The stellar initial mass function and star formation in the galaxy

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We use observational constraints on the galactic ionizing photon production, the surface mass distribution of field M dwarfs, and the mass distribution of brown dwarfs in clusters to produce an effective galactic initial mass function (IMF). We assume that the IMF can be expressed as the product of a smooth function of mass m (in units of $M_\odot$), $\psi(m)$, and a time dependent rate. We express the star formation rate per unit area per unit logarithmic mass interval as $\dot{\varsigma}_*(m) \equiv [d^2\dot{\mathcal{N}}_*(m)]/[dA \; d\ln m] \equiv \dot{\varsigma}_{*1}\psi(m) = \dot{\varsigma}_{*1}(t)\, m^{-\Gamma} \left[1 - \exp -(m/m_{\rm ch})^{\gamma+\Gamma}\right]$ for $(m \leq m_u)$, with $\gamma = 0.8$ (the asymptotic low-mass slope inferred from the mass distribution in young clusters at sub-stellar masses), $\Gamma = 1.35$ (the negative of the high-mass slope), $m_{\rm ch} = 0.24$ (producing a maximum at $m_{\rm max} \sim m_{\rm ch}$), and $m_u = 120$. For a disk age of 11 Gyr, the average value of the star formation rate per unit logarithmic mass interval at 1 $M_\odot$ at the solar circle is $\langle\dot{\varsigma}_{*1}\rangle \simeq 620$ kpc^{-2} Myr^{-1}, and the ratio of the present to the mean SFR is $b(t_0) = 1.085$, where t_0 is the age of the disk.

Keywords: Stars: formation; stars: mass function; ISM: evolution.

Se propone una función inicial de masa efectiva (FIME) para la Galaxia que satisface las siguientes restricciones observacionales: la producción de fotones ionizantes en la Galaxia, la distribución en masa de la densidad superficial de estrellas M y la distribución en masa de Enanas Marrones en asociaciones estelares jóvenes. Se supone que la FIME puede ser expresada como el producto de una función suave de la masa m (en unidades de $M_\odot$), $\psi(m)$ y una tasa dependiente del tiempo. Esta es: $\dot{\varsigma}_*(m) \equiv [d^2\dot{\mathcal{N}}_*(m)]/[dA \; d\ln m] \equiv \dot{\varsigma}_{*1}\psi(m) = \dot{\varsigma}_{*1}(t)\, m^{-\Gamma} \left[1 - \exp -(m/m_{\rm ch})^{\gamma+\Gamma}\right]$ para $(m \leq m_u)$, donde $\gamma = 0.8$ (pendiente asintótica a masas bajas inferida de la distribución de masa en la región sub-estelar en asociaciones jóvenes), $\Gamma = 1.35$ (pendiente asintótica a masas altas), $m_{\rm ch} = 0.24$ (que produce un máximo a $m_{\rm max} \sim m_{\rm ch}$), y $m_u = 120$. Para una edad del disco galáctico de 11 Gyr, el valor promedio de la tasa de formación estelar por unidad logarítmica de masa a 1 $M_\odot$ en el círculo solar es $\langle\dot{\varsigma}_{*1}\rangle \simeq 620$ kpc^{-2} Myr^{-1} y la razón entre la SFR presente y la SFR media es $b(t_0) = 1.085$.

Descriptores: Formación estelar; función inicial de masa estelar.

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1. Introduction

The Initial Mass Function (IMF) is a fundamental ingredient for the study of any system containing stars; from clusters to galaxies, to the luminous universe. Since the pioneering work by Salpeter (1955) [1], the IMF has been derived in a variety of systems such as clusters of different ages, field stars, the galactic bulge, globular clusters, and nearby galaxies. Comprehensive studies such as [2,3,4] have provided the community with standard IMFs that have allowed the construction of innumerable models in a common basis. Recent reviews of the theoretical and observational studies of the IMF are in Refs. 5 and 6, respectively. In this short paper we make use of recent observational data to constrain the effective IMF for the disk of the Galaxy.

