Observational evidence for a different IMF in the early Galaxy

Sara Lucatello[1,2], Raffaele G. Gratton [1], Timothy C. Beers[3], Eugenio Carretta [1,4]

ABSTRACT

The unexpected high incidence of carbon-enhanced, *s*-process enriched unevolved stars amongst extremely metal-poor stars in the halo provides a significant constraint on the Initial Mass Function (IMF) in the early Galaxy. We argue that these objects are evidence for the past existence of a large population of intermediate-mass stars, and conclude that the IMF in the early Galaxy was different from the present, and shifted toward higher masses.

Subject headings: stars: AGB and post-AGB — stars: binaries — Galaxy: stellar content — Galaxy: fundamental parameters

1. Introduction

The initial mass function (IMF) of stars has fundamental consequences for the evolution of stellar systems, influencing the processes of metal enrichment of the interstellar (and inter-galactic) medium, the expected mass-to-light ratios of individual galaxies and globular clusters, and the possible contribution of early-generation stars to re-ionization of the universe. Hence, it is quite important to determine the form of the IMF over a large range of physical conditions, in particular those typical of the very early evolution of galaxies, when the metal content was still quite low (less than 1% of the solar value).

Determination of the early IMF from first principles is difficult, primarily due to uncertainties related to the various processes involved in the fragmentation of clouds and protostellar collapse (e.g., cooling, heating, magnetic fields, turbulence, and rotation). A general

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[1] INAF, Osservatorio Astronomico di Padova, Vicolo dell'Osservatorio 5, 35122, Padova, Italy.

[2] Dipartimento di Astronomia, Università di Padova, Vicolo dell'Osservatorio 2, 35122, Padova, Italy.

[3] Department of Physics & Astronomy and JINA: Joint Institute for Nuclear Astrophysics, Michigan State University, East Lansing, Michigan 48824-1116.

[4] INAF, Osservatorio Astronomico di Bologna, via Ranzani 1, 40127, Bologna, Italy

expectation is that cooling is less efficient at low metallicities, leading to preferential formation of more massive objects (see, e.g., Bromm & Larson 2004), but large uncertainties still exist.

Observational determination of the IMF under conditions of very low metal abundance is hampered by the fact that, in our galaxy, stars more massive than the Sun that formed with [Fe/H] < -2.0 have already ended their nuclear burning phases, and are now faint collapsed objects such as white dwarfs, neutron stars, and black holes. Various authors (Ryu, Olive, & Silk 1990; Adams & Laughlin 1996, AL hereafter; Fields, Mathews, & Schramm 1997) have argued for an IMF that is peaked at intermediate masses for the metal-poor halo of our Galaxy. These claims are based on constraints derived from the number density of white dwarfs inferred from gravitational microlens experiments, coupled with those given at low masses by the present halo luminosity, and at large masses by nucleosynthesis limits. Such arguments are, however, still highly controversial (Fields, Freese, & Graff 2000; Gibson & Mould 1997; Méndez & Minniti 2000; Majewski & Siegel 2002).

Abia *et al.*(2001) set constraints on the early IMF on the basis of the large fraction of carbon-rich stars that have been discovered by modern surveys of extremely metal-poor (EMP) stars (*e.g.* Rossi, Beers, & Sneden 1999; Norris, Beers & Ryan 2000), and suggested that the IMF must have been biased toward higher masses in the early Galaxy. However, we emphasize that this result was based on then-incomplete knowledge of the statistics regarding the fraction of carbon-enhanced EMP (CEMP) stars, and in particular concerning their association with intermediate mass stars, hence the results obtained are highly uncertain.

