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THE GALACTIC DISK MASS FUNCTION: RECONCILIATION OF THE *HUBBLE SPACE TELESCOPE* AND NEARBY DETERMINATIONS

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ABSTRACT

We derive and parameterize the Galactic mass function (MF) below 1 $M_{\odot}$ characteristic of both single objects and binary systems. We resolve the long-standing discrepancy between the MFs derived from the *Hubble Space Telescope* (*HST*) and from the nearby luminosity functions, respectively. We show that this discrepancy stemmed from *two* cumulative effects, namely, (1) incorrect color-magnitude–determined distances, due to a substantial fraction of M dwarfs in the *HST* sample belonging to the metal-depleted thick-disk population, as corrected recently by Zheng et al., and (2) unresolved binaries. We show that both the nearby and *HST* MF for unresolved systems are consistent with a fraction ∼50% of M dwarf binaries, with the mass of both the primaries and the companions originating from the same underlying single MF. This implies that ∼30% of M dwarfs should have an M dwarf companion and ∼20% should have a brown dwarf companion, in agreement with recent determinations. The present calculations show that the so-called "brown dwarf desert" should be reinterpreted as a lack of high mass ratio ($m_2/m_1 \lesssim 0.1$) systems and does not preclude a substantial fraction of brown dwarfs as companions of M dwarfs or for other brown dwarfs.

Subject headings: Galaxy: stellar content — stars: low-mass, brown dwarfs — stars: luminosity function, mass function

1. INTRODUCTION

The determination of the disk stellar luminosity function (LF) and mass function (MF) in the low-mass star ($m \lesssim 1\ M_{\odot}$) domain is still subject to debate and remains an unsettled issue up to this date. The disagreement between the MF inferred from the photometric *Hubble Space Telescope* (*HST*) LF and from the nearby 5.2 pc LF has been a controversial issue since the Gould, Bahcall, & Flynn (1997, hereafter GBF97) paper. The MF derived from the local sample keeps rising, although moderately, down to the hydrogen-burning limit, whereas the MF derived from the *HST* LF is steadily decreasing from 0.6 down to 0.1 $M_{\odot}$ (see Fig. 1 of Méra, Chabrier, & Schaeffer 1998). The question is of prime importance for various reasons. First, the determination of the very shape of the MF bears profound consequences for our understanding of star formation. Second, whereas the luminosity of galaxies arises mostly from stars from about 1 to a few solar masses, most of their mass is contained in objects with $m \leq 1\ M_{\odot}$. The determination of the MF in the M dwarf regime is thus crucial for a proper evaluation of their mass budget and mass-to-light ratio. Third, the normalization of the MF near the hydrogen-burning limit is the cornerstone for an accurate evaluation of the brown dwarf (BD) content of the disk. Last but not least, the M dwarf present-day MF (PDMF) represents the *initial* MF (IMF) of the Galaxy, i.e., it is representative of the mass distribution of all the stars *ever* formed in the Galaxy (Scalo 1986), a central input in galactic evolution and cosmic star formation history. The unresolved discrepancy between the *HST* and nearby MF determinations thus prevents robust determinations of the aforementioned quantities. In this Letter, we reconsider this problem in light of the recently reanalyzed *HST* LF (Zheng et al. 2001).

2. INITIAL MASS FUNCTION FROM THE NEARBY SAMPLE

The LF $\Phi(M)$ requires the determination of the distance of the objects. Samples with trigonometric parallax determination require near distances from the Sun and define the so-called *nearby* LF $\Phi_{\rm near}$. A major advantage of $\Phi_{\rm near}$ is the identification of binary systems. A V band nearby LF can be derived by combining *Hipparcos* parallax data (ESA 1997) for $M_V < 12$ and the sample of nearby stars with ground-based parallaxes (Dahn, Liebert, & Harrington 1986) for $M_V > 12$ to a completeness distance $r = 5.2$ pc. On the other hand, Henry & McCarthy (1990) used speckle interferometry to resolve companions of every known M dwarf within 5 pc and obtained the complete M dwarf LF $\Phi_{\rm near}$ in the H and K bands. Their sample recovers the Dahn et al. (1986) one, plus one previously unresolved companion (GL 866B). Up to now, samples extended to a larger volume remain incomplete (see Henry et al. 1997) and are hampered by ill-determined distances (see Chabrier 2001, § 3).

