However, this peculiar phenomenon disappears when the theoretical ZAMS of D'Antona and Mazzitelli(1994) for $Z = 0.019$ and $Y = 0.28$ is applied as seen in Figure 1. According to the above abnormal effect seems to be related to the accurate definition of ZAMS suitable for the Pleiades cluster considering its metallicity.

The most of stars brighter than $M_V \approx 2$ in Figure 1 lie above the ZAMS in the C-M diagram. Therefore it is necessary to correct the evolutionary effect of these brightest stars in order to derive an ILF which is the total number of stars ever born in unit magnitude interval. For this the brightening correction due to evolution was applied to bring the brightest stars to the ZAMS position along the evolutionary tracks(for $Z = 0.02$) given by Schaller *et al.*(1992). Then the upper limit of the ILF for the cluster lowers down to $M_V = -0.5$ as seen in Figure 3. The brightening correction was also applied to other stars which show a large deviation from the ZAMS.

Considering the extension of the area measured by Hambly and Jameson(1991) to the 4° × 4° area and the decrease of star density in the outer part of the cluster(Rosvick *et al.*1992), the LF of HHJ stars was multiplized by a factor of 1.3. Then the ILF for all member stars over the 4° × 4° area is given as Table 2 where binary stars were counted as two stars with same magnitude and color, and plotted in Figure 3 where bars denote the uncertainty($\sigma = N(M_V)/\sqrt{N(M_V)}$ and dashed and dotted lines represent the LF given by Stauffer *et al.*(1991) who did not consider the brightening effect for bright stars and the ILF for MS stars in the solar neighborhood, respectively. For the derivation of this ILF, the age of the solar neighborhood stars was taken as $13Gyr$(Lee and Chun 1986) and the MS lifetimes given by the evolutionary model of Schaller *et al.*(1992) were adopted, assuming the constant birthrate during the period of $13Gyr$. The LF for field MS stars was derived from the data of Wielen(1983), Gilmore and Reid(1983), Gilmore *et al.*(1985), Hawkins and Bessell(1988) and Stobie *et al.*(1985), taking the scale height(Miller and Scalo 1979) and the fraction of MS stars given by Sandage(1957). The ILF for the field stars in Figure 3 was shifted to be fitted to the ILF for the cluster at $M_V = 7^m$.

In Figure 3, it is clearly seen that the general shape of the ILF for the Pleiades cluster is very similar to that for field stars, showing a bump at $M_V \approx 5$, a dip at $M_V = 7$ and a maximum at $M_V \sim 12$ in both ILFs. However, the brightest part($M_V = 0 \sim 1$) and the faintest part($M_V > 12$) of the cluster ILF show somewhat difference from that for the field stars, having steeper slopes. It is noted that the cluster LF for faintest stars is somewhat uncertain in completeness of star count. A deficient region of stars in ILF appears between $M_V = 0$ and 4 for the field stars and between $M_V = 2$ and 5 for the Pleiades cluster. But the deficient region appearing in the latter is less distinctive than for the field stars. This effect will be discussed later in the IMFs.

On the contary to the early investigation of van den Bergh(1957), Lee and Chun(1988) has showed the averaged ILF for well observed open clusters and associations is very similar to that for the field stars down to $M_V \simeq 8$, having deficient region between $M_V = 0$ and 4 as well as the bump and Wielen dip appearing in the LF for the field stars. This result is consistent with the Sandage's(1957) suggestion for a universality of ILF. Recently Phelps and Janes(1994) also showed the similar slope of averaged LF for 8 young open clusters to the Salpeter(1955) slope for the field stars, giving the mass spectrum index, $\alpha = -1.40$ ($\phi(m) \propto m^{-\alpha}$).

IV. MASS FUNCTION

To convert a LF for MS stars to a MF, the correct MLR is needed. Recently Andersen(1991) derived a MLR for very massive, bright MS stars($M_V < 1.5$) which is essentially the same as that given by Popper(1980), and Henry and McCarthy(1993) derived a MLR for intermediate and low mass stars fainter than $M_V \geq 1.45$. In the emprical

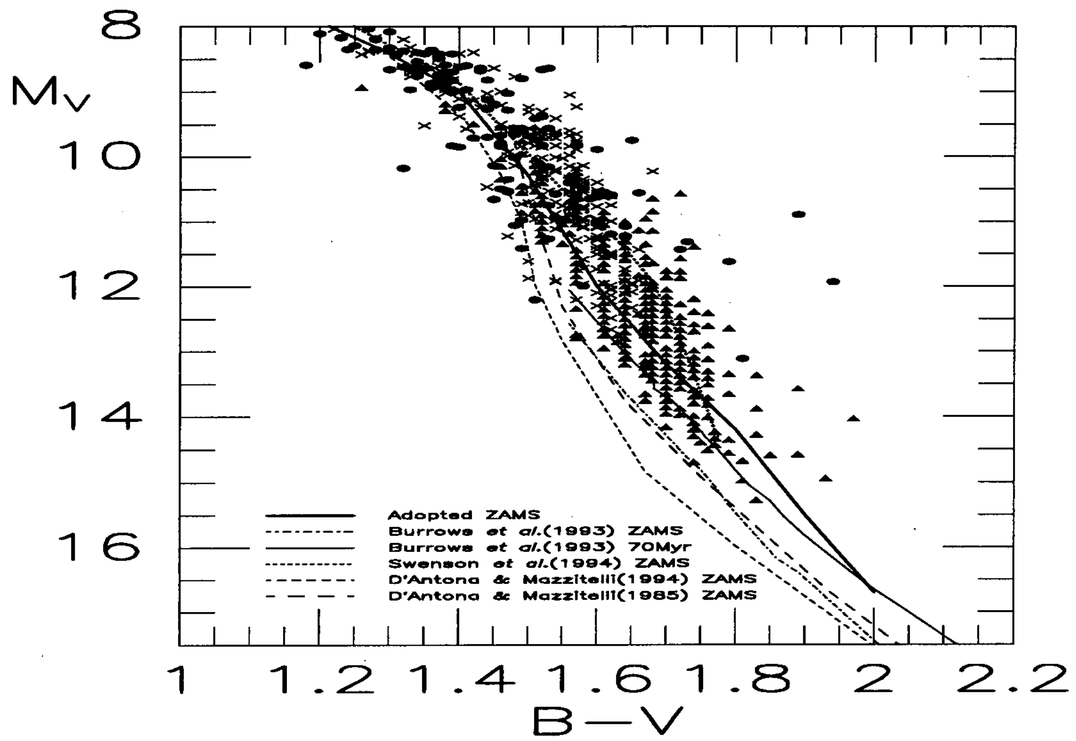

Fig. 2. Faint stars in the Pleiades cluster and ZAMSs. Symbols are the same as in Figure 1.