Three constraints are used to calibrate the best effective IMF:

(i) the high-mass IMF slope $-\Gamma$,

(ii) the low-mass IMF slope γ, and

(iii) the mass distribution of the surface density of M dwarf field stars.

Although the Present Day Mass Function (PDMF) below the hydrogen-burning mass-limit is not well established, our effective IMF is well defined there, and we use the single parameter γ to cover the plausible range of low-mass asymptotic slopes. The PDMF at high masses depends not only on the shape of the IMF but also on the very recent star formation rate (SFR). We assume that the shape of the effective IMF does not vary in time, although the overall rate can vary. Since the lifetimes of M stars exceeds the age of the Galactic disk, the time-averaged IMF for these stars is simply the PDMF divided by the age of the disk.

The current rate of star formation, as measured by the current rate of massive star formation in the Galaxy, may differ from the time-averaged rate. Determining the massive star formation rate by optical surveys for massive stars tends to underestimate the rate because these short-lived stars spend an appreciable fraction of their lives obscured by their parent molecular cloud. In addition, the local value of the current SFR may differ from the current SFR averaged over the solar circle since there can be large fluctuations in the SFR due to the low space density of large associations, which contain a significant fraction of massive stars [7]. We circumvent both of these problems by utilizing radio and far-infrared (N II $\lambda 122\ \mu$m) observations of the rate of hydrogen ionizing photons produced in the Galaxy [8]. This rate is proportional to the high-mass SFR, and because the radio and far IR observations are not affected by extinction, they do not suffer the two limitations discussed above. In addition, the radial gradient of the current SFR, and the average value at the solar-circle are inferred in Ref. 8. We can then compare the current SFR at the solar circle with that averaged over the age t_0 of the galactic disk.

2. A Four Parameter IMF

Observational data shows that the high-mass end of the IMF is appropriately described by a power law, whereas below 1 $M_\odot$ the IMF flattens and there is growing evidence that the IMF declines in the brown dwarf regime. Kroupa's compilation [4] of IMF slopes, as function of the average mass over which the slope is measured, includes data for 61 clusters and associations compiled by Scalo ([5]; with average masses over 0.3 $M_\odot$) and data at 0.5 and 0.05 $M_\odot$ for the Trapezium cluster [9]. This compilation suggests that the IMF slope declines continuously as the mass increases, from a slope ~ 1 at 0.01 $M_\odot$ to a slope 0 at ~ 0.1 $M_\odot$, where the IMF has a maximum. Hillenbrand [10] also compiles several studies providing the IMF slope as function of the mass covered by the study. Again, what Hillebrand [10] concludes is that " when authors force a power law fit through their data, the composite of these power laws is very much *not* a power law". There is no reason to expect that the IMF would have discontinuities in its slope. The first and most popular continuous function proposed to represent the IMF was the lognormal function in Ref. 2, but it becomes too steep at high masses [5]. A second degree polynomial in $\log(m)$ used in Ref. 11 was designed to fit their observational values ($0.09 < m < 1$), but again is of no use at high masses. Larson [12] proposed the form $\psi(m) \propto m^{-\Gamma} \exp[-(m_0/m)^\beta]$ which resembles the lognormal form at low masses but recovers a power-law form at high masses. Here we adopt the following functional form that gives a power law of index γ at very low masses and a power law of index $-\Gamma$ at high masses (hereafter IMF_{4p}):

$$\psi(m)=m^{-\Gamma}\left(1-\exp\left[-(m/m_{\rm ch})^{\gamma+\Gamma}\right]\right) \qquad (m\leq m_u). \quad (1)$$

The parameter $m_{\rm ch}$, in combination of the parameters γ and Γ, determines the position of the IMF maximum and the width of the transition zone between the low- and high-mass power laws. Note that the first term ($m^{-\Gamma}$) in Eq. (1) is just the high-mass IMF. The right hand term in between brackets is zero at $m = 0$, and as m increases it grows continuously toward its saturation value of 1. The product of these terms results in a function that has a slope γ at low masses and a slope $-\Gamma$ at high masses. The simple functional form in Eq. (1) describes the IMF shape at all masses with only three parameters ($m_{\rm ch}$, γ, and Γ). The fourth parameter m_u provides the IMF truncation observed at high masses. It is interesting to note that recent theories of the origin of the IMF [13-16] produce mass distributions with shapes similar to Eq. (1).

