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Mixing under stripping of extended galactic gaseous halos : numerical simulations of turbulent mixing of metals ejected by a starburst into the intergalactic medium

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We describe briefly a process of metal mixing in the intergalactic medium under stripping of a galactic gaseous halo : two-dimensional numerical model for mixing of metals ejected into the intergalactic medium by a starburst, and stripped then by ram pressure of the incoming intergalactic gas is performed. The efficiency of mixing is analyzed in terms of statistical characteristics, such as the metallicity distribution function, characteristic scale lengths occupied by a given metallicity, and others. It is shown that depending on the velocity of the incoming flow of the intergalactic gas the whole region containing metals can be as large as 200 kpc in size, however, even within this volume metallicity distribution remains rather inhomogeneous with a spread of up to three orders of magnitude.

1 Introduction

It was recognized during last several years that the intergalactic medium (IGM) at redshift $z \leq 5.5$ is already polluted with metals, as seen from observations of CIV and SiIV absorptions in Lyα forest systems in quasar spectra. The metallicity Z of the IGM averaged over a wide interval of column densities ($10^{12} \leq N(\mathrm{CIV}) \leq 10^{15}$ cm^{-2}) is $Z = -3$, close to the metallicity of most metal poor stars in our Galaxy, while in the interval $10^{13} \leq N(\mathrm{CIV}) \leq 10^{14}$ cm^{-2} metallicity is substantially lower, which shows that metals are distributed in the

IGM nonhomogeneously. The averaged metallicities in both column density intervals remain nearly independent on z up to $z \simeq 5.5$, and show decline at larger z [1]. This fact, together with observations of Gunn-Peterson effect at high redshift $z \sim 6$ (see Songaila & Cowie [2]), possibly indicate that after an initial pollution of metals from the first objects their content and the degree of the inhomogeneity in the IGM remained invariant at later epochs.

It is obvious that the enrichment of the IGM with metals is connected with star formation activity and associated supernovae explosions in young galaxies. However, the details of this process still remains not well understood. It was shown by Ferrara, Pettini & Shchekinov [3] that metals ejected out of galaxies of a quiescent star formation mode are confined within a restricted volume around the polluting galaxy, and the volume filling factor always being substantially less than one. Only in those cases when star formation activity in early galaxies approaches star-burst mode, the ejecta can form pervasive network (i.e. the volume filling factor of ~ 1, Madau, Ferrara & Rees [4]). However, even in this situation the ejected metals are far from being distributed homegeneously, as the amount of metals ejected, the volume occupied by the ejecta, and therefore the metallicity in this volume depend on individual properties of a parent galaxy [3,5]. At such conditions, only efficient mixing mechanisms can spread metals over large scales corresponding to the scales of the low density end of Lyα absorbers, $N(\mathrm{HI}) \leq 10^{14}$ cm^{-2}. In this paper we briefly describe properties of one of possible mixing mechanism connected with stripping of a metal enriched envelope around a galaxy by ram pressure of the outflowing intergalactic gas. Detailed description can be found in [6].

2 Model

We consider the following simple model: a metal-enriched gas is ejected from a galaxy by an explosive mechanism and, therefore, forms a sufficiently thin shell. We simulate numerically in 2D description dynamics of such a metal enriched thin shell with the outer radius $R = 31$ kpc and thickness $\Delta R = 1$ kpc moving through the IGM with the velocity $u = 100$ km s^{-1}. We neglect the effects of gravitational field of a parent galaxy on the shell, which corresponds to the case when the ejected gas acquires enough energy to escape from a galaxy. At the same time, for the sake of simplicity the shell is assumed to be in hydrostatic equilibrium at the initial moment. This implies $p^0_{sh} = p^0_{igm} = p^0_h$, where p^0_{sh} is the pressure in the shell, p^0_{igm} is the pressure of IGM outside the shell and p^0_h is the pressure inside the shell. These simplifications are justified, because we consider a mixing of metals in the IGM inrespective to the properties of a parent galaxy. Gas densities in the shell, outside the shell and inside the shell are assumed equal to $n_{sh} = 4.4 \times 10^{-4}$ cm^{-3}, $n_{igm} = 4.4 \times 10^{-6}$ cm^{-3} and $n_h = 4.4 \times 10^{-6}$ cm^{-3}, respectively. The corresponding temperatures are $T_{sh} = 10^4$ K, $T_{igm} = 10^6$ K, $T_h = 10^6$ K and metallicities (i.e. the ratio of metal density to gas density) are $Z_{sh} = 10^{-3}$, $Z_{igm} = 0$, $Z_h = 0$.

