Metal and Dust Build-up in the Universe: Constraints from Lyman-Break Galaxies at the Epoch of Reionization

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We discuss the constraints on the physical processes regulating the baryon cycle in Lyman-Break galaxies at the epoch of reionization ($5 < z < 10$) and in local dwarf galaxies, often considered to be the local counterparts of the former in terms of physical properties. Specifically, we constrain: a) the relative contribution of Supernovae (SNe) and of thermally pulsing asymptotic giant branch (TP-AGB) stars to the chemical enrichment of galaxies, b) the dust destruction efficiency operated by SN shocks in the interstellar medium (ISM), c) the dust growth in the ISM, d) the efficiency of conversion of gas into stars, e) the efficiency of galactic outflows in removing dust and gas from the ISM. We find that fast enrichment in metals and dust from Type II SNe followed by dust removal through galactic outflows is required to reproduce the observations, while destruction of dust by SN shocks has limited efficiency. The fast enrichment from Type II SNe is obtained assuming a top-heavy initial mass function for stars and a condensation fraction of dust of $\gtrsim 50\%$. The contribution of Type II SNe is dominant with respect to TP-AGB stars and Type Ia SNe. Dust growth in the ISM is not necessary in order to reproduce the observations.

1 Introduction

The chemical enrichment of galaxies is governed by the complex interplay of several physical processes taking place in their interstellar medium (ISM): stellar birth and evolution, reprocessing of grains in the ISM through destruction by supernova (SN) shocks and, possibly, grain growth in the ISM, large scale inflows and outflows of gas and dust. Understanding the interplay between the aforementioned processes is essential to constrain the evolution of baryons in galaxies. We here focus on the study of the evolution of baryons in Lyman-Break galaxies (LBGs) at the epoch of reionization (Burgarella et al., 2020) where the formation of the first dust grains may have taken place, and on local dwarf galaxies from the Dwarf Galaxy Survey (DGS, Madden et al., 2013; Rémy-Ruyer et al., 2015), which are the objects in the local Universe closest to LBGs in terms of physical properties (Nanni et al., 2020).

2 Method

2.1 Estimating the physical parameters of galaxies

The physical parameters of the galaxies (e.g. star formation rate, stellar and dust mass) have been derived through the Spectral Energy Distribution (SED) fitting of the photometry. All the details about the SED fitting are provided in Burgarella et al. (2020). For local DGS galaxies additional information about the metallicity and gas fraction (Rémy-Ruyer et al., 2013, 2014, and references therein) and, in a few cases, circumgalactic dust (McCormick et al., 2018), are available. The information on DGS galaxies is employed to constrain the baryon evolution in these systems and is adopted to model the evolution of baryons in LBGs for which the aforementioned measurements are not available.

2.2 Modelling the chemical evolution of galaxies

The metal enrichment of galaxies due to stellar evolution includes Type II, Type Ia SNe, and low- and intermediate-mass stars evolving along the thermally pulsing asymptotic giant branch (TP-AGB) phase. The metal enrichment of galaxies together with astration (the metal consumption due to star formation) is computed by the OMEGA code (One-zone Model for the Evolution of GAlaxies; Côté et al., 2017; Ritter et al., 2018). In the simulations here considered, we assume that the gas of pristine composition (which will be partially converted into stars) is already present in the galaxy.

The overall evolution of baryons is therefore computed based on these calculations. Galactic outflows are proportional to the star formation rate (SFR) through the "mass-loading factor" (ML, Murray et al., 2005).

All along the simulation, a fraction of the metals produced by stars is assumed to be condensed into dust either in SN remnants or in the circumstellar envelopes of TP-AGB stars. Dust destruction of the grains in the ISM from SN shocks and dust growth in the ISM are also calculated. All the details of our calculations are explained in Nanni et al. (2020).

3 Results

3.1 Constraining the efficiency of the outflow

In this section, we compare the results of the simulations with the available observations for DGS and LBGs. As shown in Fig. 1, in order to reproduce the metallicity of DGS galaxies the conversion factor of gas into stars needs to be just of a few per cent. Different efficiencies of the outflow (values of ML) are able to cover the metallicity range.

In this context, an efficient outflow is needed to reproduce the gas fraction derived for low metallicity galaxies, since astration does not consume gas efficiently enough, as shown in the left panel of Fig. 2.

The large amount of gas needed to reproduce the metallicity implies that destruction of dust grains operated by SN shocks is inefficient, as the destruction time-scale of grains is proportional to the mass of gas that needs to be swept out by SNe. In

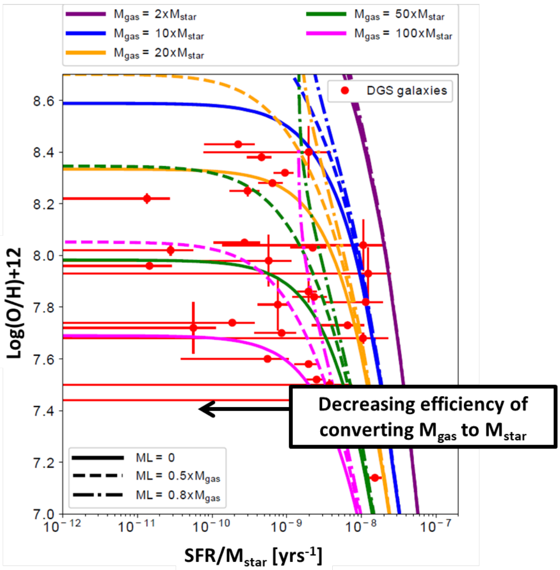

Fig. 1: Metallicity against specific star formation rate for DGS galaxies (full red points) overplotted on different models with different initial mass of gas with respect to final stellar masses and values of ML as listed in the figure (based on Fig. 5 of Nanni et al., 2020).