Kroupa (2001) and Chabrier (2001) have determined the Galactic disk M dwarf MF from the V band 5 pc $\Phi_{\rm near}$, although using different functional forms. We have redone this analysis by calculating the MF from both the aforementioned V band and K band $\Phi_{\rm near}$. Recently, Delfosse et al. (2000) and Ségransan et al. (2003b) combined adaptive optics and accurate radial velocities to determine the mass-magnitude relation (MMR) of about 20 objects between ∼0.6 and ∼0.09 $M_{\odot}$ in the V, J, H, and K bands with mass accuracies of 0.2%–5%. The MMRs derived from the Baraffe et al. (1998, hereafter B98) models reproduce these data within less than 1 σ in the J, H, and K bands (Delfosse et al. 2000, Fig. 3). The agreement is less good in the V band, with a systematic offset of a few tenths of a magnitude below ∼0.3 $M_{\odot}$ ($M_V \gtrsim 12$), as discussed at length in B98 and Chabrier et al. (2000, Fig. 1). The implications for the MF have been examined in detail by Chabrier (2001, Figs. 1 and 2) and have been found to remain modest ($\lesssim$15% in the mass determination for $m \sim 0.2$–$0.3\ M_{\odot}$). The theoretical M dwarf radii of B98 also agree within 1% or less for $m \leq 0.5\ M_{\odot}$ with the radius measurements obtained recently with the Very Large Telescope Interferometer by Ségransan et al. (2003a). This establishes the validity of deriving the MFs from the observed LFs using the theoretical B98 MMRs. However, in order to avoid any possible

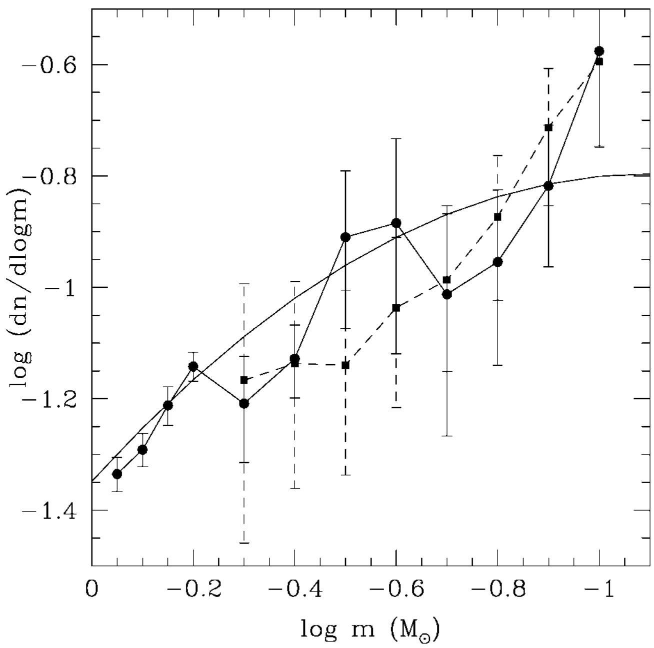

FIG. 1.—Disk IMF derived from the local *V*-band LF (*circles and solid line*) and *K*-band LF (*squares and dashed line*). The solid line displays the lognormal form (eq. [1]).