While direct observations of the early IMF are very difficult (if not impossible) to obtain, one can search for evidence of their past existence with presently observable stars. Such evidence can in particular be seen in binary systems, where one of the components is a sub-solar-mass star, with a nuclear evolutionary timescale comparable to the age of our Galaxy, and the other was an intermediate-mass star (IMS; throughout this paper a star which undergoes the third dredge-up during its Asymptotic Giant Branch–AGB–phase and becomes a C-star) that has gone through all its nuclear phases, past its AGB stage, and is now a white dwarf. During the AGB phase the IMS burns He into C in flashes; between flashes, a restricted region within the star produces significant amounts of heavy elements via the *s*-process (Straniero *et al.* 1995). AGB stars have extended outer convective envelopes, and at the end of the flashes this convective envelope penetrates into the region where nuclear burning previously occurred, dredging up to the stellar surface large amounts of freshly produced carbon as well as heavy nuclei produced through the *s*-process (Iben & Renzini 1982).

When an IMS evolves beyond the AGB stage, the carbon- and *s*-process-rich envelope is lost to the interstellar medium through a slow wind. In a binary system the companion may be able to capture part of this envelope (either through direct mass transfer or accretion from the post-AGB wind of the IMS), and mix the nucleosynthesis products with its outer layers. The presently observed spectrum of the lower-mass companion of such a binary will still exhibit the unmistakable chemical signature of AGB processing that occurred in the IMS companion.

2. Carbon-enhanced, *s*-process-Rich, Metal-Poor Stars and IMF Constraints

The existence of carbon-rich binary systems among stars of solar composition is long established (McConnell, Frye, & Upgren 1972; Luck & Bond, 1991). They are called Barium stars at solar metallicities because of the presence of strong Ba II lines, and CH stars at [Fe/H]~ -1 , due to the strong CH bands in their spectra. These stars are also referred to as *extrinsic* carbon stars, because they owe their large carbon abundances to pollution from a companion, rather than to their own internal nucleosynthetic or mixing processes. About 1% of the stars in the Solar Neighborhood are classified as Ba or CH stars (McConnell, Frye, & Upgren 1972; Luck & Bond 1991).

The fraction of IMS in a population can hence be derived by the following simple formula, which takes into account the formation scenario of these objects:

$$f(IMS) = \frac{c(IMS)}{b \times p_{\rm eff}}. \tag{1}$$

The term c(IMS) represents the fraction of stars which had IMS companions with the appropriate separations to transform them into the presently observed C- and *s*-process enhanced stars, (*i.e.* a quantity directly inferred from observation). The term b is the binary fraction, which allows one to correct to the total population, and $p_{\rm eff}$ indicates the percentage of binaries with orbital separation suitable for mass accretion to take place.

We assume that about 60% of stars with solar metallicities are in binary systems (Jahreiß & Wielen 2000), independent of metallicity. To estimate the range of initial orbital periods for effective mass transfer, a few considerations are needed.

The lower limit to the range of orbital separations is set by considering that the stellar radius of the presumed donating companion should not exceed the Roche-lobe radius during its previous evolutionary phases (*e.g.*, the red-giant branch). This was derived adopting the Y2 isochrones (Yi, Kim, & Demarque 2003) at solar metallicity (period of ~ 0.3 days).

The upper limit of the component separations has been calculated by scaling that adopted for metal-poor stars (upper limit to the orbital period of 250,000 days, see below). In fact, the separation is expected to increase in inverse proportion to the square root of the required enrichment; the latter increases by a factor of $\sim$ 60 with respect to stars of solar metallicity. The stars which we are considering have a typical metallicity of about [Fe/H]$\simeq -2.5$, but are considered as carbon-rich stars only if their [C/Fe] is at least a factor of ten higher than the solar ratio. This should be contrasted with the factor of two enhancement that is often taken as a working definition of carbon-rich stars amongst solar-metallicity stars. Therefore, the upper limit to the period for solar metallicity stars is expected to be of order $\sim$13,000 days. The fraction of binaries satisfying this assumption (*i.e.* $0.3 \leq \mathrm{P} \leq 13{,}000$) is estimated from the period distribution of Duquennoy & Mayor 1991) and is about $\sim$37%. Substituting these values in Eq. 1, we obtain that $\sim$5% of solar-neighborhood stars were IMS. We assume that the masses of the two components are independent of one another (Kroupa 1995); the adopted mass range for IMS is between 1.5 and 6 $\mathrm{M}_{\odot}$. In fact, while at solar metallicity stars up to 8 $\mathrm{M}_{\odot}$ do undergo third dredge-up during their AGB phase, the objects in the upper end of this range (6 to 8 $\mathrm{M}_{\odot}$) have quite effective hot bottom burning. C is burnt into N and thus the stars become N-rich rather than C-rich (see *e.g.* Forestini & Charbonnel 1997, Marigo 2001 and Karakas 2003). Thus adopting a mass range between 1.5 and 6 $\mathrm{M}_{\odot}$ for the IMS and mass cutoffs of 0.1 and 125 $\mathrm{M}_{\odot}$ for the lower and upper end of the stellar masses, respectively, the Salpeter (1955) and Miller & Scalo (1979; M&S hereafter) IMFs predict that, respectively, $\sim$2% and $\sim$8% of Solar Neighborhood stars should be IMS. This quite good agreement found for Population I suggests that we might derive the fraction of IMS in the total stellar population (and hence obtain strong constraints on the IMF for all stars) by simply counting the fraction of *extrinsic* carbon-enhanced stars in a given sample. The rest of this paper exploits this method to constrain the IMF of the old, metal-poor population of the Galactic halo. Of course, the first challenge is to determine the fraction of the total population of CEMP stars that are in fact extrinsic, rather than intrinsic.

