GALAXIES AND THE INTERGALACTIC MEDIUM: EVOLUTIONARY INTERRELATIONS

B.M. Shustov

Institute of Astronomy of the RAS, Pyatnitskaya str. 48, Moscow, 119017, Russia
bshustov@inasan.ru

ABSTRACT. During their life galaxies exchange in matter and energy with the intergalactic medium (IGM). This complex process is a most important factor in galactic evolution as well in evolution of the IGM. In this paper recent progress in the IGM studies and mechanisms of mass gain and mass loss from galaxies are briefly reviewed. Using a model of chemo-dynamical evolution of galaxies I discuss enrichment of the IGM with metals and origin of the radial gradients of chemical composition in disk galaxies as possible consequence of heavy elements loss. The general conclusion is simple: many problems remain unsolved but we are under way to understanding of consistent evolution of galaxies – IGM system.

1. Introduction:

One of the most fundamental questions of galactic evolution can be formulated very simply – "what are main features of evolutionary interrelations galaxies – intergalactic medium?" This question is addressed to both groups of experts: cosmologists and astrophysicists. From the commonly used terminology the galactic history is divided in two eras (Hensler, 1987):

- the time before and during protogalactic clouds on galactic mass scale grow. In this era the matter can be considered as primordial gas that is a building material for the future (clusters of) galaxies;
- the time after these protogalactic clouds have commenced to collapse as isolated systems (in this era galaxies become a dominant baryonic structures in the Universe which strongly influence on the IGM).

First item is a subject of cosmological studies. The second one – lies mostly in the domain of astrophysics. Martin Rees noted (1985) that "galaxy formation straddles the interface between cosmology an astrophysics". Recent observations and theoretical models brought valuable data about galactic evolution and arguments for considering the galactic evolution in consistence with evolution of the intergalactic medium (IGM). In this paper I briefly review this issue drawing special attention to chemical evolution.

In Sect. 2 I introduce some general facts about the intergalactic medium. Mechanisms of interaction between galaxies and IGM are discussed in Sect. 3. In Sect. 4. a simple though powerful model of chemo-dynamical evolution of (disk) galaxies is introduced and two problems related to chemical interrelations between the IGM and galaxies: enrichment of the IGM and radial gradients of chemical abundances in disk galaxies are discussed.

2. Intergalactic medium before and after galaxy formation

2.1. IGM before formation of galaxies

With the expression "intergalactic medium" one indicates the material other than ordinary galaxies. This is some analogy between stars – interstellar medium (ISM) and galaxies – IGM. Astrophysicists do not classify the ISM in the stellar clusters as separate object though detailed classification of various circumstellar structures (shells, outflows etc.) is elaborated. In the case of IGM inside clusters of galaxies (remember that most of galaxies belong to some cluster, and in contrary most of stars in galaxies are those of field) we use the expression "intracluster medium" (ICM). The properties of the IGM drastically changed in the process of evolution of the Universe. I sketch the evolution just to introduce main ingredients of the IGM and their general interrelations with galactic evolution.

According to the conventional picture of Creation Myth (see Fig. 1) the smooth baryonic plasma consisted of hydrogen, helium and light elements, produced in the first three minutes after the Big Bang, and hot black body radiation filled the expanding Universe. After few hundreds thousands of years at epoch corresponding to z~1000, the black-body radiation cooled below 3000 K and the plasma (primordial IGM) is expected to recombine and remain neutral until sources of radiation develop that are capable of reionizing it. Primordial IGM in this

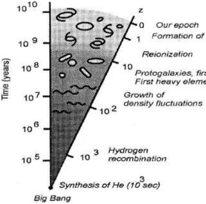

Figure1: History of the Universe

epoch ("dark ages") consists of cool gas filled with ever–faded cosmic background radiation.

Information of great importance about this primordial IGM is coming from observation of cosmic microwave background. The observed features, imprinted at z~1000, enable direct investigation of the formation of structure of the Universe as well as constraining the values of basic cosmological quantities such as the amounts of various forms of matter and vacuum energy in the Universe. The currently most favored theoretical model for describing our Universe is based on idea of inflation, which provides a natural mechanism for producing initial density fluctuation described by power-law spectrum and also predicts the Universe to be spatially flat. The initial spectrum of adiabatic density fluctuations is modulated through acoustic oscillations in the plasma phase prior to recombination and the resulting inhomogeneities are then imprinted as anisotropies in the CMB. In the inflationary scenario the CMB temperature anisotropies are predicted to follow a multivariate Gaussian distribution and so may completely described in terms of their angular power spectrum. Recent observation (Taylor et al. 2002) with the Very Small Array (a 14-element interferometer array installed at the Teide Observatory, Tenerife) at frequency 34 GHz on angular scales 3.6–0.4 degrees ($l = 150-900$) brought new confirmation of this theory. The power spectrum obtained (Scott et al. 2002) is in a very good agreement with the results of the BOOMERANG, DASI and MAXIMA telescopes. Combining the results obtained with all other CMB experiments and assuming the HST key project limits for H_0 Rubino-Martin et al. (2002) obtained the tight constraints for fundamental cosmological parameters.

In most of current models the contents of the Universe are divided into three components: baryonic (ordinary) matter, cold dark matter (CDM), which interacts with baryonic matter solely through its gravitational effect, and intrinsic vacuum energy. Some presence of so called warm dark mater is not excluded. Major difference between warm and cold dark matter is related to ability of weakly interacting particles, which the CDM or warm dark matter consists of, to wipe out part of the initial density fluctuations. For warm dark matter this scale of wiping out is much larger than for CDM. Durer&Novosyadly (2001) constructed a mixed dark matter model with some addition of massive neutrinos, which are assumed to be particles of warm dark matter. The general consensus is now almost universal that some variant of CDM including mixed models is probable. The present day contributions of these components to the overall density of the Universe are usually expressed in terms of the "omega parameter" $\Omega=\rho/\rho_{crit,}$ where $\rho_{crit}=3H_0/(8\pi G)=h^2 1.88\times10^{-29}$ g·cm^{-3} is the critical density with H_0 the present day Hubble constant $H_0=h\cdot 100$ km·s^{-1}Mpc^{-1} (most estimates of h lie in the range of 0.5-0.8). For our flat Universe $\Omega=1$. Fundamental parameters of cosmological models are contribution in Ω by vacuum energy $\Omega\Lambda$, and matter Ω_m, which consists of contribution of baryonic matter Ω_b and cold dark matter Ω_{cdm}. Rubino-Martin et al (2002) derived: $\Omega_m=0.28(+14-0.07)$ and $\Omega\Lambda=0.72(+0.07-0.13)$. Durer&Novosyadly (2001) give similar estimates, except additional term – the density of massive neutrinos $\Omega\nu=0.03(+0.07-0.03)$.

The evolution of the primordial IGM up to the end of "dark ages" is characterized by growth of the density fluctuations that eventually brings to formation of (cluster of) protogalaxies. Due to progress in numerical and analytical modeling in last decade (see e.g. review of Bertschinger 1998) most of researchers accept that clustering of small scale CDM fluctuations leads in a natural way to formation of so called "dark matter haloes", which are spheroidal non-dissipative CDM structures, governing by their gravitation the evolution (gathering and virialization) of dissipative baryonic matter in the central areas of the haloes. In such a scenario diffusely distributed baryonic material responds to the gravitational influence of the underlying dark matter. The most overdense regions collapse first to form the earliest galaxies. This leaves the remaining gas as the IGM. Rather than being a uniform medium filling the space between galaxies, the IGM itself should show structure on scales larger than that of individual galaxies. (Clusters of) galaxies are forming in the central parts of the haloes. At the heart of the hierarchical clustering process lies the fact that galaxies tend to form first near high peaks of the density field because these are the first to collapse at any given epoch. This is known as "biased galaxy formation", because the distribution of galaxies offers a biased view of the underlying distribution of mass. An important consequences of biased galaxy formation is that bright galaxies tend to be born in a highly clustered state that is strongly supported by observation (Benson et al. 2000, 2001).

It is a great challenge for scientists to find "exact" value of Ω_b i.e. to estimate amount of ordinary (baryonic) matter. This value can be estimated for a given cosmological model by measuring of primordial abundance ratio D/H. Standard nucleosynthesis models together with recent observations of deuterium yield $Y=0.247\pm0.02$ and $\Omega_b h^2=0.0193\pm0.0014$ (Burles&Tytler 1999). As some of the baryons had already collapsed into galaxies at $z=2-10$, the value of $\Omega_b h^2=0.019$ should strictly be considered as an upper limit to the intergalactic density parameter.

More direct way is to estimate relevant contributions from observations of all baryonic components. The problem is that we can only observe part of baryonic matter. The cosmic density distribution of galaxies is related to the measured luminosity density $(1.7\pm0.6)\mathrm{x}10^8 L_\odot \mathrm{Mpc}^{-1}$ in V-band. From mass-luminosity relation for galaxies the luminous matter density is estimated as $\Omega_{\mathrm{lum}} h=0.002-0.006$ (Carr 1994). Other forms of baryonic matter are believed to be:

- Intergalactic gas
- Hot gas in the ICM observed in X-ray domain
- Dim stars (only low mass first generation stars can be considered), small planet- or comet-like bodies and cloudlets.

