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Stellar and HI Mass Functions Predicted by a Simple Preheating Galaxy Formation Model *

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Abstract According to the new preheating mechanism of galaxy formation suggested by Mo et al., we construct a simple model of formation of disk galaxies within the current paradigm of galaxy formation. It incorporates preheating, gas cooling, bulge formation and star formation. The predicted stellar and HI mass functions of galaxies are discussed and compared with the observations. It is found that our model can roughly match both the observed galaxy luminosity function and the observed HI-mass function.

Key words: galaxies: halos — galaxies: formation — galaxies: bulges — galaxies: cooling flows

1 INTRODUCTION

Since the pioneering works of White & Rees (1978) and Fall & Efstathiou (1980), the popular view on galaxy formation within the cold dark matter (CDM) cosmogony is that galaxies form by gas cooling and condensation in dark matter haloes. In this scenario, the major observational properties of a disk galaxy (such as mass, luminosity and surface density profile, etc.) are mainly determined by its host halo. Assuming that baryons within a galactic halo have the same specific angular momentum distribution and density profile as those of dark matter halo initially, and conserve their angular momentum during the formation of disk, the resulting galaxy population can match observations very well in the distributions of disk sizes, kinematics, colors and morphologies, etc. (Mo, Mao & White 1998; Efstathiou 2000; van den Bosch 2000; Kauffmann, White & Guiderdoni 1993; Cole et al. 1993; Dalcanton, Spergel & Summers 1997; Navarro & Steinmetz 1997; Eke, Efstathiou & Wright 2000; van den Bosch 2001). However, there are still some open questions. One of them is that CDM models in general predict a much steeper mass spectrum $n(M) \propto M^{-2}$ than the observed faint-end slope of galaxy luminosity function $\Phi(L) \propto L^{-1}$ (Efstathiou, Ellis & Peterson 1988; Loveday et al. 1992). This discrepancy directly leads to the realization that some kind of feedback mechanism must be introduced. Feedback from supernova explosions is now commonly accepted as the most important mechanism. Either analytical models, semi-analytical models or numerical simulations are able to reproduce the observed slope of the faint-end luminosity function in the ΛCDM model, if such a feedback process is included and the feedback efficiency is taken to be sufficiently high.

Recently Mo et al. (2005) (hereafter M05) pointed out that a combination of observational constraints on the luminosity function and the HI-mass function provides important constraints on galaxy formation model, since galaxy formation is a process that involves both stars and cold gas. A successful galaxy formation model should not only reproduce the observed luminosity function, but also the observed HI-mass function. Unfortunately, most observations about galaxies in the past have mainly focused on the luminosities with less information available regarding the cold gas components. In recent years, thanks to the

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completion of relatively large blind 21-cm surveys, a large volume of observation on cold gas has become available (Rosenberg & Schneider 2002; Schneider, Spitzak & Rosenberg 1998; Zwaan et al. 2005). It becomes possible to use these data to constrain the galaxy formation model.

As in M05, although supernova feedback in galaxy formation models has a drastic impact on the stellar masses and may be tuned to yield a good match to the low-mass end of the stellar mass function, it also has some fundamental problems, e.g., galaxy formation models which include the supernova feedback often predict too large HI masses since supernova feedback prevent gas turn into stars, so leading to the over-predicted abundance of systems with low HI masses. To resolve this problem, M05 proposed a new preheating mechanism during the galaxy formation where the medium around low-mass haloes is preheated by gravitational pancaking. By implementing this new preheating mechanism to the galaxy formation model suggested by Mo, Mao & White (1998), M05 can simultaneously match the low mass end of both the HI-mass function and the stellar mass function, but there is still a discrepancy at high mass end.

In this paper, we construct a new disk galaxy formation model within the current paradigm of galaxy formation, incorporating gas preheating and cooling, bulge formation and star formation, to predict stellar and HI mass functions of galaxies and to compare them with the observations. The ΛCDM cosmogony is adopted with $\Omega_0 = 0.3$, $\Omega_\Lambda = 0.7$, $h = 0.7$ and $\sigma_8 = 1.0$. The baryon fraction f_b is chosen to be 0.17.

