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DETERMINATION OF THE LOW-MASS STAR MASS FUNCTION IN THE GALACTIC DISK

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ABSTRACT

We use the theoretical mass-luminosity relationship derived recently for low-mass stars (Chabrier, Baraffe, & Plez) to determine the lower end of the stellar mass function in the Galactic disk from observed luminosity functions. The age and metallicity spreads characteristic of the disk population are carefully examined. The mass function (MF) is shown to rise *monotonically* with decreasing mass and is reasonably well described by a power law $n(m) \propto m^{-\alpha}$ with $\alpha \approx 2 \pm 0.5$ from $\sim 0.6\ M_\odot$ down to the hydrogen-burning limit. Bimodal MFs, as derived in previous studies, are shown to be due to unresolved binaries in the photometric luminosity function, as suggested previously by Kroupa and coworkers. Such a rising MF suggests a substantial amount of brown dwarfs in the Galactic disk. The local density of main-sequence stars is found to be $\rho_* = 4.2 \pm 0.8 \times 10^{-2}\ M_\odot\ \mathrm{pc}^{-3}$, which corresponds to a surface density $\Sigma_* = 28.5 \pm 6\ M_\odot\ \mathrm{pc}^{-2}$, including the thick-disk contribution. The expected number of brown dwarfs is examined within the context of the OGLE and MACHO microlensing experiments. Although the contribution of brown dwarfs to the disk-mass budget is likely to be larger than previously thought, it still lacks in reproducing the observed optical depth.

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

1. INTRODUCTION

It has long been known that visible stars are not numerous enough to account for the dynamics of our Galaxy, yielding the so-called Galactic dark matter problem. Since it has never been established convincingly that the hydrogen-burning minimum mass (HBMM) *is* the mass limit for star formation (the fragmentation of a cloud into individual stars starts long before nuclear ignition), it is reasonable to consider brown dwarfs—objects not massive enough to sustain thermal equilibrium by hydrogen burning—as the most natural candidates to provide the sought-after hidden mass. Because of their intrinsically low luminosity, brown dwarfs are extremely difficult to detect with standard astronomical techniques and, although several very promising candidates have been proposed recently (Basri, Marcy, & Graham 1996; Rebolo, Martín, & Magazzù 1995), no genuine brown dwarf has been unambiguously identified yet, except maybe for Gliese 229B (Nakajima et al. 1995). This observational difficulty prompted Paczyński (1986, 1991) to suggest the so-called microlensing technique, i.e., the light amplification of a background star by a foreground dark object, to detect compact massive objects in the Galaxy. This idea was first applied to the detection of objects in the *halo* of the Galaxy, by the EROS (Aubourg et al. 1993) and MACHO (Alcock et al. 1993) collaborations, and then to the central part of the Galaxy, disk and bulge, by the OGLE (Udalski et al. 1994) and MACHO (Alcock et al. 1995) collaborations. The small number of events detected by the first set of experiments (MACHO plus EROS), too large to be explained by known stars in the disk (Gould, Miralda-Escudé, & Bahcall 1994), the spheroid, or the LMC itself (Bennett et al. 1996), yields a small (<50%) fraction of baryonic mass in the halo of the Galaxy (Alcock et al. 1995; Gates, Gyuk, & Turner 1995; Méra, Chabrier, & Schaeffer 1996). On the other hand, the MACHO and OGLE collaborations have monitored several billion bulge stars and discovered about 3 times more events than predicted by the standard galactic models (Udalski et al. 1994; Alcock et al. 1995). These two results from microlensing experiments—the lack of events in the halo and the excess of events in the bulge—lead to the natural conclusion that most of the Galactic dark matter, if it consists of very low mass stars and brown dwarfs, resides in the disk—a result that is in conflict with standard astronomical observations. This paradigm stresses the need to reconsider standard galactic models and to determine the contribution of substellar objects to the Galactic mass budget. A cornerstone used to address this problem is the derivation of a reliable stellar mass function (MF) near the HBMM.