I briefly describe first two constituents of the IGM.

2.2. Intergalactic gas

According to results of Burles and Tytler (1999) the proper mean density of hydrogen nuclei at redshift z may be expressed in standard cosmological terms as $n_H=1.6\mathrm{x}10^{-7}\,\mathrm{cm}^{-3}(\Omega_b h^2/0.019)(1+z)^3$. Cosmological models predict that most of the intergalactic hydrogen was reionized by the first generation of stars or quasars at $z\sim7$ or larger (this is considered as a workable definition of the "end of dark ages"). The process of reionization began as individual sources started to generate expanding HII regions surrounding IGM. As more and more sources of ultraviolet radiation switched on, the ionized volume grew in size. The reionization ended when the cosmological H II regions overlapped and filled the intergalactic space. The lack of smooth Ly-alpha absorption by HI in quasar spectra (Gunn&Peterson, 1965) led to the conclusion that diffusely distributed hydrogen is totally ionized at relevant z. From other side numerous absorption features ("Lyman alpha forest") clearly evidence for existence of clouds of neutral hydrogen in all range of z for quasars.

The term 'Ly-alpha forest' is used to denote the huge amount of narrow absorption lines whose measured equivalent widths imply N_{HI} ranging from $\sim10^{17}$ cm^{-2} down to 10^{12} cm^{-2}. A comprehensive review of properties of these absorbers is given by Rauch (1988). (An example of hydrogen Ly-α forest, observed with Keck telescope is shown below in Fig. 3.) Other class of intervening absorbers having a neutral hydrogen column density exceeding $2\mathrm{x}10^{17}$ cm^{-2} are optically thick to photons having energy greater than 13.6 eV and produces a discontinuity at the hydrogen Lyman limit, i.e. at an observed wavelength of 912(1+z)Å. These scarcer objects (Lyman Limit Systems -LLS) are associated with the extended gaseous haloes of bright galaxies near the line of sight. It is a reasonable approximation to use for the distribution of absorbers along the line of sight: $f(N_{\mathrm{HI}},z)=A\cdot N_{\mathrm{HI}}^{-1.5}(1+z)^\gamma$. The function of column density appears to provide at high redshift a surprisingly good description over 9 decades in N_{HI}, i.e. from 10^{12} to 10^{21} cm^{-2}. The γ is different for Ly-α clouds ($\gamma=2.8$) and for LSS ($\gamma=1.5$). Typical normalization value o $A=4\mathrm{x}10^7$ per unit redshift at $z=3$ produces 3 LLSs and ~150 forest lines above $N_{\mathrm{HI}}=10^{13.8}$cm^{-2}. In "Damped Ly-alpha Systems" (DLA) the HI column density is so large ($N_{\mathrm{HI}}\sim>10^{20}$ cm^{-2}, comparable with the interstellar surface density of spiral galaxies today) that the radiation damping wings of the Ly-α line profile become detectable. While relatively rare, damped systems account for most of the neutral hydrogen seen at high redshifts.

All Ly-α absorbers observed up to redshifts larger than 5 are believed to trace the potential wells of the dark matter. Except at the highest column densities, discrete absorbers are inferred to be strongly photoionized.

The most important outstanding issue regarding the DLA concerns their relationship with galaxies, though it is open question. Lanzetta et al. (1995) noted that while it is known that at least some DLA systems arise in galaxies, it is not known what range of properties (in terms, for example, of morphological type, luminosity, and surface brightness) are spanned by the absorbing galaxies, or even whether all DLAs arise in galaxies. Part of the difficulty is that the high neutral hydrogen column densities of damped Ly-α absorption systems imply small impact parameters to the lines of sight, and it is difficult to identify faint galaxies at small angular separations to bright quasars.

Pichon et al. (2001) analyzed the structure of the IGM using information on Ly-α forest from the spectra of QSO HE1122-1628 obtained with VLT/UVES and new inversion method. This method was applied to recover the temperature of the gas and underlying density field and to obtain 3D spatial distribution of the IGM from 1D information along grid of lines of sight. To test the method Pichon et al. (2001) simulated 3D distribution of

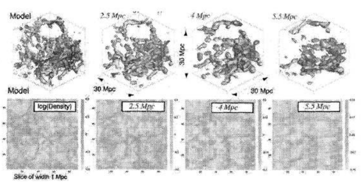

Figure 2: Top panels: the model of the IGM and the reconstructed density for distances between lines of sight 2.5, 4 and 5.5 Mpc. Bottom panels – a slice of 1x80x80 Mpc across the simulation and the reconstructed fields (the scale on the panels is in pixels) (from Pichon et al. 2001).

CDM and used the restoring technique (see Fig. 2). The technique seems to be tested successfully.

Helium is probably not reionized until z~3, as inferred from the strong HeII Ly-α absorption depressions due to Gunn-Peterson effect at (304 E)(1+z) in the UV spectra of high-z QSOs. This absorption was first observed (Heap et al. 1999) with HST spectrometer STIS along line of sight to the quasar Q0302-003 (z=3.29) (see Fig. 3).

It is an interesting discussion (see in Kriss et al. 2001) if HeII is smoothly distributed over the IGM or the depression at (304 Å)(1+z) in the UV spectra of this and other quasars is caused by HeII located in HI Ly-α absorbers and not resolved in spectra as HeII Ly-α forest only because of poor spectral resolution of UV telescopes. Kriss et al. (2001) probably elucidated the problem. They presented the FUSE observations of the line of sight to the quasar HE2347-432 in 1000-1187 Å band at a resolving power 15000 (Fig. 4). The HeII Ly-α absorption was resolved as discrete forest of absorption lines at redshif range 2.3 to 2.7. About half of these features have HI counterparts with column densities $N_{HI}>10^{12.3}$cm^{-2}. The HeII to HI column density ratio ranges from 1 to >1000 with an average ~80. These data strongly support models of photoionization mechanism of reionization of the IGM by integrated light from quasars propagated through the IGM (Madau et al., 1999, Fardal et al. 1998), which predict values of N_{HeII}/N_{HI}~30-100 for quasar spectra with the spectral indices q=1.5 to 2.1 ($f\nu \propto \nu^q$). Intrinsic spectral indices for quasars (as measured down to ~350 Å) lie in this range (Zheng et al. 1997). Recently Telfer et al. (2002) used a sample of 332 HST of 184 QSOs with z>0.33 to study the typical ultraviolet spectral properties of QSOs, with emphasis on the ionizing continuum. The sample is nearly twice as large as that from work by Zheng et al. (1997) and provides much better spectral coverage in the extreme-ultraviolet (EUV). The overall composite continuum can be described by a power law with index $\gamma_{EUV}=-1.76\pm0.12$ ($f_\nu \sim \nu^\gamma$) between 500 and 1200 Å. Ratios >100 (about 40%) indicate that localized regions of the IGM are photoionised by softer spectra. This may be additional contributions from starburst galaxies or heavily filtered quasar radiation. The 304 Å (Ly-α) lines of He II can be used to probe low-density regions of the IGM, particularly the void-like gaseous structures in the baryon distribution that develop in concert with

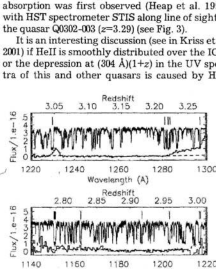

Figure 3: The HST/STIS spectrum (solid line at bottom) of the quasar Q0302 shows HeII absorption shortward of 1300 Å (Heap et al.1999) with superposed higher resolution spectrum of HI Ly-alpha from Keck/HIRES. The HI Ly-α were normalized and multiplied by 0.25 in wavelenght to match the HeII wavelenght scale (from Shull et al.1999).

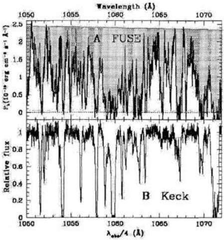

Figure 4: The upper part is a portion of the FUSE spectrum of HE2347−4342.The smooth curve across the top is the extrapolated continuum. The light-shaded area shows the fraction of the HeII opacity due to absorption features that correspond to HI absorption lines identified in the Keck spectrum (bottom). The area shaded in green shows the fraction of the opacity due to additional HeII absorption features that have no HI counterparts in the Keck spectrum. (Kriss et al. 2001).

the large-scale structures in dark matter and the reionization. The presence of HeII Ly-α absorbers with no HI counterparts indicates that that structure is common even in low-density regions. This is consistent with hydrodynamic models that predict density fluctuations due to gravitational instabilities on all scales, from the high density peaks that form galaxies to the distribution of gas in low-density voids (Hui&Gnedin 1997, Cen&Ostriker 1999).

The cloud structure is seen not only for HI and HeII but also for some highly ionized ions (e.g. OVI). Tripp et al. (2000) observed OVI absorption lines in spectrum of quasar H1821+643 (Fig. 5.). The number density of OVI absorbers with rest equivalent width >30 mÅ in the H1821+643 spectrum is remarkably high (>17). The cosmological mass density of the hot matter (under assumption that metallicity is of 1/10 solar and the fraction of oxygen in the OIV ionization stage is 0.2) is estimated as $\Omega_b h$=0.003. This is comparable to the combined cosmological mass density of stars and cool gas in galaxies and X-ray emitting gas in galaxy clusters at low redshift.

