

EMBEDDED CLUSTERS AND THE IMF

Charles J. Lada

Smithsonian Astrophysical Observatory, 60 Garden St., Cambridge, MA USA

clada@cfa.harvard.edu

Abstract Despite valiant efforts over nearly five decades, attempts to determine the IMF over a complete mass range for galactic field stars and in open clusters have proved difficult. Infrared imaging observations of extremely young embedded clusters coupled with Monte Carlo modeling of their luminosity functions are improving this situation and providing important new contributions to our fundamental knowledge of the IMF and its universality in both space and time.

1. Introduction

A fundamental consequence of the theory of stellar structure and evolution is that, once formed, the subsequent life history of a star is essentially predetermined by one parameter, its birth mass. Consequently, detailed knowledge of the initial distribution of stellar masses at birth (i.e., the IMF) and how this quantity varies through time and space is necessary to predict and understand the evolution of stellar systems, such as galaxies and clusters. Unfortunately, stellar evolution theory is unable to predict the form of the IMF. This quantity must be derived from observations. Stellar clusters have played an important role in IMF studies because they present equidistant and coeval populations of stars of similar chemical composition. Compared to the disk population, clusters provide an instantaneous sampling of the IMF at different epochs in galactic history (corresponding to the different cluster ages) and in different, relatively small volumes of space. This enables investigation of possible spatial and temporal variations in the IMF. Extremely young embedded clusters are particularly useful laboratories for IMF measurements because these clusters are too young to have lost significant numbers of stars due to stellar evolution or dynamical evaporation, thus their present day mass functions are, to a very good approximation, their initial mass functions. Embedded clusters are also particularly well suited

for determining the nature of the IMF for low mass stars and substellar objects. This is because low mass stars in embedded clusters are primarily pre-main sequence stars, and thus are brighter than at any other time in their lives. At these early ages brown dwarfs are similarly bright as low mass stars. Indeed, infrared observations of modest depth are capable of detecting objects spanning the entire range of stellar mass from 0.01 to 100 M_{\odot} in clusters within 0.5 – 1.0 Kpc of the sun.

2. From Luminosity to Mass Functions

The monochromatic brightness of a star is its most basic observable property and infrared cameras enable the simultaneous measurement of the infrared monochromatic brightnesses of hundreds of stars. Thus, complete luminosity functions, which span the entire range of stellar mass, can be readily constructed for embedded stellar clusters with small investments of telescope time. The monochromatic (e.g., K band) luminosity function of a cluster, $\frac{dN}{dm_K}$, is defined as the number of cluster stars per unit magnitude interval and is the product of the underlying mass function and the derivative of the appropriate mass-luminosity relation (MLR):

$$\frac{dN}{dm_K} = \frac{dN}{d\log M_*} \times \frac{d\log M_*}{dm_K} \quad (1)$$

where m_k is the apparent stellar (K) magnitude, and M_* is the stellar mass. The first term on the right hand side of the equation is the underlying stellar mass function and the second term the derivative of the MLR. With knowledge of the MLR (and bolometric corrections) this equation can be inverted to derive the underlying mass function from the observed luminosity function of a cluster whose distance is known.

This method is essentially that originally employed by Salpeter (1955) to derive the field star IMF. However, unlike main sequence field stars, PMS stars, which account for most of the stars in the an embedded cluster, cannot be characterized by a unique MLR. Indeed, the MLR for PMS stars is a function of time. Moreover, for embedded clusters the duration of star formation can be a significant fraction of the cluster’s age. Consequently, to invert the equation and derive the mass function one must model the luminosity function of the cluster and this requires knowledge of both the star formation history (i.e., age and age spread) of the cluster as well as the time-varying PMS mass-luminosity relation. The age or star formation history of the cluster typically can be derived by placing cluster stars on an HR diagram. This, in turn, requires additional observations such as multi-wavelength photometry or

spectroscopy of a representative sample of the cluster members. PMS models must be employed to determine the time varying mass-luminosity relation. The accuracy of the derived IMF therefore directly depends on the accuracy of the adopted PMS models which may be inherently uncertain, particularly for the youngest clusters ($\tau < 10^6$ yrs) and lowest mass objects ($m < 0.08 M_{\odot}$).

