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Enrichment history of the universe as seen from GRB statistics

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Abstract. Estimates of the cosmic star formation history from the gamma-ray burst rate predict a very slow decline of star formation at higher redshift. This implicates that at a given redshift galaxies form stars with higher rate than inferred from rest-frame optical/UV measurements. We discuss here consequences of such an enhanced star formation for the chemical evolution and reionization history of the Universe.

Keywords : star formation – cosmic history: gamma-ray bursts – host galaxies – enrichment – user guide

1. Introduction

Evolution of the post-dark ages Universe is mainly determined by energy released from formed stars, and is imprinted in its reionization and chemical history. Estimates of the cosmic star formation history (SFH) are therefore of great importance for understanding "recent" epochs of the Universe, $z < 10$, comprising more than 95 % of its lifetime. The principal probe of the SFH is the measurements of the rest-frame ultraviolet emission (Madau et al. 1996). Most recent results from Sloan Digital Sky Survey (SDSS), Galaxy Evolution Explorer (GALEX), and Spitzer Space Telescope in far-infrared, as well as optical and near-infrared data from Hubble Ultra Deep Field (HUDF) and GOODS, are believed to constrain SFH within factor of two up to $z = 7$ (see, Hopkins & Beacom (2006); Bouwens et al. (2008)). Such measurements predict growth of the star formation rate from $z = 0$ to about $z = 1 - 2$ up to $\sim 0.02\ M_\odot$ yr^{-1} Mpc^{-3}, and further decline at higher redshifts by at least an order of magnitude at $z \simeq 7$ (Bouwens et al. 2008). They, however, are contaminated by

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possible dust extinction, particularly, in UV range, and dimming of surface brightness with redshift (Lanzetta et al. 2002). As a consequence, an alternative approach based on statistics of gamma-ray bursts has been suggested (Wijers et al. 1998; Porciani & Madau 2001). However, in general, their statistics show higher star formation rate (Kistler et al. 2009) or even growing values at $z > 6$ (Firmani et al. 2004). In this contribution, we discuss briefly how these different star formation histories can manifest themselves in metal enrichment and reionization of the Universe.

2. Metal enrichment

The lower panel in Fig. 1 shows the amount of carbon produced in the Universe with the SFH scenario based on rest-frame UV and optical (Bouwens et al. 2008) measurements (UV-SFH henceforth) and compare it with the one estimated in the intergalactic medium (IGM) (Vasiliev & Shchekinov 2011).

$$\Omega_{IGM}(\mathrm{C}) = \frac{\Omega(\mathrm{CIV})}{x(\mathrm{CIV})} \tag{1}$$

where x(CIV) is the fraction of triple ionized carbon, while $\Omega(\mathrm{CIV}) = \rho(\mathrm{CIV})/\rho_c$, the relative mass density of CIV directly observed in the IGM (Ryan-Weber et al. 2009). Vasiliev & Shchekinov (2011) have shown that typical IGM conditions are ionized either in a power-law fashion or by Haard-Madau spectrum and carbon is mostly in the form of CIII, while CIV reaches at best $x(\mathrm{CIV}) \sim 0.1$ in a very narrow temperature range around $\log T = 4.5$. The amount of the carbon in the IGM that could be inferred from the observed CIV is shown therefore as the dashed line in Fig. 1. This amount relates to the total produced carbon in the Universe as

$$\Omega(\mathrm{C}) = \frac{\Omega_{IGM}(\mathrm{C})}{\delta_B} \tag{2}$$

where δ_B is the fraction of enriched gas averaged over the galactic mass spectrum blown out by galaxies via supernovae shocks. Using the approximation described in Ferrara et al. (2000) and for a Press-Schechter luminosity function one could get $\delta_B \sim 0.3$, weakly depended on z. This results in the amount shown in Fig. 1 by the dotted line. It is readily seen from here that the estimated total carbon mass in the Universe corresponding to the observed intergalactic CIV ions is consistent to the one produced by stars with the rate inferred from the rest-frame UV and optical (Bouwens et al. 2008).

In the middle panel of Fig. 1, calculated mass of the heavy elements is compared to that observed in the case of damped Ly-α (DLA) systems (Prochaska et al. 2003; Kulkarni et al. 2005; Rao et al. 2005). An order of magnitude deficit of metals in DLA systems is readily seen, which is thought to be due to the fact that the line-of-sight probes mostly in the external regions of galactic disks $dP \propto \pi r dr$, where metals are normally less abundant. The contribution to the metal mass from the inner DLA disks