3. The Importance of CEMP-s stars

The fraction of carbon-rich stars, among stars that have not yet reached the AGB, is roughly constant down to a metallicity of a few percent of solar (McConnell, Frye, & Upgren 1972). However, a number of recent studies have indicated that the fraction of carbon-rich stars increases abruptly amongst EMP stars.

One of the most surprising results of the hitherto largest wide-field spectroscopic survey for metal-poor stars, the HK survey (Beers, Preston & Shectman 1992; Beers 1999), is the high frequency of carbon-enhanced stars found among very metal-poor stars (Rossi, Beers & Sneden 1999). This result has been confirmed by the Hamburg/ESO survey (HES; Christlieb

2003), which found that ∼25-30 % of the metal-poor candidates (with [Fe/H] < -2.5) appear to be carbon-enhanced stars. These unevolved CEMP stars could have a variety of origins; Lucatello et al. (2004, Paper I) discuss at least five possible classes of CEMP stars, the great majority of which, to date, appear associated with *s*-process enrichment. Aoki et al. (2003) have demonstrated that at least 70% of a sample of 33 CEMP stars in their study exhibit elements produced by the *s*-process, which we refer to as CEMP-s stars. As discussed in Paper I, it is quite likely that *all* the CEMP-s stars are members of binary systems. The straightforward interpretation is that 15-20% of EMP stars had IMS companions with the proper separations to transform them into presently-observed CEMP stars.

4. Derivation of the IMS fraction among EMP stars

Taken at face value, the large fraction of CEMP-s stars amongst the CEMP objects in the HK survey and HES suggests that a large number of IMS were present (as companions in binary system) within this population. However, when comparing this value with that obtained for more metal-rich stars, we must make a few assumptions, and consider several possible selection effects that could bias the determination.

4.1. Selection Effects

Temperature scale: Originally, both the HK survey and HES based their temperature scales on $B-V$ colors. Estimates of the metal abundances were obtained by comparing the strength of the Ca II K line with that predicted for stars of the estimated $B-V$ color. However, it is well known that the $B-V$ color is affected by the strength of the CH G-band (and other molecular carbon features), leading to an underestimate of $T_{\rm eff}$ in stars with strong bands. Therefore, a lower metallicity was assigned to carbon-enhanced stars, with respect to carbon-normal stars with identical atmospheric parameters. Hence, the parent population to be considered when comparing the frequency of carbon-enhanced stars was larger, including stars more metal rich than the usual limit for EMP stars. However, more recent results based on a considerable fraction of the HK survey data adopt $V-K$ colors, which are more appropriate $T_{\rm eff}$ indicators, as they are negligibly affected by the strength of the CH G-band. Using these colors, it has been obtained that *at least* 20% of the stars with [Fe/H]< -2.5 are carbon-enhanced, *i.e.* with a carbon-to-iron ratio obtained from intermediate-resolution spectroscopy of [C/Fe]$> +1.0$ (Beers et al. 2004, in preparation). We adopt this value in our discussion.