2 THE MODEL AND THE PREDICTED STELLAR AND HI MASS FUNCTIONS

In our model, the dark halo is assumed to be the Navarro-Frenk-White density profile (NFW) (Navarro, Frenk & White 1996) with the dependence of its concentration on halo mass given by Bullock et al. (2001b). The total angular momentum of a halo can be described by a dimensionless spin parameter λ, which is the ratio of its rotational energy to its bounding energy. According to numerical simulations, λ follows a log-normal distribution for the galaxy population:

$$p(\lambda)d\lambda = \frac{1}{\sqrt{2\pi}\sigma_\lambda} \exp\left[-\frac{\ln(\lambda/\overline{\lambda})}{2\sigma_\lambda^2}\right] \frac{d\lambda}{\lambda}, \tag{1}$$

with $\overline{\lambda} = 0.04$ and $\sigma_\lambda = 0.5$. We take $\lambda = 0.04$ in the present Letter. Based on their high-resolution N-body simulations, Bullock et al. (2001a) (hereafter B01) suggested the following universal specific angular momentum (SAM) distribution for galactic halos in cylindric coordinates,

$$M(< j) = M_h \frac{\mu j}{j_0 + j}, \qquad \mu > 1 \tag{2}$$

where $M(< j)$ is the halo mass with SAM less than j, $j_0 = j_{\max}(\mu - 1)$, $j_{\max}$ being the maximum SAM of the halo, and μ the shape parameter. B01 found that $\mu - 1$ follows a log-normal distribution with a median value of 1.25. The range $1.06 < \mu < 2.0$ covers 90 percent of the halos population. Here we choose $\mu = 1.25$.

According to M05, the medium around a low-mass halo is preheated by gravitational pancaking to a specific entropy that is comparable to or larger than that generated by the accretion shock associated with the formation of the halo, and not all gas will be accreted into the halo. The fraction of gas that can be accreted into a dark matter halo of mass M_h is, approximately,

$$m_{\rm gas} = \frac{f_b}{(1 + M_c/M_h)^\alpha}\,, \tag{3}$$

with $\alpha = 1$ and $M_c = 5 \times 10^{11} h^{-1} M_\odot$, which is adopted in the present paper. As in previous models, it is assumed that the baryons within a galactic halo have the same specific angular momentum distribution and the same density profile as its host dark matter halo initially, and the angular momentum is conserved during the formation of disk.

The gas infall rate of a galaxy is given by

$$\dot{M}_{\rm infall} = \frac{dM}{dt}, \tag{4}$$

with $t = t_h$ if $t_h > t_{\rm cool}$ and $t = t_{\rm cool}$ if $t_h < t_{\rm cool}$, t_h being the Hubble time and $t_{\rm cool}$, the cooling timescale,

$$t_{\rm cool} = \frac{3}{2}\frac{kT_v \times 1.92}{\Lambda(T_v) n_e(r_i)}, \tag{5}$$

with k the Boltzmann's constant, n_e the electron density, and $\Lambda(T_v)$ the cooling function of Sutherland & Dopita (1993). The temperature T_v is the virial temperature derived from the equation of hydrostatic equilibrium and can be described by (Efstathiou 2000)

$$T_v \approx -v_h^2(r)\frac{\mu_p}{k}\frac{d\ln r}{d\ln \rho_b(r)}, \tag{6}$$

which is a function of the radius of the given halo.

With the conservation of mass and of specific angular momentum, the cooled down gas has a well-defined place in the disk. As gas cumulates in the disk, star formation takes place and bar instability must be considered. When the ratio of rotation velocity contributed by the disk $V_{\rm disk}$ to the total $V_{\rm tot}$,

$$q = \frac{V_{\rm disk}}{V_{\rm tot}} \tag{7}$$

exceeds a critical value q (taken to be 0.7 here), bar instability will occur and the baryons will transfer their angular momentum to the dark matter or the remaining disk, and then fall into the galactic center to form a bulge so as to make the disk stable.

Star formation occurs in the disk only when the gas surface density is higher than a critical density as shown by Kennicutt (1989). Otherwise it is abruptly suppressed. This critical density is close to Toomre's stability criterion

$$\Sigma_{\rm crit}(R) = \frac{\sigma_{\rm gas}\kappa(R)}{\pi G Q_{\rm crit}}, \tag{8}$$

where $\kappa(R)$ is the epicyclic frequency, $\sigma_{\rm gas}$ is the velocity dispersion of the cold gas and $Q_{\rm crit} \sim 1$ (Toomre 1964). For the prescription of star formation in the present paper, we set $Q_{\rm crit} = 1$ and assume that all gas with disk surface density $\Sigma_{\rm disk} > \Sigma_{\rm crit}$ goes into forming stars. To be conservative (as in M05), we take the mass of molecular gas in the disk to be one- half of the total gas mass, noting that hydrogen contributes only 71% of the total mass, when taking into account the contribution of helium and other heavier elements.

