New Astronomy 41 (2015) 48–52

Contents lists available at ScienceDirect

New Astronomy

journal homepage: www.elsevier.com/locate/newast

The role of the dark matter haloes on the cosmic star formation rate

Eduardo S. Pereira*, Oswaldo D. Miranda

Divisão de Astrofísica, Instituto Nacional de Pesquisas Espaciais, SP 12227-010, Brazil

HIGHLIGHTS

- We investigate the hole of dark matter distribution in the cosmic star formation.
- The fraction of baryons in structures is dependent of the dark matter distribution.
- Some dark matter functions could not trace the baryons without a bias parameter.
- The characteristic time-scale for star formation is dependent on the dark matter.

ARTICLE INFO

Article history:
Received 8 September 2014
Revised 4 May 2015
Accepted 4 June 2015
Available online 11 June 2015

Communicated by J. Makino

Keywords:
(Cosmology):dark matter
Stars: formation
Stars: general
Galaxies: star formation

ABSTRACT

The cosmic star formation rate (CSFR) represents the fraction of gas that is converted into stars within a certain comoving volume and at a given time *t*. However the evolution of the dark matter haloes and its relationship with the CSFR is not yet clear. In this context, we have investigated the role of the dark halo mass function - DHMF - in the process of gas conversion into stars. We observed a strong dependence between the fraction of baryons in structures, f_b, and the specific mass function used for describing the dark matter haloes. In some cases, we have obtained f_b greater than one at redshift $z = 0$. This result indicates that the evolution of dark matter, described by the specific DHMF, could not trace the baryonic matter without a bias parameter. We also observed that the characteristic time-scale for star formation, τ, is strongly dependent on the considered DHMF, when the model is confronted against the observational data. Also, as part of this work it was released, under GNU general public license, a Python package called 'pycosmicstar' to study the CSFR and its relationship with the DHMF.

1. Introduction

The conversion of gas into stars is a fundamental characteristic of the process of large-scale structure formation in the universe. In particular, the cosmic star formation rate (CSFR) represents the rate of gas that is converted into stars within a certain comoving volume and at a given time *t*, typically represented in units of $M_\odot$ Mpc^{-3} yr^{-1}. The comprehension of the star formation process in cosmological scale has an important role in modern astrophysics and, particularly, in cosmology. However, the processes associated with structure formation and their relation with the CSFR is not yet clear. Despite this, some works have shown that there is a connection between the CSFR and the growth of supermassive black holes (Franceschini, 1999; Haiman et al., 2004; Heckman, 2004; Kauffmann, 2003; Mahamood et al., 2005; Merloni et al., 2004; Pereira and Miranda, 2011; Wang et al., 2006). Also, it has been discussed that the CSFR can be used as a test for alternative cosmological models (Bessada and Miranda, 2013; Miranda, 2012) as weel as it could trace the long gamma-ray burst distribution (Hao and Yuan, 2013a; 2013b). Last but not least, a semi-analytical approach to study the CSFR can be used for understanding the physical processes occurred during the so-called cosmological dark ages. This kind of model, obtained from semi-analytical formalism, is computationally inexpensive when compared to N-body/hydrodynamical simulations (Benson, 2012).

We also developed a Python package called 'pycosmicstar' to study the CSFR and its relationship with the dark halo mass function - DHMF. This software is based on the work of Pereira and Miranda (2010), and it was written by using Python programing language (Behnel, 2011; GUPTA, 2002; Hinsen, 2007; Hinsen et al., 2006; Peterson, 2009). In order to show the scientific potential of 'pycosmicstar', we also investigate the role of DHMF on the evolution of the CSFR.

This work is organized as follows: In Section 2 is presented the general ideas of the Press–Schechter formalism and its connection to the DHMF. A short review about the self-consistent model to obtain the CSFR is discussed in the Section 3. The general structure of 'pycosmicstar' is described in the Section 4. The results of this work are discussed in Section 5 and our final remarks are presented in the Section 6.