In the present paper, we use the recently derived mass-magnitude relationships of Chabrier, Baraffe, & Plez (1996), which accurately reproduce the observations, to transform the *observed* luminosity functions (LFs) of the disk stellar population into characteristic MFs.

2. THE LUMINOSITY FUNCTION

The aforementioned observational difficulties for very low mass stars (VLMSs) lead to substantial discrepancies between the various observed LFs (Reid & Gilmore 1982; Gilmore, Reid, & Hewett 1985; Stobie, Ishida, & Peacock 1989; Tinney 1993; Kirkpatrick et al. 1994) at faint magnitudes, i.e., near the bottom of the mass distribution, whose exact behavior is still to be accurately determined. This dilemma has been solved by Kroupa and collaborators (Kroupa, Tout, & Gilmore 1993; Kroupa 1995a), who have shown convincingly that most of the discrepancies stem from incorrect Malmquist corrections and binary incompleteness. Kroupa (1995a), in particular, demonstrates that *photometric* LFs *underestimate* the number of low-mass stars near the low-mass end of the distribution ($M_V \gtrsim 12$). The difference arises essentially from unresolved binaries in the photometric samples (Kroupa 1995b), as suggested previously by Reid & Gilmore (1982). Correcting the photometric LFs for this incompleteness brings them into very good agreement with the *trigonometric*, nearby, LFs. Similar

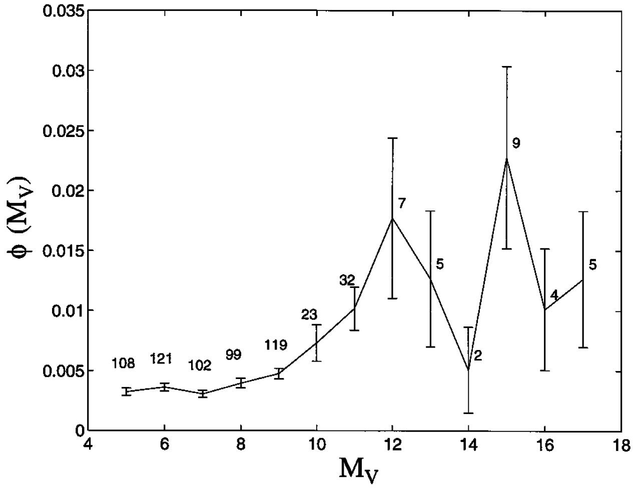

FIG. 1.—Kroupa (1995a) LF. Error bars are determined by Poisson law at 1 σ level. Indicated are the numbers of stars in each bin.

conclusions have been obtained recently by Reid, Hawley, & Gizis (1995). Note that this shortcoming of photometric LFs applies to the case of the *Hubble Space Telescope* (*HST*) (Gould, Bahcall, & Flynn 1995), whose LF is in good agreement with previously determined photometric LFs. Using an empirical mass-luminosity function (*M-L*) derived from observations of nearby binaries (Popper 1980), Kroupa and collaborators derived a power-law MF $n(m) \propto m^{-\alpha}$ with $\alpha \approx 1.3$ over the M-dwarf mass range down to $\sim$0.1 $M_\odot$. This result is in severe contradiction with previous estimates (Scalo 1986) that suggested a *bimodal* MF with a maximum around 0.2 $M_\odot$ (see, e.g., Tinney 1993). This problem, which bears essential consequences for our understanding of the Galaxy, in particular to estimate the brown dwarf contribution (and very existence!) to the Galactic mass budget, has been a subject of strong debate in the community for the past few years.

