JOURNAL OF THE KOREAN ASTRONOMICAL SOCIETY
35: 197 ~ 208, 2002

PMS EVOLUTION MODEL GRIDS AND THE INITIAL MASS FUNCTION

BYEONG-GON PARK[1], HWANKYUNG SUNG[2], AND YONG HEE KANG[3]
[1]Korea Astronomy Observatory, Daejon 305-348, Korea
E-mail: bgpark@boao.re.kr
[2]Department of Astronomy and Space Science, Sejong University, Seoul 143-747, Korea
E-mail: sungh@sejong.ac.kr
[3]Department of Earth Science Education, Kyungpook National University, Daegu 702-701, Korea
E-mail: yhkang@knu.ac.kr
(Received Nov. 26, 2002; Accepted Dec. 16, 2002)

ABSTRACT

Five contemporary pre-main sequence (PMS) evolution model grids are compared with the photometric data for a nearly complete sample of low-mass members in NGC 2264. From amongst the grids compared, the models of Baraffe et al. (1998) prove to be the most reliable in mass-age distribution. To overcome the limited mass range of the models of Baraffe et al. we derived a simple transformation relation between the mass of a PMS star from Swenson et al. (1994) and that from Baraffe et al., and applied it to the PMS stars in NGC 2264 and the Orion nebula cluster (ONC). The resulting initial mass function (IMF) of the ONC shows that the previous interpretation of the IMF is not a real feature, but an artifact caused by the evolution models adopted. The IMFs of both clusters are in a good agreement with the IMF of the field stars in the solar neighborhood. This result supports the idea proposed by Lada, Strom, & Myers (1993) that the field stars originate from the stars that are formed in clusters and spread out as a result of dynamical dissociation. Nevertheless, the IMFs of OB associations and young open clusters show diverse behavior. For the low-mass regime, the current observations suffer from difficulties in membership assignment and sample incompleteness. From this, we conclude that a more thorough study of young open clusters is necessary in order to make any definite conclusions on the existence of a universal IMF.

Key words : stars: pre-main sequence — stars: mass function — open clusters and associations: individual (NGC 2264, Orion Nebula Cluster)

I. INTRODUCTION

In the study of the young open cluster NGC 2264, Park et al. (2000, hereafter PSBK) compared the ages and masses of low-mass PMS stars estimated from several contemporary PMS evolution model grids. They showed that there are differences of up to a factor of two in the estimated ages and differences in mass distributions depending on the adopted evolution models. In three out of the five evolution models, they found a notable mass-age relationship in which the age decreases toward decreasing stellar mass. The models of Baraffe et al. (1998) show a weak or no mass-age relationship, which is in agreement with the result of White et al. (1999).

This result stimulated us to make more detailed investigations of the effect that mass-age relationships evident in PMS evolution models have on the resulting mass and age distributions of a young cluster. A comparison between the mass and age estimated from one model with those from another can give us quantitative relations between models that can be applied to the transformation of the mass and age scales of one model to those of another model. If there are any limitations in mass or age from the best fitting model, these transformation relations can be used to compensate for such shortcomings in the best model.

For this purpose, we use the census of low-mass PMS stars in NGC 2264, but with more X-ray emitting stars available in the northern part of the cluster than PSBK. There are two important reasons why we choose NGC 2264. Firstly, the cluster is almost free from foreground extinction and differential reddening across the cluster field (Sung, Bessell, & Lee 1997, hereafter SBL) and therefore, photometric properties of the PMS members can be regarded as a direct reflection of the evolutionary status of these stars. Secondly, the current low-mass membership lists are nearly complete including both classical T Tauri stars and weak-lined T Tauri stars, and the total number of stars is large enough for statistical analysis.

Once the best PMS model is selected, we can derive the mass and age distributions of NGC 2264 again using the nearly complete list of PMS members in the cluster. We also apply the model to another well-studied young open cluster, the Orion nebular cluster (ONC), and discuss our results together with those of previous investigators (Hillenbrand 1997, hereafter H97; Luh-

---

Corresponding Author: B.-G. Park

man et al. 1999).

Field stars in the solar neighborhood are thought to be formed either through isolated star formation, as in the star forming region in Taurus, or through clustered formation, as in ρ Ophiucus or in the regions L1630 and L1641. The latter hypothesis was first proposed by Lada, Strom, & Myers (1993). Comparison of the initial mass functions (IMFs) of the open clusters obtained in this study and that of the field stars in the solar neighborhood will provide a clue to the star formation history in the Galactic disk.

The IMF of the open clusters are also useful for the discussion on the universality hypothesis of the IMF, especially in the intermediate- to high-mass regime. The existence of a universal IMF has long been one of the most controversial topics. As reviewed by Kennicutt (1998), there are many observational evidences for or against a universal IMF. Extensive studies have been made on the IMF of OB associations and young open clusters in the Galaxy, as well as in the Magellanic Clouds by Massey and his collaborators (Massey, Jhonson, & DeGioia-Eastwood 1995; Massey et al. 1995). They argued that the massive part of the IMF is universal, within the uncertainties of their observations.

However, Scalo (1998) strongly argued that the interpretations of Masseys' results are highly subjective and biased by their strong bias toward the existence of a universal IMF. After examining the IMFs obtained by Massey, Johnson, & DeGioia-Eastwood (1995), Scalo concluded that the slopes of the IMF show a wide spread, rather than support for a universal IMF. Scalo also found that there are discrepancies in the interpretations of the observational results made by Massey's group and those by other investigators, even for the same star forming region with the same adopted calibrations and evolution models.

Studies on the IMF of low-mass stars is very much an expanding field. Bouvier et al. (1998) performed *RI* photometry in the field of the Pleiades and obtained the IMF of the cluster down to about 0.1 $M_\odot$. The slope of the IMF they obtained was $\Gamma = 0.4$ for stars less massive than 0.4 $M_\odot$. Also for M35, Barrado y Navascués et al. (2000) obtained a similar IMF to that of the Pleiades. From a study of the extremely young open cluster NGC 6231, Sung, Bessell, & Lee (1998) found a clear deficit of stars with masses below 2.5 $M_\odot$. Although there are more than 250 stars on or evolving away from the main sequence (MS), they found only 19 low-mass PMS stars in the cluster. Similar results were obtained from the study of the most active star forming cluster R136 in the LMC, where Sirianni et al. (1999) found a flattening or drop of the IMF below $\sim$2 $M_\odot$.

For the low-mass field stars in the solar neighborhood, there is no evidence for an increase in the slope of the IMF for stars less massive than 0.1 $M_\odot$ (Bessell & Stringfellow 1993). Reid et al. (1999) derived the mass function for the stars within 8 pc from the Sun using the new data obtained from the *Hipparcos* survey (ESA 1997). They found a simple power law gradient of $\Gamma = -0.13 \sim 0.02$ in the mass range of 0.1 to 1.0 $M_\odot$. Based on this result and using the recent results of brown dwarf surveys, such as the Deep Near-IR Surveys (Epchtein et al. 1994; DENIS) and the Two Micron All-Sky Survey (Skrutskie et al. 1997; 2MASS), combined with the brown dwarf models of Burrows et al. (1993, 1997), they suggested the slope of the IMF in the brown dwarf regime to be $-1 \leq \Gamma \leq 0$.

In spite of the apparent consistency of the IMFs at the low-mass end, the Galactic equivalent of R136, NGC 3603, does not show such a trend. From the near-IR adaptive optics study of NGC 3603, Eisenhauer et al. (1998) found that the IMF slope of the cluster was $\Gamma = -0.73$ in the mass range of $1 \sim 30$ $M_\odot$. However, the IMFs of R136 and NGC 3603 were derived from a statistical approach, and therefore the results might be strongly affected by the degree of spatial homogeneity of the field star distribution. Therefore, the existence of a universal IMF is still an open question though there is a gradual convergence towards a flat IMF at the low-mass end.

