MIXING METALS UNDER STRIPPING GALACTIC GASEOUS HALOES: RADIATIVE LOSSES

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ABSTRACT. We present two-dimensional numerical model for mixing of metals in the intergalactic medium under stripping of a galactic gaseous halo both in adiabatic and radiative cases. A particular attention is paid to influence of radiative losses on mixing efficiency. We conclude that the statistical features of metal distribution are quite similar to those in adiabatic case.

Key words: intergalactic medium, metals, enrichment, mixing.

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 $Z = -3$, 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 inhomogeneously. 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 (Songaila 2001). This fact, together with observations of Gunn-Peterson effect at redshift $z \sim 6$ (Songaila & Cowie 2002), 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.

Recent observations of absoption systems in the spectra of distant quasars (Schaye et al 2007) and environments of galaxies at $z = 2-3$ (Simcoe et al 2006) present new arguments for strong inhomogeneity of the intergalactic medium in wide range of spatial scales. Earlier the similar conclusion about inhomogeneous distribution of metals in the IGM was numerically obtained by Dedikov & Shchekinov (2004). In adiabatic conditions they have simulated the mixing mechanism connected with stripping of a metal enriched envelope around a galaxy by ram pressure of the outflowing intergalactic gas. Here we present the similar model with radiative losses.

2. Model

We consider the following simple model (more details can be found in Dedikov & Shchekinov 2004): 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. For the sake of simplicity the shell is assumed to be in hydrostatic equilibrium at the initial moment. 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 hydrodynamics code (Stone & Norman 1992) in the cylindrical coordinates (r, z). The computational area of $\Delta r \times \Delta z = 125 \times 300$ kpc is

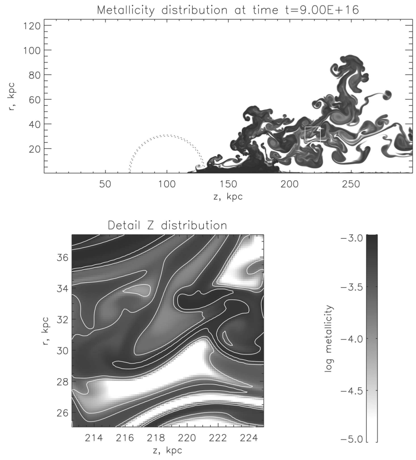

Figure 1: Metallicity distribution in the whole computational area and in the selected region. The initial position of the shell is marked by the dashed lines.

divided into 1000×2400 grid points. 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 transfer equation to the Zeus-2D code. The cooling term include Lyα losses from hydrogen and cooling in the fine structure of single ionized carbon, atomic oxygen and metastable lines of CII and OI (Penston 1970, Hollenbach & McKee 1989). We solve the energy equation using the Newton-Raphson iterative procedure.

3. Results and conclusions

General features of metal mixing are demonstrated in Figure 1, where is presented a metallicity distribution at time $t = 2.85$ Gyr for the adiabatic case. It is clearly seen that enrichment is extremely inhomogeneous in the regions of non-zero metallicity. Average metallicity in this region $\langle Z \rangle = 4.6 \times 10^{-4}$, 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. In the model with radiative losses the cooling is important in regions with greatest metal abundance, because they cool faster and therefore collapse faster. This is displayed in more extended metal distribution along z-axis while along radial direction. Another distinction consist with the time of mixing: for the case with radiative losses this value is greater.

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) for both adiabatic and radiative cases. One can find a statistically insignificant difference between two cases.

The resulted distributon of metals essentially differs from that of a diffusion process. In particular, this

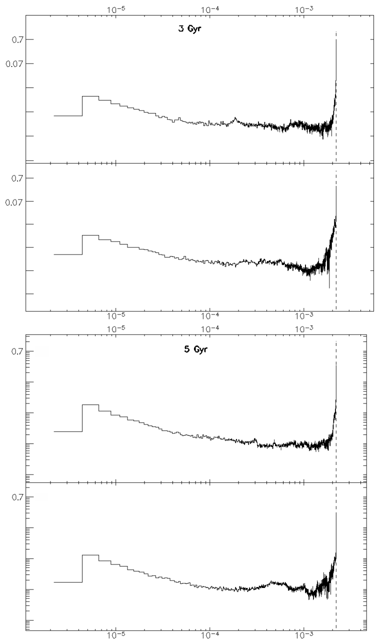

Figure 2: Metallicity distribution for adiabatic (upper) and radiative (lower) cases.

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 (Dedikov & Shchekinov 2004).

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