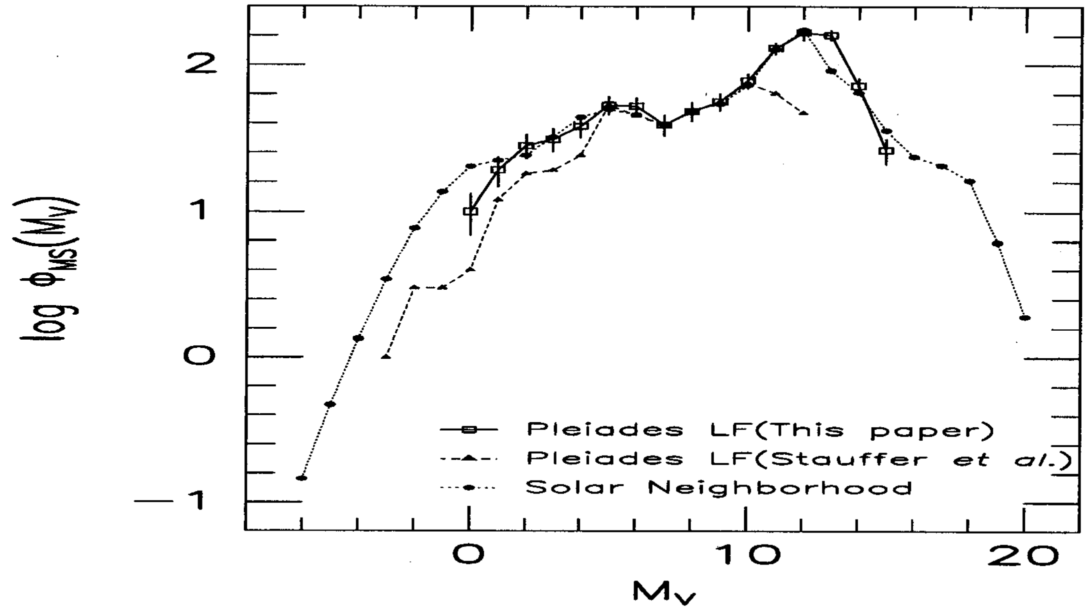

Fig. 3. Luminosity Functions. Square and triangle represents the ILF(this paper) and LF(Stauffer *et al.*1991) for the Pleiades. Closed circle represents the ILF for the solar neighborhood stars which is shifted to be fitted to the dip at $M_V = 7^m$. Bars denote the uncertainty of the data(see text).

MLR for bright stars, the evolutionary effect of stars is included in these luminosity, and hence for $M_V \leq 7.5$ we chose a theoretical MLR given by the evolutionary models of Schaller *et al.*(1992) for $Z = 0.020$ and $Y = 0.28$. And for fainter stars than $M_V = 7.5$ the Henry and McCarthy's emprical MLR was taken, smoothing the MLR between $M_V = 7.5$ and 12.3 in order to avoid the abrupt change of the MLR around $M_V = 10.25$(Case E). Particularly for faint low mass stars in the Pleiades cluster, a theoretical MLR(Case F) for given in Model X of Burrows *et al.*(1993) for age of $7 \times 10^7 yr$ was adopted for $M_V \geq 12.5$. The adopted MLRs are listed in Table 3 where the MLR given in the last two columns are for the Case F. For a comparison we considered other three cases of MLRs. One(Case D) is to use the theoretical MLR given in Table 3 for

$M_V < 7.0$ and the emprical MLR of Henry and McCarthy(1993) for $M_V \geq 7.2$, and the others are the emprical MLR(Case A) given by Andersen(1991) for $M_V \leq 1.3$ and Henry and McCarthy(1993) for $M_V > 1.3$ and the Miller and Scalo's(1979) MLR(Case B) and Popper's(1980) MLR(Case C). It is noted that Henry and McCarthy's MLR is consistent quite well with the theoretical MLR by Schaller *et al.*between $M_V = 3$ and 7.

Using the MLRs(Case E and F) given in Table 3, the ILF for the Pleiades cluster in Table 2 was converted to MFs which are equivalent to the PDMF for MS stars and they are shown in Figure 4. Here the large difference between the two PDMFs for $logm < -0.7 (M_V > 11.5)$ is entirely due to the evolutionary effect of low mass stars(possibly PMS stars). When we take into account the possible existence of PMS stars and flare stars, the use of the MLR(Case F) corresponds to age of $7 \times 10^7 yr$ should be more reasonable than the emprical MLR of Henry and McCarthy for field stars whose age is much greater than the cluster age. The validity for the application of the above PMS MLR will be seen later in a comparison with the IMF for field stars. As a consequence, from now on, we will mention the faint MF obtained only from the use of the above PMS MLR for the Pleiades cluster.

In general, the derivation of MF from an observed LF is affected by a MLR. To see this effect, we derived MFs of the Pleiades cluster by using other MLRs, and they are compared with each other in Figure 5. It can be seen in Figures 4 and 5 that the occurrence of a bump at $logm = 0 \sim -0.1$ and the Wielen dip at $log\ m = -0.12 \sim -0.15$ is likely to be intrinsic regardless of adopted MLRs although their position is slightly affected by different MLRs whereas the appearence of a sharp bump at $log\ m = -0.3 \sim -0.35$ is dependent of applied MLRs. The occurrence of the latter bump is entirely due to the abrupt change(see Kroupa *et al.*1990 for its theoretical reason) of MLRs of Henry and McCarthy(1993) and Popper(1980) between $M_V = 10$ and 11.

In Figure 6, the PDMF (Case F in Figure 4) for the cluster is compared with the IMF for the field stars which was derived from the ILF shown in Figure 3 using the MLR(Case E) given in Table 3. (IMF for solar neighborhood stars is normally defined as the number of stars ever born in unit mass(or $log\ m$) interval per pc^3.) As expected from the similar LFs in Figure 3, the positions and shapes of bump at $log\ m = 0 \sim -0.1$ and Wielen dip in the IMF for the field stars are nearly consistent with those appearing in the PDMF for the cluster. This result suggests that there must be a common mechanism for the occurrence of the bump and dip in the IMF for both the Pleiades cluster and field stars in the solar neighborhood.

As possible mechanism, bimodal star formation(Larson 1986; Lee and Chun 1986), star burst(Scalo 1988) and mass loss of A ~ early G-type MS stars(Willson *et al.*1987) have been suggested. To explain bumps appearing at $m = 1.2M_\odot$ and $3M_\odot$ in the IMF(Scalo 1986) for field stars which was derived by himself, Scalo(1988) suggested two bursts of star formation; one occurring $2 \times 10^8 yr$ ago and the second $5 \times 10^9 yr$ ago. These time intervals correspond to the MS lifetime of stars with $m = 3.5M_\odot$ and $1.2M_\odot$, respectively. Similarly the bump at $log\ m = 0 \sim -0.1$ in Figure 6 requires a burst of star formation particularly with masses $m = 0.8 \sim 1M_\odot$ about $10Gyr$ ago when we consider a single IMF. IF two different time-dependent IMFs(Lee and Chun 1986; Lee and Kim 1983) are taken into account, however, their proper combination can produce the bump and dip without the assumption of discrete star bursts at particular periods.