Establishing the epoch of reionization and reheating is crucial for determining its impact on several key cosmological issues, from the role reionization plays in allowing protogalactic objects to cool and make stars to determining the small-scale structure in the temperature fluctuations of the cosmic background radiation. Conversely, probing the reionization epoch may provide a means for constraining competing models for the formation of cosmic structures and for detecting the onset of the first generation of stars, galaxies and black holes in the Universe.

The metallicity of the IGM is not unified. The typical metallicities range from 0.3% to 1% of solar values as derived from observations of Ly-α forest absorbers (Rauch 1998). It can be measured from the strong UV resonance lines such as CIV λ1549, Si IVλ1400, CIIIλ977, SiIIIλ1206, OVIλ1035. Shull et al. (1999) remark that these UV resonance lines are the most sensitive abundance indicators available in astrophysics, and they are widely used as abundance indicators in stars, in the low-redshift interstellar medium, and in the high-redshift IGM. Current evidence at high redshift suggests that C IV/Si IV abundance ratios shift at z~3, possibly due to a spectral renaissance stimulated by the breakthrough

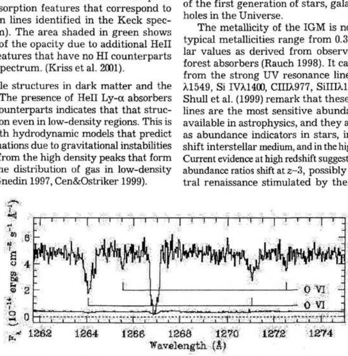

Figure 5: Spectrum of quasar H1821+643 showing the strong OVI absorption lines at $z = 0.22497$ and the weaker absorber at $z = 0.22637$. The calibrated flux is plotted vs. observed heliocentric wavelength, and the solid line near zero is the 1s flux uncertainty (Tripp et al., 2000).

and overlap of the cosmological He II ionization fronts from QSOs and starburst sources (Giroux & Shull 1997). Songaila (2001) using observation of 32 quasars with emission redshift in range 2.31−5.86 studied evolution of the intergalactic metal density at high z. The CIV column density distribution function appeared to be invariant throughout the whole z-range. The metallicity at z=5 exceeds 3.5×10^{-4}, which in turn implies that massive star formation took place beyond this redshift.

Important property of the damped Ly-α absorption systems is that they are predominantly neutral (neutral hydrogen and singly-ionized heavy elements are the dominant ionization species), allowing for heavy element abundances to be measured without the need of applying large ionization corrections. Absorption lines from low-abundance singly-ionized species, including transitions of Ti II, Cr II, Ni II and Zn II, are of particular importance because they are usually unsaturated (or only mildly saturated), allowing accurate column densities to be measured. The typical metallicities for DLA systems are about 10% of solar and do not evolve significantly over a redshift interval $0.5<z<4$ during which most of today's stars were actually formed (Lanzetta et al. 1995). Clearly, these metals were produced in stars that formed in a denser environment; the metal-enriched gas was then expelled from the regions of star formation into the IGM but it is striking that there is no pronounced trend for heavy element abundances to increase with decreasing redshift, and in particular no trend for heavy element abundances to approach solar values at redshifts z~0, as would be expected under scenarios of chemical evolution due to the conversion of gas into stars. It is not yet clear how to interpret these results.

2.3. *Hot gas and other constituents of the ICM*

It is well established (see e.g. White et al. 1993, David 1997,) that the x-ray hot gas is the main "visible" component of clusters of galaxies, its total mass varies from 1 (groups) to 7 (rich clusters) times the stellar mass present in cluster galaxies and it can reach up to 30% of the total cluster mass: "visible" plus dark matter (see Fig. 6). Such a high gas mass fraction has been deemed "the baryon catastrophe" (White et al. 1993), since it is inconsistent with Ω_m=1 and Big Bang nucleosynthesis calculations (Walker et al. 1991). However, if Ω_m=0.2, then the inferred baryon density is 6% of the critical density, which is consistent with Big Bang nucleosynthesis. ROSAT observations have shown that groups of galaxies contain significantly less hot gas than rich clusters (Mulchaey et al. 1996). In general, the mass fraction of hot gas increases from 2% in ellipticals, to 10% in groups, and up to 30% in rich clusters. The gas mass in the ICM is also highly correlated with the luminosity from ellipticals and lenticulars present in the cluster. The total mass in the hot-gas component of the ICM ranges from 2×10^{13} to 5.2×10^{14} solar masses within a 3 Mpc radius: this corresponds very roughly to a gas density of 10^{-3} atoms cm^{-3}. If one includes the X-ray emitting gas in groups and clusters in the luminous mass, the ratio of total gravitating mass to luminous mass decreases significantly between galaxies and rich clusters. This has the unexpected result that a greater fraction of the gravitating mass is observable in rich clusters than in individual galaxies. David (1993) showed, by including the mass of MACHOs in galaxies in the baryonic mass, that the baryon-mass fraction is essentially consistent among galaxies, groups, and clusters.

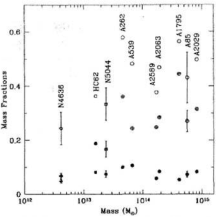

Figure 6: Mass fraction of stars (M_{stars}/M_{tot}; filled symbols), stars plus gas ($[M_{stars}+M_{gas}]/M_{tot}$; crosses in open symbols), and stars plus gas plus MACHOs ($[M_{stars}+M_{gas}+M_{MACHO}]/M_{tot}$; open symbols). Ellipticals are indicated by diamonds, groups of galaxies by squares, and rich clusters of galaxies by circles. Errors are shown at 68% confidence (David, 1997).

Studies of the effect of clumpiness of the ICM suggests clumping only overestimates ICM gas fraction <20% (Mathiesen et al. 1999).

The x-ray emission from galaxy clusters is generally interpreted as due to thermal bremsstrahlung in hot gas (gas temperature within 10^7-10^8 K): the observations of the temperature profiles of the hot gas are consistent with the gas itself being in hydrostatic equilibrium. Poor clusters have low central density, low gas mass and low temperature, whereas rich clusters have high central density, high gas mass and high temperature. The ICM mass-temperature $M_{ICM}-<T_X>$ relations was derived by Mohr at al.(1999) for a sample of 45 galaxy clusters. It is a mild dependence of ICM mass fraction $f_{\rm ICM}$ on $<T_X>$, the clusters with ICM temperatures below 5 keV have a mean ICM mass fraction $<f_{\rm ICM}>=0.160\pm0.008$, which is significantly lower than that of the hotter clusters $<f_{\rm ICM}>=0.212\pm0.006$ (90% confidence intervals).

The hot diffuse component of the ICM peaks at the center of the cluster and falls off with distance from the center, and the x-ray emission can be traced out to a distance of 3 Mpc. It is enriched with heavy elements: x-ray satellite observations done in the late 1970s revealed the presence of heavy-element emission lines in the x-ray emission associated with clusters. The elemental abundances of O, Ne, Mg, Si, S, Ca, Ar, and Fe for four clusters of galaxies (Abell 496, 1060, 2199, and AWM 7) were determined by Arnaud et al. (1996) from X-ray spectra derived from ASCA. Since the gas in the outer parts of the cluster is optically thin and virtually isothermal, the abundance analysis is very straightforward compared to the analysis of stellar or H II region spectra. Arnaud et al. (1996) found that the abundance ratios of all four clusters are very similar. The mean abundances of O, Ne, Si, S, and Fe are 0.48, 0.62, 0.65, 0.25, and 0.32, respectively, relative to solar. The abundances of Si, S, and Fe are unaffected by the uncertainties in the atomic physics of the Fe L shell. The abundances of Ne and Mg and to a lesser extent O are affected by the present uncertainties in Fe L physics and are thus somewhat more uncertain. The Fe abundances derived from the Fe L lines agree well with those derived from the Fe K lines for these clusters. The observed ratio of the relative abundance of elements is consistent with an origin of all the metals in Type II supernovae. More recent results (Dupke et al.1999) of spatially resolved ASCA spectral analysis of A496, A2199, A3571 and Perseus. Mild, but significant, central abundance enhancements are found in each. The analysis of an ensemble of individual elemental abundance ratio indicates that ~50% of the intracluster iron near the centers of these clusters is from Type Ia supernovae.

It is a challenge for theory of enrichment of the ICM with products of stellar evolution. The iron yield needed to reproduce the typical observed iron mass over stellar mass ratio in a typical cluster turns out to be 5×10^{-3} which is 5 times larger than that measured for the Milky Way galaxy. The conclusion is that one cannot account for the iron mass in the ICM using standard iron mass yield, i.e. that of our Galaxy. This implies that there was a high supernova activity in cluster galaxies in the past, either a much higher past average SNI rate as compared with the present value observed in ellipticals (at least a factor 10) or a high SNII rate (Arnaboldi, 2000). The presence of large numbers of Type II supernovae during the early stages of evolution of cluster galaxies is a very strong constraint on all models of galaxy and chemical evolution and implies either a very flat initial mass function or bimodal star formation during the period when most of the metals were created.