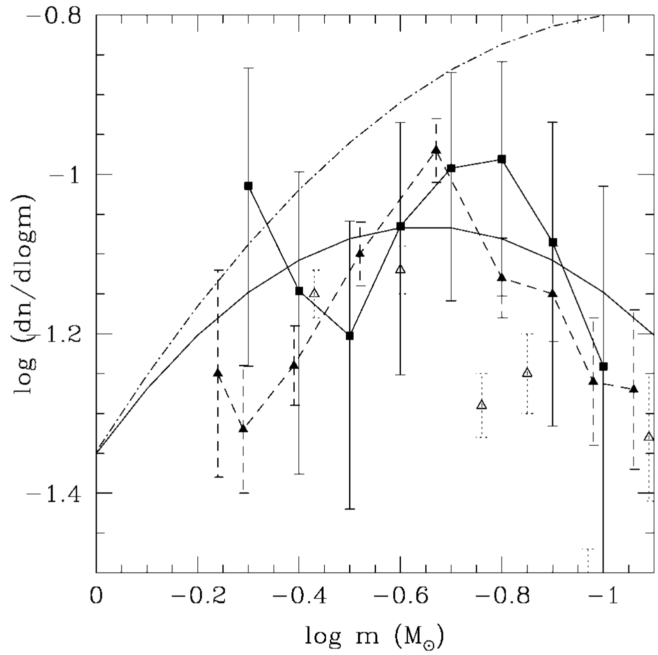

FIG. 2.—Disk MF derived from the system *K*-band LF (*squares and solid line*) and the *HST*-corrected MF (*filled triangles and dashed line*) from Zheng et al. (2001). The Zheng et al. (2001) MF has been multiplied by a factor of 7.1/8.1 to bring the *HST* normalization at 0.6 $M_\odot$, consistent with the one inferred from eq. (1). The solid line and top dot-dashed line illustrate the lognormal form given by eqs. (2) and (1), respectively. The *HST* MF obtained if all objects are assumed to have a solar metallicity (see Zheng et al. 2001) is illustrated by the open triangles.

source of error, the conversion of the *V*-band LF into a MF was done using the Delfosse et al. (2000) m-M_V relation, fitted to the data. These results are displayed in Figure 1. We note the very good agreement between the two determinations, which establishes the consistency of the two observed samples, part of the ~1.5 σ difference in the mass range $\log m \sim -0.5$ to -0.6 reflecting most likely the remaining uncertainties in the MMR.[1] The solid line displays a lognormal form that gives a fairly good representation of the results,

$$\xi(\log m) = \frac{dn}{d\log m} = 0.158$$

$$\times \exp\left[-\frac{(\log m - \log 0.08)^2}{2(0.69)^2}\right] \text{pc}^{-3} (\log\ M_\odot)^{-1}, \quad (1)$$

with the same normalization as Scalo (1986) at 1 $M_\odot$, $(dn/dm)_1 = 1.9 \times 10^{-2}\ (M_\odot)^{-1}\ \text{pc}^{-3}$, above which the PDMF and the IMF start to differ appreciably (>10%). This IMF is very similar to the IMF2 derived in Chabrier (2001), which gives a good description of the star counts in the deep field of the ESO Imaging Survey (Groenewegen et al. 2002) and whose predictions in the BD domain agree fairly well with present detections of various field surveys (Chabrier 2002).

As demonstrated by the detailed study of Kroupa, Tout, & Gilmore (1993) and Kroupa (1995), most of the discrepancy between photometric and nearby LFs for $M_V > 12$ results from Malmquist bias and unresolved binary systems in the low spatial resolution photographic surveys. Although the Malmquist bias is negligible for the *HST*, the *HST*, however, misses essentially all companions of multiple systems because of its angular resolution. GBF97 estimate that the correction arising from unresolved companions is at most a factor of 2 at 0.1 $M_\odot$, whereas the difference between the *HST* (GBF97) MF and the one derived from Φ_{near} is more than a factor of 4 in this region (see, e.g., Fig. 1 of Méra et al. 1998 or Fig. 2 above, *open triangles*). Clearly, the binary correction cannot account *by itself* for the difference. A major caveat of any photometric LF, however, is that the determination of the distance relies on a photometric determination from a color-magnitude diagram. The former analysis of the *HST* data (GBF97) used for the entire sample a color-magnitude transformation characteristic of stars with solar abundances. As shown in Figure 2 of Zheng et al. (2001), however, the vast majority of the stars in the *HST* sample lie at a Galactic height $|z| \gtrsim 800$ pc above the plane. These stars are expected to have metal-depleted abundances and fainter magnitudes for a given $V-I$ color than stars with solar abundance (Chabrier & Baraffe 2000). Assuming a solar abundance for the entire *HST* sample thus results in an overestimation of the distance and an underestimation of the number density. This point was considered recently in the new analysis and sample of Zheng et al. (2001), yielding a revised Φ_{HST}, with indeed a larger number of M dwarfs at dim absolute magnitudes. This new sample, however, does not include the correction due to unresolved binaries, and the inferred IMF still differs significantly from the one derived from the local sample. We have conducted a detailed analysis of this bias with this new LF.