The aim of this Letter is to *derive* a consistent MF for VLMSs in the Galactic disk from theoretical models to determine (1) the shape of the MF near the HBMM, and verify which one of a monotonic or a bimodal behavior is supported by theory and observations, and (2) the maximum brown dwarf contribution to the disk mass. We stress the fact that, whereas the approach of Kroupa and collaborators, who first addressed this problem, is essentially *empirical* (based upon comparisons between a model and a fit of the observations), the aim of the present paper is to *demonstrate* those results from a consistent stellar evolution *theory*. We believe the two approaches to be complementary in assessing the issue of this important problem. We use the characteristic—most complete, as mentioned above—nearby LF derived by Kroupa (see Fig. 1 of Kroupa 1995a), which gathers all observed LFs (see references above). We also completed calculations based on the uncorrected photometric LFs to examine the effect of unresolved binaries on the MF. The Kroupa LF, plotted in Figure 1, rises for $M_V \leq 12$ and flattens above this limit. Given the limited number of stars in each bin for $M_V > 12$, and then the large statistical uncertainties, it seems reasonable to say that only *qualitative* information, e.g., the overall shape of the LF, can be determined with some confidence. Yet, as mentioned above, even such a qualitative determination is of prior importance (1) to infer the contribution of brown dwarfs to the Galactic disk mass budget and (2) to determine whether the maximum around $\sim$0.2 $M_\odot$ in the MF relies on physical grounds or is a simple artifact, an essential issue for stellar formation theory.

3. THE MASS FUNCTION

The derivation of an accurate *M-L* relationship near the low-mass end of the distribution is the cornerstone for the derivation of a reliable MF. Inaccurate *M-L* relationships will yield severely erroneous MFs from the observed LFs, leading to an incorrect determination of the mass and number density of brown dwarfs in the Galaxy.

Recently, Baraffe et al. (1995) have derived evolutionary models for VLMSs, based on *nongray* atmosphere models of Allard & Hauschildt (1995), which accurately reproduce the observed Population I and II VLMS sequences in M_V-$(V-I)$ diagrams (Monet et al. 1992). The related mass-radius-magnitude relationships accurately reproduce, for the first time, the observationally determined parameters of the eclipsing binaries CM Draconis ($m \approx 0.2$ $M_\odot$) and YY Geminorum ($m \approx 0.6$ $M_\odot$) (Chabrier & Baraffe 1995). These calculations have been improved recently by including the latest generation of nongray atmosphere models (Allard et al. 1996; Brett 1995a, b). The stellar evolutionary models based on these two different, independent sets of atmosphere models are in excellent agreement (Chabrier et al. 1996, hereafter CBP96). These results suggest that the uncertainties in the theory of VLMSs are now reaching an acceptable level and that reasonably reliable mass determinations can be obtained for given luminosities. Most importantly for the present study, the accuracy of the theoretical mass-M_V relationship derived from these most recent models has been assessed by comparison with the *observationally determined* relationship (Henry & McCarthy 1993), which extends the observations of Popper (1980) to lower masses, down to the HBMM. The theory reproduces accurately the observed relation over the entire M-dwarf mass range ($0.07 \leq M/M_\odot \leq 0.6$), down to the region where the luminosity drops drastically with decreasing masses, therefore probing the very end of the stellar mass distribution (CBP96). Such an agreement between theory and observation assesses the validity of the present mass-M_V relation to derive a MF from the observed $\phi(M_V)$ LFs.[1]

Figure 2 shows the MF derived from the LF of Kroupa, with the CBP96 mass-M_V relation for solar metallicity and an age $t = 10$ Gyr. The MF rises slowly in the mass range $m \sim 0.6$–0.2 $M_\odot$ ($M_V \lesssim 12$) and then steepens significantly near the HBMM. As shown on the figure, the MF is reasonably well described by a power law $dN/dm \propto m^{-\alpha}$ with a coefficient $\alpha \approx 2$ over the entire mass range. An excellent fit is obtained with $\alpha \approx 1.3$, as suggested by Kroupa and collaborators (Kroupa et al. 1993; Kroupa 1995a), in the range 0.6 to $\sim$0.25 $M_\odot$, and $\alpha \approx 2.5$ below. Although, as mentioned previously, the *exact* determination of the slope of the MF at the very end of the distribution requires larger statistics, it is likely to be bracketed between $\alpha \approx 1.3$ and $\alpha \approx 2.5$, as shown on the figure. In any case, these results strongly suggest that the VLMS MF *rises* substantially and *monotonically* from 0.6 $M_\odot$ down to the HBMM, so that we expect a substantial number of brown dwarfs in the Galactic disk. We stress that we obtain

[1] We stress that, although the V band is not the more appropriate passband for VLMSs, it does, however, provide reliable estimations of the luminosities and masses of VLMSs down to the HBMM (see, e.g., Monet et al. 1992; Henry & McCarthy 1993).