* Corresponding author. Tel.: +55 01234313188; fax: +55 1232087200.
E-mail addresses: pereira.somoza@gmail.com, eduardo.pereira@inpe.br, edu.estelar@gmail.com (E.S. Pereira), oswaldo.miranda@inpe.br (O.D. Miranda).

http://dx.doi.org/10.1016/j.newast.2015.06.001
1384-1076/

In this work was considered the standard cosmological model ΛCDM (Cold Dark Matter plus cosmological constant) with the following parameters: $\Omega_m = 0.24$; $\Omega_b = 0.04$; $\Omega_\Lambda = 0.73$; $h = 0.7$

2. The dark halo mass function

The standard cosmological model (ΛCDM) considers that the present energy content of the universe is dominated by dark energy followed by dark matter and ordinary matter (baryonic). In this scenario the distribution of dark matter haloes can be described by a Press–Schechter-like formalism (PSF) (Press and Schechter, 1974). The ansatz of the PSF considers that the fraction of mass in haloes more massive than M is related to the fraction of the volume in which the smoothed initial density field is above some density threshold δ_c (Pereira and Miranda, 2010). Thus, haloes are the peaks in the density distribution being the natural sites for galaxy formation. From the knowledge of the variance of linear density field and as the cosmological density perturbations grow, it is possible to obtain the halo mass function which gives the number density of collapsed dark matter haloes per unit interval in $\ln\sigma^{-1}$. In particular, we use the functional form of Jenkins et al. (2001) to describe the halo abundance. That is

$$\frac{dn}{dM} = f(\sigma)\frac{\rho_{DM}}{M}\frac{d\ln\sigma^{-1}}{dM}, \tag{1}$$

being $f(\sigma)$ the σ-weighted distribution function, σ is the variance of the linear density field, and ρ_{DM} is the comoving dark matter density. In the literature is possible to find different forms of $f(\sigma)$. Particularly, in this work are considered the following distributions[1]

1. Press and Schechter (1974):

$$f(\sigma) = \sqrt{\frac{2}{\pi}}\nu\exp\left(-\frac{\nu^2}{2}\right), \tag{2}$$

2. Sheth and Tormen (1999):

$$f(\sigma) = A\sqrt{\frac{2a}{\pi}}\nu\exp\left(-\frac{a\nu^2}{2}\right)\left[1+\left(\frac{1}{a\nu^2}\right)^p\right] \tag{3}$$

where $A = 0.3222$, $a = 0.707$ and $p = 0.3$,

3. Reed (2007) (also known as the modified Sheth–Tormen mass function)

$$f(\sigma) = A\sqrt{\frac{2a}{\pi}}\nu\exp\left[\frac{ca\nu^2}{2} - \frac{0.03\nu^{0.6}}{(n_{eff}+3)^2}\right] \times\left[1+\left(\frac{1}{a\nu^2}\right)^p + 0.6G_1(\sigma) + 0.4G_2(\sigma)\right], \tag{4}$$

where $A = 0.3222$, $a = 0.707$, $p = 0.3$ and $c = 1.08$, with:

$$n_{eff} = 6\left(\frac{d\log\sigma^{-1}}{d\log M}\right) - 3,$$

$$G_1(\sigma) = \exp -[\ln(\sigma^{-1} - 0.4)^2]/0.72,$$

$$G_2(\sigma) = \exp -[\ln(\sigma^{-1} - 0.75)^2]/0.08,$$

4. Watson (2013):

$$f(\sigma) = A\left[\left(\frac{b}{\sigma}\right)^a + 1\right]\exp(-c/\sigma^2), \tag{5}$$

being, $A = 0.282$, $a = 2.163$, $b = 1.406$ and $c = 1.21$. Note that this is a modified version of Tinker (2010) mass function for redshift range $z = [0, 30]$.

