PECULIARITIES OF MIXING METALS IN INTERGALACTIC AND INTERSTELLAR MEDIA

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ABSTRACT. We review the current status of the problem of metal mixing in the intergalactic and interstellar media. We give simple arguments for inefficiency of mixing metals because of a saturation of hydrodynamic (Rayleigh-Taylor and Kelvin-Helmholz) instabilities. We describe mixing in two typical processes: stripping of a galactic gaseous halo and cloud-cloud collision. We show that statistical features of metal distribution observed in the intergalactic medium is close to those obtained in our numerical simulations.

Key words: interstellar and intergalactic medium, metals, enrichment, mixing, hydrodynamic instabilities

1. Observations vs. simulations

After the reionization the metallicty of the intergalactic medium (IGM) reaches a value [Z]~ -3 and is kept at this level during a very long time, at least between redshifts $z = 2 - 5$ (Songaila 2001). This fact contradicts to the conventional theoretical models of the enrichment of the IGM with metals, which predict the increase of metallicity with age of the universe (Nath & Trentham 1997, Ferrara et al 2000). A possible solution can be connected with a strong and fast enrichment of the IGM by first stellar systems at $z \sim 10$ (Madau et al 2001). The spatial distribution of metals in this model appears to be more or less homogeneous. Moreover, the assumption of homogeneity is very often utilized in the estimates of metal budget in the IGM (Songaila 2001, Ferrara et al 2005). However, recent observations of metal absorptions in the intergalactic medium show extremely inhomogeneous distribution of metals on wide spatial scales (Simcoe et al 2006, Schaye et al 2007, Hao et al 2007). Inhomogeneous distribution of metals in the IGM was predicted theoretically by Dedikov & Shchekinov (2004) on the basis of numerical simulations of stripping of galactic gaseous haloes. In general this result can be obtained from a simple analisys of hydrodynamic (Rayleigh-Taylor and Kelvin-Helmholtz) instabilities, which are mainly responsible for metal mixing in the IGM (Dedikov & Shchekinov 2004).

The distribution of metals in the interstellar medium (ISM) is believed to be homogeneous due to multiple actions from stellar winds, supernovae explosions and other dynamic processes. However, recent observations suggest that the distribution of species such as deuterium (Jenkins et al. 1999) and oxygen (Meyer et al 1998) in the ISM are far from being homogeneous. De Avillez & MacLow (2002) have numerically simulated mixing of metals in a mono-phase ISM. They concluded that the timescale for complete mixing is quite long, ~ 350 Myr, and the mixing efficiency strongly changes with spatial scales. Moreover, in realistic coinditions of a multi-phase ISM mixing time obviously increases.

In this paper we briefly describe general properties of mixing process and how they manifest themself in the IGM and ISM.

2. Instabilities and mixing of metals

Mixing or erasing of chemical inhomogeneites in the IGM and ISM acts under irregular gaseous motions, which in turn are often supported by hydrodynamic instabilities, such as Rayleigh-Taylor (RT) and Kelvin-Helmholtz (KH) instabilites, developed when an enriched gas clump moves through diffuse medium. During the motion of a cloud through the intercloud medium the development of KH instability begins from a characteristic scale equal initially to the cloud radius (Klein et al 1994, Vietri et al 1997). Further on such large scale vortices cascade to produce inhomogeneities of smaller scales. As a result the cloud surface increases and the dynamic friction

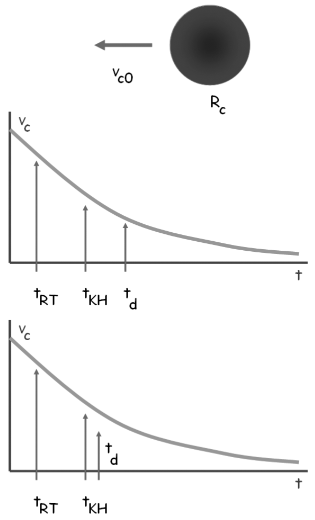

Figure 1: Schematic description of the saturation of instabilities: upper graph shows the interrelation between the characteristic times: the dynamic friction time t_d, the time scales of KH and RT instabilities $t_{\rm KH}$ and $t_{\rm RT}$ – in the initial state; lower graph shows this interrelation after a few KH time scales when the cloud surface increases due to progressive cascading of vortices (Dedikov & Shchekinov 2004, Shchekinov et al 2008).

time shortens. The cloud decelerates progressively, its velocity gradually decreases, $v_c \to 0$, and KH instability slows down proportionally. This process manifests as a saturation of the instability. Once the saturation is reached the mixing freezes out. As KH and dynamic friction time scales are usually close to each other, as schematically shown in Figure 1, the instability saturates quickly.