3. BINARY CORRECTION TO THE LOCAL AND *HST* LUMINOSITY FUNCTIONS

3.1. *Analysis of the Mass Ratio Distribution*

Although the multiplicity rate for *stellar* companions of M dwarfs still remains ill-determined, a reasonable estimate is starting to emerge, with a value $X_* \approx 30\% \pm 5\%$ (Marchal et al. 2003). Mass ratios of binaries have been determined ac-

[1] The last bin is very likely contaminated by young/massive BDs or still contracting very low mass stars with $m \lesssim 0.12\ M_\odot$. As shown in Chabrier (2002), an IMF including this bin extrapolated into the BD regime would overestimate significantly the number of such objects.

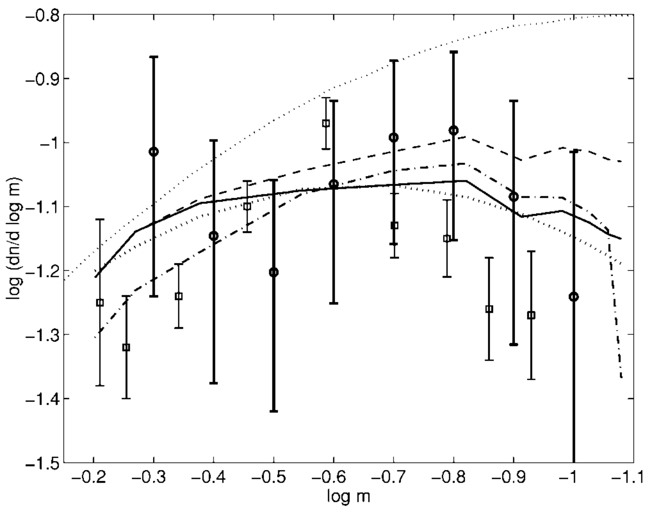

FIG. 3.—Effect of unresolved binaries on the local and *HST* MFs. *Circles*: Nearby system MF; *squares*: *HST* MF corrected for metallicity gradient, as in Fig. 2. *Solid and dashed lines*: Reconstructed local system MF, for 50% (*solid curve*) and 30% (*dashed curve*) of unresolved binaries, respectively; *dot-dashed line*: reconstructed *HST* system MF for 50% of unresolved binaries. *Top dotted line*: Single object IMF (eq. [1]); *bottom dotted line*: system IMF (eq. [2]).

curately only for F and G stars (Duquennoy & Mayor 1991, hereafter DM91). Similar M dwarf studies are in progress (Delfosse et al. 1999; Marchal et al. 2003), but extended observations (∼10 yr) are required to get unbiased results. The studies conducted by Mazeh, Latham, & Stefanik (1996), restricted to short-period binaries, give a linear fit of mass ratio distribution whose slope is compatible with 0, the uncertainty being large. The recent determinations by Marchal et al. (2003) point to a mass ratio close to unity for short-period binaries ($P <$ 100 days) but a distribution compatible with a DM91 or a uniform one for longer periods.

We have conducted Monte Carlo simulations in order to estimate the effect of such unresolved binaries on the local and *HST* MF. The mass of the single stars and primaries m_p is drawn randomly according to MF (eq. [1]). A fraction X of these stars are then selected with a uniform probability distribution and are attributed a companion. The mass of the companion is drawn from a mass fraction distribution $P(q)$ ($q = m_2/m_1 \le 1$), assuming that this distribution does not depend on the mass of the primary. In order to estimate the dependence of the binary correction upon the parameters, we have conducted calculations with several binary fractions and mass ratio distributions, namely, $P(q) = \text{constant}$, $P(q) \propto \exp[-(q-\mu)^2/2\sigma_q^2]$, $P(q) \propto q$, and $P(q) \propto (1-q)$. These distributions correspond to a uniform mass ratio distribution, a DM91 distribution for $\mu = 0.23$, $\sigma_q = 0.42$, and distributions biased toward equal masses and low mass ratio, respectively. The resulting distribution $dN = N_{\rm tot}/N_p$, i.e., the total number of stars $N_{\rm tot} = N_p + N_s$ over the number of primaries increases with decreasing mass approximately as $dN \propto m^{-0.16}$ from ∼0.5 to 0.1 $M_\odot$, with a maximum of ∼(30 ± 10)% at $m = 0.1\ M_\odot$, for $X = 0.5 \pm 0.1$. The shape of the correction is found to depend only weakly on the $P(q)$ distribution.

