Publ. Astron. Obs. Belgrade No. 60 (1998), 5 – 15 *Contributed paper*

THE INTERGALACTIC PRESSURE AND SIZES OF THE GASEOUS HALOS OF FIELD GALAXIES

M. M. ĆIRKOVIĆ
Astronomy Program, Department of Physics and Astronomy
SUNY at Stony Brook, Stony Brook, NY 11794–3800, U.S.A.

Astronomical Observatory, Volgina 7, 11160 Belgrade-74, Yugoslavia
E–mail cirkovic@sbast3.ess.sunysb.edu

Abstract. The problem of influence of the ambiental intergalactic pressure on extended gas associated with normal field galaxies is briefly discussed. It seems that characteristic radius of absorption in the context of simple two-phase halo model can not be explained as natural consequences of pressure equilibrium of the hot halo with the smooth intergalactic medium. This conclusion is based upon the stringent constraints on the temperature and density of the intergalactic plasma obtained through the CMBR measurements. On the other hand, ram-pressure stripping caused by the peculiar motion of galaxies does present a viable alternative for the hot halo truncation. It is shown that for a particular set of chosen parameters, a simple model is capable of producing the absolute upper limit on the extent of gas associated with the galaxy. The values obatined are quite compatible with the results of the recent QSO absorption-line studies. This indicates more important role of "environmental" effects on field galaxies than it is usually assumed.

1. INTRODUCTION

The question of existence and physical properties of the intergalactic medium (IGM) is one of the very active problems of foremost importance to a wide variety of cosmological and astophysical topics. Hereafter, we use the expression "intergalactic medium" in the sense of true ambiental, smooth (or weakly inhomogeneous) component of the baryonic content of the universe, in contradistinction to the intracluster medium (ICM), which is X-ray emitting gas which fills rich clusters of galaxies on one hand, and those high-velocity or halo clouds which are actually gravitationally associated with the individual galaxies, comprising the extended gaseous coronae, or halos. True IGM, therefore, must be mainly cosmological in origin, being the remnant of the processes of galaxy formation. However, it is not necessary to assume that the IGM is of primordial chemical composition, since a degree of mixing with the enriched gas expelled by normal galaxies is conceivable, and a possibility of existence of a generation of pregalactic Population III objects which could contribute to enrichment of the IGM with heavy elements remains open.

Historically, two major physical justifications for introducing the smooth IGM component were (1) the confinement of Lyα clouds (Sargent *et al.* 1980; Ostriker & Ikeuchi 1983), and (2) origin of the soft X-ray background (Marshall *et al.* 1980; Guilbert &

Fabian 1986). As it frequently happens in a dynamical branch of science, both of these were soon shown to be irrelevant. Namely, it is now clear, from the COBE constraints on the CMBR distorsion that the thermal pressure of the IGM is quite insufficient to provide confinement for the clouds with observed column density and the Doppler parameter distribution, and can hardly posses other properties required for creating the observed X-ray background (Barcons, Fabian, & Rees 1991, hereafter BFR). Even recently detected He II Gunn-Peterson effect (Davidsen, Kriss, & Zheng 1996) which comes nearest to the positive confirmation of elusive IGM, is not the final word, since very low-column density Lyα forest may as well be the source of the observed signal (Songaila, Hu, & Cowie 1995).

On the galactic side of the story, the focus of the recent discussions of dark matter in galaxy halos has shifted back to the dark matter in the form of baryons, since it seems clear that Big Bang nucleosynthesis (BBN) requires much more baryons than observed in the stars, interstellar medium (ISM) and ICM. In particular, the observations of rich cluster seem to indicate the cosmological density in baryons Ω_b higher than was suspected (Babul & Katz 1993). On the other hand, deep optical searches severely limit mass-to-light ratio of the dark matter in the halo of our Galaxy and the Local Group (Richstone *et al.* 1992; Hu *et al.* 1994; Flynn, Gould, & Bahcall 1996); similar limits come from gravitational microlensing (Dalcanton *et al.* 1994). In this situation, it seems natural to re-investigate the possibility that at least a part of the baryonic dark matter is in the form of gas—pressumably the same, or tightly related, gas which produces QSO absorption lines at low redshift, although other interpretations are possible (e.g. Pfenniger, Combes, & Martinet 1994; Gerhard & Silk 1996).