On the other hand, Willson *et al.*(1987) noted the deficient region(i.e. wide dip) of A ~ early G-type MS stars in the LF for field stars as well as a bump of late G-type stars. As seen in Figures 3 and 6, this deficient region appears between $M_V = 0 \sim 4$ in the ILF and between $log\ m = 0.2 \sim 0.6$ in the IMF for field stars. But such a deficient region is not clearly seen in the LF and MF for the Pleiades cluster. Willson *et al.*(1987) proposed that the above deficient region formed by a rapid mass loss(few times $10^{-9} M_\odot/yr$) of A ~ early G-type MS stars(initial mass = $1.2 \sim 3.5M_\odot$) which fall within the Cepheid instability strip, leading to the formation of bump and dip at the lower mass region($m < 1M_\odot$). This proposal is based on the assumption that the IMF for field stars is a single,

Table 2. Luminosity Functions for the Pleiades Cluster and field stars in the Solar Neighborhood

	Field Stars			Pleiades		Field Stars			Pleiades
M_V	$log\phi(M_V)$	$log\phi_{ms}(M_V)$	$log\Phi(M_V)$	$log\Phi(M_V)$	M_V	$log\phi(M_V)$	$log\phi_{ms}(M_V)$	$log\Phi(M_V)$	$log\Phi(M_V)$
-6	2.25	4.168	-2.136	-	8	7.58	10.393	0.393	1.681
-5	2.90	4.837	-1.626	-	9	7.62	10.433	0.433	1.748
-4	3.55	5.487	-1.170	-	10	7.75	10.563	0.563	1.892
-3	4.20	6.154	-0.759	-	11	8.00	10.813	0.813	2.114
-2	4.85	6.813	-0.412	-	12	8.13	10.943	0.943	2.223
-1	5.48	7.460	-0.166	-	13	7.85	10.663	0.663	2.204
0	6.08	8.083	0.007	1.000	14	7.70	10.513	0.513	1.857
1	6.52	8.580	0.047	1.279	15	7.44	10.253	0.253	1.415
2	6.86	9.033	0.084	1.447	16	7.26	10.073	0.073	-
3	7.11	9.522	0.208	1.491	17	7.20	10.013	0.013	-
4	7.37	9.972	0.346	1.580	18	7.10	9.913	-0.087	-
5	7.51	10.281	0.397	1.724	19	6.68	9.493	-0.507	-
6	7.56	10.363	0.363	1.716	20	6.17	8.983	-1.017	-
7	7.48	10.293	0.293	1.591					

$\phi(M_V)$: LF(+10) for MS and giant stars, $\phi_{ms}(M_V)$: LF(+10) for MS stars, $\Phi(M_V)$: ILF for field stars,

Table 3. Mass-Luminosity Relation*

M_V	$log\ m$	M_V	$log\ m$	M_V	$log\ m$	M_V	$log\ m$	M_V^+	$log\ m^+$
-6.1	2.080	0.2	0.575	7.00	-0.122	12.3	-0.647		
-6.0	2.050	0.6	0.506	7.20	-0.135	12.5	-0.680	12.50	-0.772
-5.8	1.971	1.0	0.441	7.50	-0.156	12.8	-0.730	12.91	-0.824
-5.4	1.831	1.4	0.379	8.00	-0.188	13.4	-0.775	13.32	-0.903
-5.0	1.706	1.8	0.322	9.00	-0.253	13.6	-0.813	13.58	-0.959
-4.6	1.594	2.2	0.269	9.25	-0.271	14.0	-0.849	13.84	-1.000
-4.2	1.491	2.6	0.221	9.50	-0.289	14.4	-0.899	14.11	-1.046
-3.8	1.395	3.0	0.177	9.75	-0.308	15.0	-0.931	14.37	-1.086
-3.4	1.303	3.4	0.137	10.00	-0.327	15.6	-0.976	14.58	-1.119
-3.0	1.214	3.8	0.100	10.25	-0.349	16.2	-1.017	14.82	-1.155
-2.6	1.128	4.2	0.067	10.50	-0.375	16.8	-1.054	15.05	-1.187
-2.2	1.043	4.6	0.037	10.75	-0.407	17.4	-1.087	15.29	-1.222
-1.8	0.960	5.0	0.009	11.00	-0.435	17.6	-1.097	15.53	-1.260
-1.4	0.879	5.4	-0.018	11.25	-0.474	18.2*	-1.125*	15.82	-1.301
-1.0	0.800	5.8	-0.044	11.50	-0.511	18.8*	-1.149*	16.58	-1.398
-0.6	0.722	6.2	-0.069	11.80	-0.562	19.4*	-1.170*	17.79	-1.523
-0.2	0.647	6.6	-0.095	12.00	-0.596	20.0*	-1.187*	19.80	-1.182

$\star$ $M_V < 7.^m0$: Schaller *et al.*'s(1992) MLR, $7.5 \leq M_V < 12.3$: Smoothed MLR of Henry and McCarthy(1993), $M_V \geq 11.5$: Henry and McCarthy's(1993) MLR, $*$: extrapolated MLR of Henry and McCarthy(Case E), $+$: Burrows *et al.*(1993) MLR for $7 \times 10^7 yr$ (Case F) smoothed function with stellar mass without dip and bump.

When we consider the young age($7 \sim 10 \times 10^7 yr$) for the Pleiades cluster, it cannot be expected for the deficient region and bump to be formed by the mass loss of A ~ early G-type MS stars in this short period. However, a clear bump and Wielen dip appear in this cluster without having the deficient region in the MF. This implies that the rapid mass loss of A ~ early G-type MS stars cannot be a major effective mechanism for the formation of bump and dips appearing in the MFs for both the cluster and field stars. Then among the three mechanisms mentioned above, the most plausible one seems to be a time-dependent bimodal IMF. We will examine this in the following section.

V. BIMODAL IMF

Lee and Chun(1986) has shown that the Wielen dip in the LF for the field stars can be explained by the time-dependent bimodal IMF but not by a single IMF. The another form of time-dependent IMF has been applied to open clusters by Lee and Kim(1983) and Lee and Park(1993). Here we chose these two different forms of time-dependent bimodal IMF of which variations with time are shown in Figure 7. The bimodal IMF(Model A) of Lee and Chun(1986) is the combination of two time-dependent IMFs; one for massive star formation and the other for low mass star formation. And in the bimodal IMF(Model B) of Lee and Kim(1983), one IMF covers the star formation over a whole range of mass and the other controls the star formation around solar mass, starting star formation after about two times the free-fall time scale. The latter case is comparable to the model of star burst(Scalo 1988) around one solar mass. The above models can produce a bump at $log\ m \approx 0$ and a dip at $log\ m \approx -0.1$, which appear at the very early stage of star formation in the Model A and at the relatively later stage in the Model B as shown in Figure 8.

Taking the time-dependent star formation rate given by Lee and Hong(1982) and the above bimodal IMFs, theoretical PDMF and ILF for MS stars in the Pleiades cluster were computed, producing a bump and the Wielen dip. They are compared with the observed PDMF and ILF in Figure 9, where histogram represent observed values. Also the C-M diagram can be derived by using the above models as seen in Figure 10. Here the total number of brightest stars between $M_V = -.5 \sim +1.5$ in the ILF given in Table 2 was used as a constraint for the modeling, allowing the fluctuation of $\Delta N = \pm 1$. For faint stars in the C-M diagram, we adopted the PMS models of Swenson *et al.*(1994) for $m \leq 0.8 M_\odot$ and D'Antona and Mazzitelli(1994) for $m \leq 0.15 M_\odot$. In Figure 10, the PMS obtained from the latter model was shifted redward to be fitted to the PMS obtained from the former model. It is noted that recently a few PMS models(Burrows *et al.*1994; D'Antona and Mazzitelli 1994; Swenson *et al.*1994) have been presented, but there is no close consistency among the various models. The above adopted PMS models were used only for the estimate of total mass and number of stars in the cluster.