In the following sections, we describe the membership census of NGC 2264 (section II), the comparison between various PMS models and the derivation of the best model (section III). In section IV, the IMFs of NGC 2264 and the ONC are constructed and compared, and both IMFs are also compared with the IMF of the field stars in the solar neighborhood. We discuss the IMF at the low-mass end and the origin of the field stars in the solar neighborhood, along with the universality hypothesis of the IMF in section V. Section VI is the summary.

II. A NEW CENSUS OF PMS MEMBERS IN NGC 2264

PSBK made a membership database which included massive MS stars and low-mass PMS stars with Hα emission and/or X-ray emission. The database was regarded as almost complete because they collected both types of PMS stars. However, since X-ray emitting PMS stars identified by Flaccomio et al. (1999) were only in the southern region of the cluster, we need to select X-ray emitting stars in the northern region in order to make a more complete discussion on the mass and age distributions of the cluster.

Recently, Flaccomio et al. (2000) published a new list of X-ray sources in NGC 2264. For the remaining sources in the northern region, we adopt the optical counterparts identified by Flaccomio et al. (2000) and use the photometric data by SBL. We also complement the membership of both MS stars and PMS stars in the whole region by re-analyzing the positions of the stars in the photometric diagrams.

The total number of member stars brighter than $V =$ 18 mag is 312, comprising 35 MS stars and 277 low-mass PMS stars. The low-mass PMS stars consist of 77 stars with Hα emission, 38 PMS candidates, 105 X-ray emitting stars, and 57 stars with both Hα and X-ray emission. In the common region between SBL and PSBK, there are 78 stars. Among them, 21 stars show differences in V or $V - I$ greater than 0.1 mag. We adopt both values of magnitude and colors for these potential variables, and take weighted mean values for the remaining stars. Member stars of NGC 2264 are listed in Table 4.1 of Pàrk (2001).

Reddenings to bright MS stars are corrected individually, with the reddening law derived by PSBK. A mean reddening value is adopted for the low-mass PMS stars. Also, we adopt the same calibrations used in PSBK.

III. COMPARISON OF PMS EVOLUTION MODELS

(a) The models

Presentlty there are a number of PMS evolution models, each of them has its own approximations and limitations to describe the evolution of PMS stars. We choose five of them, all of which are widely used by most investigators. Models by D'Antona & Mazzitelli (1994, hereafter DM94), D'Antona & Mazzitelli (1997; revised in 1998*, hereafter DM98), Swenson et al. (1994, hereafter SFRI) are chosen. Also, we choose two nongray atmospheric models by Baraffe et al. (1998), one which assumes a ratio of mixing length to pressure scale height as 1.0 (hereafter BCAH98-I) and the other which assumes the ratio as 1.9 (hereafter BCAH98-II). By adopting these five models we derive masses and ages of PMS members in NGC 2264 and the ONC to analyze possible existence of systematic behaviour between mass and age estimation, and look for a best model.

(b) Comparisons of stellar masses and ages

In Figure 1, the masses from models by DM94, DM98, BCAH98-I, and the massive part of BCAH98-II are compared with those from SFRI. We chose SFRI as the abscissa because their models cover the widest range of mass. Also in Figure 2, stellar ages from the five models are compared in the same way as in Figure 1. In Figure 3, the masses and ages from two DM models and two BCAH98 models are compared.

A common feature seen in the model comparisons in Figure 1 is the strong correlation between masses for solar type PMS stars except for BCAH98-I. In Figures 1a and 1b, DM models estimate masses smaller than SFRI toward decreasing mass, which is more significant in DM98 than in DM94. The lower derived masses from the DM models places in the brown dwarf regime

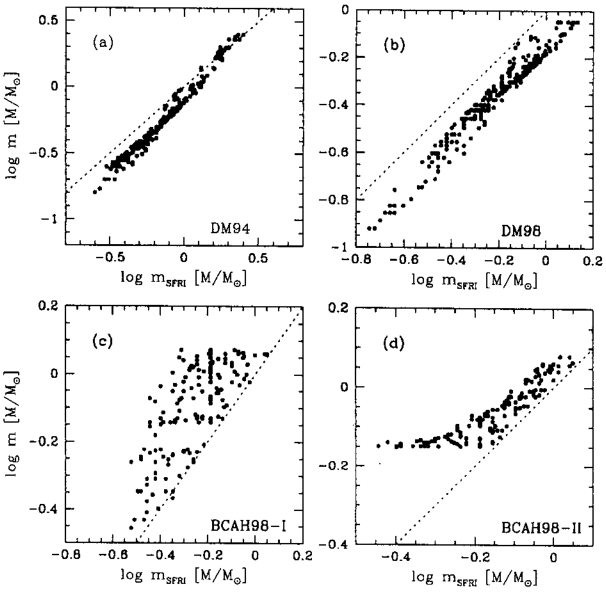

Fig. 1.— Comparison of stellar masses among PMS evolution models. Masses from each model are compared to those from SFRI model. A dotted line of slope 1 is drawn as a reference for easy comparison.

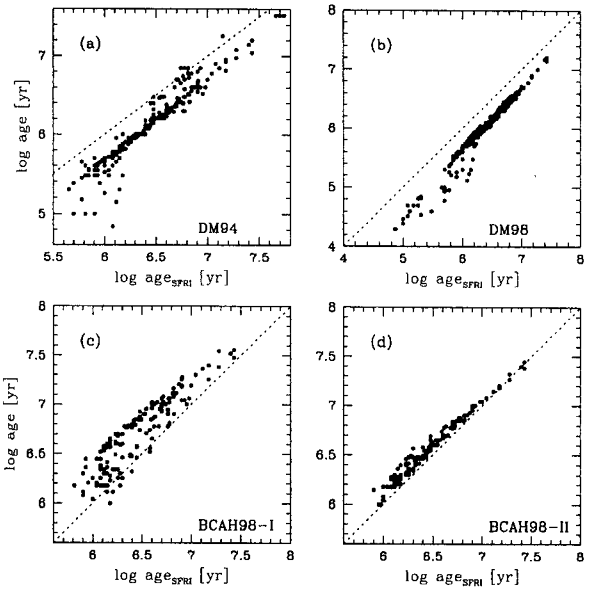

Fig. 2.— Comparison of stellar ages among PMS evolution models. Ages from each model are compared to those from SFRI models.

---

*This revision was not published, but available at http://www.mporzio.astro.it/~dantona.

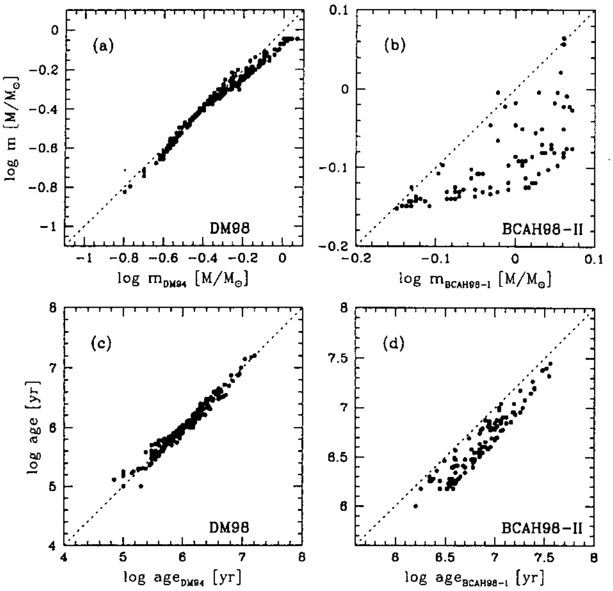

Fig. 3.— Comparison of stellar mass and age between two DM models and between two BCAH98 models.

some groups of low-mass stars which as estimated from the other models are normal PMS stars. Masses from BCAH98-I and SFRI show little correlation, as shown in Figure 1c. It is, therefore, impossible to draw any reliable relationship between these two models. However, the massive part of BCAH98-II, shown in Figure 1d, has a relatively well-defined correlation with SFRI in the mass range of 0.8 ~ 1.2 M$_\odot$, with BCAH98-II masses greater than those of SFRI.

