Mass–to–Light ratio, Initial Mass Function and chemical evolution in disc galaxies

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Abstract

Cosmological simulations of disc galaxy formation, when compared to the observed Tully–Fisher relation, suggest a low Mass–to–Light (M/L) ratio for the stellar component in spirals. We show that a number of “bottom–light” Initial Mass Functions (IMFs) suggested independently in literature, do imply M/L ratios as low as required, at least for late type spirals (Sbc/Sc). However the typical M/L ratio, and correspondingly the zero–point of the Tully–Fisher relation, is expected to vary considerably with Hubble type.

Bottom–light IMFs tend to have a metal production in excess of what is typically estimated for spiral galaxies. Suitable tuning of the IMF slope and mass limits, post–supernova fallback of metals onto black holes or metal outflows must then be invoked, to reproduce the observed chemical properties of disc galaxies.

Keywords: Galaxies: spirals, chemical and photometric evolution; stars: Initial Mass Function

Figure 1: Straight lines: observed Tully–Fisher relation for Sbc–Sc disc galaxies (Dale et al. 1999; h=0.7 adopted here), for different assumptions about the stellar M/L ratio. Triangles: simulated galaxies by Sommer–Larsen et al. (2003). Also shown is the location of the Milky Way and NGC 2841.

1 Introduction

Recent N–body+SPH cosmological simulations of the formation of disc galaxies reproduce the observed Tully-Fisher (TF) relation (Dale et al. 1999), provided the mass–to–light (M/L) ratio of the stellar component is rather low, M/L\textsubscript{I}=0.7–1 in the I–band (Sommer-Larsen & Dolgov 2001; Sommer-Larsen et al. 2003; Fig. 1). The location of the simulated galaxies in the (M\textsubscript{*, V\textsubscript{c}}) plane of Fig. 1 is quite independent of the adopted Initial Mass Function (IMF) or feedback efficiency: the baryonic mass that cools out to form a galactic disc and its resulting circular velocity correlate so that data points tend to move along the TF relation, hardly affecting the zero–point (Navarro & Steinmetz 2000ab). However, the IMF is crucial for the M/L ratio, to translate the stellar masses M\textsubscript{*} to luminosities and compare the simulated TF relation to the empirical one.

Although the zero–point of the simulated TF may change with the concentration of the dark matter halos, and hence with the normalization of the power spectrum \sigma_8 (Navarro & Steinmetz 2000ab; Eke et al. 2001), many other arguments support a low stellar M/L ratio in spiral galaxies:

The stellar mass of the Milky Way is M\textsubscript{*} \approx 5 \times 10^{10} M_{\odot}; to lie on the observed TF relation as other spirals, its M/L\textsubscript{I} must be \lesssim 1 (Sommer-Larsen & Dolgov 2001; Fig. 1). A low M/L\textsubscript{I} < 0.8 is also derived for the massive Sb galaxy NGC 2841, when compared to the observed TF relation (Portinari et al. 2004a, hereinafter PST; Fig. 1).

Based on bar instability arguments, Efstathiou et al. (1982) suggest an upper limit of M/L\textsubscript{B} \leq 1.5 h for discs, i.e. M/L\textsubscript{B} \lesssim 1 for h=0.7. (h indicates the Hubble constant H\textsubscript{0} in units of 100 km sec\textsuperscript{-1} Mpc\textsuperscript{-1}).

The stellar M/L ratio is related to the issue as to whether discs are maximal or sub–maximal, i.e. as to whether they dominate or not the dynamics and rotation curves in the inner galactic regions. Even in the case of maximal stellar discs, lower M/L ratios for the stellar component are required, than those predicted by the Salpeter IMF (Bell & de Jong 2001). And it is still much debated whether discs are maximal or sub–maximal; for his favoured sub-maximal disc model, Bottema (2002) finds M/L\textsubscript{I} \sim 0.82.

Finally, two recent dynamical studies of individual spiral galaxies yield M/L\textsubscript{I}~1 in the B, V and I band for the Sc galaxy NGC 4414 (Vallejo et al. 2002) and M/L\textsubscript{I}=1.1 for the disc of the Sab spiral 2237+0305, Huchra’s lens (Trott & Webster 2002).

In this paper we discuss if M/L ratios so low are compatible with our understanding of stellar populations and chemical evolution in disc galaxies. We also address the effects of different star formation histories on the TF relation for different Hubble types.

2 Star Formation History and Initial Mass Function

The M/L ratio of the stellar component of a galaxy (including both living stars and remnants) depends on the stellar
these values for trate our discussion on objects with SFHs corresponding to \( M \) over the mass range \([0.1–100]\) with respect to the Salpeter IMF.

A turn–over at low masses, and hence is "bottom–light" evidence that the IMF flattens below \( (\text{Fig. 4, top left}) \). There is however plenty of observational evidence that the IMF cut–off at low masses as favoured by recent determinations \((\text{Chabrier} 2001, 2002)\) and of \( 0.1 \)–\( 1 \) for late–type spirals, though one probably needs slightly “lighter” IMFs than the local Kroupa one.

4 Offsets of the TF relation with Hubble type

From Fig. 4, the stellar M/L ratio is expected to vary with Hubble type due to the differences in SFH parameterized by \( b \). This effect implies systematic offsets with Hubble type of the luminosity zero–point of the TF relation \((\text{Rubin et al. 1985; Giovanelli et al. 1997; Kannappan et al. 2002})\).