According to the model calculation by using the above bimodal IMFs, the computed characteristics of the Pleiades cluster are given in Table 4. The age is given by $\sim 8 \times 10^7 yr$ which is similar to those estimated by others(Stauffer 1980; Stauffer *et al.*1984; Maeder and Meynet 1991). This age is a photometric age which is defined by the number of brightest ZAMS stars in the two magnitude range from the brightest magnitude, reproducing them in the C-M diagram. In the Model B, the massive stars ($log\ m > 0.5$) seen in the present C-M diagram has the mean age of $7.3 \times 10^7 yr$. which is greater by $2 \times 10^6 yr$ than the low mass stars($log\ m < -0.5$). However, in the Model A the massive stars with the mean age of $7.1 \times 10^7 yr$ is younger by $7 \times 10^6 yr$ than the low mass stars($log\ m < -0.5$). It has been suggested that the nuclear age(isochrone age : Maeder and Meynet(1991) or turn-off age : Stauffer *et al.*(1984), Mermilliod(1981)) is smaller by a few times $10^7 yr$(Stauffer 1980) than the turn-on age(PMS contraction age). This large age difference is often contributed to the age spread of star formation as shown in the other young open clusters(Iben and Talbot 1966; Kwon and Lee 1983; Cohen and Kuhi 1979). In this point of view, the Model A seems more reasonable than the Model B for the Pleiades cluster. In the present models the star formation ceases completely at the early stage after 6 ~ 8 times the free-fall time scale($12 \sim 17 \times 10^6 yr$), which is equivalent to the age spread of star formation. Accordingly the stars with mass smaller than $0.8 M_\odot (M_V > 6.5)$ lie within two PMS isochrones of $\sim 7 \times 10^7 yr$ and $\sim 8 \times 10^7 yr$, and the color width corresponding to these isochrones is narrower than the observed color dispersion in the C-M diagram(Fig. 1). Therefore the difference between the nuclear age of bright upper MS stars and the contraction age of PMS stars cannot be clearly seen in the present model(see Fig. 10). This result is supported by the fact that all the stars in the cluster lie on a relatively well confined, continuous single age

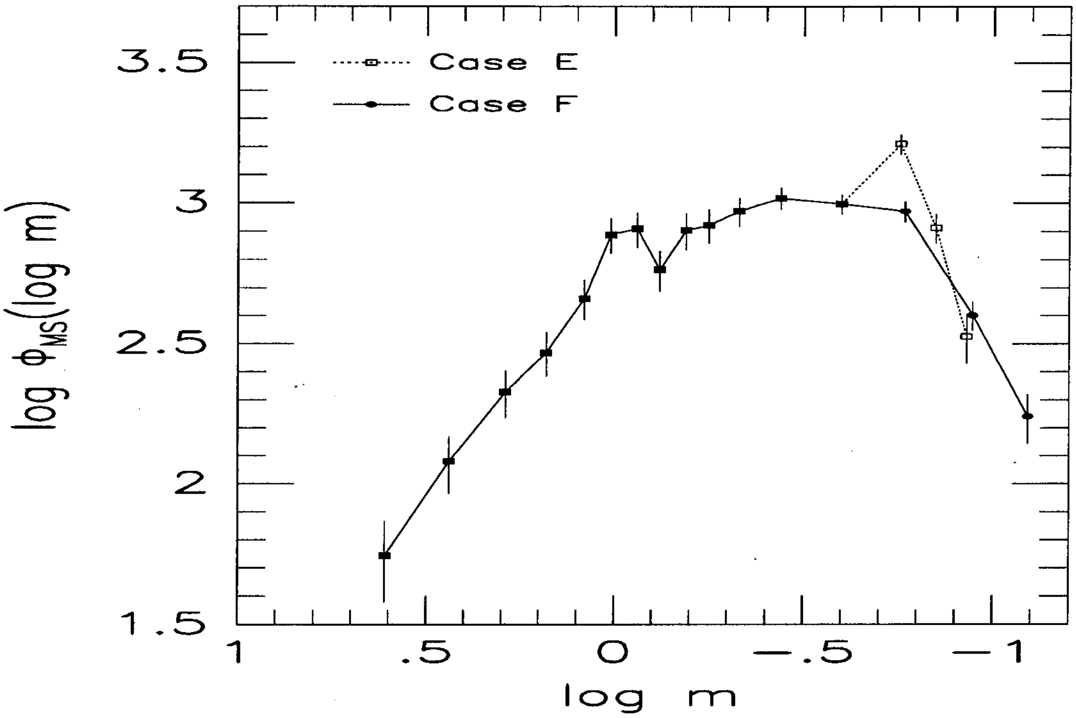

Fig. 4. PDMFs for the Pleiades cluster. Closed and open circles represent the PDMFs derived from the MLR of Case F and Case E, respectively. Bars denote the uncertainty.

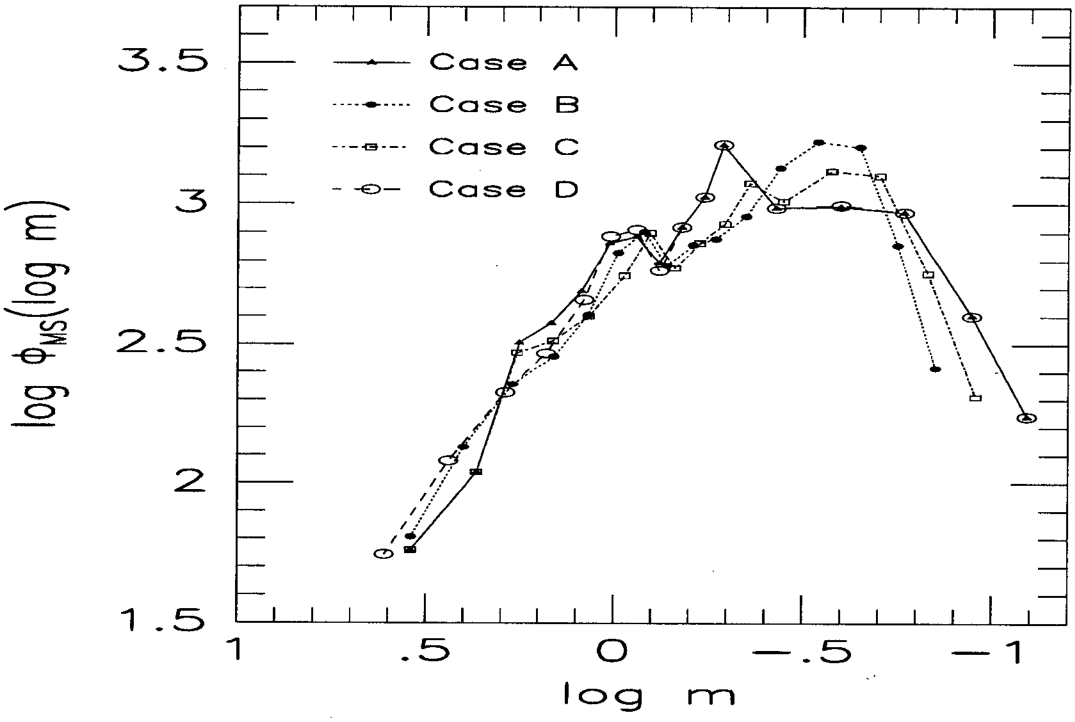

Fig. 5. PDMFs for the Pleiades cluster derived from various MLRs.