In Figure 2, the ages estimated from different evolution models show tighter correlations than the masses from different models. Among all models, there is a concentration of stars in a narrow strip, which could be used to convert one age scale to the other. There is a trend that the two DM models shown in Figures 2a and 2b estimate younger ages than SFRI, while the two BCAH98 models shown in Figures 2c and 2d estimate ages greater than SFRI.

Finally, we compare the two pairs of models of DM and BCAH98 in Figure 3. As expected from the comparisons made in Figure 1, the masses from BCAH98-I and BCAH98-II in Figure 3b show a poor correlation. In Figure 3a, the masses deduced from DM98 are slightly smaller than those from DM94 in the mass range 0.4 ~ 0.9 M$_\odot$. With regard to ages, while DM94 and DM98 give nearly identical ages, ages from BCAH98-I are greater than those from BCAH98-II.

(c) Mass-age relationships

Since the number of low-mass PMS members of NGC 2264 used in this study is sufficiently large, the distribution of age with respect to mass will give a reliable statistical test to the intrinsic systematic behaviors, if any, of each evolution models.

Figure 4 shows the distribution of age with respect to mass of each star in the four different evolution models. Each panel corresponds to one evolution model except in Figure 4d, where BCAH98-I and II are identical for masses less than 0.7 M$_\odot$. Figures 4e and 4f show the massive parts of BCAH98-I and BCAH98-II, respectively. At a glance, one can see that there is a decrease in stellar age affected by the incompleteness of low-mass stars in the database. Since this trend is not a real relation between mass and age, we have to restrict ourselves to the stars above the completeness limit in the following discussions.

A feature to be noted in Figure 4 is the overall trend of age with respect to mass. In Figure 4a, the mean age decreases monotonically with decreasing mass, but in the models of DM94, DM98, and BCAH98-I, the trend shows a rather more complex behavior. Such a correlation may alter the derived mass and age of PMS stars, and therefore affect the star formation history in a cluster (Iben & Talbot 1966; H97) and the cluster formation scenario (Herbig 1962; see SBL for more detailed discussion). For a restricted mass range of log $m \approx -0.1 \sim 0.1$, where the sample of stars is most complete, there is no systematic trend with the BCAH98 models.

Above the completeness limits, there are clear signs of decreasing age with decreasing mass in Figures 4a, 4b, and 4c. The trend is contrary to the expectations from the sequential star formation scenario where low-mass stars are formed earlier than massive stars. Since we expect all stars to be formed coevally with some age spread, i.e., cluster formation time scale, in a small star forming region like NGC 2264, the deduced mass-age relationship is inherent to the models and not a real feature. BCAH98 models do not show such a trend as obviously as the other models.

(d) Adopted relation

In conclusion, we confirm that there is a mass-age relationship in SFRI, DM94, and DM98 models, while the models of BCAH98 show only a weak relationship or no such relationship. If we give up the sequential star formation scenario of Herbig (1962) that is supported by Herbst & Miller (1982) and adopt instead the suggestion of Elmegreen (2000) that stars in a cluster are formed in a time scale less than a few times the crossing time of the natal cloud, the BCAH98 models are the best from amongst the five PMS models. This conclusion had previously been arrived at by White et al. (1999) from the PMS quadruple GG Tau, by Sung, Chun, & Bessell (2000) for NGC 6530 and PSBK for NGC 2264.

Therefore, the mass and age distribution of cluster stars derived from BCAH98 will be the most consistent with the observations. However, there is a limitation

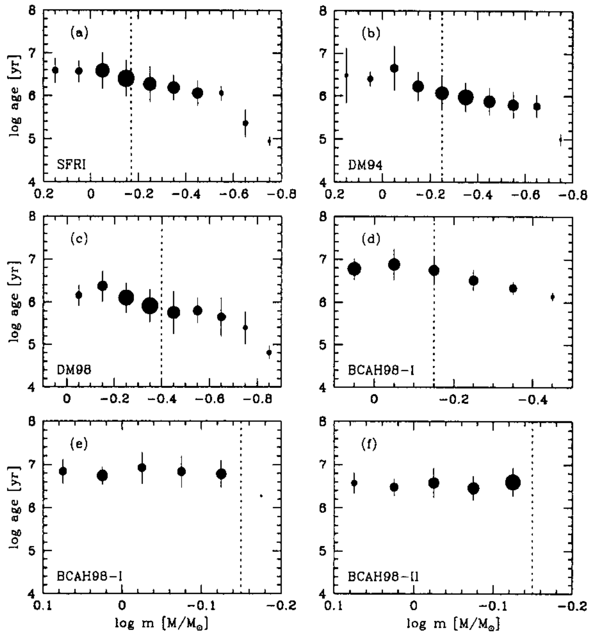

Fig. 4.— Distribution of ages with respect to the masses estimated from five PMS evolution models. Masses are binned by 0.1 in log m for (a) through (d), and 0.05 for (e) and (f). Sizes of the symbols are proportional to the number of stars in each mass bin and the error bars are based on the standard deviation of the ages. Vertical lines denote the completeness limit of the sample.

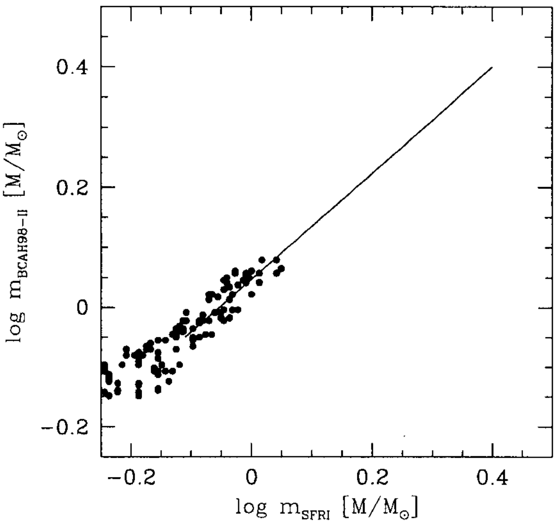

Fig. 5.— Adopted relation between SFRI and BCAH98-II for mass transformation.

in the BCAH98 models due to lack of evolution models for PMS stars more massive than 1.2 M$_\odot$. To overcome this limitation, we utilize the well-defined relationship between stellar masses from SFRI and those from BCAH98-II found in the previous section for stars more massive than 1.2 M$_\odot$.

Stellar masses from SFRI and BCAH98-II in Figure 1d show a quasi-linear relation in the mass range of 0.7 $\sim$ 1.2 M$_\odot$. We extend the relation towards higher mass up to 2.5 M$_\odot$ which is shown in Figure 5.

For stars more massive than 2.5 M$_\odot$, which have already arrived at the ZAMS, the masses from SFRI are nearly identical to those from the MS model by Schaller et al. (1992, hereafter Geneva). Thus the masses for massive stars are either estimated from the SFRI or Geneva models, depending on the positions of the stars in the H-R diagram. To distinguish this from the original BCAH98-II, we call this model BCAH98-IIe, where the postfix 'e' denotes 'extended' version of BCAH98-II.

IV. THE IMF OF NGC 2264 AND THR ORION NEBULA CLUSTER (ONC)

(a) NGC 2264

Using the adopted relation BCAH98-IIe, we calculate the IMF of NGC 2264 with a new census of members obtained in section II. The resulting IMF is shown in Figure 6, where the calculation of the IMF is done as in PSBK except for the inclusion of S Mon and X-ray sources in the northern region, and the mass range that is now $-0.7 \leq \log\ m \leq 2.0$.