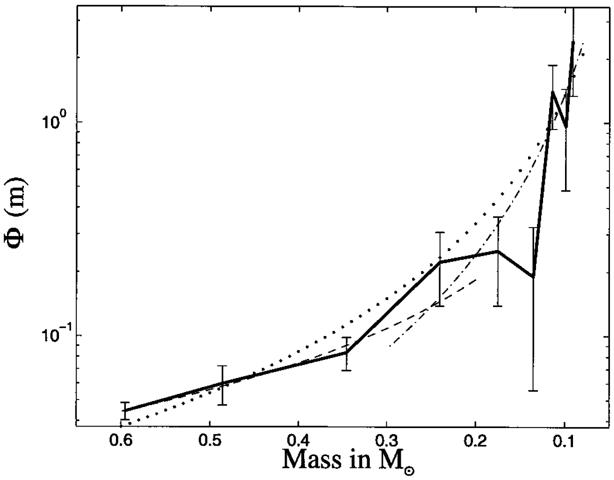

FIG. 2.—The MF derived from the LF of Fig. 1 with the CBP96 *M-L* relationship (*thick solid line*) for solar metallicity. Note that the two minima around 0.1 $M_\odot$, which correspond to $M_V = 14$ and 16, respectively, have the smallest statistics (two and four objects). Also shown are power-law MFs $dN/dm \approx m^{-\alpha}$ with $\alpha = 2.5$ (*dot-dashed line*), $\alpha = 2$ (*dotted line*), and $\alpha = 1.3$ (*dashed line*).

similar results with other LFs derived recently from complete samples (Reid et al. 1995). Figure 3 shows the MFs obtained from *photometric* LFs *uncorrected* for unresolved binaries, thus, *not* including the binary companions. The resulting MFs clearly exhibit a maximum around ~0.25 $M_\odot$ and then drop below this value. For 0.1 $M_\odot$, the difference between the correct and the photometric MFs is more than a factor of 10! This changes drastically—and erroneously—the insight on the distribution (and existence) of brown dwarfs and on star formation processes. These calculations demonstrate convincingly that a bimodal MF is the unphysical consequence of unresolved binaries in the photometric LF, as shown initially by Kroupa and collaborators (Kroupa, Tout, & Gilmore 1991, 1993), using empirically determined MFs.

Integration of the previously derived MF yields a contribution of M dwarfs to the local stellar mass density $\rho_{M*} = 2.1 \pm 0.7 \times 10^{-2}$ $M_\odot$ pc^{-3} for $0.55 \geq m \geq 0.1$ $M_\odot$. Adding the

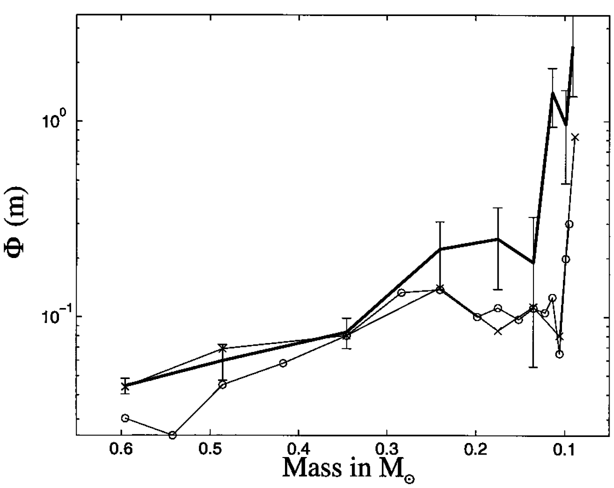

FIG. 3.—The same MF as in Fig. 2 (*thick solid line*) and the MFs obtained with the same *M-L* relation from the *photometric* LFs uncorrected for unresolved binaries (*circles*, Stobie et al. 1989; *crosses*, *HST* [Gould et al. 1995]) (For the sake of clarity, error bars are not shown for the photometric MFs.)