Chemical evolution models, which make use of bimodal star formation or a higher SNII rate, are able to predict the iron masses (typically of the order of 10^{12} solar masses) in the ICM, but the total ejected masses of gas are always an order of magnitude smaller than the observed ones (Matteucci&Vettolani, 1988). This would imply that the bulk of gas observed in the hot x-ray emitting component of the ICM has a primordial origin, i.e. it is pristine material produced during the big bang and was never used to form stars. The agreement between the prediction of the chemical evolution model for early-type galaxies and the observed heavy element content of the ICM is based on the assumption that there had been a complete mixing of the galactic heavy-element-enriched gas with the unprocessed ICM gas on a time scale shorter than the age of the Universe.

Another constraints comes from the observed trend of increasing gas mass fraction between groups (poor clusters) and rich clusters. The efficiency of galaxy formation could not be greater in groups compared to rich clusters since groups and clusters produce the same light per unit mass (David&Blumental, 1992). If groups and clusters are closed systems (i.e., they retain all gas shed by evolving stars), then $M_{\rm gas}/M_{\rm stars}$ should be a constant. Since this is contrary to observations, groups cannot be closed systems and must have experienced significant gas loss. (David 1997).

Very recent observations (see e.g. Arnaboldi et al. 2002) have shown that direct detection of individual stars in the ICM is possible. Studies of the ICM in the Virgo and Fornax clusters have detected several hundreds of point-like emissions from individual stars in their post-AGB phase of planetary nebulae. The planetary nebulae are very easy to detect because their nebular outer shell encircling the central star emits nearly 15% of the total energy from the central star in the [O III] emission line at 5007 Å: by simply taking an image through a narrow-band filter centered at the planetary nebulae redshifted [O III] emission and in its adjacent continuum, it has been possible to identify nearly a hundred planetary nebulae emissions in nearby clusters. Simulations based on the overall number of detected planetary nebulae emissions and the properties of their luminosity function in early-type galaxies indicate that the diffuse stellar component in the ICM can contribute up to 50% of the total light emitted by galaxies in the Virgo and Fornax clusters. The detailed spatial distribution of this diffuse stellar component is not known yet on the Mpc scale, and its distribution may be related to the origin of this ICM component itself. Tidal interactions between galaxies in a cluster are expected to be frequent and cause galaxies to lose a substantial fraction, 30–70%, of their stars to the cluster potential where they become the stellar component of the ICM. Because this diffuse component would then originate from tidal tails, one expects its spatial distribution to be quite inhomogeneous. The debris can be relaxed in the cluster core but the further out one goes, the more unrelaxed the population might become.

3. Mechanisms of interaction of galaxy and IGM

Galaxies and pregalactic stars (if they exist) and IGM are closely evolutionary interrelated. Mechanisms responsible for interrelations can be separated in two groups according to the "direction" of influence: galaxies→IGM and IGM→galaxies. In first group I include ionization of the IGM by stellar radiation and massive black holes in central parts of galaxies, heating of the IGM (not only by ionization but also via hot wind), and replenishment the IGM with (chemically processed) matter (accretion, infall). In second group there are process of providing galaxies with (chemically different) matter, dynamical stripping of gaseous component of galaxies and dynamical friction that could play significant role in structural evolution of clusters of galaxies (e.g. formation of gravitational leader in a clusters – cD galaxy (Gorbatskii, 1984)). I do not consider violent exchange processes during the close galactic encounters (collisions). In this section I only discuss mechanisms important for chemical evolution of galaxies and the IGM: galactic wind, expelling of dust and briefly comment on other mass loss and mass gain mechanisms.

3.1. Galactic wind

The galactic wind is believed to be produced by multiple supernovae events in galaxies. Galactic winds in elliptical galaxies play an important role in the evolution of the interstellar medium in these systems. According to conventional theory at early stages massive SN explosions lead to sweeping out of remaining gas and stopping star formation. High intensity rate of the outflow will pollute the surroundings with metals. The impact of supernova-driven galactic winds on the formation and evolution of galaxies depends on how well the high-velocity gas in the wind can couple to the rest of the gas in the galaxy and its halo. Numerical simulations demonstrate that this coupling will generally be rather poor, as the wind tends to follow the shortest path to vacuum. As a result, winds will generally not carry off great amounts of mass from a galaxy, but may carry substantial amounts of kinetic energy and metals generated in the supernova explosions driving them. If galactic winds escape their host galaxies and impact the intergalactic medium (IGM) then probes of the diffuse IGM, such as the Lyman-alpha forest, should reflect this tremendous energy input. Surprisingly, simulations that do not include winds accurately reproduce the observed Lyman-alpha absorption properties. On the other hand, metal-line observations indicate that the low-density IGM has been polluted with metals (presumably via galactic outflows).

There are numerous observations of the galactic wind. I just mention one, which evidences for galactic wind developing at very early stages of galactic evolution. Dawson et al (2002) report the serendipitous detection in high-resolution optical spectroscopy of a strong, asymmetric Lyб emission line at z=5.190. The detection was made in a 2.25 hr exposure with the Echelle Spectrograph and Imager on the Keck II telescope through a spectroscopic slit of dimensions 1"x20". The progenitor of the emission line lies in the Hubble Deep Field-North northwest flanking field, where it appears faint and compact. The Ly-alpha line profile shows the sharp blue cutoff and broad red wing commonly observed in star-forming systems and expected for radiative transfer in an expanding envelope. The Lyα profile is consistent with a galaxy-scale outflow with a velocity of v>300 km·s^{-1}. This value is consistent with wind speeds observed in powerful local starbursts (typically 10^2-10^3 km·s^{-1}).

Most authors are dealing with the galactic winds from ellipticals, starburst galaxies (wind is expected to be very might from these) and dwarf galaxies. Dwarf galaxies are very numerous and low gravitational potential makes easier the expelling of hot metal enriched material into the IGM. In next section we will discuss the role of disk galaxies in enrichment of the IGM with heavy elements. These will be based on the model of blowout presented by Igumentshchev et al. (1990). Based on this model we estimated metal mass loss rate due to wind as ~0.01 $M_\odot$ yr^{-1} (Shustov et al., 1997). Relative efficiency of loss strongly depends on the mass of galaxy. The dependence on mass of galaxy is presented in Fig. 7 from paper of Wiebe et al. (1999), in which oxygen and iron mass loss rate are compared with estimates of David et al. (1991) and Matteucci&Gibson (1995) for ellipticals. As we see metal mass loss rate from spiral galaxies is quite comparable with that from ellipticals. It s important that according to our model the mass loss rate from unit of the disk area for same galaxy varies depending on radial distance. In outer part of disk galaxies it is higher. Observationally it is supported by larger radii of supershells at

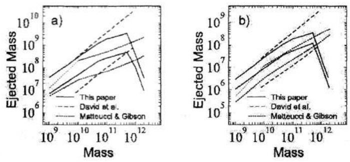

Figure 7: Dependence of theoretical oxygen (a) and iron (b) ejected masses on the mass of a galaxy for spirals (Wiebe et al 1999) and ellipticals (David et al. 1991, Matteucci et al. 1995).

larger distances from galactic center. However for some galaxies decrease of star formation activity in galactic outskirts can reduce this effect.

3.2. *Dust expelling from galaxies*

Recent studies have proven that dust is an important constituent of intergalactic matter. In particular, the emission spectra of quasars have been found to exhibit intergalactic absorption bands that are also typical of the interstellar extinction curve and that are commonly explained by the presence of graphite grains in the interstellar medium (Chens et al. 1991). Data on a few clouds of intergalactic dust obtained from direct observations of grain infrared radiation are presented by Wszoiek & Rudnicki (1990).

Outside galaxies the conditions necessary for dust to be formed – low temperature and high gas density -are not fulfilled. Therefore, one has to assume that dust produced in galaxies is brought to the intergalactic space by one or several mechanisms. The sweeping of dust out of galaxies as they move through the intergalactic gas or dust motion driven by the intergalactic wind have been proposed for such mechanisms. The latter is discussed by Faber and Gallagher (1976) who argued that this mechanism can be efficient only in elliptical galaxies. Alton et al. (2000) observed dust outflows from quiescent spiral disks. They have conducted a search for «dust chimneys» in a sample of 10 highly-inclined galaxies. The have procured B-band CCD images for this purpose and employed unsharp-masking techniques to accentuate the structure of the dust lane. Three of these galaxies possess numerous curvi-linear chimney structures stretching up to 2 kpc from the midplane and the fraction of total galactic dust contained in such structures is of order 1%. Optical extinction offers a lower limit to the amount of dust contained in the extra-planar layer but, by examining the transparent sub-mm thermal emission from NGC 891 the limit was fixed of 5%. These results are consistent with a similar recent study by Howk & Savage (1999) which indicates that about half of quiescent spiral disks possess detectable dust chimneys.