Note that these distributions imply that a fraction of the companions are below the hydrogen-burning limit ($m <$ 0.072 $M_\odot$). For the sample studied by DM91, about 60% of the observed stars have a companion of mass larger than 0.1 $M_\odot$ and the DM91 distribution predicts ∼10% of substellar companions. If the same distribution is applied to a 0.2 $M_\odot$ M dwarf, then about 50% of the companions are BDs. This means that the observed *frequency* of *stellar* binaries depends on the mass of the primary. In a sample including only stellar objects, the present calculations predict an *observable* (stellar) fraction of companions ∼60% among M dwarf primaries, the remaining ∼40% fraction being BD companions. For a $X = 50\%$ binary frequency (see below), this implies ∼30% of M dwarf systems and ∼20% of systems composed of an M dwarf with a BD companion. This is in good agreement with the currently observed M dwarf binary fraction in the solar neighborhood (Delfosse et al. 1999; Marchal et al. 2003) and with the present estimates of BD companions of M dwarfs at large orbital separations (Gizis et al. 2001). The correction to the LF and to the MF is examined below.

3.2. *Effect of Binary Correction on the Luminosity Function and Mass Function*

We first consider the effect of unresolved binaries on the MF derived from the nearby LF $\Phi_{\rm near}$. For that, we have merged the identified companions in the Dahn et al. (1986) and Henry & McCarthy (1990) samples into unresolved systems.[2] This yields the nearby system LF, from which we have calculated the system MF, following the same procedure as in § 2. Figure 2 displays this system MF as well as the recent *HST* MF (Table 4 of Zheng et al. 2001). The two MFs are compatible at the less than 1 σ level. For comparison, the figure also displays the *HST* MF obtained from a color-magnitude distance determination, assuming that all the objects have a solar abundance, as done in GBF97 [Zheng et al. 2001, Fig. 4, with their color-magnitude relation CMR (1)]. The latter is much more difficult to reconcile with the local system MF below $m \lesssim$ 0.25 $M_\odot$, as mentioned earlier. For further purposes, it is interesting to parameterize this system MF, as done in equation (1) for the single objects, as

$$\xi(\log m)_{\rm sys} = \frac{dn}{d\log m} = 0.086 \times \exp\left[-\frac{(\log m - \log 0.22)^2}{2(0.57)^2}\right]\ {\rm pc}^{-3}\ (\log\ M_\odot)^{-1}, \quad (2)$$

with the same normalization as MF (eq. [1]) at 1 $M_\odot$, where the binary correction is negligible. It is displayed by the solid line in Figure 2.

In order to verify this correction due to unresolved binaries on the local LF $\Phi_{\rm near}$, we have applied the same type of Monte Carlo simulations as described above. However, in the present case, we have explored the possibility that the primary and the secondary are drawn randomly from the *same* single object MF (eq. [1]). The *system* LF is then calculated by attributing a magnitude $M_{\rm sys} = -2.5\log(10^{-0.4M(m_1)} + 10^{-0.4M(m_2)})$ to the unresolved binary and the system MF is derived with the same MMRs as in § 2. The resulting system MF is displayed in Figure 3 for a binary fraction $X = 50\%$ (*solid line*) and $X = 30\%$ (*dashed line*). As seen in the figure, the agreement with the observed local system MF is excellent, and the system MF for $X = 50\%$ agrees surprisingly well with the parameterized form (eq. [2]).