contribution from more massive stars, i.e., 0.02 $M_\odot$ pc^{-3} (Miller & Scalo 1979), we get a stellar local mass density $\rho_* = 4.1 \pm 0.7 \times 10^{-2}$ $M_\odot$ pc^{-3}, in very close agreement with the value of the Bahcall and Soneira model (see Bahcall, Flynn, & Gould 1992 and references therein). The surface density is obtained from the integration of the volume density along the direction perpendicular to the Galactic plane, assuming an exponential law with the scale height given in Table 1 of Miller & Scalo (1979). This yields $\Sigma_* = 24.0 \pm 5$ $M_\odot$ pc^{-2}. Including a thick disk with a local density equal to 4% of the thin-disk density and a scale height of 1000 pc (Gilmore, Wyse, & Kuijken 1989) yields a slightly larger stellar surface density of $\Sigma_* = 27.0 \pm 5$ $M_\odot$ pc^{-2}.

4. EFFECTS OF AGE AND METALLICITY

As mentioned above, the former MF has been obtained for solar metallicity and an age of 10 Gyr. Metallicity for disk stars ranges from about [M/H] = −0.5 to +0.5 (see, e.g., Leggett 1992). We conducted calculations for these three cases and verified that the present results remain qualitatively unaffected. Decreasing the metallicity yields essentially a steeper slope for the lowest masses (because of the larger HBMM). In other words, lower metallicities lead to a larger number of low-mass objects, below ~0.2 $M_\odot$, a direct consequence of the decreasing mass for a given luminosity for decreasing metallicity (see, e.g., CBP96). The MFs obtained within the aforementioned metallicity range remain bracketed by the values determined previously for the solar value.

We now discuss the influence of the age on the MF. Stars with $m > 0.08$ $M_\odot$ have all reached the main sequence (MS) after $t \sim 1$ Gyr (CBP96) and, for masses below ~0.6 $M_\odot$, will stay there for a Hubble time. Thus, the *M-L*, and then the aforedetermined MF, remain unaffected after 1 Gyr. This is not true for substantially younger objects that are still on the contracting pre-MS phase, which have larger luminosities than older stars for the same mass. This misidentification of low-mass contracting objects as more massive MS stars at the same luminosity yields an overestimation of the number of *massive* stars in the MF but does not significantly affect the bottom of the distribution. We verified that the *only* case that yields a *decreasing* MF near the end of the mass distribution corresponds to the (highly unrealistic) situation where *all* the stars are 0.1 Gyr old and *all* have a metallicity [M/H] = +0.5.

When considering the *maximum* age and metallicity dispersions, i.e., assuming that *all* stars have the aforementioned extreme ages and metallicities, the local stellar density ranges from 3.2×10^{-2} to 5.2×10^{-2} $M_\odot$ pc^{-3}. However, the assumption that all disk stars have [M/H] = +0.5 and are 0.1 Gyr old is unrealistic. A more realistic estimate is obtained with a constant stellar formation rate (90% of disk stars are then older than 1 Gyr) and an equidistribution in metallicity between −0.5 and +0.5 (see, e.g., Leggett 1992). This yields a local volume density of $4.2 \pm 0.8 \times 10^{-2}$ $M_\odot$ pc^{-3} and a surface density of 25.3 ± 6 $M_\odot$ pc^{-2}. Including the thick-disk contribution leads to a surface density of 28.5 ± 6 $M_\odot$ pc^{-2}, close to the values obtained in the previous section.