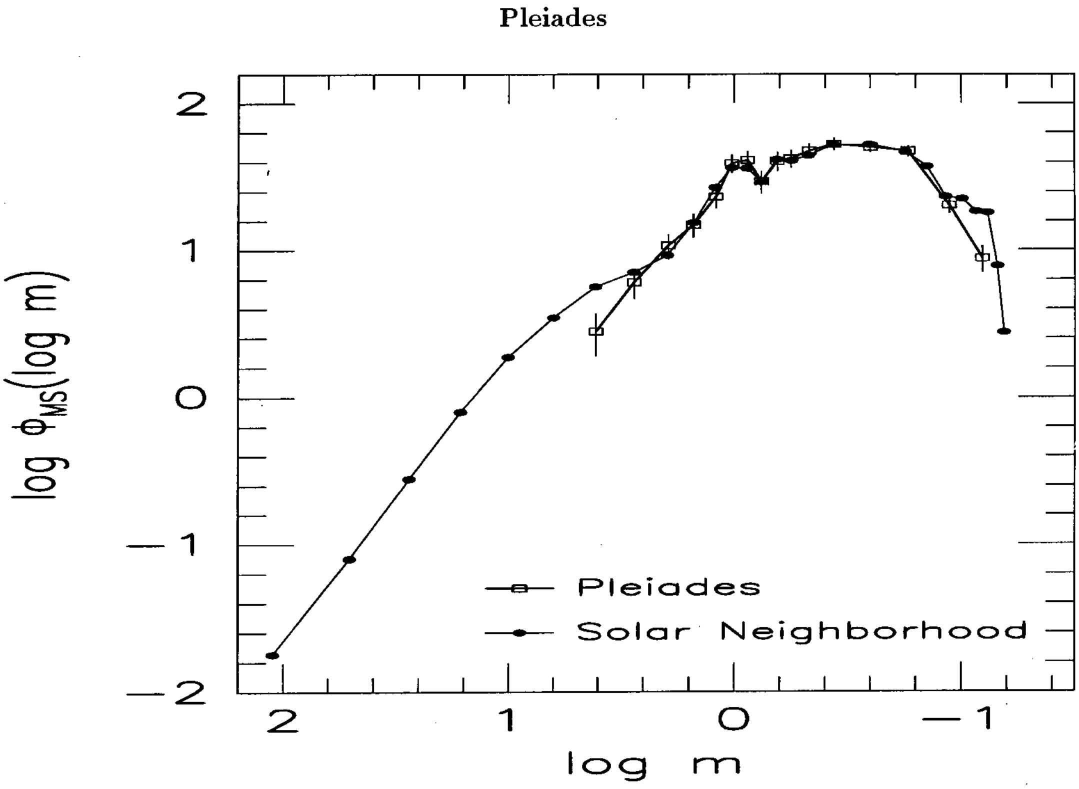

Fig. 6. Comparison of the PDMF for the Pleiades cluster with the IMF for solar neighborhood stars.

Table 4. Model Calculation

	Model A	Model B	Comparison
Age($10^6 yr$)	83.1	77.4	70(1), 100(2)
N_{total}	1010	1050	
$M_{total}(M_\odot)$	684	706	$\geq$ 1000(3,6)
N_{dead}	9	10	
$M_{dead}(M_\odot)$	74	71	
N_{BD}	25	29	> 30(5,6)
N_{WD}	$3^+(0)$	$4^+(0)$	1(4)

(1): Stauffer *et al.*(1984), (2): Maeder and Meynet(1991), (3): van Leeuwen(1983)
(4): Luyten and Herbig(1960), (5): Hambly and Jameson(1991), (6): Simon and Becklin(1992)
upper mass limit of progenitor of white dwarfs : + for $5 \leq m < 6M_\odot$; () for $m < 4.5M_\odot$

sequence in the C-M diagram and particularly faint stars lie on or near the ZAMS without showing the considerable age spread in the C-M diagram as seen in Figure 1.

The total number of stars ever born is estimated to be about 1000 among which more than a half are low mass stars with $m < 0.5M_\odot$, and their total mass in the cluster is $\sim 700M_\odot$. This is smaller than the dynamical mass($\sim 1000M_\odot$) estimated by van Leeuwen(1983) from the velocity dispersion and the photometric mass($\sim 1200M_\odot$) deduced by Simon and Becklin(1992) assuming a Salpeter MF tied to van Leeuwen's(1983) MF at $1M_\odot$. This mass

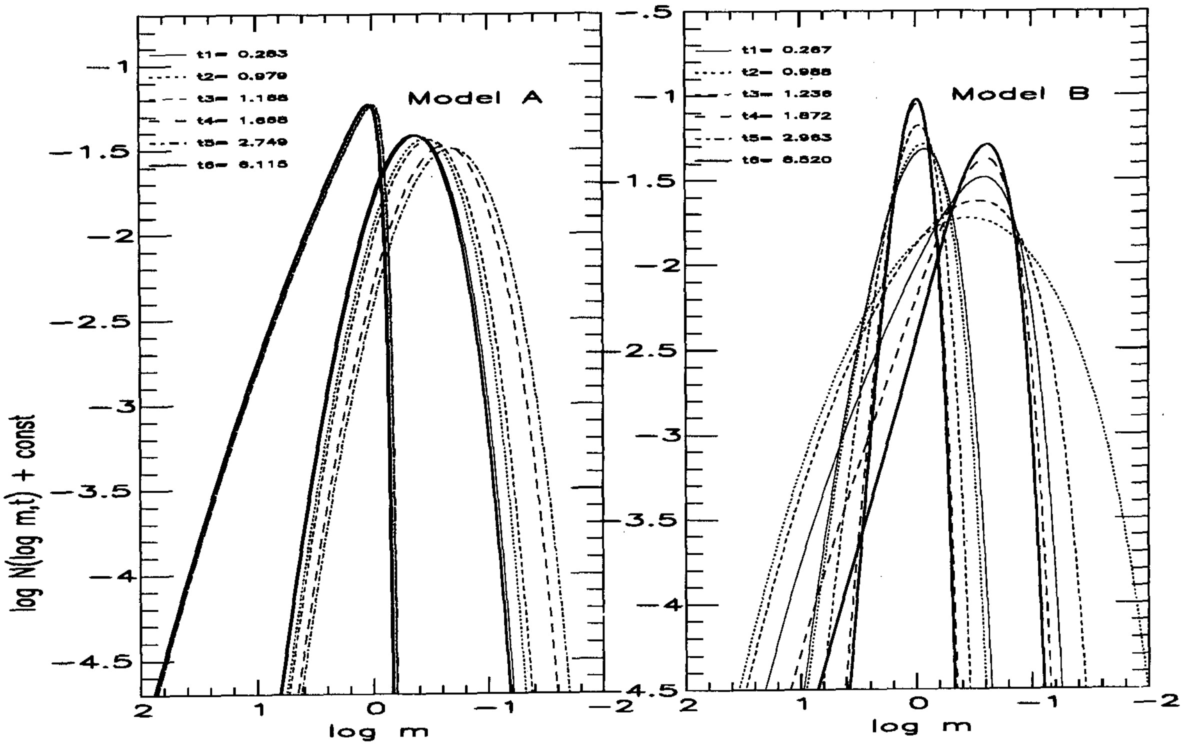

Fig. 7. Temporal variation of bimodal each IMFin given bimodal IMFs. Time unit is a free-fall time given in each model.