These are only some of plethora of arguments for invoking the galactic hot halo model (Bahcall & Spitzer 1969; Bregman 1981; Mo 1994; Mo & Miralda-Escudé 1996, hereafter MM96; Chiba & Nath 1997). According to general qualitative picture, the formation of the galactic structure left vast quantities of metal-poor gas in the halo heated by pregalactic shocks to the virial temperature (10^6 to 10^7 K). This is collisionally ionized hot phase (MM96). However, thermal instabilities set in, and the cold phase forms by cooling the fraction of the hot gas, and condensing into clouds at $T \sim 10^4$ K, mainly photoionized by the metagalctic ionizing background, in the pressure equilibrium with the hot halo. Clouds of the cold phase gradually sink toward the halo center in the galactic gravitational potential, but only some of them can reach the center before next major reheating - which occurs in mergers of equals. In the meantime, these clouds are actually what we see as (some of) the QSO absorption systems (Chiba & Nath 1997).

There are several merits in this picture. First, it is now clear that at least a fraction of low-redshift QSO absorption systems (both metal and Lyα) arise in galaxies: for metal lines that was shown, among others, by Sargent, Steidel & Boksenberg (1988), Bechtold & Ellingson (1992) and Petitjean & Bergeron (1994), and observations of redshift coincidences for low-redshift Lyα systems were performed by Lanzetta *et al.* (1995; hereafter LBTW), and recently strengthened by Chen *et al.* (1998). Second issue is its agreement with the necessity of having the extended gaseous halo to explain observed features of our Galaxy, for example both the high-velocity clouds (present day infall), and chemical composition of the disk (infall in early epochs); other infall models are developed in order to explain the redshift evolution of galactic luminosities (e.g. Phillipps 1993). Furthermore, the discovery of a highly-ionized species like O VI in QSO metal-line systems (Lu & Savage 1993) provided additional argument in favor of the hot, collisionally ionized halo model.

What is the characteristic size of these galactic halos? LBTW showed that, at low redshift, Lyα absorption is likely to arise at galactocentric radii smaller than $R_0 = 160\ h^{-1}$ kpc for a typical L_* galaxy. Chen *et al.* (1998) confirmed that result, slightly correcting the optimal value for R_0 to 149 h^{-1} kpc. This is obviously to be regarded as a lower limit for the extent of gas associated with a galaxy, since it is very difficult to imagine cold phase extending more than hot phase in which it originated. * On the other hand, these numbers are so large in comparison to the Holmberg radius (23 kpc for an L_* galaxy and $h = 0.5$), that it is highly improbable that hot gas can be extended *much* further than R_0. Even if the hot phase can be, at some point in the early galactic evolution, located at much greater distances, even a tiny interaction with nearby galaxies, or with an ambiental IGM (as we shall see) would strip off this very extended material. The physics of the cold phase formation also suggests that characteristic radii of hot and cold phase cannot be very different. In the further discussion, we shall assume that entire gas associated with a galaxy is located within the radius R, which is related to the galaxy luminosity (Chen *et al.* 1998) as

$$R = R_0 \left(\frac{L}{L_*}\right)^{0.35}, \tag{1}$$

R_0 being equal to 160 h^{-1} kpc (LBTW). However, the question of physical mechanisms for R_0 having that particular value has not been tackled yet. It is our goal in this paper to estimate the importance of both thermal and ram pressure of a smooth ambiental IGM for the sizes of hot halos of field galaxies. Both the enormous improvement in our understanding of the absorption properties of galaxies and the advent of new observational constraint on the elusive IGM represent a strong motivation in such an attempt.