5. CONCLUSION AND DISCUSSION

We have derived the low-mass star MF characteristic of the disk stellar population from parallax-determined LFs, down to the hydrogen-burning limit. We stress the fact that this MF is derived from the recently determined mass-magnitude relationship for M dwarfs (CBP96), which accurately reproduces available observations and thus relies on a consistent stellar evolution theory, and on physical grounds. We examined the effect of the age and metallicity dispersion on the MF. Although the age effect is inconsequential, the metallicity substantially affects the low-mass end of the MF. The lower the metallicity, the larger the density of objects near the hydrogen-burning limit, a direct consequence of the increasing luminosity for a given mass with decreasing metallicity. The MF is found to exhibit a *monotonically increasing behavior* from 0.6 $M_\odot$ down to the hydrogen-burning limit. It is reasonably well described over the whole mass range by a power-law function $dN/dm \propto m^{-\alpha}$ with $\alpha \approx 2 \pm 0.5$. The previously suggested bimodal behavior, with a maximum around $\sim$0.2 $M_\odot$ and a drop near the HBMM, is shown to be an artifact due to the unresolved binaries in the photometric LF, as suggested initially by Kroupa et al. (1993).

Interestingly enough, the present MF for the Galactic disk is similar to the one derived recently for the Galactic *spheroid* (Méra et al. 1996). This bears important consequences for the distribution of dark matter in the Galaxy (Gates et al. 1995; Méra et al. 1996).

The local density of main-sequence stars, when taking into account both age and metallicity dispersions, is $\rho_* = 0.042 \pm 0.01$ $M_\odot$ pc^{-3}, and the corresponding surface density is $\Sigma_* = 25.3 \pm 6\, M_\odot$ pc^2. The brown dwarf contribution depends essentially on the minimum mass for starlike object formation for solar metallicity. Assuming this limit to be the minimum Jeans mass 0.01 $M_\odot$ (Silk 1977), as expected for the halo (Méra et al. 1996), we get a *maximum* ($m_{\rm inf} = 0.01$ $M_\odot$, $\alpha = 2.5$) brown dwarf mass density $\rho_{\rm BD} = 0.059$ $M_\odot$ pc^{-3} and number density $n_{\rm BD} = 3.0$ pc^{-3} in the solar neighborhood. A slope $\alpha = 2$ yields $\rho_{\rm BD} = 0.029$ $M_\odot$ pc^{-3} and $n_{\rm BD} = 1.3$ pc^{-3}. Therefore, the presence of brown dwarfs might solve the problem of dark matter in the disk between the two extreme cases proposed by Bahcall et al. (1992) on one side (about a factor 2 in the dynamical/visible local density, which corresponds to the maximum brown dwarf contribution obtained in the present calculations) and by Gilmore et al. (1989) or Bienaymé, Robin, & Crézé (1988) on the other side (*no* dark matter, and thus no brown dwarf). The whole issue depends on the minimum mass to which the MF can be extended, the determination of which is constrained by microlensing experiments.

The exact consequences for microlensing, and in particular the expected time distribution, are out of the scope of the present Letter and require detailed calculations that will be presented in a forthcoming paper. However, a first estimate can be derived easily. Adding the aforedetermined stellar and *maximum* brown dwarf contributions leads to a total local density for the disk of $\sim$0.1 $M_\odot$ pc^{-3}, i.e., an optical depth toward bulge $\tau \approx 1.3 \times 10^{-6}$. This corresponds to the most optimistic case calculated by Kiraga & Paczyński (1992). Therefore, although the contribution of disk brown dwarfs to the mass budget of the Galactic disk is likely to be larger than thought previously, it still lacks in reproducing the observed optical depth $\tau \approx 3.3 \times 10^{-6}$ by about a factor 2–3. This clearly favors the presence of a central bar to explain such an optical depth (Zhao, Spergel, & Rich 1995).

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