3. The Star Formation Rate

The stellar birthrate per unit area of Galactic disk $\dot{\varsigma}_*(m)$ can be expressed as the product of the smooth function of mass $\psi(m)$ given in Eq. (1) and the time dependent rate of star formation $\dot{\varsigma}_{*1}(t)$. That is,

$$\dot{\varsigma}_*(m) = \frac{d^2\dot{\mathcal{N}}_*(m)}{dA\, d\ln m} = \frac{d\dot{\mathcal{N}}_{*1}}{dA}\psi(m) \equiv \dot{\varsigma}_{*1}\psi(m), \quad (2)$$

where, $\dot{\mathcal{N}}_{*1}$ is the stellar birthrate per unit logarithmic mass interval at 1 $M_\odot$; note that $\psi(1)$ is very close to 1 for all plausible values of γ, Γ and $m_{\rm ch}$. The ratio of the current SFR to the value averaged over the age of the disk is [3]:

$$b(t_0) \equiv \frac{\dot{\varsigma}_{*1}}{\langle\dot{\varsigma}_{*1}\rangle}, \quad (3)$$

where

$$\langle\dot{\varsigma}_{*1}\rangle \equiv \frac{1}{t_0}\int_0^{t_0} \dot{\varsigma}_{*1}\ dt. \quad (4)$$

For massive stars, the IMF can be approximated as a cut-off power law that extends up to a mass m_u [8],

$$\psi(m) = \psi(m_h)\left(\frac{m_h}{m}\right)^{\Gamma} \qquad (m_{\rm ch} \ll m \leq m_u). \quad (5)$$

Even though observations indicate that the power law in Eq. (5) is valid for values down to about 1 $M_\odot$, the normalization constant m_h is chosen to be the minimum mass of what we call here a high-mass star. We adopt $m_h = 8$, since that is the minimum mass of a core-collapse supernova [17].

The high-mass star formation rate is

$$\dot{\mathcal{N}}_{*h} = \dot{\mathcal{N}}_{*1}\int_{m_h}^{m_u} \psi(m) d\ln m = \left(\frac{\phi_h}{\Gamma}\right)\dot{\mathcal{N}}_{*1}\psi(m_h), \quad (6)$$

where

$$\phi_h \equiv 1 - (m_h/m_u)^{\Gamma}. \quad (7)$$

Therefore,

$$\dot{\varsigma}_{*1} = \left(\frac{\Gamma m_h^{\Gamma}}{\phi_h}\right)\dot{\varsigma}_{*h}. \quad (8)$$

The stellar birthrate of massive stars $\dot{\varsigma}_{*h}$ can be inferred from the total ionizing photon production rate of the Galaxy which is estimated to be $S_T = 2.6 \times 10^{53}$ photons s^{-1} from radio surveys [8]. If each star produces $Q(m) = s(m)t_{\rm ms}$

ionizing photons during its lifetime $t_{\rm ms}$, then in a steady state the expected value of the ionizing luminosity from a group of stars is

$$S = \int Q(m) d\dot{\mathcal{N}}_* = \dot{\mathcal{N}}_{*h} \langle s \rangle_h \langle t_{\rm ion} \rangle, \tag{9}$$

where $\langle s \rangle_h$ is the characteristic ionizing luminosity of a typical high mass star in a group of stars following the IMF, and $\langle t_{\rm ion} \rangle$ is the mean lifetime of an ionizing star. Then,

$$\dot{\varsigma}_{*1} = \left(\frac{\Gamma m_h^\Gamma}{\phi_h} \right) \frac{S_T}{A_{\rm eff} \langle s \rangle_h \langle t_{\rm ion} \rangle}, \tag{10}$$

where $A_{\rm eff} \simeq 530\,{\rm kpc}^2$ is the effective area for massive star formation in the Galaxy [7].