2. THERMAL PRESSURE AT THE HOT HALO BOUNDARIES

In the simplest model of virialized halo parametrized by its circular velocity V_c, its density and temperature profile are given by the relations (MM96):

$$\rho(r) = \rho(r_c)\left[1 - K \ln\frac{r}{r_c}\right]^{\frac{3}{2}} \tag{2}$$

and

$$T(r) = T(r_c)\left[1 - K \ln\frac{r}{r_c}\right]. \tag{3}$$

The radius r_c where the cooling time of the gas is equal to t_m is the *cooling radius.* Inside it, the conditions of adiabaticity and hydrostatic equilibrium, lead to the equation of state $P \propto \rho^{5/3}$. Other notation is as follows: K is a dimensionless constant

---

* At least so for the normal-sized galaxies. Hereafter, we exclude the dwarf galaxies from our discussion (but see Wang, 1995).

equal to $K = \frac{2}{5}\frac{\mu V_c^2}{k_B T(r_c)}$, k_B being the Boltzmann constant, μ average mass per particle, and $T(r_c)$ is the temperature at the cooling radius, by assumption equal to the virial temperature: $T(r_c) \equiv \mu V_c^2/2k_B$. For a typical $V_c \simeq 220$ km s^{-1} corresponding to an L_* galaxy, this temperature is $T(r_c) = 3.9 \times 10^6$ K, and the constant K has the value $K = 0.8$. For $t_m = 5$ Gyr, cooling radius is $r_c = 102$ kpc.

In further discussion, we shall assume a constant global metallicity of the halo gas equal to $Z = 0.01\ Z_\odot$. This choice has several advantages. It characterizes extreme Population II objects, but in the same time is thermodynamically indistinguishable in comparison to the Population III properties, since so diluted metals are not efficient coolants any more, and the cooling curve stays practically the same down to the primordial chemical abundances $Z = 0$ (Böhringer & Hensler 1989). Its practical advantage is that we can use a nice analytical expression for the cooling function between 10^5 K and 10^7 K, i.e. in the interesting range (e.g. Lepp *et al.* 1985):

$$\Lambda(T) \approx 1.3 \times 10^{-19}\, T^{-\frac{1}{2}}\ \text{erg cm}^3\ \text{s}^{-1}. \tag{4}$$

For the more exact numerical treatment see Sutherland & Dopita (1993). In the extension of this work, we shall investigate the effects of changing metallicity, as well as allowing metallicities to vary with galactocentric radius (as expected from scarce empirical data). We shall also take the parameter f_g in MM96 to be equal to 0.05, the value in agreement with the BBN predictions of the total baryon density. The average interval between reheating is set to $t_m = 5$ Gyr, although it can be shown that relevant results depend quite weakly on our choice for this parameter (Ćirković 1998).

As an illustration of the viability of the hot halo model, we briefly discuss the pressure at the halo-ISM interface. Inner boundary condition for hot halo model is that the pressure of coronal gas is to be equal to the pressure of ISM. One should be careful in choosing the inner boundary radius of the hot gas, since in the innermost regions it can not be in the hydrostatic equilibrium any more; instead, it will probably be in complicated dynamic disk-halo interaction through some form of the "galactic fountain" or wind mechanism (Shapiro & Field 1976; Norman & Ikeuchi 1989), which will generally tend to make the slope of the pressure curve shallower (when averaged over individual clouds) at small radii. Following Mo (1994), we choose as the core radius boundary the approximate size of the disk $R_d = 20$ kpc. The pressure of hot halo for our choice of parameters is then

$$\log \frac{P(R_d)}{k_B} = 3.2\ \text{K cm}^{-3}. \tag{5}$$

On the empirical basis, pressure in the local ISM was estimated as $\log P/k_B = 3.23$ K cm^{-3} (Spitzer 1978), or at large sample of measured clouds (Jenkins, Jura, & Loewenstein 1983) we have on the average