Starburst galaxies also reveal the presence of dust in circumgalactic vicinity. Alton et al. (1999) presented SCUBA images of the nearby, starburst galaxies NGC 253, NGC 4631 and M82 (primarily at wavelengths of 450 and 850 mcm). The existence of a dust outflow along the minor axis of M82 and make a similar (but somewhat more tentative report) for the other two galaxies NGC 253 and NGC 4631. The scale-size of the "vertical" features is 0.7-1.2 kpc. A mass of $10^{6-7}\,M_{\odot}$ is inferred for the outflowing grains in M82. This amount of grain material could either have accrued from an inflow along the disk (e.g. a bar) or, if the lower mass limit applies, have been synthesized by massive stars in the starburst. The ejected grains are probably travelling close to the escape velocity of the host galaxy and assuming, hypothetically, that they do manage to breach the halo Alton et al. (1999) expect superwinds to expel up to 10% of the dust residing in interstellar disks into the intergalactic medium.

The motion of dust under the action of radiation pressure is most commonly considered in the vicinity of individual stars, notably the Sun. Only a few authors have explored the possibility of large-scale motion of dust caused by this mechanism. The problem of the possible blowing of dust out of galaxies by radiation pressure from stars is raised by Pecker (1974) who concluded that the radiative force on dust does not exceed the gravitational attraction and cannot result in large-scale sweeping of dust out of galaxies. Having considered this possibility, Chiao et al (1972) reached an opposite conclusion; however, they used a simplified galaxy model. This process has been more thoroughly studied in Ferrara et al. (1991). The authors considered the motion of graphite and silicate grains under the effect of the total radiation field and the gravitational field of a spiral galaxy. It was important results of their calculations that dust grains can be raised by this mechanism to a considerable height above the galactic

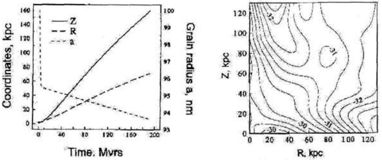

Figure 8: Left panel: Evolution of radius *a*, radial distance *R* and height *Z* of silicate grain; right panel – density distribution of silicate grains (Shustov&Wiebe 1995).

disk in a time of the order of 10^8 yr, virtually escaping into the intergalactic space. However, many important points are only outlined in this paper or are not treated at all. The entire study was carried out for a single dust grain, and no detailed analysis of the motion of dust as an assembly of grains characterized by a size distribution and an initial number-density distribution was given. Furthermore, underestimated values of the interstellar gas density (0.1 cm^{-3} at the Galactic center) were used to integrate the equation of motion of the grain, resulting in the effects of braking processes and dust destruction being underestimated. Shustov and Wiebe (1995) improved this approach and included all considered factors. They calculated the density distribution of dust near a spiral galaxy (for definiteness, near the Milky Way) established as a result of its sweeping by radiation pressure from stars. This mechanism is most efficient for grains with radii of $(0.7-2)\text{x}10^{-5}$ cm, which escape into the intergalactic space mainly with velocities of the order of 1000–2000 $\text{km}\cdot\text{s}^{-1}$. Grains with smaller radii also leave the disk but are completely destroyed at distances of the order of 30–70 kpc. Graphite grains are swept out of the Galaxy more effectively, because they are less prone to destruction. In Fig. 8 evolution of silicate dust grain and dust density field at high z are shown. The rate of mass loss from the Galaxy in the form of dust is estimated for the Milky Way as $\sim 0.04 M_\odot\,\text{yr}^{-1}$. This value should be decreased (3-5 times) because of Lorenz force in magnetic field of the Milky Way. The role of magnetic field is hard to estimate because of poorly known structure of the field. The latter conclusion is confirmed by the fact that our values of dust density (10^{-32}–10^{-31} $\text{g}\cdot\text{cm}^{-3}$) in the circumgalactic space are consistent with observations.

It is important that effectiveness of dust expelling depends on the galactic mass similar to that for the wind. For low mass galaxy $5\text{x}10^9 M_\odot$ it is 5 times relatively higher while for massive galaxy $10^{12} M_\odot$ becomes negligible.

3.3. Other mechanisms

Ram pressure by ICM causes stripping of interstellar matter from galaxies. Since Gunn&Gott (1972) introducedthe concept of ram pressure stripping this mechanism has been invoked to explain different observational phenomena, such as HI deficiency of spiral galaxies in clusters (Giovanelly & Haynes, 1985) and low star formation activity (Dressler et al. 1999). Many theoretical studies of this process were made e.g. Faruoki&Shapiro (1980), Kritsuk (1984). A comprehensive analysis of physical processes of interaction of galaxies with IGM was done by Gorbatskii (1986) and I will comment only on some recent results. Vollmer et al. (2001) investigated the role of ram pressure stripping in the Virgo Cluster using *N*-body simulations. Radial orbits within the Virgo Cluster's gravitational potential are modelled and analyzed with respect to ram pressure stripping. The N-body model consists of 10,000 gas cloud complexes that can have inelastic collisions. Ram pressure is modeled as an additional acceleration on the clouds located at the surface of the gas distribution in the direction of the galaxy's motion within the cluster. Several simulations were made, changing the orbital parameters in order to recover different stripping scenarios using realistic temporal ram pressure profiles. It was demonstrated that ram pressure can lead to a temporary increase of the central gas surface density. In some cases a considerable part of the total atomic gas mass (several $10^8 M_\odot$) can fall back onto the galactic disk after the stripping event. A quantitative relation between the orbit parameters and the resulting HI deficiency is derived containing explicitly the inclination angle between the disk and the orbital plane. It is concluded that the scenario in which ram pressure stripping is responsible for the observed HI deficiency is consistent with all HI 21 cm observations in the Virgo Cluster.

Gas flows in galaxies are fundamental ingredients for studying their chemical evolution. Moreover the formation of galaxy itself in accretion mode can be considered as intensive infall. There are direct observations of infall of HI clouds onto galaxies. Oort in 1970 first (see in Matteucci 2001) discussed the possibility of matter infalling onto the disks of spiral galaxies. He envisioned that the penetration into the Galaxy of extragalactic neutral gas clouds with very high velocities ($|V_{VHVC}|>$ 140 $km \cdot sec^{-1}$) can trigger the formation of high velocity clouds (HVC; $80<|V_{HVC}|$ $km \cdot sec^{-1} < 140$) when they interact with galactic matter and suggested that the present time infall rate onto the Galaxy should be of the order of $1 M_{\odot} yr^{-1}$. Mirabel and Morras (1990) presented observations at 21 cm of HI in the direction of the galactic anticenter showing that a stream of VHVC has reached the outer Galaxy and is interacting with galactic matter. Their HI survey provided evidence for the accretion of gas onto the Galaxy at very high velocities: more than 99% of the VHVC in the direction of the galactic anticenter and 84% of the VHVC in the inner Galaxy have negative (approaching) velocities. Mirabel and Morras (1990) derived from a survey of VHVC a total infall rate onto the galactic disk of 0.2–0.5 $M_{\odot} yr^{-1}$. Estimates of the infall rate should be regarded as still uncertain. Chemical composition of the high velocity in models is typically assumed to be primordial.

4. Modeling galactic evolution

In recent years, various models have been widely used for the study of the evolution of galaxies (see a comprehensive book of Matteucci (2001). Basic equations of any model include the conservation laws of mass of gas and mass of i-th element. Four basic processes are used to be taken into account: star formation, the return of gas to the interstellar medium by evolved stars, the accretion of intergalactic gas, and the ejection of matter into the intergalactic space. For multi-zone models additional terms describing transfer and interaction between zones should be added.

I will not analyze all model approaches. Modern numerical models are complex codes, which include to some extent all the approaches (stellar dynamics, gas dynamics, chemical evolution) and are able to produce impressive evolutionary scenario. Very impressive is quick progress in N-body and SPH technique is developing quickly (see e.g. Klypin et al.1999, Berzik 1999, Westera et al. 2002). Nevertheless basic principles of all models are same and for quick look some simple and clear model remains a useful instrument. Below I demonstrate some results, obtained with a simple model ("our model") which includes most important ingredients of chemo-dynamical evolution of the galaxy. For details see Shustov et al.(1997) and Wiebe et al.(1998). The dynamic basis of the model is the idea proposed by Firmani and Tutukov (1992), who assumed that the thickness of the gaseous disk is determined by two competing processes: the input of energy from supernova explosions and the dissipation of energy in cloud-cloud collisions. This assumption makes it possible to obtain the halo-disk transition in a self-consistent manner and to avoid artificial assumptions about the character and rate of accretion onto the gaseous disk from the halo. Later basic improvements to the model were the inclusion of galactic mass loss in the form of stellar wind and due to the sweeping out of dust grains by stellar radiation pressure as it was described in the previous section.