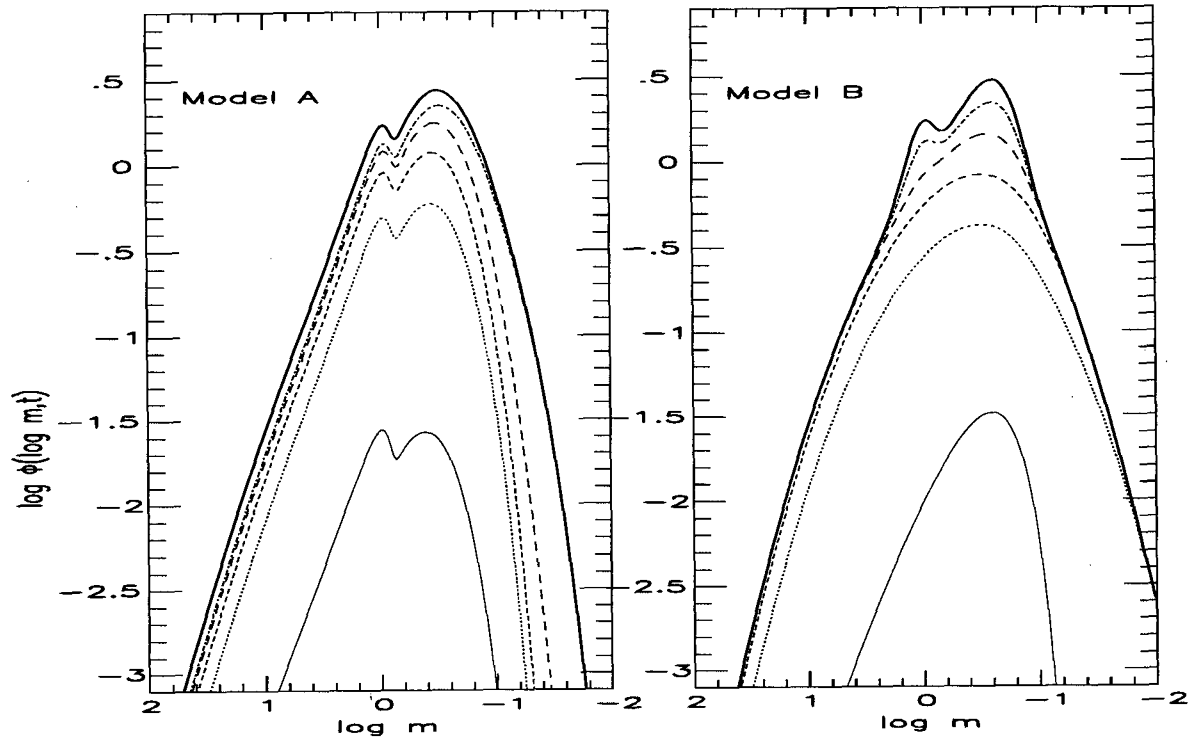

Fig. 8. Time-dependent MF Symbols are the same as in Fig. 7.

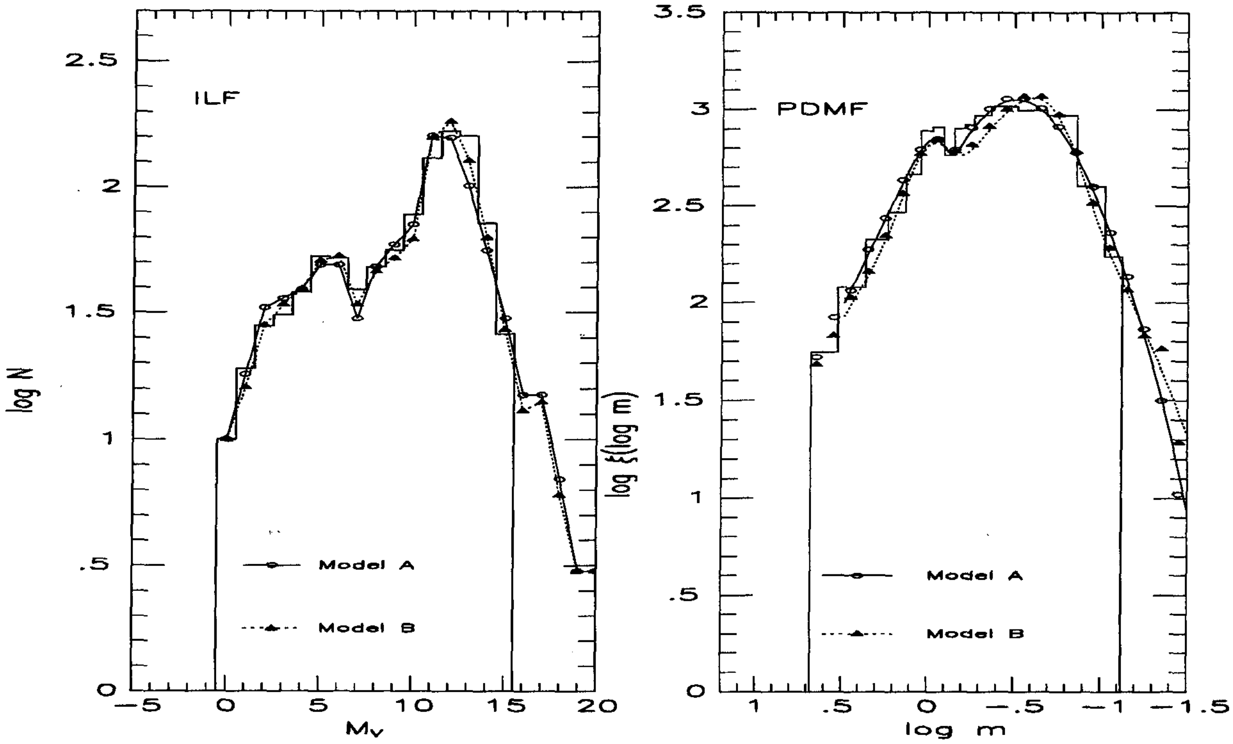

Fig. 9. Comparison of observed ILF and PDMF(histograms) with computed ones.