Luminosity effect: Carbon-enhancement, *per se*, does not affect the bolometric luminosity of a given star. However, the presence of strong molecular bands of CH and C_2 lowers the B flux (and, to a smaller extent, the V flux as well). Therefore, B- magnitude-limited surveys, such as the HK survey and the HES, will be biased against CEMP stars, given their lower luminosity in the B filter with respect to carbon-normal stars with the same abundance at the same evolutionary stage. This effect leads to a small *underestimate* of the CEMP fraction. In fact, the typical difference in B magnitude is of order ∼20%; the volume sampled for carbon-enhanced stars will then be smaller by ∼30% than that considered for carbon-normal stars. We do not take this effect into account in our analysis, but we remark that the adopted value is in fact a conservative one.

Carbon-enhancement selection effect: In order to be positively identified as carbon-enhanced star, we have adopted the criterion that a given star must display an overabundance of $[C/Fe]>+1.0$. Subgiants and RGB stars which are the surviving companions of a binary pair including an IMS have already undergone first dredge-up, thus diluting the accreted material in their convective envelopes. It is expected that such dilution could be as much as a factor of 20, with the net effect of decreasing the observed atmospheric carbon abundance[1]. Therefore, many of the evolved stars which, in their main-sequence phases, had a carbon overabundance well above the chosen threshold, dropped below this value after the first dredge-up episode, and are thus identified as carbon-*normal* stars rather than carbon-enhanced ones, affecting the measured fraction of the latter. Given their high luminosity, the evolved stars are expected to make up the majority of the sample in these surveys, thus this effect could be very important. In order to avoid this bias, the statistics should be limited exclusively to dwarf stars. Indeed, recent results from the Sloan Digital Sky Survey, e.g. Downes *et al.* (2004), have indicated that the number of dwarf carbon stars account about 60% of all high-latitude C stars. If it indeed proves to be the case that the dwarf carbon stars have their origin from mass transfer from an IMS companion, which we suspect is likely, the appropriate fraction of IMS may be substantially larger than the value adopted in the present discussion.

4.2. Assumptions

In making our calculations we are forced to adopt a number of assumptions, several of which are still not well constrained. We discuss these assumptions in detail below.

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[1] This is confirmed by the decrease of the Li abundance (see *e.g.,* Gratton *et al.* 2000; Spite et al. 2004)

Binary fraction: The binary fraction for EMP stars is still not well known. However, for slightly more metal-rich stars (e.g., [Fe/H] ~ -2.0) it is quite similar to that found for stars of solar metal abundance (see *e.g.* Carney *et al.* 2003; Zapatero-Osorio & Martin 2004). We will henceforth assume that the binary fraction is independent of metallicity, and adopt the binary fraction of Jahreiß & Wielen (2000), ∼60%.

Separation range: A metal-poor object is easily transformed into a carbon-rich star, since, given its low Fe content, even a moderate amount of processed matter accretion can produce the enhancement ([C/Fe]>+1) required to identify an EMP star as CEMP. Therefore, the range of (original) separations between components of a binary system that might be involved in the formation of such objects is larger, as discussed in Paper I. The lower limit on the range of component separations is set by considering that the stellar radius of the presumed donating companion should not exceed the Roche-lobe radius during its previous evolutionary phases (red-giant branch). We adopted this limit from the the Y2 isochrones (Yi, Kim, & Demarque 2003) at [Fe/H]=−2.5.

For the present purpose, we estimate that the range of initial orbital periods for CEMP-s stars ranges from $-0.65 \leq \log P \leq 5.4$ (*i.e.* 0.2 to 250,000 days). Given the discussion in Paper I , this is very likely an overestimate of the period range; however this can be considered as a conservative estimate for such an interval. Adopting the period distribution of Duquennoy & Mayor (1991), this period range includes 59% of all binaries. It is worth noting that, while this period range is not well determined, its accuracy is not crucial for our conclusion. In fact, the majority of binaries have separations within the useful range.