All models typically have a large number of free parameters. It is desirable to check the agreement with observations of «final» (current) characteristics of a galaxy, and data on evolution of similar galaxies with time. In studies of our Galaxy, it is customary to use G-dwarf problem and

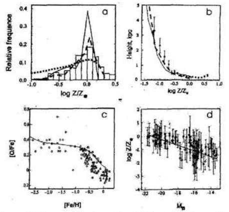

Figure 9: General test results obtained with model (Shustov et al.(1997) and Wiebe et al.(1998)for the Galaxy: a) The calculated metallicity distribution for stars (dashed curve) compared to the data of the catalog of Cayrel de Strobel (1992), estimates for Simple close model (dots) an close model with dynamically changing half thickness of the disk (solid line); b) The observed metallicity (filled circles) as a function of height above the disk plane (Grenon 1990). The calculated dependence is shown by the solid line – for closed model, dashed line– for our model; c) The observed [O/Fe]-[Fe/H] relations from (Barbuy 1988, 1989) (circles) and [Edvardson (1988) (triangles). The solid line corresponds to the chemical composition obtained in our model; d) Dependence of iron abundance on galactic luminosity. Observations – from Brodie&Huchra (1991); our model is shown by solid line.

the «age-metallicity» relation for this purpose. However, the latter test is not conclusive: the wide spread of age and metallicity determinations for galactic objects makes it impossible to sufficiently constrain the choice of model parameters. In Fig. 9 some general test results obtained with our model for the Galaxy are shown.

As it can be seen from Fig. 9. our model reasonably well passed the tests. Now I briefly comment some items related to the topic of the paper: enrichment of the IGM and radial gradients of chemical composition in the disk galaxies.

5. Enrichment of the IGM with heavy elements by galaxies

As it was discussed above the studies of quasar absorption lines reveal that the low-density intergalactic medium (IGM) at z~3 is enriched to between 10^{-3} and 10^{-2} solar metallicity. This enrichment may have occurred in an early generation of Population III stars at redshift z>~10, by protogalaxies at ~6<z<~10, or by larger galaxies at ~3<z<~6. One introduces the episodes of pre-galactic star formation as a possible explanation for the widespread existence of heavy elements (such as carbon, oxygen and silicon) in the IGM. Evolution of massive PopIII stars is now popular subject to investigate. In our Galaxy we never observed such stars, though this research direction seems to be promising. Nevertheless galaxies remain to be believed as the most effective producers of metals.

It is recent tendency that model appear in which chemical evolution of galaxies and the IGM are followed in consistent way starting from cosmological simulations. Aguirre et al. (2001) constructed a model (cosmological simulation), to which they add a prescription for chemical evolution and metal ejection by winds, assuming that the winds have properties similar to those observed in local starbursts and Lyman break galaxies. Aguirre et al (2001) found that winds of velocity >~200-300 km· s^{-1} are capable of enriching the IGM to the mean level observed, although many low-density regions would remain metal free. Calibrated by observations of Lyman break galaxies, their calculations suggest that most galaxies at z>~3 should drive winds that can escape and propagate to large radii. The primary effect limiting the enrichment of low-density intergalactic gas in their scenario is then the travel time from high- to low-density regions, implying that the metallicity of low-density gas is a strong function of redshift.

As we discused in Section 2.2 measurements of the chemical compositions of distant objects-quasars and galaxies-show that their heavy element abundances are high and do not increase appreciably as z decreases, i.e. with approach to the current epoch (Pettini et al. 1997). This is usually taken as evidence that most of the heavy elements in galaxies were synthesized shortly after the formation of the galaxies, on a very short timescale of the order of 10^8–10^9 yr. The high rates of heavy-element formation at high z should correspond to high SFRs (>$100 M_\odot$ yr^{-1} for a massive galaxy) and large bolometric luminosities exceeding the current luminosities by an order of magnitude or more.

The early activity of star forming galaxies: heating and outflows from dwarf galaxies can substantially influence on the subsequent formation of larger galaxies and on chemical evolution of the IGM. E.g. Scannapiesco (2001) using semianalytic and numerical techniques, showed that the winds identified with high-redshift low-mass galaxies may strongly affect the formation of stars in more massive galaxies that form later. Winds typically strip baryonic material out of pre-virialized intermediate mass halos, suppressing star formation. More massive halos trap the heated gas but collapse later, leading to a larger characteristic metallicity. This scenario accounts for the observed bell-shaped luminosity function of early-type galaxies, explains the small number of Milky-Way satellite galaxies relative to standard CDM prescriptions, and provides a reasonable explanation for the lack of metal-poor disk stars in the Milky Way and in other massive galaxies.

Elliptical galaxies are widely assumed to be the primary source of heavy elements in the intracluster medium (ICM), with a role of other morphological types being negligible. In this paper we argue that contribution of spiral galaxies into the chemical evolution of the ICM is also important. This statement rests upon our recent calculations of the heavy element loss from a disk galaxy, invoking two mechanisms: hot steady-state galactic wind and dust expulsion by the stellar radiation pressure. This model reproduces main properties of our Galaxy and, being applied to galaxies of various masses, describes well the observed correlation between spiral galaxy mass (luminosity) and metallicity. In our model this correlation develops as a result of the mass dependence of both loss mechanisms, in the sense that less massive galaxies lose metals more efficiently. We showed that a typical disk galaxy is nearly as effective in enriching the ICM as an elliptical galaxy of the same mass.

We calculated integrated mass of O and Fe ejected by spiral galaxies in a galactic cluster (Fig.10). To assess the overall production of O and Fe in disk galaxies one has to integrate mass of the element ejected from a single galaxy over the galactic mass function. It is now widely assumed that the present galactic luminosity function (LF) can be described by Schechter (Schechter 1976) law with reasonable accuracy. We take Schechter function in its original form, assuming that the spiral luminosity function

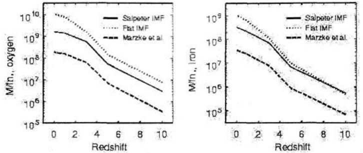

Figure 10: Integrated oxygen (a) and iron (b) ejected mass vs. redshift for different choices of stellar and galactic mass function: f – share of spirals, n_* - richness of cluster according Schechter (1996). From Wiebe et al. (1999).

is proportional to it (universality of LF for all morphological types was recently argued by Andreon (1998) and Marzke et al. (1998)).

We demonstrated that "effective" loss (per unit luminosity) from spiral galaxies is only slightly lower than loss from ellipticals. The dominant role of early-type galaxies in rich clusters is caused by that they outnumber spirals. We present some observational arguments to this point, based on recent determinations of the ICM abundances, emphasizing the fact that the ratio of total iron mass to cluster luminosity does not depend on the fraction of cluster spirals in a wide range of the latter, contrary to what one might expect if they do not contribute into the ICM heavy element abundance.

In recent years the problem of mixing attracts attention of researchers. Ferrara et al. (2000) emphasised that from one side galaxies are believed to be primary sources of heavy elements injected into the IGM, however from the other side it remains still far from being clearly understood what mechanisms spread metals over Mpc scales from parent galaxies. Many open questions related to a production of heavy elements and enrichment of the IGM with them are discussed by Shchekinov (2002).

6. Radial gradient in the Galaxy

In most disk galaxies, negative radial gradients of abundances of heavy elements are observed. This has been the subject of many observational and theoretical studies (see reviews of Pagel (1977), Henry&Wortney 1999)). In the disk of our Galaxy, all the most abundant elements (C, N, 0, Ne, S, Fe, Ar, Al) show radial gradients (see e.g. Fig. 11) The gradients for many types of objects with ages from 10 to 10^{9} Myr within R~5–15 kpc of the Galactic center (open clusters, HII regions, planetary nebulae, B stars) have similar values of -0.04 to -0.08 dex kpc^{-1}. However, the uncertainties are fairly high, even if we consider a single element and type of object. For example, estimates of the oxygen abundances in HII regions vary from -0.13 to -0.05. Nevertheless, it can be considered well established that heavy element abundances are a factor of two to five higher in the central part of the Galaxy than at its periphery. The similarity between the gradients inferred from young and old objects indicates that they do not depend significantly on age, at least during most of the Galaxy's lifetime. For other disk galaxies gradients of about -0.03 to -0.1 dex kpc^{-1} are typical (Kennicutt & Garnett 19946, Garnett et al 1997, van Zee et al. 1998), so that the Milky Way is typical in this respect. Recent results of Andrievski et al. (2002a) of determination the galactic abundance gradient in the range 6-11 kpc using most accurate data on 77 galactic Cepheides brought similar estimates though even more recent detrermination of metallicity using Cepheides at galactocentic distances 4–6 kpc (of Andrievski et al. (2002b)) revealed that radial metallicity distribution is more likely bimodal: it is flatter in the solar neighbourhoud and steepens to the center starting from ~6.5 kpc.

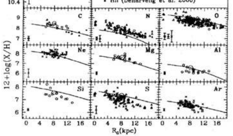

Figure 11: Chemical gradients in MW disk (from Hou et al. 2000)

There have been many attempts to explain the origin of radial gradients of chemical composition. The «static» models (i.e., including only star formation and the return of gas to the interstellar medium by evolved stars) fail to reproduce the gradients: it is necessary to take into account gas motions in one way or another. The dynamical factors involved can be subdivided into two groups: (1) accretion at a rate that depends on time and galactocentric distance and (2) radial gas flows in the galactic disk.