3. Mixing in the IGM

General features of metal mixing in the intergalactic medium under stripping of a galactic gaseous halo are presented in Figures 2 and 3, where the metallicity, density and temperature maps at times 1.27 and 2.54 Gyr are shown for an adiabatic (nonradiative) case. Note that although radiative losses by hydrogen and metals change the maps qualitatively, statistical properties of the metal distribution remain essentially unchanged (see Dedikov et al., this volume).

Figure 4 demonstrates the metallicity histogamm for stripping of a galactic gaseous halo. The resulted distributon of metals differs substantially from that produced by turbulent diffusion (the distribution corresponding to mixing by turbulent diffusion is depicted as dash line in Figure 4, the details can be found in Dedikov & Shchekinov 2004). This reflects the fact

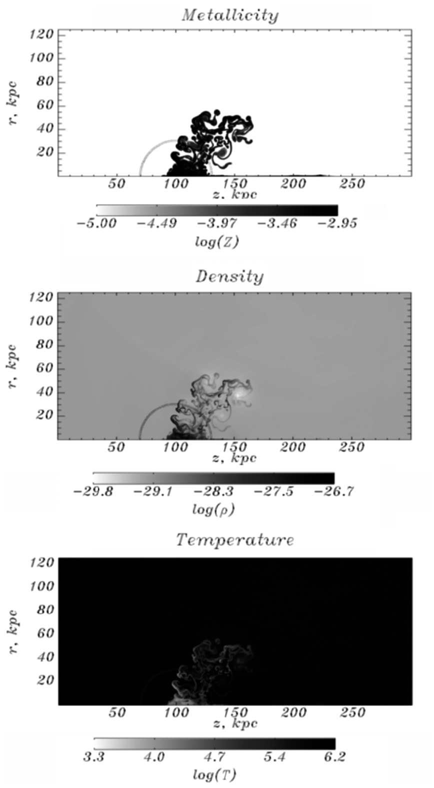

Figure 2: Metallicity, density and temperature distributions for stripping of a galactic gaseous halo at time $t = 1.27$ Gyr.

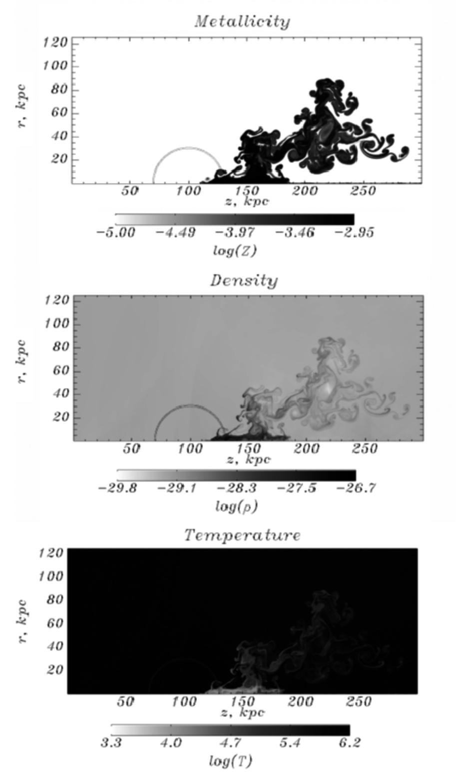

Figure 3: Same as in Figure 1 at time $t = 2.54$ Gyr.