Mass range: The mass threshold for stars to become carbon-rich when on the AGB is likely to be smaller at lower metallicity. Fujimoto, Ikeda, & Iben (2000) argue that at metallicities below [Fe/H]~ -3.5, stars with masses as low as $0.8\,\mathrm{M}_\odot$ do indeed become carbon-enhanced in their AGB phase. However, the typical metallicity for our objects is of about [Fe/H]=−2.5, therefore we adopt $1.2\,\mathrm{M}_\odot$ as a more realistic lower limit for our sample (Lattanzio 2003, private communication).

The maximum mass for the third dredge-up during the AGB is expected to increase with decreasing metallicity. However, the upper limit to the mass for becoming a C-star does decrease with metallicity, possibly reaching values as low as ∼3-4 for EMP stars (see Karakas 2003 and references therein). Keeping this in mind, we adopt as our definition of IMS at low metallicity stars with masses in the range 1.2 to 6 $\mathrm{M}_\odot$, noting that this is a *conservative* estimate.

When all of the above factors are taken into account, substituting the adopted values into Eq. 1, *i.e.*, $c(IMS) = 14\%$, $b = 60\%$ and $p_{\rm eff} = 59\%$, we find that the fraction of IMS companions amongst EMP stars is 40%, a factor of eight larger than for solar-metallicity stars. Even if we assume the most conservative scenario, wherein the binary fraction of EMP stars is 100%, and demand that all IMS in binaries produce a carbon-rich companion (irrespective of the initial system separation), the derived fraction of IMS among EMPs is 14%. The expected fraction of IMS, adopting a M&S IMF is ∼10%, smaller than this (conservative) lower limit[2] . This result seems to favor an IMF peaked at IMS for low-metallicity stars, as put forward by AL.

Let us now assume for the IMF a log-normal form,

$$\ln f(\ln m) = A - \frac{1}{2 < \sigma >^2}[\ln(\frac{m}{m_c})]^2 \tag{2}$$

where $f = \frac{dN}{d\ln m}$. This general form for the IMF is motivated by star- formation theory and by general statistical considerations (Larson 1973; Elmegreen & Mathieu 1983; Zinnecker 1984; Adams & Fatuzzo 1996; Adams & Laughlin 1996). This form for the IMF is also sufficiently flexible to assume a wide variety of behaviors. The parameter A gives the overall normalization of the distribution; m_c is the mass scale, in solar masses, and sets the center of the distribution, while the dimensionless parameter $< \sigma >$ is the width of the distribution. Fitting such a function to our results, we obtain values of 1.18 and 0.79 $M_\odot$ respectively, for $< \sigma >$ and m_c. The corresponding values for the M&S IMF are $< \sigma > \simeq 1.57$ and m_c =0.1 $M_\odot$, while AL found, respectively, 0.44 and 2.3 $M_\odot$.

As can be noted from inspection of Figure 1, which compares the three above mentioned IMF's, as well as from the simple comparison of the curve parameters, the IMF derived by fitting our results is not very different from that of M&S, showing basically a simple shift of the mass peak. On the other hand, the shape of the AL IMF is peaked at much larger mass, and the mass range for which the distribution function is not negligible is much narrower. We do *not* claim that the IMF obtained by our fitting is an actual prediction of the early IMF; in fact we do not have any direct information about high mass stars. However, we point out that, in order to perform the fit we assumed the same mass cutoffs as the M&S IMF, *i.e.*, that the fraction of high-mass stars formed is almost negligible.