The first hypothesis is especially popular, since introducing accretion makes it possible to simultaneously resolve the "G-dwarf problem". To reproduce the observed gradients, we must assume that the time scale for accretion depends on galactocentric distance R, so that gas accumulates at the center of a galaxy and heavy elements are produced at a higher rate there (Portinari&Chiosi 1999, Chiappini et al. 1997, Pranzos&Boissier 2000). The accreting gas could originate from (1) the galactic halo (in this case, accretion corresponds to the ongoing formation of the disk) and (2) matter swept up by the galaxy as it moves through the intergalactic medium. Kennicut (1996) summarized arguments against sustained gas infall onto the Galactic disk. Modern observational data can be reconciled with the accretion scenario only if the accretion rate is much lower than the current star-formation rate. Direct observations of gas accretion onto the Galactic disk are available only for individual high-velocity clouds and say nothing about the role in the disk's evolution played by the periodic accretion of such clouds. Even if these clouds provide an infall of intergalactic gas onto the disk at a mean rate of $0.5 M_{\odot} yr^{-1}$, due to its episodic nature, this process cannot produce a regular and sustained heavy-element distribution across the disk. Moreover, the typical sizes of high-velocity intergalactic clouds (up to 25 kpc) substantially exceed the interval of Galactocentric distances where the gradient is observed (about 10 kpc). Another argument against a radial dependence of the accretion rate is that the accumulation of gas by a galaxy can be a self-regulating process. An enhanced accretion rate in the central region of a galaxy should lead to more active star formation and, consequently, to more intense energy release by young stars. This energy (e.g., in the form of galactic fountains and wind) can act against the infall of gas onto the disk, weakening the dependence of the accretion rate on R.

A possible alternative scenario to radially dependent accretion could be radial gas flows in the galactic disk. Lacey and Fall (1985) identified three main origins for the development of radial gas motions in a galactic disk: (1) infall onto the disk of a material with low angular momentum; (2) viscosity of the gaseous disk; (3) gravitational interaction between the gas and spiral density waves. It has been shown that taking these processes into account together with radially dependent accretion can explain the development of chemical-composition gradients. However, thus far, radial gas flows lack a sound theoretical basis and must be artificially added to models. Moreover, to equalize the radial gas distribution and solve the G-dwarf problem, a model must include radially dependent accretion even if radial inflows are present.

We (Wiebe et al. 2001) used our model in two-zone modification. The galactic disk was divided in two parts (zones): zone A: R=5 kpc M=0.5x10$^{11}M_{\odot}$ and zone B: R=5-15 kpc M=1.5x10^{11} $M_{\odot}$. Four variants (models) were calculated:

- closed model (just to compare with, we name it standard or reference model),

- closed with dark matter as a parameter (just to try to stop some discussion concerning possible role of dark matter),

- open with radially dependent accretion (in zone A M_{infall}=0, in zone B M_{infall}=2$M_{\odot}$/yr. Such accretion rates are expected for a galaxy moving at a velocity of 100-300 km/s through intergalactic space of density 10^{-3}-10^{-4} cm^{-3}.with capture efficiency 1). We assumed lowest metallicity Z (O,N)=0 of accreted material. Note – extreme values were chosen. This was to make most favorable environment for this hypothesis)

- open with loss of heavy elements up to 30%, depending on radial distance.

Results are shown in Fig. 12., that presents its main characteristics: star formation rate (SFR) and abundances of oxygen Z_O and nitrogen Z_N as functions of time for the four variants of model. At the initial stage of the Galaxy's life, the gradient of the oxygen and nitrogen abundances is about 0.05 kpc^{-1}. This gradient arises because the initial density in the inner regions is a factor of three higher than in the outer regions. Combined with the adopted of the SFR on the gas density (Smidt law), this means that the time scale for star formation at the Galactic center is shorter than at the periphery, implying a faster accumulation of heavy elements at the center. Therefore, the closed model can adequately explain the chemical-composition gradient for old objects. However, the O-gradient disappears by the time the Galaxy reaches an age of t~3x10^{9} yr. The situation is similar for nitrogen; however, since this element is synthesized in long-lived, intermediate-mass stars, the nitrogen abundances in the outer and inner regions equalize at a later stage, when the Galaxy is t~5x10^{9} yr old. This absence of a gradient is typical of models in which the star-formation parameters (and the rate of gas accretion onto the disk) are independent of R (Portinari&Chiosi 1999).

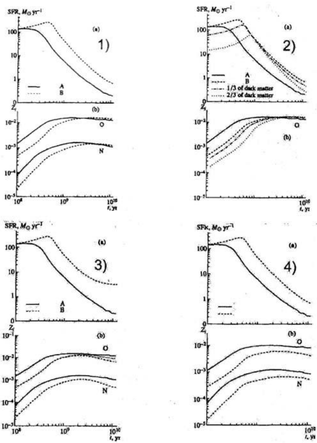

Figure 12: Star formation rate: panels (a) and abundance distributions for O and N: panel (b) for different variants of the evolutionary model (Wiebe et al. 2001 - 1) closed model; 2) closed model with dark matter; 3) model with radially dependent accretion; 4) standard model. The solid and dashed curves correspond to zone A and B respectively. See explanations in text.

A decrease in the gradient with time was also noted in models with radially varying accretion, such as those in paper of Pranzos&Boissier (2000).

The absence of any significant dependence of Z_O and Z_N on time in our model is due to the fact that we take into account the finite lifetime of stars. When the star formation rate decreases with time, the enrichment of the ISM with heavy elements synthesized in massive stars at late stages of the Galaxy's evolution is compensated by the supply to the ISM of gas with low Z ejected by long-lived, low-mass stars formed during the main episode of star formation and whose lifetimes are shorter than the age of the Galaxy. As a result, Z is maintained at an approximately constant level. The "asymptotic" values Z_N and Z_O are determined by fixed parameters of stellar evolution and the shape of the IMF and are, accordingly, virtually the same in outer and inner regions. Evolution of of galaxy whose outer regions contain some mass fraction of dark matter is shown in panel 2). We considered two cases, with the dark mass fractions equal to one-third and two-thirds of the initial mass of the zone B. It is evident from the figure that the gradient increases during the initial evolution of the Galaxy; however, even in this case, it eventually levels off. Note that the adopted dark mass fractions for the disk are probably strongly overestimated and that, in reality, dark matter accounts for a much smaller fraction of the disk mass.

Results for the model with radially dependent accretion are shown in panel 3). In this case, the negative abundance gradients of both oxygen and nitrogen vary little throughout the evolution of the Galaxy, in agreement with observations. However, there are two arguments against this possibility. First, it is not obvious why accretion of intergalactic gas should be more efficient at the periphery than at the center of the Galaxy. Second, the metallicities of intergalactic gas (and of high-velocity clouds) are lower than the solar value but are not equal to zero. The dashed curve in Fig.12 corresponds to the case when the value of Z_N and Z_O of the accreted gas is one-third of the current oxygen abundance in the ISM at any time. We can see that the gradient levels off with time, even if accretion is present. In panel 4) the curves for zonel A again correspond to the standard case, while Model B assumes that 30% of the heavy elements synthesized in the disk of the Galaxy are ejected into the surrounding space via Galactic wind and the expulsion of dust by stellar radiation pressure. It is evident that these models are characterized by very constant gradients. This is due to the fact that a fixed fraction of heavy elements is ejected from the Galaxy at any given time.

Possible explanations of the negative gradient of chemical composition are not confined to accretion of gas and loss of heavy elements by the Galaxy. A similar gradient also develops if radially dependent star formation parameters are introduced into the model. For example, the IMF and the coefficient of proportionality in Schmidt law could depend on R. However, issues connected with quantitative estimates of these parameters are not sufficiently well understood to be included in realistic evolutionary models of the Galaxy and we, accordingly, do not discuss them further here.

Conclusion

Let me conclude very generally. Many problems remain still unsolved, new will appear, but we are under way to understanding of consistent evolution of galaxies – IGM system.

References

Aguirre A., Hernquist L., Schaye J., Weinberg D.H., Katz N., Gardner J., 2001, *ApJ*, **560**, 599

Alton P. B., Rand R. J., Xilouris E. M., Bevan S., Ferguson A. M., Davies J. I., Bianchi S., 2000, *A&AS*, **145**, 83

Alton P. B., Davies J. I., Bianchi S., 1999, *A&A*, **343**, 51

Andreon S., 1998, *A&A.*, **336**, 98

Andrievsky.M., Kovtyukh V.V., Luck R.E., Lepine J.R.D., Bersier D., Maciel W.J., Barbuy, B., Klochkova V.G., Panchuk V.E., Karpishek R.U., *A&A*, **381**, 32

Andrievsky M., Bersier D., Kovtyukh V.V., Luck R.E., Maciel W.J., Lepine J.R.D., Beletsky Yu.V., *A&A*, **384**, 140

Barbuy B, 1988, A&A, 191, 121.