Comparing the IMF in Figure 6 with that in Figure 10 of PSBK, we can find a striking difference between the two IMFs. The lack of stars or a gap present near 1 M$_\odot$ in Figure 10 of PSBK has completely disappeared in the new IMF. The filling of the gap is partly due to adding more X-ray emitting stars and partly due to higher mass estimates for low-mass stars from BCAH98-IIe than those deduced from DM94 or SFRI.

The IMF shown in Figure 6 matches well with the IMF of field stars in the solar neighborhood by Scalo (1986) over the full range of mass where the sample is complete. There are a few bump-like features in the IMF of NGC 2264, which makes it hard to fit the IMF to a single power laws. Nevertheless, if we are forced to calculate the slope Γ, the value is $\Gamma = -2.0 \pm 0.4$ in the mass range $0 \leq \log\ m \leq 0.8$, which is slightly steeper than that obtained in PSBK. More important is the clear match of the overall trend of the IMF of NGC 2264 to that of the field stars in the solar neighborhood. This fact strongly implies that there is a close link between the low-mass star formation in open clusters and the origin of the field stars in the solar neighborhood.

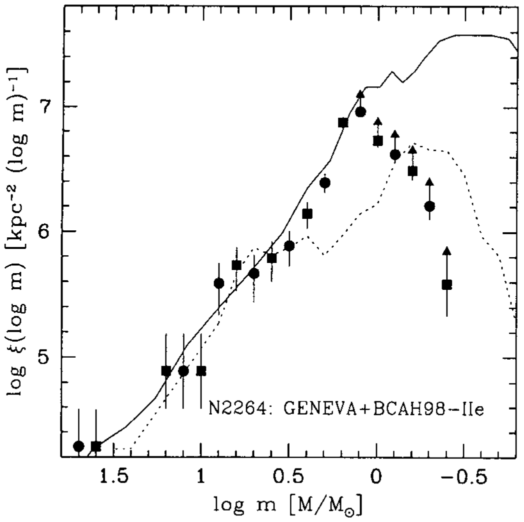

Fig. 6.— The IMF of NGC 2264 with new stellar masses estimated from the transformation relation. Masses of MS stars are estimated from Geneva models. The IMF calculation is binned by 0.2 in log m, except for the most massive bin, where the size is 0.8. Also, the bins are shifted by 0.1 in log m to avoid possible binning effects. The thin solid line is the IMF of field stars in the solar neighborhood by Scalo (1986) after adjusting for the mean difference between the two IMFs weighted by the number of stars in each bin. The dotted line is the IMF of the northern region of NGC 2264 obtained by SBL. Arrow heads represent the incompleteness of data and the error bars are based on the square root of the number of stars in each bin.

(b) The Orion Nebula Cluster

i) The data

In this section, we investigate further the relations between the IMF of young, low-mass dominant open clusters and that of the field stars in the solar neighborhood, looking for more support for the hypothesis proposed in the last paragraph of the previous section. The ONC is the best cluster for this purpose, because it is one of the most active star forming regions and extensive studies of the star formation history and the IMF have been performed. The most recent and comprehensive study was conducted by H97 so we decided to use her data for the discussion in this section.

H97 performed *VI* CCD photometry and spectroscopy on the stars in the region of the ONC within 0.6° × 0.5° centered near $\theta\ ^1C$ Ori. In addition to her own data, she compiled data from the literature and selected members based on the positions of the stars in the photometric diagrams and proper motion data. We adopted the luminosity and effective temperature of the members of the ONC derived by H97 rather than deriving them by ourselves; the reason is explained as

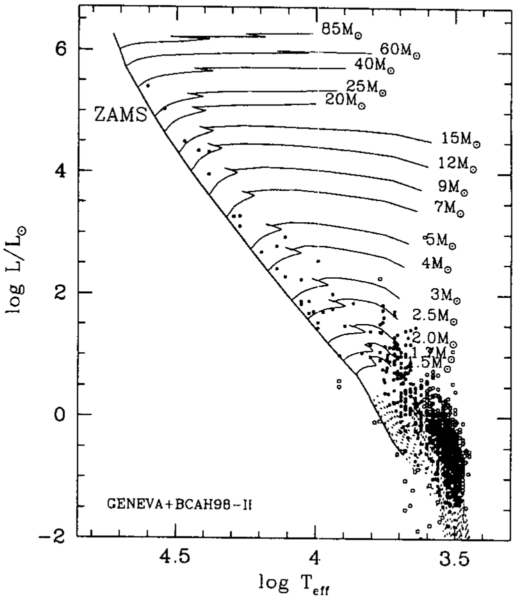

Fig. 7.— H-R diagram of the Orion Nebula Cluster (ONC). Geneva evolution tracks (*solid lines*) are superposed, with corresponding masses specified on each track. Filled circles denote the stars whose mass and age are estimated in this study and open circles denote stars of which DM94 mass and age are estimated by Hillenbrand (1997). Open squares denote possible BMS stars.

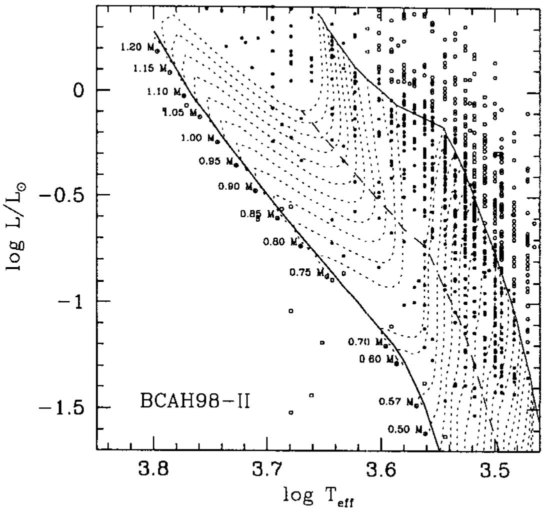

Fig. 8.— Lower part of the H-R diagram of the Orion Nebula Cluster. BCAH98-II PMS evolution tracks are superposed with the mass specified on each track. The solid line is the 1 Myr isochrone for the median age and the dashed line is the 8.5 Myr isochrone showing the age spread of the cluster. Symbols are the same as in Fig. 7.

follows. Since differential reddening among the member stars is generally large and the value of total extinction ranges from about 0.5 mag to about 7.0 mag, we have to depend on the extinction measured from spectral type determination by H97. The calibration relations for deriving luminosity and effective temperature of individual stars adopted by H97 (references therein) are not much different from the relations adopted in this study. Therefore, with the same photometric data, the same reddening corrections and similar calibration relations, there would be no significant difference between Hillenbrand's luminosities and effective temperatures and ours, were they derived by us.

The adopted distance by H97 is 470 pc ($V_0 - M_V = 8.36$) and mean extinction for the stars brighter than $V = 7$ is $A_V = 1.7$. Since a normal reddening law can be applied to the stars that are not obscured by dust cloud, the above mean extinction corresponds to a mean reddening of $E(V-I) \simeq 0.7$. We extracted the luminosity and temperature of 977 stars from Table 3 of H97 whose mass and age were derived. †

ii) H-R diagram

H-R diagrams of the ONC are shown in Figures 7 and 8, where the Geneva MS evolution models and BCAH98-II PMS evolution tracks are superposed for estimating the mass and age of individual stars. Since the youngest isochrone of BCAH98-II is 1 Myr, we cannot derive the mass and age of about one third of the stars less massive than 1.2 $M_\odot$ that lie above the 1 Myr isochrone.