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[2] If the lower end of the IMS range is set to 0.9 $M_\odot$, the M&S IMF predicts the *lower* limit of IMS derived from the data. However, models do not expect such low values for the typical metallicity ([Fe/H]=−2.5) of our sample, see *e.g.* Fujimoto, Ikeda & Iben (2000)

5. Discussion

The primary objection against the existence of a large population of IMS in the early Galaxy, including stars with metal abundances up to [Fe/H]=-2.0, is the very large predicted production of carbon (Gibson & Mould 1997; Fields, Freese, & Graff 2000). However, this objection does not apply to the EMP stars, which comprise at most a few percent of the total halo population. In fact, the EMP IMS contributed to the Galactic metal enrichment only at the end of their nuclear-burning lives. Stars born with metallicities [Fe/H]≈ -3 enrich the ISM after a time ranging from 1.5 Gyr (1.5 $M_\odot$) down to 100 Myr (6 $M_\odot$) (Girardi *et al.* 1996). At $\sim 10^8$ years, the metal abundance of the interstellar medium is likely to have been elevated to about [Fe/H]=-1.5 (Prantzos 2003), possibly reaching a metal abundance as high as [Fe/H]=-1.0 (Chiappini, Romano, & Matteucci 2003). A shift in the peak mass of the IMF also likely affects slightly larger mass stars, such as those those with masses 6-8 Mo, which have shorter lifetimes (a few 10^7 years for a metallicity of [Fe/H]$\simeq -3$, Girardi *et al.* 1996) and thus could in principle have an impact on the chemical composition of the other EMP stars. We do not have information about the mass distribution within the IMS range, however it is quite likely that the fraction of stars slightly more massive than IMS, although probably larger than among presently forming stars, was still very small and thus their effect on the ISM composition quite limited.

It is noteworthy that, the lower the metallicities, the shorter the nuclear burning lifetimes of IMS stars (see Chieffi *et al.* 2001), thus in principle, stars with metallicities lower than about [Fe/H]≤ -3.5 could contribute early on in the Galactic chemical evolution. Moreover, an early IMF biased toward larger masses could also have an impact on the white dwarf fraction, and thus on the SN Ia rate in the early Galaxy, which in turn affects chemical evolution. However, when considering these effects, it is important to keep in mind that EMP stars account for only a very small fraction of the stellar content of the Galaxy, therefore a moderate shift of the early IMF towards higher masses should have a small impact on Galactic chemical evolution. Hence, it is expected that:

- i EMP IMS have likely not contributed significantly to the presently observed elemental compositions of other EMP stars, except for the outer envelopes of their companions in binary systems
- ii The effect of EMP IMS on more metal-rich stars is diluted due to the contribution of the much larger population of moderately metal-poor ([Fe/H]~ -1.5) stars born from a “conventional” IMF

In order to properly assess the effect of an IMF biased toward higher masses on the chemical evolution of the Galaxy, calculation of an accurate chemical evolution model would be necessary, which is beyond the scope of the present paper.

An interesting consequence of the bias of the early IMF toward stars of higher mass regards globular clusters (GC, hereafter). In fact, a GC forming with this IMF would soon undergo large loss of gas from the system due to a population of IMS. This gas could either result in the formation of new stars, be captured by a pre-existing black hole in the cluster, or be lost to the ISM. The first two hypotheses appear to be ruled out based on observations. There is no sign of enrichment by s-process elements in GCs (with the exception of ω-Cen, which is, however a quite unusual case), and there is no evidence for the presence of black holes in GCs with a mass comparable to that that expected to be lost by the IMS population (see, *e.g.*, Gerssen *et al.* 2003). Therefore, the only remaining possibility is that the material shed from the IMSs is ejected into the ISM. This mass loss would have clear consequences on the GC potential well, and eventually lead to the disruption of the cluster itself. This could be the reason why there are no GCs at metallicities lower than [Fe/H]=-2.5, and very few below -2 dex.

6. Concluding remarks

Our results indicate that the IMF of stars formed at early times in the evolution of the Galaxy was different from that observed at present. In these early epochs stars more massive than the Sun formed far more frequently than now. *This is the first direct observational evidence that the IMF of stars is not universal over time, lending support to the idea that the first generations of stars included a substantial number of objects with very high mass.*

This result, based on local samples of halo stars with well-measured elemental abundances, provides stringent constraints on theoretical work aimed at deriving the early IMF, as well as the interpretation of the abundance patterns in distant objects such as those responsible for the Ly-α forest systems (e.g., Songaila 2001; Pettini *et al.*2003).