[1] We defined $\nu \equiv \delta_c/\sigma$. The parameter $\delta_c = 1.686$ (that is calculated for an Eintein de-Sitter Universe) is the linearly extrapolated overdensity of a top-hat spherical density perturbation at the moment of maximum compression (Reed, 2007).

We chose these mass functions because they are valid for a large range of redshifts and they have been commonly used for representing the DHMF over the last years.

3. Cosmic star formation rate

The self-consistent model of star formation obtained by Pereira and Miranda (2010) is centred on the fact that dark haloes are gravitational wells. Then, when a dark halo collapses, the baryonic infall processes are started. If a dark halo has mass greater than a certain threshold, the star formation will occur in a very similar way as that observed in 'normal' galaxies. In the hierarchical models for galaxy formation the first star-forming haloes are predicted to collapse at redshift $z \gtrsim 20$, having masses $\sim 10^6\,M_\odot$ (Salvadori et al., 2007). The DHMF and the CSFR are connected by the baryon accretion rate $a_b(t)$ (Pereira and Miranda, 2010). Generally speaking, the CSFR is obtained by the solution of the equation

$$\dot\rho_g = -\frac{d^2M_\star}{dVdt} + \frac{d^2M_{ej}}{dVdt} + \epsilon a_b(t), \tag{6}$$

where the CSFR is given by:

$$\frac{d^2M_\star}{dVdt} \equiv \dot\rho_*(t) = \frac{\rho_g(t)}{\tau}, \tag{7}$$

being $\dot\rho_g$ the gas density rate taking part in the star formation process, $d^2M_\star/dVdt$ is the rate of gas that is converted into stars within a certain volume and at a given time t, $\dot\rho_*$ is the cosmic star formation rate, and τ is a parameter that represents the time-scale for star formation.

On the other hand, the baryon accretion rate $a_b(t)$, in Eq. (6), accounts for the increase in the fraction of baryons in structures and it is given by

$$a_b(t) = \Omega_b\rho_c\left(\frac{dt}{dz}\right)^{-1}\left|\frac{df_b(z)}{dz}\right|, \tag{8}$$

where $\rho_c = 3H_0^2/8\pi G$ is the critical density of the universe, and dt/dz relates the age of the universe with the redshift.

Here is important to stress that ϵ in Eq. (6) represents the fraction of $a_b(t)$ really incorporated into stars. This parameter is calculated in order to produce $\dot\rho_* = 0.016\,M_\odot\,yr^{-1}\,Mpc^{-3}$ at $z = 0$. With this value it is possible to obtain a good agreement with both the present value of the CSFR derived by Springel and Hernquist (2003), who employed hydrodynamic simulations of structure formation, and the observational points taken from Hopkins (2004, 2007). Thus, the fraction $(1-\epsilon)a_b(t)$ will represent the baryons that were added to the haloes, by the infall process, but which are in the form of gas not used in the star formation process.

Note that the fraction of baryons, f_b, contained in structures is given by (see, in particular, Daigne et al., 2006; Pereira and Miranda, 2010)

$$f_b(z) = \frac{\int_{M_{min}}^{M_{max}} f(\sigma)MdM}{\rho_{DM}(z)}, \tag{9}$$

where we have used $M_{min} = 10^6\,M_\odot$ - $M_{max} = 10^{18}\,M_\odot$ (see Pereira and Miranda, 2010 for details). It is implicit in Eq. (9) that the baryon distribution traces the dark matter distribution without any bias so that the density of baryons is just proportional to the density of dark matter.

The term $d^2M_{ej}/dVdt$ takes into account the mass ejected from stars that returns to the interstellar medium of the system. In particular:

$$\frac{d^2M_{ej}}{dVdt} = \int_{m(t)}^{M_{sup}} (m - m_r)\Phi(m)\dot\rho_*(t-\tau_m)dm, \tag{10}$$

where $m(t)$ corresponds to the stellar mass whose lifetime is equal to t, m_r is the mass of the remnant, which depends on the progenitor mass. Table 1 shows the masses of remnants as functions of the