By assuming a one to one correlation between stellar ages from SFRI and those from BCAH98-II and accounting for the stars located above the 1 Myr isochrone in Figure 8, we derive the median age of 1 Myr and an age spread of 8.5 Myr for the ONC. The age spread is defined as the value where 95% of the stars are accumulated in the cumulative age distribution, as was done in PSBK.

iii) BMS stars

It is worth discussing the existence of stars near or below the ZAMS (below or near ZAMS star : BMS star) in the H-R diagram shown in Figure 7. If these stars are members of the ONC and the low luminosities of these stars real, then star formation in the ONC should have begun more than a few 10^7 years ago. Such a large age spread is improbable, as long as the current estimate of the age spread of the stars in the ONC is valid. H97 also finds an age spread in the ONC of around 2 Myr (using DM94 isochrones) or 5 Myr (using SFRI isochrones).

If we accept the membership assignment of these stars by H97, the low luminosity of these stars cannot be explained simply by a large visual extinction, because the direction of the extinction vector is nearly parallel to the ZAMS. One possible explanation is that these stars are T Tauri stars with nearly edge-on disks to the line of sight. A T Tauri star with a nearly edge-on disk will show significantly lower luminosity because the light from the central star will be highly obscured by the disk material. In the discussion of two BMS stars in NGC 2264, SBL suggested that the low luminosity of these stars can be explained by an optically thick dust shell containing large particles which absorb, non-selectively, all but 5% of the visible radiation from the underlying star.

Using the Wide Field Planetary Camera 2 (WFPC2) on board the *HST*, O'Dell & Wong (1996) observed 489 non-Herbig-Haro emission sources and identified 145 objects that showed the properties of proplyds. Of these 145 proplyds, they found seven sources that were dark disk objects similar to the proplyd 163-323, which is seen only in silhouette against the nebular background. They also identified 12 objects that showed emission in Hα and [N II], but were dark in [O III], and suggested that these were objects intermediate between entirely dark disk proplyds and those with emission lines. If these 12 sources, though not all, can be regarded as PMS stars with a nearly edge-on disk, we can estimate the fraction of such systems in the ONC.

A point to note is that the 145 sources in the study of O'Dell & Wong (1996) do not represent a complete fraction of stars with disks amongst all 489 sources in the list. One reason comes from the selection effects explained by O'Dell & Wong for their own data, i.e., in the outer region of the ONC where the nebula is much fainter than in the inner region, their sample will easily be biased to non-proplyd stars. Also, their identification of proplyd was mainly based on the appearance of the sources, resulting in some proplyds that are nearly indistinguishable from stellar sources classified as non-proplyds. Moreover, the externally ionized nature of a proplyd indicates that these objects have an accretion disk. Thus a large fraction of stars with non-accreting circumstellar disks are not included in the proplyd list of O'Dell & Wong.

Independently, the fraction of circumstellar disks in the ONC was estimated by Hillenbrand et al. (1998). From the near-IR color excess of the stars, they estimated the fraction to be between 55% and 90%. Therefore, we can estimate the number of stars with a circumstellar disk in the sample of O'Dell & Wong (1996) to be between 269 and 440 objects, by taking 55% as the minimum and 90% as the maximum. The corresponding fraction of nearly edge-on disks is therefore between 3% and 5%, if we consider all 12 sources discussed above to be edge-on systems.

For the current sample of the members in the ONC, we can suppose that stars less massive than 2 $M_\odot$ are

---

†The number of stars in Table 3 of H97 is 934. The discrepancy exists because Hillenbrand made some modification to the database after publication of her paper.

in their PMS stage. From the distribution of stars in the H-R diagram shown in Figure 7 we see that the number of PMS stars is 942. If we apply the above estimated fraction of nearly edge-on disk systems, the number of probable BMS stars in the ONC is 26. This value is in good agreement with the number of possible BMS stars in Figure 7 of about 20.

In the case of NGC 2264, SBL selected 83 PMS members with strong Hα emission and 30 PMS candidates with weak Hα emission. They found two BMS stars (W90 & SBL 589). In the southern region of NGC 2264 (the Cone nebula), the total number of PMS stars with strong or weak Hα emission selected in PSBK was 78. Then, from the above rough estimate, we expect there to be one or two nearly edge-on disk systems amongst them; two possible BMS stars are seen in the H-R diagram shown in Figure 8 of PSBK. Another example is found in the study of NGC 6530, in which Sung, Chun, & Bessell (2000) found one BMS star out of 46 PMS stars with Hα emission.

Even though roughly estimated, the observed frequency of BMS stars is in a good agreement with the expected value from the hypothesis that these stars are nearly edge-on disk systems. However, in such cases, as there is no photometric method to determine the total extinction, we should exclude these stars in the construction of the IMF.

iv) The IMF

With the effective temperatures and bolometric magnitudes, the masses of the stars are derived from the adopted Geneva evolution models and the BCAH98-IIe PMS evolution models. Derivation of the IMF is done in the same way as for NGC 2264.

We show the IMF of the ONC in Figure 9, where the IMFs of the ONC constructed by H97 and Luhman et al. (2000), and the IMF of the field stars in the solar neighborhood by Scalo (1986) are also shown for comparison. For the completeness test of the sample, we show the $V - I$ versus V color-magnitude diagram in Figure 10, which is the same as Figure 8 of H97 but BCAH98-II evolutionary tracks are superposed instead of DM94. According to the completeness data in Table 2 of H97, the stars whose masses are derived are about 70% complete around $V = 18$, corresponding to 0.5 $M_\odot$ estimated by DM94. This mass is about 0.7 $M_\odot$ if estimated from BCAH98-II, and if we consider the effect of extinction on the completeness which is more serious in low-mass stars than in intermediate-mass stars, the incompleteness will be more significant. Since the mass of stars above the 1 Myr isochrone of BCAH98-II could not be estimated, the completeness limit of BCAH98-IIe IMF is about 1.2 $M_\odot$.

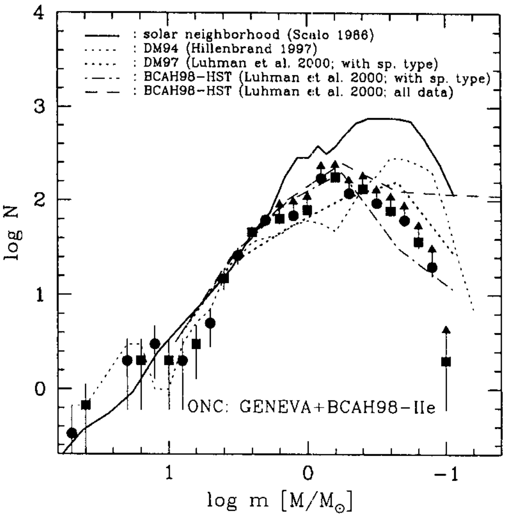

Fig. 9.— IMF of the Orion Nebula Cluster. Symbols denote the IMF constructed in this study by adopting the models of Geneva and BCAH98-IIe. Derivation of the IMF was done in the same way as for NGC 2264 in section IV.-(c). The meanings of symbols, error bars and the arrow heads are the same as in Fig. 6. The field star IMF of the solar neighborhood (Scalo 1986; *thick solid line*), the IMF of the ONC calculated by Hillenbrand (1997; *dotted line*), the IMFs determined by Luhman et al. (2000) for stars with determined spectral types (from DM97 models, *thick dotted line*; from BCAH98-HST models, *dot-dashed line*), and for all stars (from BCAH98-HST models, *dashed line*) are shown for comparison. All the IMFs are normalized to best fit each other in the intermediate mass range.

The most notable difference between the IMF of Hillenbrand and ours is the mass where the IMF peak occurs, that is now around 0.8 $M_\odot$. Thus the deficit of stars in Hillenbrand's IMF has disappeared. Although incomplete, it is evident in Figure 9 that the IMF peak is near 0.8 $M_\odot$ rather than near 0.2 $M_\odot$. In the intermediate- to high-mass region of the IMF, BCAH98-IIe IMF matches fairly well with the IMF of field stars in the solar neighborhood.