We use the Zeus-2D numerical hydrodynamics code. A usual set of hydrodynamics equations in the cylindrical coordinates (r, z) is solved using the method of finite-differences with a time-explicit, operator split solution procedure explained in detail by Stone & Norman [7,8]. The computational area of $\Delta r \times \Delta z = 125 \times 300$ kpc is devided into 1000×2400 grid points. The shell is centered at $r = 0$, $z = 100$ kpc. The intergalactic gas flows with velocity $u = 100$ km s^{-1} at z direction. Metallicity as a passive scalar variable is accounted for by adding the following transfer equation to the Zeus-2D code:

$$\frac{\partial Z}{\partial t} + \mathbf{u}\nabla Z = 0,$$

which is solved simultaneously with other hydrodynamics equations. With such an addition the Zeus-2D code rests conservative and keeps the accuracy and stability.

We terminate our simulations at time 1×10^{17} s (3.17 Gyr). At this moment the metal-enriched region occupies ≈ 200 kpc. We do not consider here the effects of a Hubble expansion. Indeed, the necessity of its inclusion at such distances from a galaxy is not obvious at all (even in the case of a field galaxy the effects of galactic gravitational potential dominate under the Hubble field up to distances ≈ 100 kpc, depending on galaxy mass and redshift z).

3 Results and conclusions

General features of metal mixing in a moving intergalactic gas are demonstrated in Figure 1. Here a metallicity distribution on a grid at time $t = 9 \times 10^{16}$ s (2.85 Gyr) is shown. It is seen that enrichment is extremely inhomogeneous in the regions of non-zero metallicity. Average metallicity in this region $< Z >= 4.6 \times 10^{-4}$, but a major contribution is due to high-metallicity spots $Z \geq 6.0 \times 10^{-4}$, which volume fraction is 12.5% in all.

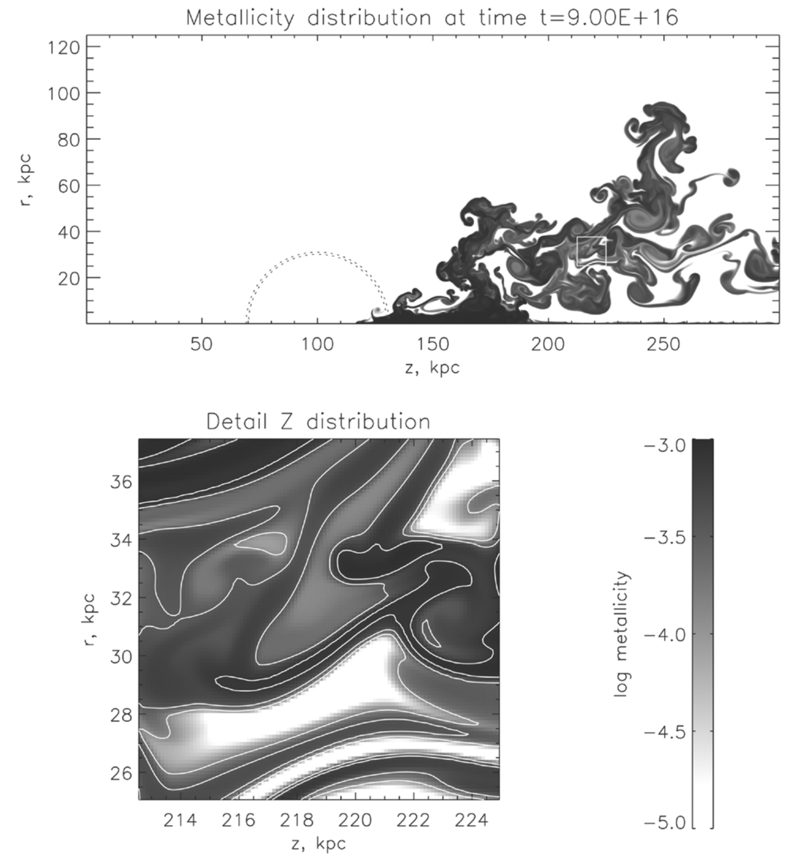

Figure 1. Metallicity distribution in the whole computational area and in the selected region. The initial position of the shell is marked by the dashed lines

