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# THE COSMIC STAR FORMATION HISTORY

M. A. Muñoz-Gutiérrez[1] and V. Avila-Reese[1]

RESUMEN

Se presenta y compara con observaciones un modelo para calcular la historia de la densidad de la tasa de formación estelar cósmica en un universo ΛCDM jerárquico. Se discuten el rol de diferentes procesos astrofísicos como la función de la masa y época, así como potenciales problemas.

ABSTRACT

A model for calculating the cosmic star formation rate density history in a hierarchical Λ Cold Dark Matter (ΛCDM) universe is presented and compared with observations. The role of different astrophysical processes as a function of mass and epoch, and potential shortcomings are discussed.

*Key Words:* cosmology: theory — galaxies: formation



## 1. INTRODUCTION

The star formation rate density (SFRD) measured at different redshifts resumes the complexity of galaxy and star formation. Recent observational efforts allowed to improve the determination of the global SFRD history (up to $z \sim 8$) and decompose it by galaxy mass up to $z \sim 2$. In the context of the popular ΛCDM cosmological scenario, the assembly of galaxies is primarily driven by the hierarchical mass assembly of their dark matter halos, which trap into their centers a fraction of the hot/ionized gas; the cooled gas then form galaxies, where the gas is partially transformed into stars. Stars, mainly through SN explosions, exert feedback to the gas that, specially in low mass halos, is even ejected from the halo (galaxy outflows). In the case of massive galaxies, the powerful AGNs formed in their centers, inject energy to the intrahalo medium, avoiding its further infall to the galaxy.

*What is the role that play the* ΛCDM *"backbone" and these different astrophysical effects on the global* SFRD *history? What is the contribution of different masses to the* SFRD *at each epoch?* In order to answer to these questions, we have implemented an economical approach for modeling the SFRD history and dissect it by halo masses and peak heights (Muñoz-Gutiérrez 2010).

## 2. THE MODEL

The global SFRD at a given $z$ is calculated as:

$$\dot{\rho}_*(z) = \int_{M_{\min(z)}}^{\infty} N_h(M,z) \times \dot{M}_{\rm SF}(M,z), \qquad (1)$$

where $N_h(M,z)$ is the halo mass function at a given $z$ and

$$\dot{M}_{\rm SF}(M,z) = \epsilon_{\rm SF} f_{b,\rm cold} \langle \dot{M} \rangle, \qquad (2)$$

is the SFR associated to a halo of mass $M$ at epoch $z$; $M_{\min(z)}$ is the minimum halo mass at $z$ able to host galaxy formation. We assume that the SFR is driven by the (average) halo mass aggregation rate, $<\dot{M}>$; this average rate as a function of $M$ and $z$ has been given as a fit to the results of the dark matter Millenium I and II Simulations in Fakhouri et al. (2010).

By assuming that a universal fraction $f_U$ ($=\Omega_b/\Omega_m$) of $M$ are baryons, the cosmic *baryon aggregation rate density* (BARD) of galaxies is then:

$$\dot{\rho}_b(z) = \int_{M_{\min(z)}}^{\infty} N_h(M,z) \times f_U \langle \dot{M} \rangle. \qquad (3)$$

In our approach, $f_{b,\rm cold}$ in equation (2), the fraction of cold gas inside the halos, initially is equal to $f_U$ but the inclusion of several astrophysical processes reduce it as a function of $M$ and $z$. These processes are:

- Capture of gas by halos in the presence of an UV radiation background.
- Radiative cooling of the trapped gas.
- Galaxy outflows of gas driven by SN feedback.
- AGN-driven feedback to the intrahalo medium.

The efficiency of SF in equation (2), $\epsilon_{\rm SF}$, is related to instabilities in the cold gas and we approach it as the ratio of the global dynamical time to a typical SF instability time: $t_{\rm dyn}/t_{\rm SF}$. Halos emerging from high density peaks, i.e. large values of $\nu \equiv \delta_c/\sigma(M)$ at a given $z$, are highly clustered and are expected to assemble galaxies by major mergers; since these mergers at high $z'$s are plenty of gas,

[1]Instituto de Astronomía, Universidad Nacional Autónoma de México, Apdo. Postal 70-264, 04510 México, D.F., Mexico (mmunoz@astro.unam.mx).