Despite these complexities, Monte Carlo modeling of the infrared luminosity functions of young clusters (Muench, Lada & Lada 2000) has demonstrated that *the functional form of an embedded cluster's luminosity function is considerably more sensitive to the form of the underlying cluster mass function than to any other significant parameter* (i.e., stellar age distribution, PMS models, etc.). In particular, despite the significant differences between the parameters that characterize the various PMS calculations (e.g., adopted convection model, opacities, etc.), model luminosity functions were found to be essentially insensitive to the choice of existing PMS mass-to-luminosity relations. This indicated that, given smoothly varying mass-luminosity relations and knowledge of their ages, the monochromatic luminosities of PMS stars can provide very good proxies for their masses. *This is a direct result of the steepness of the mass-luminosity relation for PMS stars.*

The top panel of Figure 1 shows the K luminosities (magnitudes) for million-year-old PMS stars predicted by a suite of the best known PMS models in the literature. The excellent agreement between the various models reflects the steep dependence of luminosity on stellar mass, a consequence of the basic stellar physics of Kelvin-Helmholtz contraction. Any intrinsic variations or uncertainties in the models are dwarfed by the sensitivity of luminosity to stellar mass. This is in contrast to the situation for the predicted stellar effective temperatures as a function of mass. The bottom panel of Figure 1 shows that the predicted effective temperatures are much less sensitive to stellar mass. The intrinsic variations in the models are roughly similar in magnitude to the overall variation in effective temperature with mass.

3. The IMF from OB stars to Brown Dwarfs

The rich Trapezium cluster in Orion represents the best nearby target for determining the IMF of a young stellar population. Muench et al. (2002) obtained deep infrared images of the Trapezium cluster and derived its IMF by using a suite of Monte Carlo calculations to model the cluster's K-band luminosity function (KLF). The observed shape of a cluster luminosity function depends on three parameters: the ages of the cluster stars, the cluster mass-luminosity relation, and the

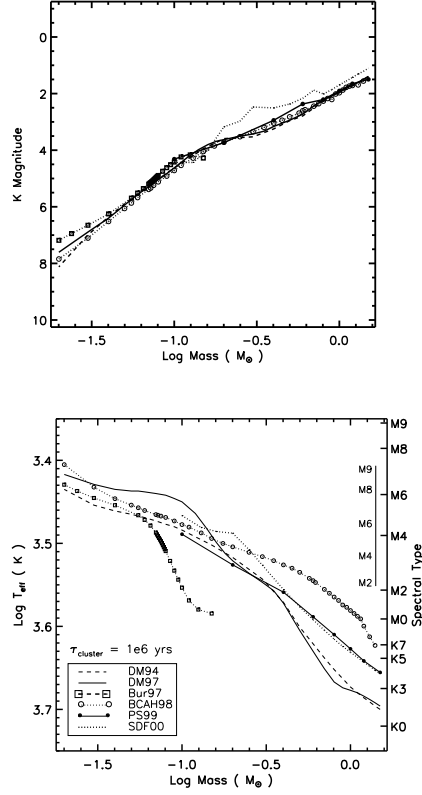


Figure 1. Comparisons of theoretical predictions for the infrared luminosities and effective temperatures of million-year-old PMS stars as a function of mass from a suite of standard PMS models (Burrows et al. 1997; Baraffe et al. 1998; D’Antona & Mazzitelli 1994; 1997; Palla & Sthaler 1999; Seiss et al. 2000). Note that the predicted PMS K magnitudes (top) appear to be in excellent agreement across the entire mass range whereas the predicted PMS effective temperatures (bottom) are not. This is a result of the steepness of the infrared mass-luminosity relation and clearly demonstrates how sensitive PMS luminosity is to variations in stellar mass.

underlying IMF (i.e., Equation 1). With the assumptions of a fixed age distribution, derived from an existing spectroscopic study of the cluster by Hillenbrand (1997), a composite theoretical mass-luminosity relation adopted from published PMS calculations and an empirical set of bolometric corrections, Muench et al. varied the functional form of the underlying IMF to construct a series of synthetic KLFs. These synthetic KLFs were then compared to the observed, background corrected, Trapezium KLF in a Chi-Squared minimization procedure to produce a best-fit IMF. As part of the modeling procedure, the synthetic KLFs