Fig. 5 shows the M/L ratio as a function of \( b \), normalized to the value corresponding to \( b=1 \). The scale on the right axis indicates the corresponding shift in magnitude. With respect to Sb/Sc spirals, we predict a systematic offset of \( 0.3–0.4 \) mag for Sb's \( (b ∼0.35) \) and of \( 0.6–0.8 \) mag for Sa/Sab's \( (b ∼0.1) \), as a result of the different characteristic SFHs. These offsets are only slightly reduced when bulges are added to discs in the computation of the total M/L ratios of galaxies \((\text{PST})\). The offsets we predict are larger than the empirical ones found by \( 0.1 \) mag for Sb spirals and \( 0.32 \) mag for earlier types. However, the extent of the observed offsets in the TF relation is still a matter of debate: for instance, the larger offsets found by \( 0.76 \) mag for Sa's, are in good agreement with our predictions.

The characteristic SFH of a galaxy is traced by its colours, so that the offsets in M/L ratio due to different SFHs can be corrected for, by applying suitable M/L vs. colour relations \((\text{Bell & de Jong 2001; PST})\).
5 Bottom–light IMFs and chemical evolution

Besides simple models with exponentially declining SFHs, we also computed more realistic, multi-zone chemo-photometric models of galactic discs, including infall, inside–out formation and radially varying star formation efficiency. Chemical evolution is followed with the code by Portinari et al. (1998), Portinari & Chiosi (1999) and the models are calibrated to reproduce the typical metallicity and metallicity gradient of Sbc/Sc discs (PST). Six sets of models have been computed for the six IMFs in §2. The corresponding photometric properties are calculated by convolving the SFH and metal enrichment history of each annulus of the disc, with a grid of SSPs of metallicities between $5 \times 10^{-4} Z_{\odot}$ and $5Z_{\odot}$ (PST).

For each IMF, the chemo-photometric models confirm the M/L ratios predicted, as a function of $b$, by the simple models in Fig. 4; see the example for the Kennicutt IMF models in Fig. 6, top panel. The results of §3 are thus confirmed: the “bottom–light” IMFs considered here imply $M/L_I <1$ for Sbc/Sc spirals, as required in §1. This conclusion remains valid also when the contribution of the bulge to the global M/L ratio is included (PST).

Chemo-photometric models allow also an insight on the implications of “bottom–light” IMFs for chemical evolution. Some of the IMFs considered (Kennicutt, Larson and Chabrier) are too efficient in metal production to reproduce the observed properties of spirals. In particular, the resulting gas fraction is much larger than the observed $M_{\text{gas}}/L_B \sim 0.5 M_{\odot}/L_{\odot}$ (solid dots in Fig. 6, bottom panel). For a given IMF and corresponding metal production, the final gas metallicity predicted by chemical models increases at decreasing gas fraction (Tinsley 1980, Pagel 1997). Our models, calibrated to reproduce the observed metallicities, tend to predict too high gas fractions. Conversely, if they were calibrated to reproduce the observed gas fractions, they would result in too high metallicities.

This excessive metal production is readily understood since the enrichment efficiency of a stellar population, or its “net yield”, is inversely proportional to the mass fraction that remains forever locked in low–mass stars and remnants (Tinsley 1980; Pagel 1997); and for “bottom–light” IMFs the locked–up fraction is small. This effect can be compensated by a steep slope at the high-mass end, which reduces the number of massive stars and the related metal production: the Kroupa or modified–Larson IMFs, for instance, with a steep Scalo slope do not overproduce metals (see PST for details). A steep slope for the integrated field stars IMF is expected, in fact, if stars form in star clusters of finite size even from an intrinsically shallower IMF (Kroupa & Weidner 2003).

For those bottom–light IMFs that do imply an excess in metal production, one way to reconcile models with observations is to tune the upper mass limit of the IMF, again reducing the number of massive stars and related metal...
production — or equivalently assume that above a certain progenitor mass, the metals produced by a supernova fall back onto a black hole after the explosion. The observed gas fractions can then be matched without altering the stellar M/L ratio significantly (green triangles in Fig. 6).

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 low gas fractions. This behaviour is reminiscent of that of elliptical galaxies, responsible for the enrichment of the hot gas in clusters.

With “standard” IMFs suited to model the chemical evolution of the Solar Neighbourhood (e.g. the Kroupa IMF) it is impossible to account for the observed metal enrichment in clusters (Portinari et al. 2004b). Possibly, some of the “bottom–light” IMFs advocated here to reproduce low disc M/L ratios, suggest a scenario where the IMF and the enrichment efficiency may be the same in spiral and cluster galaxies, and in both cases much of the metals are dispersed into the intergalactic medium. However, substantial outflows would challenge our understanding of disc galaxy formation: in galactic discs, 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 in 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 to major winds from disc galaxies is that the metal production in spirals is much lower than in galaxy clusters, because of a different IMF (Portinari et al. 2004b). The IMF may change out of Jeans–mass variations with redshift (Moretti et al. 2003 and references therein); or be a universal function within star clusters, but lead statistically to more high–mass stars in massive ellipticals, where in regimes of intense star formation larger star clusters can be formed (Kroupa & Weidner 2003).

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