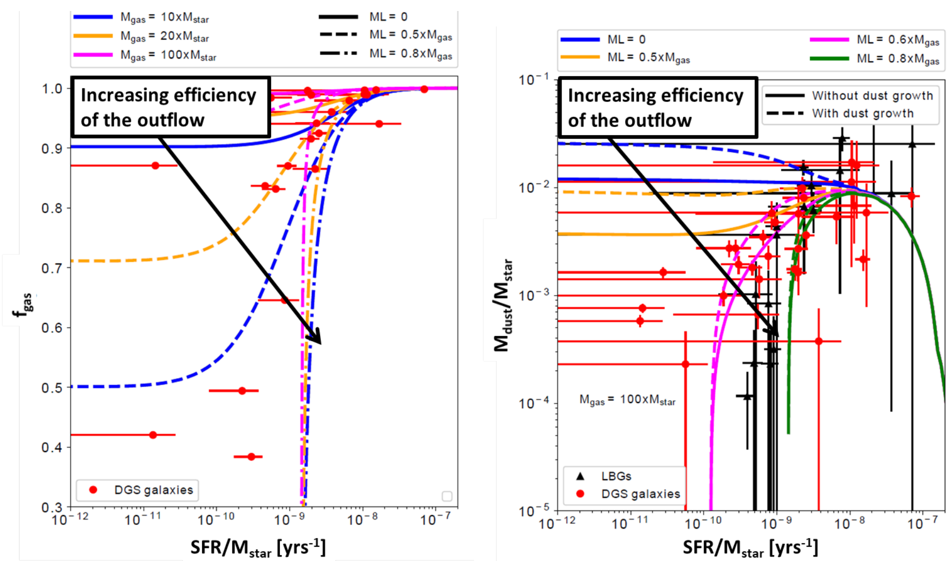

Fig. 2: *Left*: similar to Fig. 1 but for the gas fraction against specific star formation rate (based on Fig. 7 of Nanni et al., 2020). *Right*: specific mass of dust against specific star formation rate for DGS galaxies (red) and LBGs (black) overplotted on models with different values of ML as specified in the figure, with and without dust growth in the ISM (based on Fig. 6 of Nanni et al., 2020).

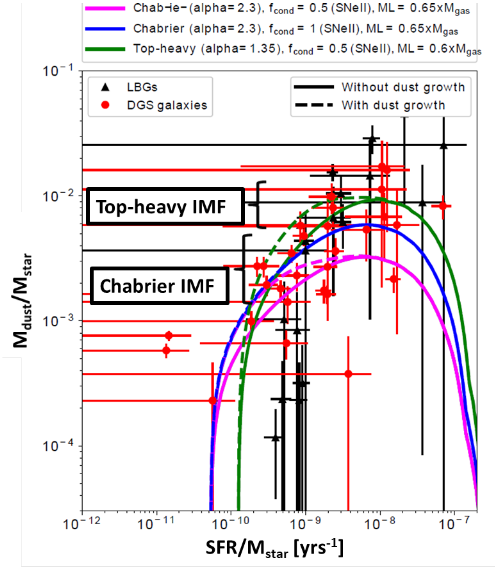

Fig. 3: Specific mass of dust against specific star formation rate for DGS galaxies (red) and LBGs (black) overplotted on models with different condensation fractions of dust as specified in the figure, with and without dust growth in the ISM. The calculations are performed for a Chabrier and a top-heavy IMF (based on Fig. 4 of Nanni et al., 2020).

this scenario, dust removal from outflow is an important mechanism to reproduce the observed trends for the specific mass of dust (M_{dust}/M_{star}), as shown in the right panel of Fig. 2.

3.2 Constraining dust production from Type II SNe

In Fig. 3 we show the specific mass of dust overplotted on models with different initial mass functions (IMFs) for stars, and condensation fractions of dust. We consider a Chabrier (2003) IMF and a top-heavy one (e.g. Larson, 1998). A top-heavy IMF coupled with a dust condensation fraction $\gtrsim 50\%$ helps to reproduce the large values of the specific dust mass derived from the SED fitting. On the other hand, with a Chabrier IMF not enough dust is produced in order to attain the values of the specific mass of dust at the beginning of the baryon cycle. A top-heavy IMF also implies that most of the dust in these galaxies is produced by Type II SNe rather than by Type Ia and TP-AGB stars.

3.3 Dust growth in the ISM

As shown in the right panel of Fig. 2 and in Fig. 3 dust growth in the ISM is not necessary in order to explain the dust content in the galaxies here analysed. This is because most of the dust is assumed to be produced by Type II SNe, and, therefore, little is available to form fresh dust in the ISM, and because of the efficient galactic outflows which efficiently remove the dust produced.

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