Luhman et al. (2000) performed an *HST* Near-IR Camera and Multi-Object Spectrometer (NICMOS) survey on a small region of 140″ × 140″ in the ONC. Combining the data and the ground-based K-band spectra along with the spectral types from H97, they obtained a large number of low-mass members of the ONC extending down to the brown dwarf regime. They derived the effective temperature and luminosity of each star based on spectral type, and estimated the mass and age by adopting the PMS evolution model of D'Antona & Mazzitelli (1997; hereafter DM97) and the model of BCAH98-I for the *HST* filter set (BCAH98-HST). For a number of faint stars whose spectral types were not determined, they estimated the mass of each star using a statistical method based on the age distribution of stars with known spectral type. Since the youngest isochrone of BCAH98-HST is 1 Myr, the statistically determined mass from BCAH98-HST is more uncertain than that from DM97.

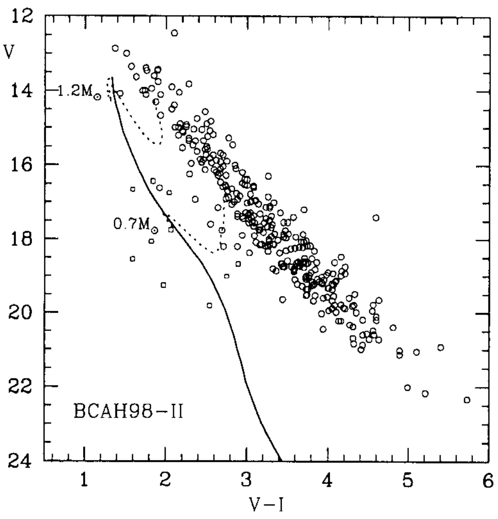

Fig. 10.— $V-I$ vs. V color-magnitude diagram of the Orion Nebula Cluster. Reddened ZAMS (*thick solid line*) and evolutionary tracks for 1.2 M$_\odot$ and 0.7M$_\odot$ (*dotted lines*) of BCAH98-II are superposed. The adopted mean reddening, distance modulus and total extinction are $E(V-I)=0.7$, $V_0-M_V=8.36$ and $A_V=1.7$, respectively. Symbols denote stars whose masses were derived by Hillenbrand (1997) using DM94 models, but which could not be estimated from BCAH98-II models because they are located above the 1 Myr isochrone (*open circles*), and possible BMS stars (*open squares*).

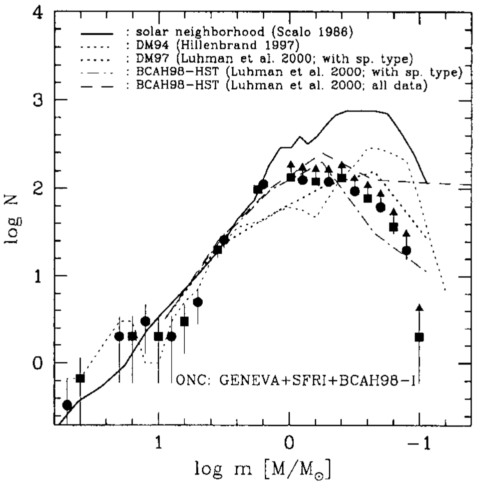

Fig. 11.— The IMF of the Orion Nebular Cluster constructed using Geneva, SFRI and BCAH98-I models. The IMF is constructed using a similar method to that of Luhman et al. (2000); see text for detailed explanation. The meanings of symbols, error bars, arrow heads and various reference lines for different IMFs are the same as in Fig. 6.

In constructing the BCAH98-HST IMF, Luhman et al. adopted BCAH98-HST models for stars with masses equal to or smaller than 1 M$_\odot$ and DM97 for stars larger than 2 M$_\odot$. For the stars whose masses are between 1 M$_\odot$ and 2 M$_\odot$, they put all stars into one large mass bin of $-0.05 \leq \log\, m \leq 0.35$, instead of estimating an individual mass for each star. The DM97 IMF by Luhman et al. shows a different behavior as that by H97 who used DM94. The mass where the IMF reaches its maximum value is similar for both IMFs. But the flattening of Hillenbrand's IMF around 1.2 M$_\odot$ and the deficit of stars around 0.8 M$_\odot$ is not seen in the IMF of Luhman et al. Hillenbrand & Carpenter (2000) found the same change of trend by deriving the IMF of the ONC using the same set of data as H97 and DM98. Thus the flattening of the IMF around 1.2 M$_\odot$ is caused by the models of DM94.

For the peak of Hillenbrand's IMF around 0.2 M$_\odot$, D'Antona (1998) suggested that it would be removed by using DM97 which adopted a different treatment of external convection (D'Antona & Mazzitelli 1998) for masses lower than 0.2 M$_\odot$. However, the same peak still exists in the DM97 IMF of Luhman et al. (2000).

Comparing the BCAH98-HST IMF of Luhman et al. (2000) and that of this study, while the BCAH98-HST IMF continues to rise between $\log\, m = 0.2$ and $\log\, m = -0.2$, the IMF of this study is flat in the same mass interval. This is because BCAH98-HST models estimate stellar masses more massive than BCAH98-II in the mass range of $0.7 \sim 1$ M$_\odot$. In order to confirm this explanation, we constructed the IMF of the ONC by estimating stellar masses using BCAH98-I models following a similar method to Luhman et al. (2000), i.e., since there is no correlation between SFRI and BCAH98-I in mass estimation, we put all stars between the 1.2 M$_\odot$ track of BCAH98-I and the 2.5 M$_\odot$ track of SFRI in one large mass bin. The resulting IMF is shown in Figure 11, where both IMFs of Luhman et al.'s and ours match well in the mass interval $\log\, m = 0.2 \sim 0$.

In conclusion, the five IMFs after normalization fit very well with the field star IMF in the intermediate- to high-mass range in Figure 9. This again implies that there is a link between the star formation in open clusters and the origin of the field stars in the solar neighborhood.

V. DISCUSSION

(a) The IMF at the low mass end

Hillenbrand & Carpenter (2000) performed near-IR photometry for a wider region of the ONC than H97. Their observations were nearly complete around $K \approx 16.5$ mag. By adopting DM98 models, they argued that the completeness of their data reaches down to about 0.02 M$_\odot$, far below the hydrogen burning limit. They concluded, on the basis of the above completeness limit, that the turnover of the IMF occurs near the hydrogen burning limit. However, as was dis-

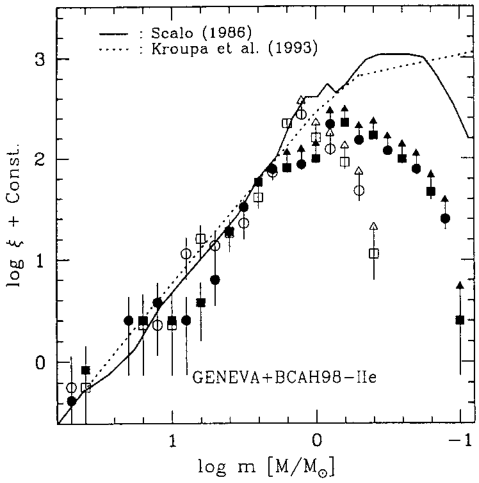

Fig. 12.— The IMF of NGC 2264 and the ONC for comparison with the field star IMF of the solar neighborhood. Filled symbols denote the IMF of the ONC while open symbols denote that of NGC 2264. The meanings of the circles and squares, error bars and arrow heads are the same as in Fig. 6. The field star IMF of the solar neighborhood by Scalo (1986; *thin solid line*) and Kroupa, Tout, & Gilmore (1993; *dotted lines*) are shown for comparison.

cussed in section IV-(c), the DM evolution models estimate smaller stellar masses than the other models. If a more reliable model were adopted for mass estimation, say BCAH98-II, then the turnover or flattening of the IMF would be shifted toward higher mass.

The BCAH98-HST IMF for the ONC constructed by Luhman et al. (2000) shows a flattening toward lower mass below 0.1 M⊙. However, according to the completeness test performed by them, the completeness of their sample of stars in this mass range is only about 60%. Thus the flattening of the IMF in this mass range is still uncertain.