4. The Galactic IMF and SFR

The strategy used here to calibrate an effective IMF (*i.e.* the IMF averaged over the solar circle and over the age of the galactic disk) is as follows.

i) The star formation rate of high mass stars $\dot{\varsigma}_{*h}$ necessary to match the ionizing photon production rate of the Galaxy S_T is determined. This step (see §3) involves only the parameter Γ and provides a measure of $\dot{\varsigma}_{*h}$, at present. For Γ=1.35 and m_u=120 [1-6,18-20], and the stellar parameters we have adopted in Refs. 21 to 23, $\langle s \rangle_h = 0.42\,10^{49} {\rm s}^{-1}$, and $\langle t_{\rm ion} \rangle = 4.0 \times 10^6$ yr, so that $\dot{\varsigma}_{*h} \rightarrow 29.4 {\rm kpc}^{-2} {\rm Myr}^{-1}$, and $\dot{\varsigma}_{*1} \rightarrow 670 {\rm kpc}^{-2} {\rm Myr}^{-1}$.

ii) For the adopted value of γ, the values of $m_{\rm ch}$ and $\langle \dot{\varsigma}_{*h} \rangle$ are determined by fitting the function $\langle \dot{\varsigma}_{*1} \rangle \times \psi(m)$ to the M stars PDMF derived by Zheng *et al.* [24]. This step provides $t_0/b(t_0)$ since the absolute values of the low mass PDMF depend on the product $\langle \dot{\varsigma}_{*h} \rangle \times t_0$. The various estimates of the low-mass IMF slope γ involves a variety of observational techniques and the variety of transformations between the observations and stellar masses that are used [9,10,25-30]. However, the estimated values of γ show a relatively small scatter in comparison to the scatter in the high mass IMF slope [10]. For the average low-mass IMF slope ($\gamma = 0.8$), the best fit to the M stars PDMF data in [24] is obtained for $m_{\rm ch} = 0.24$ and $t_0/b(t_0) = 10.14$ Gyr. For a galactic disk age $t_0 = 11$ Gyr the ratio of the present to the mean SFR is $b(t_0) = 1.085$.

Therefore, our standard IMF$_{4p}$ is characterized by the parameters γ=0.8 (the asymptotic low-mass slope), Γ=1.35 (the negative of the high-mass slope), $m_{\rm ch}$=0.24 (producing a maximum at $\sim m_{\rm ch}$), and m_u=120. The average value of the star formation rate per unit logarithmic mass interval at 1 $M_\odot$ at the solar circle is $\langle \dot{\varsigma}_{*1} \rangle = \dot{\varsigma}_{*1}/b(t_0) \simeq 620\,{\rm kpc}^{-2}\,{\rm Myr}^{-1}$.

What fraction of the objects formed are predicted to be substellar objects, or brown dwarfs, and what fraction of stars formed are high mass stars? The maximum mass of a brown dwarf is the "hydrogen-burning minimum mass," which we denote as $m_{\rm bd}$. For solar metallicity, $m_{\rm bd} \simeq 0.075$ $M_\odot$ [29,30]. The fraction of stars (or objects, where objects include both brown dwarfs and stars) born with masses greater than m can be written as $F_n(>m) = \dot{\mathcal{N}}_*(>m)/\dot{\mathcal{N}}_*(>m_{\rm bd})$ (or $F_{n,{\rm obj}}(>m) = \dot{\mathcal{N}}_*(>m)/\dot{\mathcal{N}}_*$), where $\dot{\mathcal{N}}_*(>m_{\rm bd})$ is the total number of stars formed per unit time, and $\dot{\mathcal{N}}_*$ is the total number of objects formed per unit time. The fraction of stars that are high mass ($m > m_h$=8) stars is then given by: $F_h \equiv F_n(>m_h) = \dot{\mathcal{N}}_{*h}/\dot{\mathcal{N}}_*(>m_{\rm bd})$; the fraction of objects that are high mass stars is given by: $F_{h,{\rm obj}} \equiv F_{n,{\rm obj}}(>m_h)$. The fraction of the mass in stars (or objects) born with masses above m is defined as $F_m(>m)$ (or $F_{m,{\rm obj}}(>m)$). Similarly, for brown dwarfs, we define $F_{n,bd} \equiv F_{n,{\rm obj}}(<m_{\rm bd})$ the fraction of sub-stellar objects and $F_{m,bd}$ the fraction of the mass in sub-stellar objects.