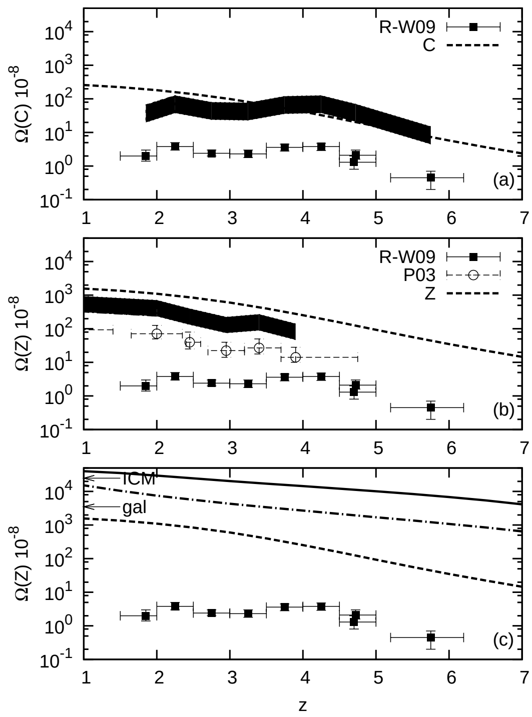

Figure 1. *Upper panel.* Dash line shows the total amount (mass density in units of the critical density ρ_c) of carbon: $\Omega(\mathrm{C}) = \rho(\mathrm{C})/\rho_c$) produced in the Universe within the Bouwens et al. star formation scenario; filled squares with error bars represent the observed amount of CIV (Ω(CIV)) in the IGM Ryan-Weber et al. (2009), the upper limit of the filled region show the total mass density of carbon in the IGM (Ω(C)) estimated with accounting the fact that CIV comprises atmost 0.1 of total carbon Vasiliev & Shchekinov (2011), the lower limit of the filled region converges carbon in the IGM (as shown by dashed line) to the total carbon in the Universe under the assumption that only dwarf galaxies $M_G < 10^{12}(1+z)^{-3/2}\ M_\odot$ can efficiently eject metals Ferrara et al. (2000). *Middle panel.* Same as in the *upper* panel but compared with metals observed in DLA systems (open circles with error bars; DLA data are taken from Prochaska et al. (2003); Kulkarni et al. (2005); Rao et al. (2005)). *Lower panel.* Same as in the *middle* panel but with metal production by star formation within the UVY-SFH (dash-dotted line) and GRBF-SFH (solid line) scenarios; for comparison metal production within UV-SFH is also shown by lower dash line as in the other panels; two arrows indicate the present day metal content in galaxies (gal) and cluster of galaxies (ICM).

is however also proportional to $dM_Z \propto \pi r dr$

$$\langle Z \rangle = R^{-2} \int_0^R Z(r) r dr. \tag{3}$$

Normally $Z(r)$ can be represented as $Z(r) = Z_0 e^{-kr}$ with the decrement k providing an order of magnitude drop on the galactic scale of $\simeq$ 5 kpc. For instance, for a galaxy at $z = 1.5$ (Yuan et al. 2011) infer $k = 0.37$ and $Z_0 \sim Z_\odot$, which then gives $\langle Z \rangle = 0.16 Z_0 \sim 0.1 Z_\odot$ close to the number detected in the inner DLA disks. Similar results are found by (Jones et al. 2010) for a $z = 2$ strongly lensed galaxy. In total, one can expect thus that the amount of metals confined in DLA systems is still half of the metals produced by stellar nucleosynthesis with the Bouwens et al. SFH. This discrepancy was fist formulated by (Pettini 1999) as the missing metal problem. This problem seems to reflect only the fact that for some reasons metals escape detection in distant ($z > 1$) Universe, while the metallicity in the local ($z \simeq 0$) Universe: $\Omega_Z \sim 10^{-5}$, is consistent with the predictions based on UV-SFH scenario.

An obvious flaw in determination of the SFH through rest-frame UV and optical emission can be understood from the Hubble diagram of the GRB hosts (Sokolov et al. 2001; Yan et al. 2010) and is connected to rather lesser number density of low-luminosity galaxies, $M_{AB} > -16$ (Bouwens et al. 2008). Indeed, low-luminosity galaxies dominate in the early Universe: for instance, recent observations show variation of the median galactic magnitude M^* from $\simeq -21$ at $z = 2$ to $M^* \simeq -17$ at $z = 8$ (Finkelstein et al 2010). Therefore, when integrating with the *HST* Wide Field Camera up to $M = -15$ (Yan et al. 2010) obtained at $z > 6$ almost two orders of magnitude higher SFR than inferred by Bouwens et al. (2008), and even more important is that such a high SFR continues to $z \simeq 10$. Similar value is predicted by (Firmani et al. 2004) – GRBF-SFH. (Kistler et al. 2009) determined several times smaller star formation rate from GRB statistics, which is consistent with the star formation rate determined from more deep rest-frame UV and optical observations accounting weaker galaxies (Yan et al. (2010)) (UVY-SFH), which though still looks continuing almost constant up to at least $z = 9$. In the lower panel of Fig. 1 we show metal production in the two scenario's of star formation: one corresponds to the GRBK-SFH, the other to the GRBF-SFH; in both cases we integrated metal production rate from $z = 10$. A significant overproduction of metals at the present day Universe compared to the mass of metals contained in galaxies and even in the cluster of galaxies is obvious. The only way to escape overproduction of metals can apparently be found in an assumption that GRB hosts are isolated, in the sense that the mass exchange between them and the surrounding medium is restricted and from this point of view they are distinct from non-GRB host galaxies. It can be connected with an existence of extended gaseous halos around them extinguishing mass outflows.

