THE INITIAL MASS FUNCTION IN DISC GALAXIES AND IN GALAXY ClUSTERS: THE CHEMO-PHOTOMETRIC PICTURE

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Abstract
The observed brightness of the Tully-Fisher relation suggests a low stellar M/L ratio and a “bottom-light” IMF in disc galaxies, but the corresponding efficiency of chemical enrichment tends to exceed the observational estimates. Either suitable tuning of the IMF slope and mass limits or metal outflows from disc galaxies must then be invoked.

A standard Solar Neighbourhood IMF cannot explain the high metallicity of the hot intra-cluster medium: a different IMF must be at work in clusters of galaxies. Alternatively, if the IMF is universal and chemical enrichment is everywhere as efficient as observed in clusters, substantial loss of metals must occur from the Solar Neighbourhood and from disc galaxies in general; a ”non-standard” scenario challenging our understanding of disc galaxy formation.

1. The M∗/L ratio and the IMF in disc galaxies

Cosmological simulations of disc galaxy formation show good agreement with the observed Tully-Fisher relation, provided the mass–to–light ratio of the stellar component is as low as M∗/L_I = 0.7–1; a low M∗/L is as well derived when locating onto the Tully–Fisher relation real disc galaxies of known stellar mass, such as the Milky Way or NGC 2841 (Fig. 1; Sommer-Larsen et al. 2003; Portinari et al. 2004a, hereinafter PST). Several other arguments support a low M∗/L in spiral galaxies:

Based on bar instability arguments, Efstathiou et al. (1982) suggest an upper limit of M/L_B ≤ 1.5 h for discs, i.e. M/L_B ≤ 1 for h=0.7 (h indicates the Hubble constant H_0 in units of 100 km sec^{-1} Mpc^{-1}).

The stellar M∗/L is also related to the “maximality” of discs, i.e. to whether they dominate or not the dynamics and rotation curves in the inner galactic regions. For his favoured sub–maximal disc model, Bottema (2002) finds M∗/L_I ≈ 0.82; and even assuming maximal stel-
Figure 1. Observed Tully–Fisher relation for Sbc–Sc spirals (Dale et al. 1999; $h=0.7$), assuming different $M_*/L_I$. Triangles: simulated galaxies; full dots: Milky Way and NGC 2841.

Figure 2. I–band M/L ratio at varying $b$–parameter of the SFH, for different IMFs. The red shaded area marks the range $M_*/L_I=0.7$–1 observed for Sbc–Sc discs ($b=0.7$–1).

lar discs, lower $M_*/L$ ratios are required than those predicted by the Salpeter Initial Mass Function (IMF)$^1$ (Bell & de Jong 2001).

Finally, recent dynamical studies of individual galaxies yield $M_*/L_I\sim1$ in B, V, I for the Sc NGC 4414 (Vallejo et al. 2002) and $M_*/L_I=1.1$ for the disc of the Sab 2237+0305 (Huchra’s lens, Trott & Webster 2002).

The $M_*/L$ ratio of the stellar component of a galaxy, including both living stars and remnants, depends on the stellar IMF and on the star formation history (SFH) of the system.

IMF. Ample observational evidence in the Solar Neighbourhood, in globular and open clusters, and in the Galactic bulge show that the IMF presents a bend-over below $\sim1M_\odot$, and is “bottom–light” with respect to a single–slope Salpeter IMF (see the reviews by Scalo, Chabrier, Zoccali and De Marchi in this conference). A bend–over is expected as well from theory (see Session III in this conference).

In this paper, we consider the following IMFs: the “Salpeter” IMF (in the sense of footnote 1); the Kroupa (1998) IMF, derived for field stars in the Solar Vicinity; the Kennicutt IMF, derived from the global

$^1$Criticism of the Salpeter IMF is quite unappropriate in a conference held in honour of Ed Salpeter himself. Let me thus underline, that criticized in this paper is not the original result by Salpeter (1955), who derived the IMF slope between $[0.4–10] M_\odot$; but rather what has become in literature the default meaning of “Salpeter IMF”: a power law with Salpeter slope, extending over $[0.1–100] M_\odot$. 
properties of spiral galaxies (Kennicutt et al. 1994); the Chabrier (2001, 2002) IMF, derived from observations of local low mass stars and brown dwarfs. (Further cases are discussed in PST.) With respect to Salpeter, the other IMFs are “bottom–light”; at the high mass end, slopes range between the Salpeter \((x = 1.35)\) and the Scalo one \((x = 1.7)\).