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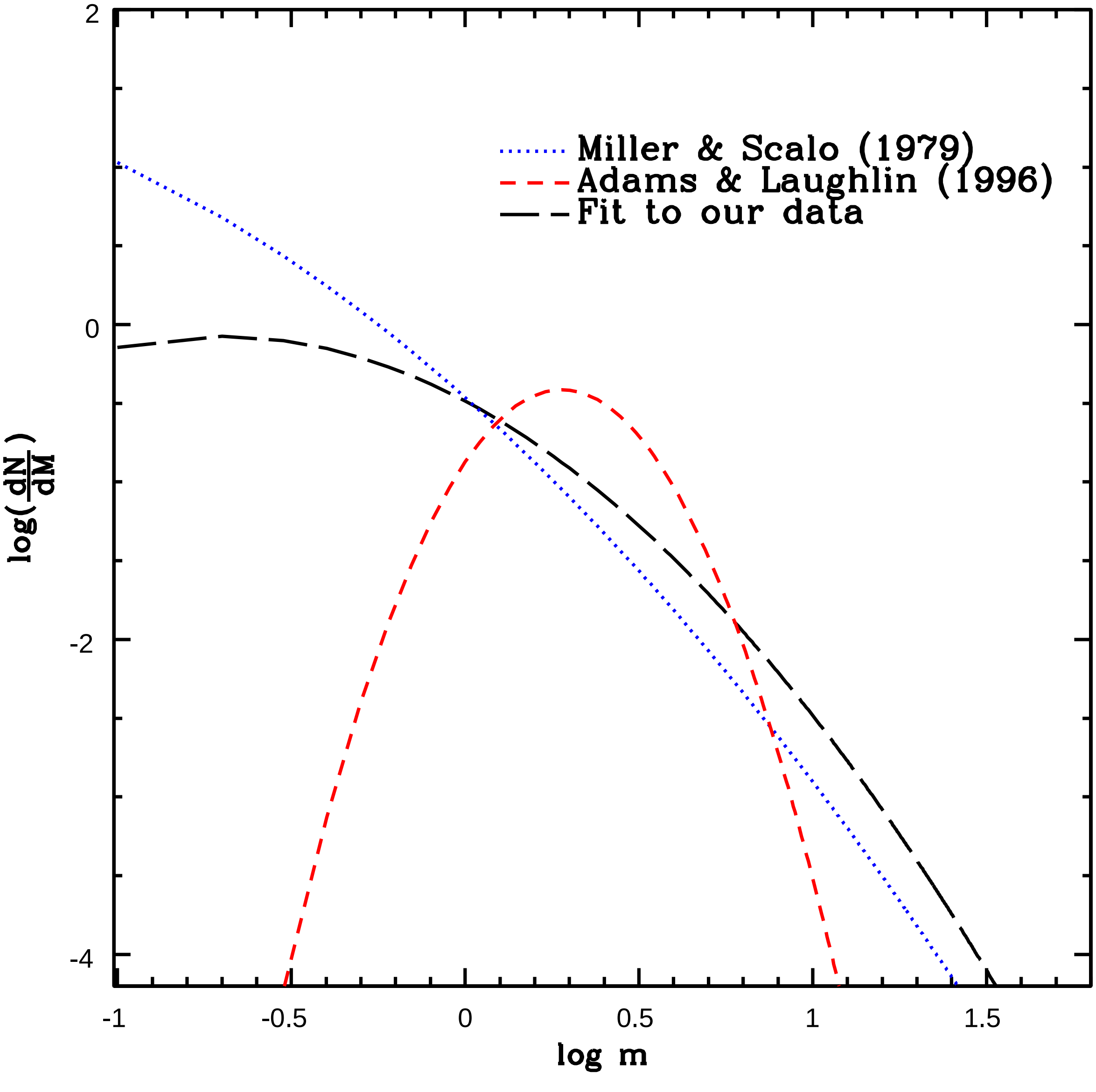

Fig. 1.— Comparison of the IMF obtained assuming a log-normal form and fitting the measured IMS fraction (see text) with those for M&S and AL (1996).