3. Reionization of the Universe

Another possible consequence of the enhanced star formation within the GRB-SFH scenario is an overproduction of the ionizing photons, which can change ionization history of the Universe: in general, early enrichment is expected to produce early reionization. The details depend though on many factors like: gas clumpiness, fraction of ionizing photons that escape the regions of active star formation, and so forth (see, in Barkana & Loeb (2001); Ferrara & Salvaterra (2006)). A rough estimate of the porosity factor of the ionized regions produced by star-forming galaxies could be written as

$$Q_{\rm HII} = \frac{4\pi}{3}\int dM \frac{d\phi}{dM} R_M^3, \text{ with } \frac{4\pi}{3} R_M^3 = \frac{L_i(M) f_e}{\delta^2(z) C \bar{n}^2(z)\alpha_r} \tag{4}$$

where $\phi(M)$ is the galaxy luminosity function, $L_i(M)$ is the ionizing photon luminosity of a galaxy with mass M, f_e is the fraction of ionizing photons able to escape a parent galaxy, $\delta(z)$, the environmental over-density: $\delta(z) > 1$ for the walls and $\delta(z) < 1$ in voids, $C = n^2/\bar{n}^2$, the clumping factor, α_r is the recombination rate. Note that the recombination is inefficient, i.e. takes longer than Hubble time, if $\delta^2 C \leq 1$ (Barkana & Loeb 2001). It is obvious that the porosity factor $Q_{\rm HII}$ is proportional to the star formation rate. Rough estimates of the $Q_{\rm HII}$ for the three scenarios of the cosmic SFH: GRBF-SFH (Firmani et al. 2004), UVY-SFH (Yan et al. 2010) and UV-SFH (Bouwens et al. 2008) are

$$Q_{\rm GRBF} : Q_{\rm UVY} : Q_{\rm UV} \sim \left[3\times 10^3 : 2\times 10^2 : 50\right] f_{e,0.1}(1+z)^{-3}, \tag{5}$$

where we have assumed the SFR constant $SFR \sim 0.6$ at $z = 6-20$, $SFR \sim 0.04$ at $z = 8-20$, and $SFR \sim 2\times 10^{-3}[M_\odot\ {\rm yr}^{-1}{\rm Mpc}^{-3}]$ at $z = 8-20$, respectively. Note that the UVY-SFH and the SFH scenario inferred from GRB statistics by (Kistler et al. 2009) (GRBK-SFH) are very close and therefore have similar effects on the reionization. For a fiducial value $f_e \sim 0.1$ (see, e.g. (Dove et al. 2001; Steidel et al. 2001)) the GRBF-SFH scenario completes reionization too early – at $z > 15$, the UVY-SFH reionizes the Universe at $z > 6$ in concordance with the observations, while the UV-SFH produces not sufficient amount of ionizing photons for the reionization. More recently, based on numerical simulations, Wise & Cen (2009) and Razoumov & Sommer-Larsen (2010) found arguments in favor of much higher photon escape fraction $f_e \simeq 0.8$, in which case the full reionization described by the three scenarios shifts toward $z \simeq 28$, $z \simeq 12$ and $z \simeq 7$, respectively. For a conservative estimate of the escape fraction, $f_e \sim 0.1$, the star formation scenario based on more deep UV and optical observations accounting weak galaxies – UVY-SFH (or equivalently, GRBK-SFH), predicts reionization history consistent with observations. The production of ionizing photons by GRBF-SFH scenario seems excessive in both cases. However, it is to be noted that extended gaseous halos around the host galaxies can confine ionizing radiation within the galaxy itself.

4. Summary

The cosmic star formation history inferred from GRB statistics predicts too early reionization and overproduction of metals in the Universe inconsistent with the observations. This difficulty can be avoided only if one assumes the GRB hosts to be distinct from non-GRB host galaxies. One can assume, for example, that GRB hosts have extended gaseous halos, able to absorb both the mechanical energy from supernovae explosions and the ionizing radiation. In this case, even though their contribution to the total star formation rate can be considerable, the excessive metals and ionizing photons should remain confined in their closer vicinity. On the other hand, it is suggested that the high star formation rate inferred from GRB statistics can be due to higher GRB/SN ratio if the hosts are low-mass and low-metallicity galaxies and have, as a consequence, a top-heavy initial mass function. From the first glance, this suggestion seems to conflict observations which show that GRB host galaxies are not metal-poor (Savaglio 2008). It has to be noted though that the high spread of abundances observed in the GRB hosts (Savaglio 2008) might reflect a highly patchy distribution of metals in their ISM due to poor mixing. Depending on the specific (per unit volume) SN rate mixing of metals in galaxies can take from $\sim$ 100 Myr (de Avillez & Mac Low 2002) to $\sim$ 1 Gyr (Vorobyov et al. 2009). This might mean that even in well evolved galaxies with high mean metallicity one can find metal-poor clumps of star formation with a top-heavy IMF. This suggestion is supported by observations of a nearby SN (2009de, ($z < 0.3$) with a low metallicity host reported by Moskvitin et al. (2010).

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