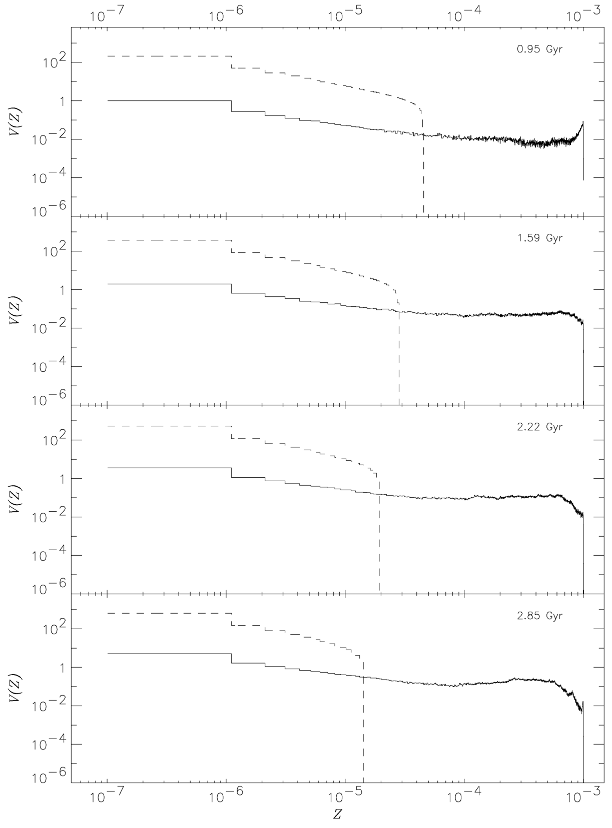

Figure 4: Metallicity histogamm for stripping of a galactic gaseous halo. The corresponding distribution produced by turbulent diffusion is depicted by dash line.

that metals mixed by cascading vortices remain confined into restricted pockets contrary to a diffusion model where they are redistributed homogeneously through the whole computational zone. Such pockets are surrounded by the background low-metallicity medium. This picture resembles an intermittent distribution (Dedikov & Shchekinov 2004).

Overall, asymptotically a highly inhomogeneous spacial metal distribution establishes with a numerous spots of low and high metallicity. From intuitive arguments one can expect an interrelation between the metallicity in such spots and their size. In order to determine this interrelation we applied a procedure similar to the cluster analysis: the metal distribution is presented as a relief map, which then is cutted at a given metallicity level Z_0, so that the regions with the metallicity $Z > Z_0$ isolate each other, and their surfaces can be explicitly calculated. If one assumes that the size of a given region is a square root of its surface, the “metallicity-size” relation in the form shown in Figures 5 and 6 can be found (Dedikov & Shchekinov 2004, Dedikov et al., 2009): Figures 5 presents the “metallicity-size” relation for stripping of a galactic gaseous halo at time 1.27 Gyr, while Figure

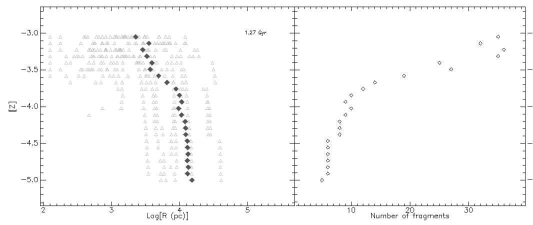

Figure 5: “Metallicity-size” (left panel) and number of fragments-metallicity (right) distributions for stripping of a galactic gaseous halo at time $t = 1.27$ Gyr. The metallicity and size for each isolated region is depicted by open symbols. Filled symbols present the mean size for a given metallicity.

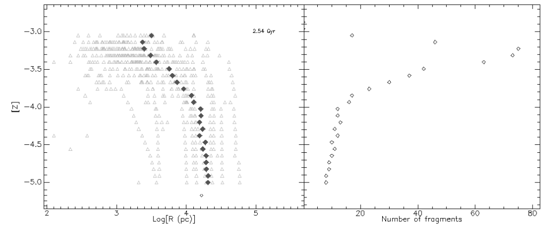

Figure 6: Same as in Figure 5 at time $t = 2.54$ Gyr.