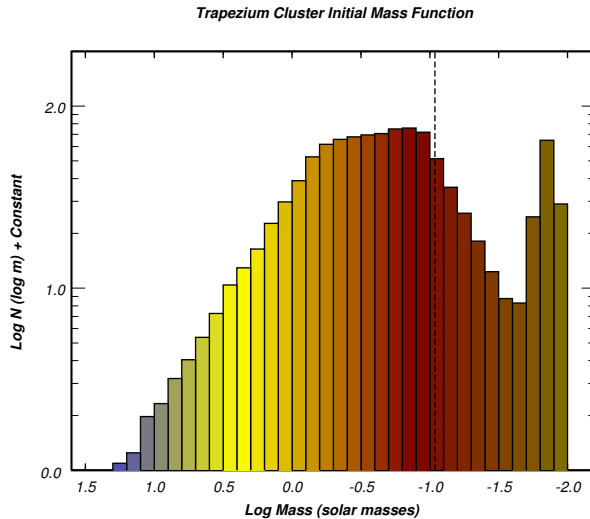


Figure 2. The IMF derived for the Trapezium cluster from Monte Carlo modeling of its luminosity function (Muench et al. 2002). This plot displays the binned mass function of the synthetic cluster whose luminosity function was found to best fit the observed KLF of the Trapezium cluster. A vertical dashed line marks the approximate location of the hydrogen burning limit. The derived IMF extends deep into the substellar regime.

were statistically corrected for both variable extinction and infrared excess using Monte Carlo probability functions for these quantities that were derived directly from multi-color observations of the cluster.

The derived mass function is displayed in Figure 2 in the form of a histogram of binned masses of the stars in the best-fit synthetic cluster. This model mass function represents the IMF of the young Trapezium cluster. This mass function agrees very well with Trapezium IMFs derived from a number of other different deep infrared imaging surveys using a variety of methods (Lucas & Roche 2000; Hillenbrand and Carpenter 2000; Muench et al. 2000; Luhman et al. 2000). The main characteristics of this IMF are: 1) the sharp power-law rise of the IMF from about $10 M_{\odot}$ (OB stars) to $0.6 M_{\odot}$ (dwarf stars) with a slope (i.e., $\beta = -1.2$) similar to that of Salpeter (1955), 2) the break from the single power-law rise at $0.6 M_{\odot}$ followed by a flattening and slow rise reaching a peak at about $0.1 M_{\odot}$, near the hydrogen burning limit, and 3) the immediate steep decline into the substellar or brown dwarf regime.

The most significant characteristic of this IMF is the broad peak, extending roughly from 0.6 to $0.1 M_{\odot}$. This structure clearly demon-

states that **there is a characteristic mass produced by the star formation process in Orion.** That is, the typical outcome of the star formation process in this cluster is a star with a mass between 0.1 and $0.6 M_{\odot}$. The process produces relatively few high mass stars and relatively few substellar objects. *Indeed, no more than $\sim 22\%$ of all the objects formed in the cluster are freely floating brown dwarfs.* The overall continuity of the IMF from OB stars to low mass stars and across the hydrogen burning limit strongly suggests that the star formation process has no knowledge of the physics of hydrogen burning. Substellar objects are produced naturally as part of the same physical process that produces OB stars.

The derived IMF of the Trapezium cluster spans a significantly greater range of mass than any previous IMF determination whether for field stars or other clusters (e.g., Kroupa 2002). Its statistically meaningful extension to substellar masses and the clear demonstration of a turnover near the HBL represents an important advance in IMF studies. For masses in excess of the HBL the IMF for the Trapezium is in good agreement with the most recent determinations for field stars (Kroupa 2002). This is to some extent both remarkable and surprising since the field star IMF is averaged over billions of years of galactic history, assuming a constant star formation rate, and over stars originating from very different locations of galactic space. The Trapezium cluster, on the other hand, was formed within the last million years in a region considerably less than a parsec in extent. Taken at face value this agreement suggests that the IMF and the star formation process that produces it are very robust in the disk of the Galaxy.

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