The completeness test in stellar mass range inevitably involves uncertainty in mass estimation by the adopted model and the behavior of the IMF at the low-mass end. There is also a confusion between incompleteness and a real turn-over or flattening. For the IMF of the ONC, both IMFs of H97 and Luhman et al. (2000) seem to suffer from incompleteness at the low-mass end in view of the more reliable PMS model derived in this study. Therefore, more detailed discussions of the behavior of the IMF at the low-mass end still await deeper photometry and spectroscopy.

(b) The origin of the solar neighborhood

In section IV, we showed that the IMFs of NGC 2264 and the ONC fit well with the IMF of the field stars in the solar neighborhood. For better comparison, we plot the IMFs of the two open clusters in Figure 12. Also shown are the solar neighborhood IMFs by Scalo (1986) and Kroupa, Tout, & Gilmore (1993) for comparison. All the IMFs shown in Figure 12 match well for the stars more massive than about 3 M⊙.

Luhman et al. (2000) compared their resulting BCAH98-HST IMF of the ONC with the IMFs of IC 348 (Luhman, Engelbracht, & Luhman 1998; Luhman 1999) and ρ Oph (Luhman & Rieke 1999). They found that the IMFs of the three clusters are the same within the uncertainties in the intermediate mass range.

From these results, we can arrive at the conclusion that the IMFs of the open clusters and the solar neighborhood are consistent, at least for the intermediate-mass stars. This consistency in the IMF strongly supports the idea proposed by Lada, Strom, & Myers (1993) that field stars are predominantly formed in clusters and later disperse.

(c) The universality of the IMF

We found that the IMF of NGC 2264 and that of the ONC are very similar, and the same similarity exists in the IMFs of IC 348 and ρ Oph. The IMFs of these clusters also match fairly well with the IMF of the field stars in the solar neighborhood. This result apparently strongly supports the existence of a universal IMF.

Nevertheless, there are diverse results on the IMF in the intermediate- to high-mass region from observations of several active star forming clusters with many massive OB stars. While there are signs of flattening toward the low-mass region in the IMFs of NGC 6231 and R136, the IMF of NGC 3603 shows no such trend, as mentioned in the introduction. A recent 2MASS near-IR observations on a star forming region with a large content of OB stars, Cyg OB2 (Knödlseder 2000), show that its IMF is compatible with the field star IMF of Kroupa, Tout, & Gilmore (1993) for stars more massive than 1 M⊙. However, the IMF of NGC 2244 derived in Park & Sung (2002) is much flatter than other clusters. And the IMF slopes of OB associations and young open clusters containing relatively large numbers of massive stars (Massey, DeGioia, & Eastwood 1995) show a range of values of Γ between -0.7 to -1.3. For the low-mass region, there are difficulties in membership assignment as well as sample incompleteness. Moreover, the low-mass content of the Galactic disk depends not only on the IMF, but also on the star formation history of the disk.

In conclusion, the current observational results show diverse interpretations of the massive part of the IMF. Especially for the low-mass regime of the IMF, the lack of completeness prevents us from stating any conclusive remark on the universality of the IMF. Therefore, a more thorough study of the star forming clusters should be performed to allow further discussions on this subject.

VI. SUMMARY

In this study, we have performed a test for five PMS evolution models by examining internal systematic trends in the estimation of stellar masses and ages using a nearly complete census of low-mass PMS stars in NGC 2264. Among five stellar evolution models, the models of BCAH98-II are found to be the most reliable in mass-age distribution. To overcome the upper mass limit of BCAH98 models, we derived a simple linear relation between the mass scale of SFRI and that of BCAH98-II to transform the masses estimated from SFRI to mass svale of BCAH98-II.

Using the derived relation BCAH98-IIe, we constructed the IMFs of NGC 2264 and the ONC, and compared them with previous results. In the new IMF of NGC 2264, the deficiency of stars around 1 $M_\odot$ seen in the previous IMF obtained in PSBK disappears. Also in the new IMF of the ONC, we found that the deficiency of stars around 0.8 $M_\odot$ in the IMF derived by H97 was caused by the adoption of the DM94 evolution models. The turnover of Hillenbrand's IMF at about 0.2 $M_\odot$ is shown to be the result of sample incompleteness, not a real feature of the IMF at the low-mass end. We also discussed from a statistical approach, that the stars below or near the ZAMS in the H-R diagram of the ONC are probably PMS stars obscured by a nearly edge-on disk to the line of sight.

The understanding of the behavior of the IMF at the low-mass end still awaitis more dedicated observational studies. By comparing the IMFs of NGC 2264 and the ONC with the IMF of the field stars in the solar neighborhood, we suggest that the field stars are formed through clustered formation mechanism, a hypothesis originally proposed by Lada, Strom, & Myers (1993).

The similarity in the IMFs of several open clusters such as NGC 2264, the ONC, IC 348, ρ Oph and the massive star forming region Cyg OB2, as well as the IMF of the field stars in the solar neighborhood seems to support the hypothesis of a universal IMF. But for some clusters with many massive stars, evidence for a flattening of the IMF in the low-mass range is found in NGC 6231 and R136 in the LMC. The same trend of flattening of the IMF toward the brown dwarf regime is also found in the open clusters M35 and the Pleiades, and for the field stars from the results of the 2MASS and DENIS surveys.

Even though the results obtained so far strongly support the existence of a universal IMF, the fraction of low-mass stars is still uncertain due to difficulties in membership assignment as well as sample incompleteness. There are also several observational results against a universal IMF. The IMF of NGC 2244 obtained in Park & Sung (2002) is much flatter than that for other clusters in the intermediate- to high-mass range. Although the IMF of R136 becomes flatter toward the low-mass range, that of NGC 3603 continues to rise. Therefore, we conclude that it is not possible to make any definite conclusion on the existence of a universal IMF, and a more thorough study of star forming clusters is needed for further discussions.

ACKNOWLEDGEMENTS

BGP wishes to thank the referee, H. B. Ann for careful reading and kind advices. YHK acknowledges the partial support from the Kyungpook National University Research Team Fund 2002 and Grant No. R01-2001-00026 from the Korea Science and Engineering Foundation.

REFERENCES

Baraffe, I., Chabrier, G., Allard, F., & Hauschildt, P.H. 1998, Evolutionary models for solar metallicity low-mass stars: mass-magnitude relationships and color-magnitude diagrams, A&A, 337, 403 (BCAH98)

Barrado y Navascués, D., Stauffer, J.R., Bouvier, J., & Martín, E.L. 2000, From the Top to the Bottom of the Main Sequence: A Complete Mass Function of the Young Open Cluster M35, ApJ, 546, 1006

Bessell, M.S., & Stringfellow, G.S. 1993, The faint end of the stellar luminosity function, ARA&A, 31, 433

Bouvier, J., Stauffer, J.R., Martín, E.L., Barrado y Navascués, D., Wallace, B., & Bejar, V.J.S. 1998, Brown dwarfs and very low-mass stars in the Pleiades cluster: a deep wide-field imaging survey, A&A, 336, 490

Burrows, A., Hubbard, W.B., Saumon, D., & Lunine, J.I. 1993, An expanded set of brown dwarf and very low mass star models, ApJ, 406, 158

Burrows, A., Marley, M., Hubbard, W.B., Lunine, J.I., Guillot, T., Saumon, D., Freedman, R., & Sudarsky, D. 1997, A Nongray Theory of Extrasolar Giant Planets and Brown Dwarfs, ApJ, 491, 856

D'Antona, F. 1998, The Conversion from Luminosity Functions to Mass Functions, in ASP Conf. Ser. 142, The Stellar Initial Mass Function, 38th Herstmonceux Conference, eds. G. Gilmore, & D. Howell (San Francisco: ASP), 157