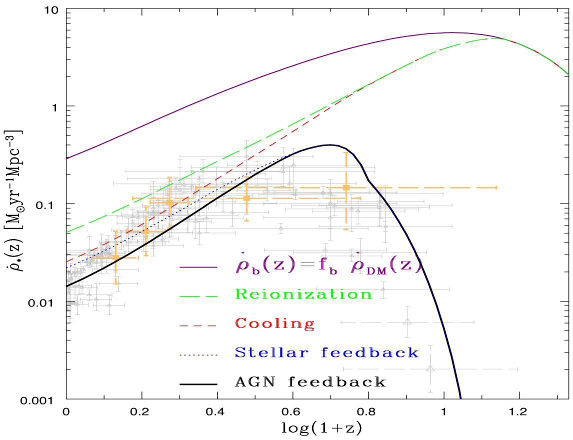


Fig. 1. Predicted SFRD histories by introducing different astrophysical ingredients as indicated in the panel. The final model is in good agreement with observations, showed by gray triangles (UV-based inferences) and orange squares (submm-based inferences) taken from the compilation of Hopkins & Beacom (2006).

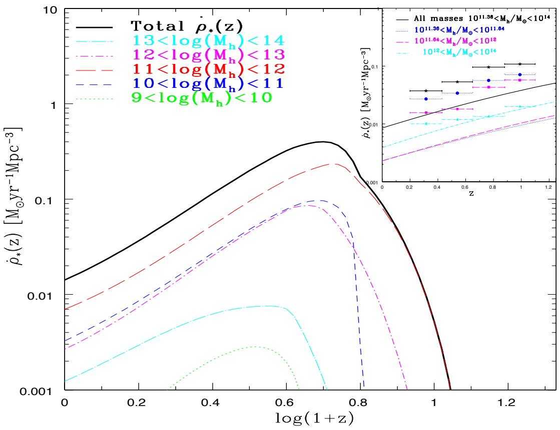


Fig. 2. Dissection by mass of predicted SFRD. Astrophysical ingredients alter the hierarchy of ΛCDM backbone. Massive halos ($M_h > 10^{12}\ M_\odot$) are in good agreement with observations (shown in the inset as dots with error bars taken from Mobasher et al. 2009). Low mass halos cannot reproduce recent observations of downsizing. The mass ranges in the main panel and the inset are different.

strong SF bursts (sub-millimeter galaxies?) are expected in such a way that $\epsilon_{\rm SF} \rightarrow 1$. At low $z'$s, mergers are typically dry in such a way that no starbursts are expected. Halos formed from"normal" peaks ($\nu \approx 1$) host normal disk galaxies, where SF is self-regulated and quite ($\epsilon_{\rm SF} \ll 1$). By taking into account all these arguments, we approximate $\epsilon_{\rm SF}$ as $1/\left[5 - 12\log(1+z)\log(\nu)\right]$.

## 3. RESULTS AND CONCLUSIONS

Figure 1 shows the effects over the SFRD history of introducing consequently the 4 astrophysical processes mentioned above. We start from the BARD history (equation 3, purple solid line), which is basically an imprint of the hierarchical ΛCDM halo asssembly. Before re-ionization, $M_{\min(z)}$ corresponds to halos with $T_{\rm vir} = 300$ K, and after it, is determined by the UV background according to Hoeft et al. (2006). The SFRD is not affected significantly by these effects (green long-dashed line), being the difference with the preceding curve mainly due to $\epsilon_{\rm SF}$. The delay of gas infall due to radiative cooling diminishes SFR for massive haloes, which are formed at late times (red short-dashed line). SN driven outflows strongly decrease the SFRD in low mass halos, which are abundant at early epochs (blue dotted line). Finally, AGN feedback diminishes even more the SFR in massive halos at low $z'$s (black solid line).

Figure 2 shows the dissection by mass in equally spaced intervals (1 dex) of the final model. At all $z'$s, the main contribution to the SFRD comes from halos of $10^{11} - 10^{12}\ M_\odot$, which at $z \gtrsim 3$ are associated to very high peaks ($\nu > 2-3$), but at latter epochs, become typical $\nu \sim 1$ halos. Galaxies in very large and very small halos almost do not contribute to the SFRD. The astrophysical ingredients produce some inversion of the ΛCDM hierarchy but not enough at intermediate/low masses as to agree with observations which evidence strong 'downsizing': low-mass galaxies contribute more to the SFRD at late epochs than the larger ones (see inset in Figure 2).

We conclude that at a global level, our ΛCDM-based model is able to explain the observed cosmic SFRD history (Figure 1), showing that the SN-driven outflows in low-mass halos and radiative cooling/AGN feedback in massive halos are relevant ingredients for this agreement. When dissecting the SFRD history by $M$, our results for massive galaxies agree with observations but the SFRD contribution of low-mass galaxies at low $z'$s is below the observed one (downsizing). Some extra astrophysical process should delay the active SF in low-mass halos (the less massive the halo, the more efficient should be this delay).

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