**SFH.** The sequence of Hubble spiral types is a sequence of different SFHs in the discs, traced by the birthrate parameter \(b = \frac{SFR}{<SFR>}\) i.e. the ratio between the present and the past average star formation rate (SFR). The observational Tully–Fisher relation in Fig. 1, indicating \(M_\ast/L_I=0.7–1\), refers to Sbc–Sc spirals whose “typical” SFH corresponds to \(b=0.8–1\) (Kennicutt et al. 1994; Sommer–Larsen et al. 2003).

In PST we computed chemo–photometric models for disc galaxies predicting the \(M_\ast/L_I\) ratio for different IMFs, as a function of \(b\). Fig. 2 shows that, while the Salpeter IMF yields far too high \(M_\ast/L\), the other “bottom–light” IMFs do yield the observed \(M_\ast/L_I=0.7–1\) for late–type spirals \((b = 0.8–1)\), which agrees very well with our present understanding of the shape of the IMF at the low–mass end.

As to the implications for chemical evolution, some “bottom–light” IMFs (e.g. Kennicutt and Chabrier) are too efficient in metal production, as is evident from the gas fractions predicted by the models, far larger than observed (Fig. 3b): metal enrichment is so efficient that the models reach the typical metallicities of spirals without much gas processing.

This excessive metal production is readily understood since the enrichment efficiency of a stellar population, or its “net yield”:

\[
y = \frac{1}{1-R} \int_{M_i}^{M_s} p_z(M) \Phi(M) dM
\]

is inversely proportional to the mass fraction 1–\(R\) that remains forever locked in low–mass stars and remnants: for bottom–light IMFs the locked–up fraction tends to be small. The yield can be reduced by reducing the number of the massive stars responsible for the bulk of the metal production, i.e. by tuning the upper mass limit (triangles in Fig. 3) or by a steep slope at the high-mass end: for example, the Kroupa IMF is bottom-light but it does not overproduce metals due to the steep Scalo slope above \(M = 1 M_\odot\) (see PST). A steep slope for the integrated field stars IMF is expected, in fact, if stars form in clusters of finite size from an intrinsically shallower IMF (Kroupa & Weidner 2003).

Alternatively, we need to invoke substantial outflows of metals from disc galaxies into the intergalactic medium, to reconcile the high enrichment efficiency with the observed metallicities and low gas fractions. This behaviour would be reminiscent of that of elliptical galaxies, responsible for the enrichment of the hot gas in clusters of galaxies.
2. The IMF in clusters of galaxies

Can a “standard” Solar Neighbourhood (SN) IMF account for the observed level of metal enrichment in clusters of galaxies? We can qualitatively address this question by comparing the respective “effective” yield $y_{\text{eff}}$, obtained as the ratio between the metals globally contained in the system and the mass in living stars and remnants; this is the observational counterpart of the theoretical yield $y$ in Eq. 1:

$$y_{\text{eff, SN}} = \frac{Z_\odot \times M_\star + Z_{\text{gas}} \times M_{\text{gas}}}{M_\star} \sim \frac{Z_\odot \times M_\star + Z_\odot \times (0.2 M_\star)}{M_\star} = 1.2 Z_\odot$$

$$y_{\text{eff, cl}} = \frac{Z_\odot \times M_\star + Z_{\text{ICM}} \times M_{\text{ICM}}}{M_\star} \sim \frac{Z_\odot \times M_\star + 0.3 Z_\odot \times (5 - 10 M_\star)}{M_\star} = 2.5 - 4 Z_\odot$$

The estimated metal enrichment efficiency in clusters is thus about 3 times larger than in the SN, and the chemical evolution of clusters is often modelled with non-standard IMFs (Portinari et al. 2004b, hereinafter PMCS; and references therein). On the other hand, the following arguments are often given in favour of a universal standard IMF: the Iron Mass–to–Light Ratio (IMLR) in clusters agrees with the predictions of...
the Salpeter IMF, and the observed \([\alpha/Fe]\) ratios in the ICM are compatible with those in the SN (Renzini et al. 1993; Renzini 1997, 2004; Ishimaru & Arimoto 1997; Wyse 1997).