Barbuy, B. and Erdelyi-Mundes, M., 1989, *A&A*, **214**, 239

Benson A. J., Cole S., Frenk C. S., Baugh C. M., Lacey C. , 2000, *MNRAS*, **311**, 793

Benson A. J., Pearce F. R., Frenk C. S., Baugh C., Jenkins A., 2001, *MNRAS*, **320**, 261

Bertschinger E., 1998, *Ann.Rev.A&A.*, **36**, 599

Berzik P., 1999, *A&A*, **348**, 371

Brodie J.P., Huchra J.P., 1991, *ApJ*, **379**, 157

Burles S., Tytler D., 1999, *ApJ*, **499**, 699

Carr B., 1994, *Ann.Rev.A&A.*, **32**, 531

Carr B.J., Rees M.J., 1984, *MNRAS*, **206**, 315

Cayrel de Strobel G., Hauck B., Francois P., Thevenin F., Friel E., Mermilliod M., and Borde S., 1992, *A&AS*, **95**, 273

Cen R., J. P. Ostriker J. P., 1999, *ApJ*, **514**, 1

Chens F.H., Gaskell C.M., Koratkar A.R, 1991, *ApJ*, **370**, 487

Chiao R.Y. and Wickramasinghe, N.C., 1972, *MNRAS*, **159**, 361

Chiappini C., Matteucci F., Gratton R., 1997, *ApJ*, **477**, 765

David L.P., 1997, *ApJ*, **484**, L11

David L.P., Forman W., Jones C., 1991, *ApJ*, **380**, 39

David, L. P., Blumenthal, G., 1992, *ApJ*, **389**, 510

Dawson S., Spinrad H., Stern D., Dey A., van Breugel W., de Vries W., Reuland M., 2002, *ApJ*, **570**, 92

Dressler A., Smail I., Poggianti B.M., Butcher H.., Couch W.J., Ellis R.S.,Oemler A.Jr., 1999, *ApJS*, **122**, 51

Dupke R.A. White R. E. III, Arnaud, K. A. 1999, *Bulletin of the American Astronomical Society*, **31**, 700

Durrer R., Novosyadly B., 2001, *MNRAS*, **324**, 560

Edvardsson B., Andersen J., Gustafsson B., Lambert D.L., Nissen P.E., Tomkin J., 1988, *A&AS*, **102**, 603

Faber S.M., Gallagher J.S., 1976, *ApJ*, **204**, 365

Faruoki R., Shapiro, S.L., 1980, *ApJ*, **241**, 928

Fardal M. A., Giroux M. L., Shull J. M., 1998, *Astron.J*, **115**, 2206

Ferrara A., Ferrini F., Franco J., Barsella, B., 1991, *ApJ*, **381**, 137

Ferrara A., Pettini M., Shchekinov Yu., 2000, *MNRAS*, **319**, 539

Firmani C., Tutukov A., 1992, *A&A*, **264**, 37

Fukugita M., Hogan C.J., Peebles P.J.E., 1998, *ApJ*, **503**, 518

Garnett D.R., Shields G.A., Skillman E.D., Sagan S.P., Dufour R.J., 1997, *ApJ*, **489**, 63

Grenon M., 1990, *Chemical and Dynamical Evolution of Galaxles*, Pisa: ETS Editrice, p. 26

Giovanelli R., Haynes M.P., 1985, *ApJ*, **292**, 404

Giroux M.L., Shull J.M., 997, *Astron.J.*, **113**, 1505

Gorbatskii V.G., 1986, *Introduction in Physiscs of Galaxies and Cluster of Galaxies*, Nauka, Moscow, 256p

Gunn J.E.,Gott J.R.III, 1972, *ApJ*, **176**, 1

Gunn J., Peterson B., , 1965, *ApJ*, **142**, 1633

Haardt F., Madau P., 1996, *ApJ*, **461**, 20

Henry R.B.C, Worthey G., Publ. Astron. Soc. Pacif., 1999, **111**, 919

Hensler G., 1987, *Mitt. Astron. Ges.*, **70**, 141

Hou, J. L.; Prantzos, N.; Boissier, S., 200, *A&A*, **v. 362**, 921

Howk J.C., Savage B.D., 1999, *Astron J.*, **117**, 2077

Hui L., Gnedin N.Y., 1997, Zhang Y, *ApJ*, 486

Igumentshchev I.V., Shustov B.M., Tutukov A.V., 1990, **234**, 396

Kennicutt R.C., Garnett D.R., 1996, *ApJ*, **456**, 504

Kennicut R.C., 1996, *Proc. IAU Symp.* No 171., Eds R. Bender, R.L. Davies. *Dordrecht*: Kluwer. p.11

Klypin A., Kravtsov A.V., Valenzuela O., Prada F., 1999, *ApJ*, **52**, 82

Kriss G.A., Shull J.M., Oegerle W., Zheng W., Davidsen A. F.; Songaila A.; Tumlinson J.; Cowie L. L.; Deharveng J.-M.; Friedman S. D.; Giroux M. L.; Green R. F.; Hutchings J. B.; Jenkins E. B.; Kruk J. W.; Moos H. W.; Morton D. C.; Sembach K. R.; Tripp T. M., 2001, *Science*, **293**, 1112

Kritsuk A.G., 1984, *Astrophysics*, **19**, 263

Lacey C.G., Fall S.M., 1985, *ApJ*, **290**, 154

Lanzetta K.M., Wolfe A.M., Turnshek D.A., 1995, *ApJ*, **440**, 435

Madau P., Haardt F., Rees M.J., 1999, *ApJ*, **514**, 648

Marzke R.O., da Costa L.N., Pellegrini P.S., Willmer C.N.A., Geller M.J., 1998, *ApJ*, **503**, 617

Mohr J.J., Mathiesen B., Evrarad A.E., 1999, *ApJ*, **517**, 627

Mathiesen B., Evrarad A.E., Mohr J.J., 1999, *ApJ*, **520**, L21

Matteucci F., Vettolani G., 1988, *A&A*, **202**, 21

Matteucci F., Gibson B.K., 1995, *A&A*, **304**, 11

Matteucci F., 2001, *The Chemical Evolution of the Galaxy*, Kluwer Academic Publisher

Mirabel I.F., Morras R., 1990, *ApJ*, **356**, 130

Mulchaey J. S., Davis D. S., Mushotzky R. F., Burstein D. 1996, *ApJ*, **456**, 80

Pagel B.E.J., 1997, *Nucleosynthesis and Chemical Evolution of Galaxies*. Cambridge: Cambridge University Press

Pecker J.C., 1974, *A&A*, **35**, 7

Pettini M., Smith L.; King D. L.; Hunstead R.W., 1997, *ApJ*, **486**, 665

Pichon, C., Vergely, J.L., Rollinde, E., Colombi, S. Petitjean, P., 2001, *MNRAS*, **326**, 597

Portinari L., Chiosi C., 1999, *A&A*, **350**, 827

Prantzos N., Boissier S., 2000, *MNRAS*, **313**, 338

Rauch M., 1988, *Ann. Rev. A&A*, **36**, 267

Rees M.J., 1985, in "Cosmological Processes", eds, W.D.Arnett et al., *VNU Science Press Utrecht*, p.44

Rubino-Martin J.A., Rebolo R., Carierra P., Clearly K., et al, 2002 astro-ph/0205367

Scannapiesco E., 2001, *AAS*, **198**, 2001S

Scott P.F., Cariera P., Clearly K., Davies R.D., et al, 2002 astro-ph/0205380

Shchekinov Yu.A., 2002, Astro-ph/0205320

Schechter P., 1976, *ApJ*, **203**, 297

Shull J.M., Savage B.D., Morse J.A., Neff S.G., Clarke J.T., Heckman T., Kinney A.L., Jenkins E.B., Dupree A.K., Baum S.A., Hasan H., 1999, *"The Emergence of the Modern Universe: Tracing the Cosmic Web (White paper of the UV-Optical Working Group (UVOWG)*

Shustov B., Wiebe D., 1995, *Astonomy Reports*, **39**, 650

Shustov B., Wiebe D., Tutukov A., 1997, *A&A*, **317**, 397

Taylor A.C., Carierra P., Clearly K., Davies R.D., et al, 2002 astro-ph/0205381

Telfer R.C., Zheng W., Kriss G.A., Davidsen A.F. 2002, *ApJ*, **565**, 773

Tripp T.M., Savage B.D., Jenkins E.B., 2000, *ApJ*, Lett., **534**, L1

van Zee L., Salzer J.J., Haynes M.P., O'Donoghue A.A., Balonek Th.J., 1988, *Astron. J.*, **116**, 2805

Vollmer B., Cayatte V., Balkowski C., Dushl W.J., 2001, *ApJ*, **561**, 708

Walker T. P., Steigman G., Schramm D. N., Olive K. A., Kang H., 1991, *ApJ*, **378**, 186

Westera P., Samland R., Buser R., Gerhard O.E., 2002, *A&A*, **348**, 371

Wiebe D.S., Tutukov A.V., Shustov B., 1998, *Astron. Zh.*, **75**, 1

Wiebe D.S., Shustov B.M, Tutukov A.V., 1999, *A&A*, **345**, 93

Wiebe D.S., Tutukov A.V., Shustov B.M, 2001, *Astronomy Report*, **45**, 854

White S.D.M, Navarro J.F., Evrard A.E., Frenk C.S., 1993, *Nature*, **366**, 429

Wszoiek B. and Rudnicki K., 1990, *The Galactic and Extragalactic Background Radiation*, Proc. *IAU Symp.* No. 139, 385

Zheng W., Kriss G.A., Telfer R.C., Grimes J.P., Davidsen A.F., 1997, *ApJ*, **475**, 469