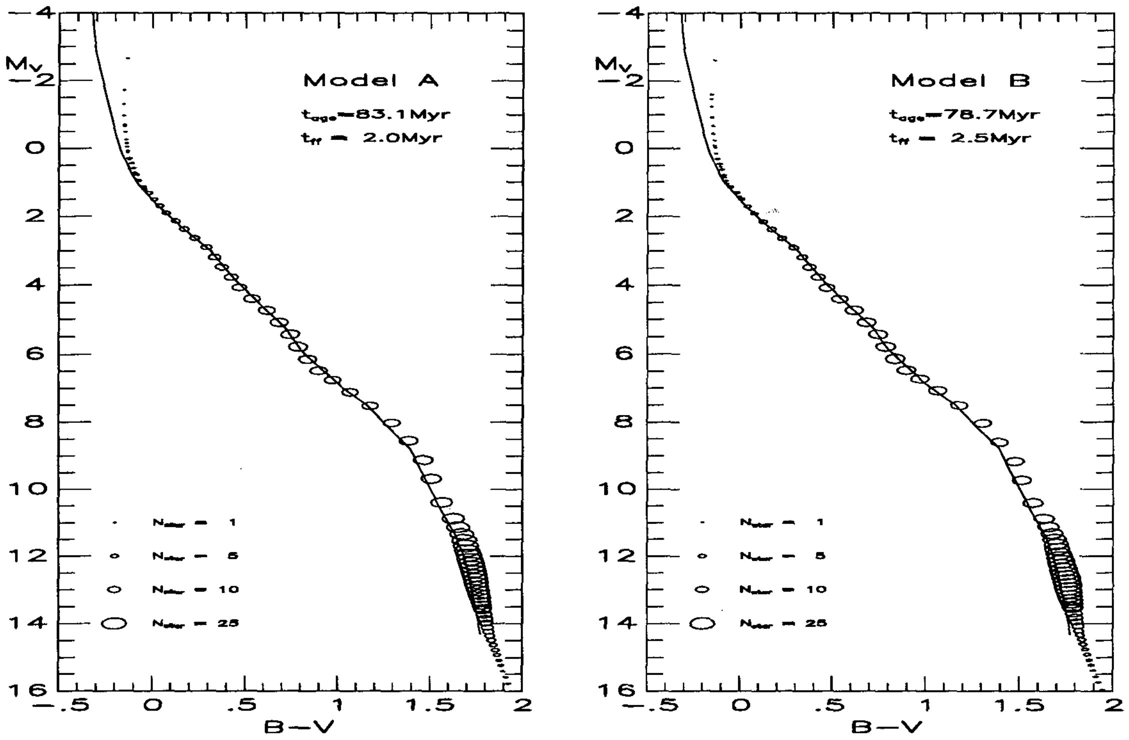

Fig. 10. Computed C-M diagrams. Solid line represents the adopted ZAMS for $M_V < 6.5$ and Swensonson *et al.*'s(1994) ZAMS for $M_V > 6.5$.

difference may be explained by a complete LF of faint stars which will be obtained in the future. The present models produce 25 $\sim$ 29 brown dwarfs which are comparable to the lower limit of 30 brown dwarfs estimated by Hambly and Jameson(1991) but are much smaller than the number(a few thousands) deduced by Simon and Becklin(1992) from the MF similar to the Salpeter MF.

The total number of dead stars which have exhausted nuclear fuel, are 9 $\sim$ 10 and their total mass is $\sim 70M_{\odot}$ which is $\sim$ 10% of total cluster mass given in Table 4. Among these dead stars, 3 $\sim$ 4 white dwarfs are expected if the upper mass limit of progenitor of white dwarf is $5 \leq m < 6M_{\odot}$, but no white dwarf if the upper mass limit is smaller than $4.5M_{\odot}$. Luyten and Herbig(1960) reported one white dwarf in the Pleiades. If this white dwarf is really a member of the Pleiades cluster, the upper mass limit of progenitor of white dwarf is greater than $4.5M_{\odot}$ at least in the Pleiades cluster.

In Table 4, the two models with different IMFs show similar results at the present stage of cluster evolution. But their main differences appear at the different periods of massive star formation and of the occurrence of bump at $log\ m \sim 0$ and dip at $log\ m \sim -0.2$. That is, in the Model B, all massive stars($m \geq 3M_{\odot}$ are born at the early stage of the star formation before the half of the cluster age, and the bump and dip appear after about two times the free-fall time scale($\sim 4 \times 10^{6} yr$). On the other hand, in the Model A, two thirds of these massive stars are formed at the later stage after the half of the age, and the bump and dip appear from the very early stage of star formation. In extreme young clusters it has been known that very massive stars in upper MS are formed at the later stage of star formation than the low mass stars(Herbig 1962; Iben and Talbot 1966; Cohen and Kuhi 1979). When we consider this observational results, the Model A which has a low mass IMF($m < 0.8M_{\odot}$) with a peak around $log\ m = -0.5$ and a high mass IMF($m \geq 0.8M_{\odot}$) with a peak around $log\ m = 0$ seems more reasonable than the Model B with enhanced IMF around one solar mass as seen in Figure 8. At present the observation of the appearence of dip and bump is very difficult particularly for very young clusters and associations because of lack of low mass stars for which the reason is not certain whether the paucity of low mass stars an intrinsic property in star formation or due to the incompleteness of star counts in these star clusters. Therefore, this problem must be testified with more carefully, extensively surveyed clusters with different ages.

VI. CONCLUSION

In the best observed Pleiades cluster, the LF for MS stars over the 4° x 4° area around the cluster center is derived down to $M_V \approx 15$, but the LF for fainter stars(Hambly *et al.*1993) than $M_V \approx 13$ is incomplete. This cluster LF is very similar to the ILF for field stars in the solar neighborhood, showing a bump at $log\ m \sim 0$ and the Wielen dip at $log\ m \simeq -0.12$ but no deficient region which is seen between $M_V = 0$ and 4 in the ILF for the field stars. The bump and Wielen dip also appear in the MF for MS stars in both the cluster and the field stars and it is found that their appearance as intrinsic property is nearly independent of known MLRs. These characteristics of MF could be explained by the combination of high mass IMF with a peak at $log\ m \simeq 0$ and low mass IMF with peak at $log\ m \approx -0.5$(Lee and Chun 1986; Lee and Kim 1983) rather than by the star burst(Scalo 1988) occurred at particular periods and/or mass loss of A $\sim$ early G-type MS stars within the Cepheid instability strip(Willson *et al.*1987).

According to the model calculation by using the bimodal IMF, the total mass of the Pleiades cluster is given by $\sim 700M_{\odot}$ which is smaller than the dynamical mass deduced by van Leeuwen(1983), and more than half the total mass is attributed to low mass stars with $m \leq 0.5M_{\odot}$. The estimated number of white dwarfs depends on the upper mass limit of progenitor of white dwarf. If this upper mass limit is $\sim 5.5M_{\odot}$, about three white dwarfs are expected in the Pleiades cluster.

Recently Simon and Becklin(1992) estimated $\sim 3,400$ objects in the range of $0.04 < m(M_{\odot}) < 0.1$ from the near IR measurements, showing a Salpeter type MF for brown dwarfs. In this survey, a large uncertainty is involved in estimating the membership of faint stars because their proper motions are not known. The present model gives $\sim$ 25 brown dwarfs with $m < 0.08M_{\odot}$, which is comparable to the lower limit for brown dwarf candidates deduced by Hambly and Jameson(1991).