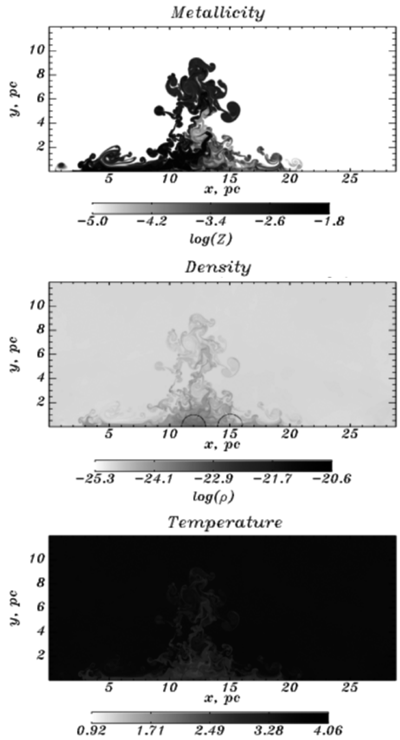

Figure 7: Metallicity, density and temperature distributions for cloud-cloud collision at time $t = 4.76$ Myr. The contours in the middle panel correspond to the initial positions of the clouds.

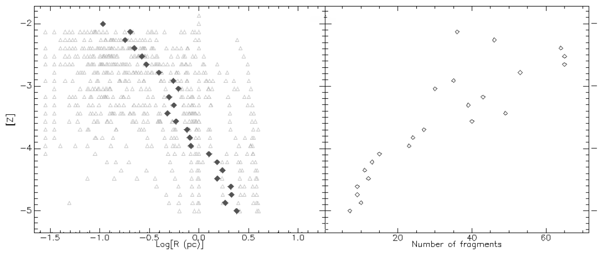

Figure 8: "Metallicity-size" (left panel) and number of fragments-metallicity (right) distributions for cloud-cloud collision at time $t = 4.76$ Myr.

6 – at 2.54 Gyr. Right panels in Figures 5 and 6 represent the number of fragments-metallicity relations. It is clearly seen from here that more metallic regions are smaller in size and more numerous. Thus, the detection of such regions in the IGM can be difficult and the metal bugdet in the IGM is underestimated.

4. Mixing in the ISM

Mixing of chemical species in the ISM obviously takes shorter characteristic time in comparison with that in the IGM, mainly because of highly developed turbulent motions supported by numerous shock waves from supernovae explosions and stellar winds. However, mixing still remains quite slow (de Avillez & Mac Low 2002), which is determined by the rate of shock waves passing through a given volume of the ISM. Another reason is connected with the enrichment from newly formed stellar clusters. Thus, one can expect that metal distribution in the ISM reveals strong spacial variations as it occurs in the IGM.

Another possible mixing process in the ISM is connected with cloud-cloud collisions. Here we present results for collisions of nearly equal clouds (5% difference in radius) with $n = 10$ cm^{-3}, $T = 100$ K, with metallicities $[Z] = 10^{-1}$ and 10^{-3}, and equal velocities $v = 5$ km s^{-1} (Vasiliev et al., in preparation). We apply the same statistical procedure to analyze the distribution of metals resulting in this process. Figure 7 presents the maps of metallicity, density and temperature for this model, while Figure 8 shows the corresponding "metallicity-size" and number of fragments-metallicity diagramms. One shoud note that the dependence of "metallicity-size" looks similar to that for stripping of gaseous halos (Figures 5 and 6).

5. Conclusion

In this paper we briefly reviewed properties of metal mixing in the intergalactic (IGM) and interstellar (ISM) media, which can be summarized as follows

- slowing down relative gas motions leads to saturation of hydrodynamic instabilites and results in a freezing of chemical inhomogeneities;
- mixing of metals remains therefore incomplete, and the distribution of metals is kept highly inhomogenious on small scales, so that the most metal-rich material is confined into small-sized pockets.

Recent observations confirm indeed fairly inhomogeneous distribution of metals in the IGM and ISM. We found that statistical characteristics of metal distribution oberved in the intergalactic medium looks similar to those obtained in the numerical simulations, and show the features usual for gaseous flows with saturation of hydrodynamic instabilities.

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