The halo mass function can be obtained by the PS formalism (Press & Schechter 1974) for a given cosmogony. Assuming that each halo hosts a single disk galaxy, we can predict the HI and stellar mass functions by generating a modeled galaxy population through Monte Carlo simulations according to the individual physical prescriptions above, shown respectively by circles and triangles in Figure 1.

3 COMPARING WITH OBSERVATIONS AND DISCUSSION

Panter et al. (2004), using the MOPED algorithm, calculated the stellar mass function for 96,545 galaxies in the Sloan Digital Sky Survey data release. They fitted the galaxy stellar mass function with a Schechter function and found that their result is in good agreement with the previous studies. For comparison, we reproduce their fitting function in Figure 1 as the solid curve. On the other hand, Zwaan et al. (2005) recently used the catalogue of 4315 extragalactic HI 21-cm emission line detections from the HI Parkes All Sky Survey (HIPASS) and obtained the most accurate measurement of the HI mass function of galaxies to date. They found that the HI-mass function is also well fitted by a Schechter function with a power-law slope at the low mass end of about -1.3 ± 0.1, which is slightly steeper than in the stellar mass function. This is plotted as the dashed curve in Figure 1.

From the figure it can be concluded that our model predictions can roughly match the observed stellar and HI mass functions. Since we have considered the preheating and gas cooling processes (for example, the hot gas in the massive halos can not completely cooling down), our model appears to have a sharp cutoff for both HI and stellar mass functions at the massive end. Such decline in halo mass function occurs at a mass that corresponds to a much lower abundance (Yang et al. 2003). In our model, we do not need to cut

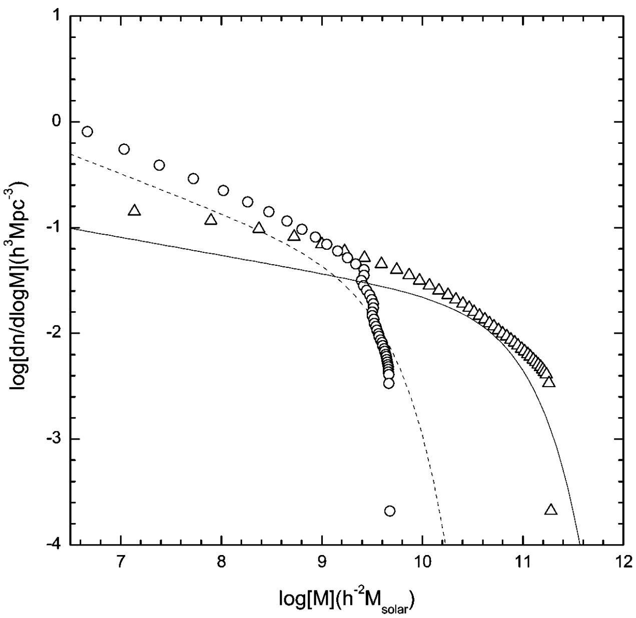

Fig. 1 The solid line and triangles represent, respectively, the observed and predicted stellar mass function. The dashed line and circles, the observed and predicted HI mass function.

the halo mass function at high mass end as previous studies. For instance, M05 only focused in low-mass haloes and hence their model did not include any processes that may affect gas assembly in massive halos, while we consider this process by introducing the gas cooling timescale.

From the figure we can also see that our model over-predicts the HI mass function and stellar mass function at the low mass end and under-predicts them at the high mass end. There are three reasons which could lead to these discrepancies. First, following M05, we set, in the preheating equation (Eq. (4)), α to 1 and M_c to $5 \times 10^{11} h^{-1} M_{\odot}$ for both halos, but we could have adjusted these two parameters to make our results better match the observations. For example, we can change the values of α and M_c to make the preheating more effective, hence to make the mass of baryons within the halos smaller and to lower the stellar and HI mass functions at the low mass end. Secondly, supernova feedback, which can lead to galactic winds and mass outflows, was not taken into account here. This feedback is more effective in lower mass halos (Shu, Mo & Mao 2005). Thirdly, different value of $Q_{\rm crit}$ in Equation (8) can also change both the HI and stellar mass functions.

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