We can define a photometric age, reproducing the observed LF by theoretical model on the constraint that a computed LF of brightest ZAMS stars within a two magnitude range from the brightest magnitude in the C-M diagram is equal to the observed LF within the fluctuation of $\Delta = \pm 1$. Then the present model with time-dependent bimodal IMF gives a photometric age of $\sim 8 \times 10^7 yr$. This age is close to the turn-off age($7 \times 10^7 yr$:Stauffer *et al.*1984) of bright upper MS stars and isochrone age($10^8 yr$:Maeder and Meynet 1991).

The existence of PMS stars among stars fainter than $V \approx 13$ in the Pleiades cluster has been suggested by Landolt(1979) and Stauffer(1980) from their dispersed positions above the ZAMS in the C-M diagram. Later Stauffer(1984) showed that a significant number of these stars may be binary stars, presenting the binary frequency of 26% for late type stars in the cluster. Breger(1985) draw some doubt about the true existence of PMS stars in the cluster from polarimetric measurements. This problem can be checked by computing LF for faint stars in corperation with theoretical IMF and PMS evolution model. However, a few PMS models(D'Antona and Mazzitelli 1985, 1994; Burrows *et al.*1993; Swenson *et al.*1994) recently proposed do show significant inconsistency among them. Consequently the true nature of PMS stars in the Pleiades cluster cannot be explained at present, although PMS models indicate the existence of PMS stars with mass smaller than $0.8M_\odot$.

REFERENCES

Andersen,J. 1991, A&AR, 3, 91
Bessell,M. 1986, PASP, 98, 1303
Bessell,M. 1991, AJ, 101, 662
Bettis,C. 1975, PASP, 87, 707
Breger,M. 1986, ApJ, 301, 311
Burrows,A., Hubbard,W.B., Saumon,D., Lunine,J.I. 1993, ApJ, 406, 158
Cohen,M., Kuhi,L.V. 1979, ApJS, 41, 743
D'Antona,F., Mazzitelli,I. 1985, ApJ, 296, 502
D'Antona,F., Mazzitelli,I. 1994, ApJS, 90, 467
Gilmore,G., Reid,N. 1983, MNRAS, 202, 1025
Gilmore,G., Reid,N., Hewett,P. 1985, MNRAS, 213, 257
Guzik,J.A., Struck-Marcell,C. 1988, AJ, 95, 1735
Hambly,N.C., Jameson,R.F. 1991, MNRAS, 249, 137
Hambly,N.C., Hawkins,M.R.S., Jameson,R.F. 1991, MNRAS, 253, 1
Hambly,N.C., Hawkins,M.R.S., Jameson,R.F. 1993, A&AS, 100, 607
Hawkins,M.R.S., Bessell,M.S. 1988, MNRAS, 234, 177
Henry,J.J., McCarthy,D.W. 1993, AJ, 106, 773
Herbig, G.H. 1962, ApJ, 135, 736
Hertzsprung,E. 1947, Ann. Sterrenwarte Leiden, 19, No1A
Iben,I.Jr, Talbot,R.J. 1966, ApJ, 144, 968
Johnson,H.L. 1957, ApJ, 126, 121
Jones,B.F. 1970, AJ, 75, 563
Jones,B.F. 1973, AAS, 9, 313
Jones,B.F. 1981, AJ, 86, 290
Kwon,S.M., Lee,S.-W. 1983, J. Korean Astr. Soc., 16, 7
Kroupa, P., Tout, C.A., Gilmore, G. 1990, MNRAS, 244, 76
Landolt,A.U. 1979, ApJ, 231, 468
Larson,R.B. 1986, MNRAS, 218, 409
Lee,S.-W., Chun,M.Y. 1986, J. Korean Astr. Soc., 19, 51
Lee,S.-W., Chun,M.Y. 1988, J. Korean Astr. Soc., 21, 37
Lee,S.-W., Hong,S.S. 1982, J. Korean Astr. Soc., 15, 71
Lee,S.-W., Kim,Y.H. 1983, J. Korean Astr. Soc., 16, 43
Lee,S.-W., Park,W.K. 1993, J. Korean Astr. Soc., 26, 47

Luyten,W.J., Herbig,G.H. 1960, Harvard Ann. Card, No1474
Maeder,A., Meynet,G. 1991, A&AS, 89, 451
Mermilliod,J.-C. 1981, A&A, 97, 235
Mermilliod,J.-C. 1988, Bull. Inform. CDS, No35, 77
Miller,G.E., Scalo,J.N. 1979, ApJS, 41, 513
Phelps,R.L., Janes,K.A. 1993, AJ, 106, 1870
Popper,D.M. 1980, ARA&A, 18, 115
Prihet,G. 1983, AJ, 88, 1476
Reid,N. 1982, MNRAS, 201, 51
Rosvick, J.M., Mermilliod, J.-C., Mayor, M. 1992, A&A, 225, 130
Salpeter,E.E. 1955, ApJ, 121, 161
Sandage,A.R. 1957, ApJ, 125, 422
Savage,B.D., Mathis,J.S. 1979, ARA&A, 17, 73
Scalo, J.M. 1986, Fundamentals of Cosmic Physics, 11, 1
Scalo,J.M. 1988, in *Starburst and Galaxy Evolution*, ed. by T. Montmerle, (Frontieres; Paris), p445
Schaller,G., Schaerer,G., Meynet,G., Maeder,A. 1992, A&AS, 96, 269
Schmidt-Kaler, Th. 1982, in *Astronomy and Asprophysics*, Vol.2, eds. by K. Schaifers and H.H. Voght, p15
Simon,D.A., Beckiln,E.E. 1992, ApJ, 390, 431
Stauffer,J. 1980, AJ, 85, 1341
Stauffer,J. 1982, AJ, 87, 1507
Stauffer,J. 1984, ApJ, 280, 189
Stauffer,J., Hartmann,L.W. 1987, ApJ, 318, 337
Stauffer,J., Hartmann,L.W., Soderblom,D.R., Burnhan,N. 1984, ApJ, 266, 747
Stauffer,J., Klemola,A., Prosser,C., Probst,R. 1991, AJ, 101, 980
Stobie,R.S., Ishida,K., Peacock,J.A. 1989, MNRAS, 238, 709
Swenson,F.J., Faulkner,J., Rodgers,F.J., Iglesias,C.A. 1994, ApJ(submitted)
Thé,P.S., Bakker, R., Antalova, A. 1980, A&AS, 41, 93
Trumpler,R.J. 1921, Lick Obs. Bull. 10, 110
Upgren,A.R., Armandroff,T.E. 1981, AJ, 86, 1898
VandenBerg,D.A., Poll,H.E. 1989, AJ, 98, 1451
van den Bergh,S. 1957, ApJ, 125, 455
van Leeuwen,F. 1983, PhD dissertation(Leiden Univ)
van Leeuwen,F., Alphenaar,P., Brand,J. 1986, A&AS, 65, 309
Wielen,R. 1974, IAU Highlight of Astronomy, Vol.13, ed. by G. Contopoulos, p395
Wielen,R., Jahreiss,H., Kröger,R. 1983, in *Nearby Stars and Stellar Luminosity Functions*, IAU colloq. No76, ed. by A.G.Davis Philip and A.R. Upgren, (Schenectady; NY), p163
Willson,L.A., Bowen,G.H., Struck-Marcell,C. 1987, Comments on Astrophysics, 12, 17
Yoshii,Y., Ishida,K., Stobie,R.S. 1987, AJ, 93, 323