TABLE I. Characterization of IMF$_{4p}$

	– Parameters –		(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)
				<——		Objects	——>		<—— Stars ——>		
Γ	γ	$m_{\rm ch}$	$\langle m \rangle$	$F_{n,bd}$	$F_{m,bd}$	$F_n(>8)$	$F_m(>8)$	$\langle m \rangle$	$F_n(>8)$	$F_m(>8)$	μ_h
1.35	0.8	0.239	0.39	0.28	0.0234	0.00356	0.177	0.53	0.00493	0.181	109
1.50	0.6	0.275	0.30	0.36	0.0332	0.00199	0.118	0.46	0.00312	0.122	153
1.20	1.0	0.211	0.51	0.22	0.0158	0.00629	0.259	0.64	0.00802	0.263	81

a.- Average mass of IMF$_{4p}$ objects (objects include stars and brown dwarfs).

b.- Fraction of objects in the IMF$_{4p}$ with masses below $m_{\rm bd} = 0.075$ (the brown dwarf fraction).

c.- Fraction of mass in brown dwarfs.

d.- Fraction of objects in the IMF with masses above $m_h = 8$ (fraction of high mass stars).

e.- Fraction of mass in high mass stars.

f.- Average mass of IMF stars (objects with $m > m_{\rm bd}$).

g.- Fraction of stars in the IMF with masses above $m_h = 8$ (fraction of high mass stars).

h.- Fraction of mass in high mass stars.

i.- Mass of stars formed per high mass star ($\sim$ mass of objects formed per high mass star).

Additional characteristic quantities are: $\langle m \rangle$ (or $\langle m \rangle_{\rm obj}$), the mean stellar (or object) mass; and

$$\mu_h \equiv \frac{\dot{M}_*(> m_{\rm bd})}{\dot{\mathcal{N}}_{*h}} \quad \text{or} \quad \mu_{h,\rm obj} \equiv \frac{\dot{M}_*}{\dot{\mathcal{N}}_{*h}}, \qquad (11)$$

is the total mass of stars (or objects) formed per high mass star, where $\dot{M}_*(> m_{\rm bd})$ is the star formation rate and $\dot{M}_*$ is the object formation rate. Note that $\mu_h = \langle m \rangle / F_h$. Table I shows the above quantities we use to characterize the IMF for various combinations of Γ and γ. The value of $m_{\rm ch}$ is adjusted in each case to provide the best fit to the PDMF data in Ref. 24.

5. Conclusions and future work

The simple functional form in Eq. (1) describes the IMF shape at all masses with only three parameters ($m_{\rm ch}$, γ, and Γ). The fourth parameter m_u provides the IMF truncation observed at high masses. These four parameters were estimated from the observed mass distributions in cluster and field stars (for the standard case: $\gamma = 0.8$, $\Gamma = 1.35$, $m_{\rm ch} = 0.24$, and $m_u = 120$). We have used observational constraints on the galactic ionizing photon production, and the surface mass distribution of field M dwarfs to estimate the values of the present and the average value of the star formation rate per unit logarithmic mass interval at the solar circle ($\dot{\varsigma}_{*h} \sim 29.4$ and $\dot{\varsigma}_{*1} \sim 670\,\mathrm{kpc}^{-2}\,\mathrm{Myr}^{-1}$; for a galactic disk age $t_0 = 11$ Gyr the ratio of the present to the mean SFR is $b(t_0) = 1.085$ implying $\langle \dot{\varsigma}_{*1} \rangle = \dot{\varsigma}_{*1}/b(t_0) \simeq 620$ kpc^{-2} Myr^{-1}).

In a forthcoming paper, we shall discuss these results in detail and examine the effect of multiple systems. We shall study the consistency of IMF$_{4p}$ with other observational constraints such as the surface density of white dwarf stars, which depends on the intermediate-mass $[0.8 < m < 8]$ IMF. We shall also consider the effect of an intermittent star formation history [31].

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