D'Antona, F., & Mazzitelli, I. 1994, New pre-main-sequence tracks for M less than or equal to 2.5 solar mass as tests of opacities and convection model, ApJS, 90, 467 (DM94)

D'Antona, F., & Mazzitelli, I. 1997, The evolutionary status of high lithium, high activity cool dwarfs, Mem. Soc. Ast. Italiana, 68, 807 (DM97)

D'Antona, F., & Mazzitelli, I. 1998, A Role for Superadiabatic Convection in Low Mass Structures?, in ASP Conf. Ser. 134, Brown Dwarfs and Extrasolar Planets, eds. R. Rebolo, E.L. Martín, & M.R. Zapatero Osorio (San Francisco: ASP), 442

Eisenhauer, F., Quirrenbach, A., Zinnecker, H., & Genzel, R. 1998, Stellar Content of the Galactic Starburst Template NGC 3603 from Adaptive Optics Observations, ApJ, 498, 278

Elmegreen, B.G. 2000, Star Formation in a Crossing Time, ApJ, 530, 277

Epchtein, N., et al. 1994, in Science with Astronomical Near-Infrared Sky Surveys, eds. N. Epchtein, A. Omont, B. Burton, & P. Persei (Dordrecht: Kluwer), 3

ESA 1997, The *Hipparcos* and *Tycho* Catalogs, ESA SP-1200

Flaccomio, E., Micela, G., Sciortino, S., Favata, F., Corbally, C., & Tomaney, A. 1999, BVRI photometry of the star-forming region NGC 2264: the initial mass function and star-forming rate, A&A, 345, 521

Flaccomio, E., Micela, G., Sciortino, S., Favata, F., Harnden Jr., F.R., & Schachter, J. 2000, HRI observations of PMS stars in NGC 2264, A&A, 355,651

Herbig, G.H. 1962, Spectral Classification of Faint Members of the Hyades and Pleiades and the Dating Problem in Galactic Clusters, ApJ, 135, 736

Herbst, W., Miller, D.P., Warner, J.W., & Herzog, A. 1982, R associations. VI - The reddening law in dust clouds and the nature of early-type emission stars in nebulosity from a study of five associations, AJ, 87, 98

Hillenbrand, L.A. 1997, On the Stellar Population and Star-Forming History of the Orion Nebula Cluster, AJ, 113, 1733 (H97)

Hillenbrand, L.A., & Carpenter, J.M. 2000, Constraints on the Stellar/Substellar Mass Function in the Inner Orion Nebula Cluster, ApJ, 540, 236

Hillenbrand, L.A., Strom, S.E., Calvet, N., et al. 1998, Circumstellar Disks in the Orion Nebula Cluster, AJ, 116, 1816

Iben, I.Jr., Talbot, R.J. 1966, Stellar Formation Rates in Young Clusters, ApJ, 144, 968

Kennicutt, R.C. Jr. 1998, Overview: The Initial Mass Function in Galaxies, in ASP Conf. Ser. 142, The Stellar Initial Mass Function, 38th Herstmonceux Conference, eds. G. Gilmore, & D. Howell (San Francisco: ASP), 1

Knödlseder, J. 2000, Cygnus OB2 - a young globular cluster in the Milky Way, A&A, 360, 539

Kroupa, D., Tout, C., & Gilmore, G. 1993, The distribution of low-mass stars in the Galactic disc, MNRAS, 262, 545

Lada, E.A., Strom, K.M., & Myers, P.C. 1993, Environments of star formation - Relationship between molecular clouds, dense cores and young stars, in Protostars and Planets III, eds. E.H. Levy, J.I. Lunine, & M.S. Mathews (Tucson: Univ. of Arizona Press), 245

Luhman, K.L. 1999, Young Low-Mass Stars and Brown Dwarfs in IC 348, ApJ, 525, 466

Luhman, K.L., Engelbracht, C.W., & Luhman, M.L. 1998, Near-Infrared Spectroscopy of Photodissociation Regions: The Orion Bar and Orion S, ApJ, 499, 799

Luhman, K.L., & Rieke, G.H. 1999, Low-Mass Star Formation and the Initial Mass Function in the ρ Ophiuchi Cloud Core, ApJ, 525, 440

Luhman, K.L., Rieke, G.H., Young, E.T., Cotera, A.S., Chen, H., Rieke, M.J., Schneider, G., & Thompson, R.I. 2000, The Initial Mass Function of Low-Mass Stars and Brown Dwarfs in Young Clusters, ApJ, 540, 1016

Massey, P., Johnson, K.E., & DeGioia-Eastwood, K. 1995, The Initial Mass Function and Massive Star Evolution in the OB Associations of the Northern Milky Way, ApJ, 454, 151.

Massey, P., Lang, C.C., DeGioia-Eastwood, K., & Garmany, C.D. 1995, Massive stars in the field and associations of the magellanic clouds: The upper mass limit, the initial mass function, and a critical test of main-sequence stellar evolutionary theory, ApJ, 438, 188

O'Dell, C.R., & Wong, S.K. 1996, Hubble Space Telescope Mapping of the Orion Nebula. I. A Survey of Stars and Compact Objects, AJ, 111, 846

Park, B.-G. 2001, Ph. D. thesis, Star Formation and the IMF of the Young Open Clusters in Monoceros, Kyungpook National Univ., Korea

Park, B.-G., & Sung, H. 2002, UBVI and Hα Photometry of the Young Open Cluster NGC 2244, AJ, 123, 892

Park, B.-G., Sung, H., Bessell, M.S., & Kang, Y.H. 2000, The Pre-Main-Sequence Stars and Initial Mass Function of NGC 2264, AJ, 120, 894 (PSBK)

Reid, I., Kirkpatrick, J.D., Liebert, J. et al. 1999, L Dwarfs and the Substellar Mass Function, ApJ, 521, 613

Scalo, J. 1986, The stellar initial mass function, Fund. Cosmic. Pys., 11, 1

Scalo, J. 1998, The IMF Revisited: A Case for Variations, in The Stellar Initial Mass Function, ASP Conf. Ser. Vol 142, eds. G. Gilmore & D. Howell, (San Francisco: ASP), 201

Schaller, G., Schaerer, D., Meynet, G., & Maeder, A. 1992, New grids of stellar models from 0.8 to 120 solar masses at Z = 0.020 and Z = 0.001, A&AS, 96, 269 (Geneva)

Sirianni, M., Nota, A., Leitherer, C., Clampin, M., & De Marchi, G. 1999, The Low End of the Initial Mass Function for the R136 Cluster in the LMC, in IAU Symp. 190, New Views of the Magellanic Clouds, eds. Y.-H. Chu, N. Suntzeff, J. Hesser, & D. Bohlender (San Francisco: ASP), 410

Skrutskie, M.F., et al. 1997, in The Impact of Large-Scale Near-IR Sky Survey, eds. F. Garzon, et al. (Dordrecht: Kluwer), 187

Sung, H., Bessell, M.S., & Lee, S.-W. 1997, UBVRI Hα Photometry of the Young Open Cluster NGC 2264, AJ, 114, 2644 (SBL)

Sung, H., Bessell, M.S., & Lee, S.-W. 1998, UBVRI and Hα photometry of the young open cluster NGC 6231, AJ, 115, 734

Sung, H., Chun, M.-Y., & Bessell, M.S. 2000, UBVRI and Hα Photometry of the Young Open Cluster NGC 6530, AJ, 120, 333

Swenson, F.J., Faulkner, J., Rodgers, F.J., & Iglesias, C.A. 1994, The Hyades lithium problem revisited, ApJ, 425, 286 (SFRI)

White, R.J., Ghez, A.M., Reid, I.N., & Schultz, G. 1999, A Test of Pre-Main-Sequence Evolutionary Models across the Stellar/Substellar Boundary Based on Spectra of the Young Quadruple GG Tauri, ApJ, 520, 811