Figure 2 presents histograms of the number of cells with metallicity at a given interval (since the number of intervals is large, the histogram practically corresponds to the metallicity distribution function). It is seen that even at the early times a considerable fraction of metals is spread over a larger volume than is initially occupied by the shell (see panels 1-4 which correspond increasing times).

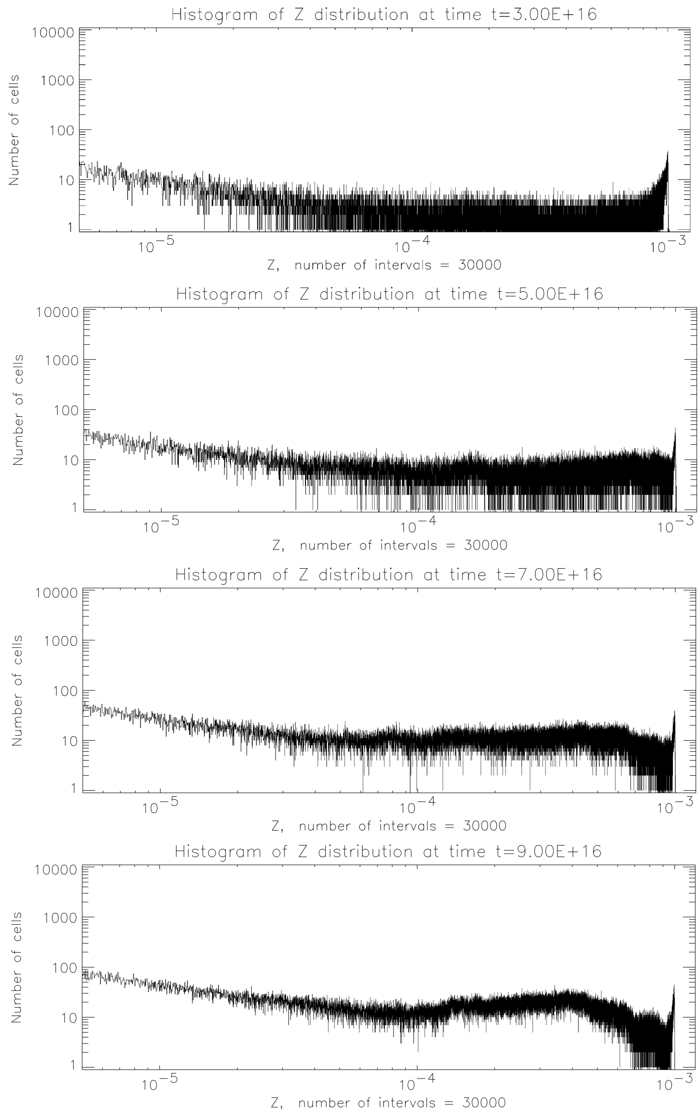

Figure 2. Histograms of the metallicity distribution at different times

The resulted distributon of metals essentially differs from that of a diffusion process. In particular, this reflects the fact that metals in our numerical model are spread over a larger number of numerical cells with high metallicity than in a simple diffusion model. Moreover, the sufficient scatter in number of cells with near values of metallicities is observed in regions with high metallicities. It argues that on the small scales metals are distributed in well isolated spots and exchange between them is limited. Such properties of the mixing process correspond to the process with intermittency [6].

In the present work we limit ourselves to an adiabatic model when processes of radiative cooling are not considered. In reality, a role of radiative cooling may be important because in this case regions with greatest metal abundance cool faster and therefore collapse faster, so their participation in mixing will be obstructed. In the next paper we will demonstrate new effects of a mixing to which radiative losses can bring about.

Acknowledgements

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