The quantification of the effect of unresolved binaries on the *HST* MF is more complicated, for in that case the Galactic scale height variation must be taken into account. We use the same

[2] For the Henry & McCarthy sample, we have also merged the binaries GL 15 A and B into one system to get the complete system LF from their Fig. 10*b*.

Monte Carlo calculations, with the disk density profile $\rho(R, z)$ determined by Zheng et al. (2001, eq. [4]). We then proceed exactly as for the local LF, with a simulated stellar population, including X% binary systems, drawn randomly from this spatial distribution, with masses given by equation (1). We use the same M_V–$(V-I)$ relation and color cut $1.53 < V-I < 4.63$ as Zheng et al. (2001). We then reconstruct the *HST* observed LF obtained with the $1/V_{\max}$ method ($\Phi = \Sigma V_{\max}^{-1}$), assuming that all binary systems are unresolved. The reconstructed MF from this system LF is compared to the one derived by Zheng et al. (2001) on Figure 3 (*squares*) for $X = 50\%$ (*dash-dotted line*). The *HST* data have been multiplied by a factor of 7.1/8.1 to bring the *HST* normalization at 0.6 $M_\odot$ into consistency with the one inferred from equation (1) (see Zheng et al. 2001, § 3.3). The simulated *HST* MF including the effect of unresolved companions is consistent at the less than 2 σ level with the observed one, the remaining discrepancy arising most likely from the MMR metallicity-dependent correction used in the *HST* analysis or from incompleteness of the observed samples at dim magnitudes. Surprisingly, the main difference between the reconstructed *HST* system MF and the local system MF (eq. [2]) occurs for the larger masses ($m \gtrsim 0.4\,M_\odot$). The reason is the Malmquist bias in the $1/V_{\max}$ method used in the present simulations and in GBF97 due to the saturation threshold of the *HST* camera, $I_{\min} = 18.75$, which excludes a nonnegligible fraction of the simulated stars. This bias, however, is corrected in the maximum likelihood analysis done by Zheng et al. (2001). The simulations for the *volume*-limited local sample are not affected by this bias and yield agreement between the simulated and system MF (eq. [2]) over the entire considered mass range.

4. CONCLUSION

In this Letter, we have derived the single and systemic MF for the Galactic disk in the M dwarf regime, from both the *V*- and *K*-band local LFs. Both determinations are well reproduced by a lognormal form, normalized at 1 $M_\odot$ on the value derived by Scalo (1986). We have shown that the disk stellar MF determined from either the nearby parallax LF or the *HST* photometric LF are consistent and that the previous source of disagreement was due to *two* cumulative effects, namely, (1) incorrect color-magnitude–determined distances in the original LF derived by GBF97, due to the fact that a large fraction of the *HST* M dwarf sample belongs to a metal-depleted population high above the Galactic plane, a point corrected in the recent analysis of Zheng et al. (2001), and (2) unresolved binaries in the *HST* sample.[3] We have shown that the *HST* MF is very similar to the local system MF. This latter is consistent with a fraction $X \sim 50\%$ of binaries, with masses for the primary and the companions determined by the same underlying aforementioned single MF. This yields roughly equal fractions of M dwarf and M dwarf BD systems, in agreement with present observations.

These results yield a reinterpretation of the so-called brown dwarf desert. This brown dwarf desert, expressing the deficit of small-separation BD companions to solar-type stars, as compared with stellar or planetary companions, has sometimes been interpreted as an IMF of substellar companions to solar-type stars significantly different from the one determined for the field. The present calculations, however, show that this desert should be reinterpreted as a lack of high mass ratio ($q \lesssim 0.1/1$) systems and does not preclude a substantial fraction of BDs as companions of M dwarfs or other BDs. Moreover, BD companions of stars, i.e., systems with large mass ratio, may form preferentially at large separations, requiring long-time basis for detection, as suggested by the recent analysis of Marchal et al. (2003). The present calculations and the ones developed in Chabrier (2001, 2002) suggest that stars, BDs, and companions originate from the same universal IMF (eq. [1]).

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[3] Multiple systems besides binaries will bring further correction. This, however, is likely to be small. Indeed, out of the known 39 M dwarfs within 5 pc, eight belong to binaries but only two to a triple system (Henry & McCarthy 1990).

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