In PMCS we demonstrated that a “standard” IMF (e.g. the Kroupa IMF) which reproduces the chemical properties of the SN, is unable to enrich the ICM to the observed levels. For a Single Stellar Population (SSP) we computed the rate of supernovae of type II and type Ia, and the corresponding production of metals in time (Fig. 4b); the ratio between these and the evolving luminosity (Fig. 4c) gives the global IMLR\(_{SSP}\), SiMLR\(_{SSP}\) etc. relevant to the chosen IMF (Fig. 4d). Not all of the metals produced contribute to the ICM enrichment: a non-negligible fraction must be locked-up by subsequent stellar generations to build up the observed stellar metallicities \(Z_*\) of cluster galaxies. The amount of metals locked in the stellar component must be \(M_{Z_*} = Z_* \times (1 - R)\), where \(1 - R\) is the locked-up fraction consistent with the adopted IMF (Fig. 4a). Once the metals produced are properly partitioned between the stars and the ICM, it is evident that a standard IMF such as the Kroupa IMF cannot possibly reproduce the observed IMLR and SiMLR in the ICM (Fig. 4e,f): it does not match the global amount of metals observed in the ICM and it predicts significantly sub-solar \([\alpha/Fe]\) ratios, at odds with observations (Fig. 4g). Henceforth, observing solar \([\alpha/Fe]\) ratios in the ICM per se does not suffice to conclude that the same IMF is at play in both environments.

In Fig. 4d we also compare the global IMLR\(_{SSP}\) for the Kroupa and the Salpeter IMF. The latter is about twice more efficient in metal production, and is known to be too efficient to reproduce the SN (PST, PMCS and references therein; Romano, this conference); henceforth, though matching the IMLR in the ICM, it is not the same IMF as in the Milky Way. Besides, the Salpeter IMF (in the sense of footnote 1) fails at reproducing the observed \(\alpha\)MLR in the ICM, also predicting significantly subsolar \([\alpha/Fe]\) ratios in the ICM (Matteucci & Vettolani 1988; Renzini et al. 1993; Pipino et al. 2002; PMCS).

3. Conclusions

A “standard” IMF suited to model the chemical evolution of the Solar Neighbourhood cannot account for the observed metal enrichment in clusters: either the IMF differs between the two environments, or the local IMF has a much higher yield than usually assumed. The latter option is in line with some of the “bottom-light” IMFs advocated in §1 to reproduce low disc \(M_*/L\) ratios. In this case, disc galaxies must disperse much of the metals they produce into the intergalactic medium, just
like early type galaxies in clusters. However, substantial outflows would challenge our understanding of disc galaxy formation: disc star formation proceeds at a smooth, non burst–like pace and the observed “fountains” and “chimneys” do not have enough energy to escape the galactic potential; winds are far less plausible than from spheroids. Moreover, strong ongoing stellar feedback and outflows could significantly hamper the dynamical formation of galactic discs from the cool–out of halo gas.

The alternative scenario is a variable IMF with a higher yield in clusters than in disc galaxies. The IMF may vary after Jeans–mass dependence on redshift, and its variation should be more significant than expected from the increasing temperature of the cosmic background (e.g. Chabrier, this conference; Finoguenov et al. 2003; Moretti et al. 2003 and references therein); or, the IMF may be a universal function within star clusters, but generating statistically more high–mass stars in larger star clusters and in regimes of intense star formation like in massive ellipticals (Kroupa & Weidner 2003).

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