$$3.2 \leq \log P/k_B \leq 3.8. \tag{6}$$

(See also Figs. 4, 5, 6, 7 and 8 in Wolfire *et al.* [1995] and the discussion therein.) All these measurements were made at galactocentric distances considerably smaller than R_d, so we expect them to be systematically (but not significantly) larger than our estimated value. We conclude that for a typical choice of parameters of the two-phase model, hot halo is in the global pressure equilibrium with the ISM at the inner boundary, as expected. Note that local conditions may be well outside of equilibrium, especially if a dynamical phenomenon like the galactic fountain takes place.

In discussing the thermal pressure at the outer boundary of the hot halos, it is necessary to have several restrictions in mind. It is far from certain that the gas outside of the cooling radius is in equilibrium, and that equations (eq. (2)) and (eq. (3)) are correctly describing state of matter at such large galactocentric distances. Nevertheless, we take it as a working hypothesis, with hope that future theoretical work will result in constructing more detailed picture of cooling and other relevant processes (thermal conduction, KH instability, etc.). The pressure of an ambiental IGM having the temperature $T_{\rm IGM}$ and cosmological density parameter $\Omega_{\rm IGM}$ can be written as

$$P/k_{\rm B} = 8.02 \times 10^{-6}\, T_{\rm IGM}\Omega_{\rm IGM}h^2(1+z)^3 \ {\rm K\ cm^{-3}}. \tag{7}$$

This is only the pressure of the completely smooth component, and any over- or under-densities should be superimposed on the values obtained from eq. (7). The strongest constraints on the physical state if the intergalactic medium come from simultaneous consideration of the Gunn-Peterson limit, COBE measurements of the smoothness of CMBR and X-ray absorption against bright QSOs (BFR; Aldcroft *et al.* 1994). These results suggest only a relatively narrow range of admissible intergalactic pressures. Completely smooth IGM density is limited from above by the BBN constraint $\Omega_{\rm IGM} < 0.026\ h^{-2}$. We shall, therefore, assume $\Omega_{\rm IGM} = 0.1$ as the absolute upper limit to the quantity of smooth intergalactic gas. As discussed above, there is no established lower limit on $\Omega_{\rm IGM}$, but one can assume $\Omega_{\rm IGM} = 0.01$ as a typical "conservative" value. Note that with intergalactic density so low, the formation of galaxies must be a highly efficient process, much more efficient than actually implied by the recent numerical simulations (Cen & Ostriker 1993).

Low-temperature limit on $T_{\rm IGM}$ for any assumed density is given by the Lyα Gunn-Peterson effect (Giallongo, Cristiani, & Trevese 1992; Giallongo *et al.* 1994). It turns out that $T_{\rm IGM} > 10^5$ K is the necessary condition to be satisfied for all reasonable choices of $\Omega_{\rm IGM}$. On the other hand, Fig. 1a of BFR shows the maximal values of $T_{\rm IGM}$, as determined from the COBE data. It is generally between 10^6 and 10^7 K. Accordingly, in Fig. 1 of the present work, we took the highest possible values of pressure for a given $\Omega_{\rm IGM}$. The allowed variation of $P_{\rm IGM}/k_{\rm B}$ lies between the two horizontal lines, and is not only suprisingly small (testifying on the strength of the COBE constraints), but also quite discrepant with the pressure of the hot halo within the two-phase model and any reasonable galactocentric radius. Just for comparison, on the Fig. 1, we have marked the *maximal* extent of the cold (absorbing) phase, according to LBTW. We see that discrepancy between the halo and intergalactic thermal pressure is spanning about three orders of magnitude, and there is practically no possibility for the two to be in any sort of pressure equilibrium. Again, it is necessary to emphasize that this conclusion applies explicitly only to $z = 0$; as is seen, *inter alia*, from the Fig. 1b of BFR, situation may be profoundly different at early epoch of the galactic history.

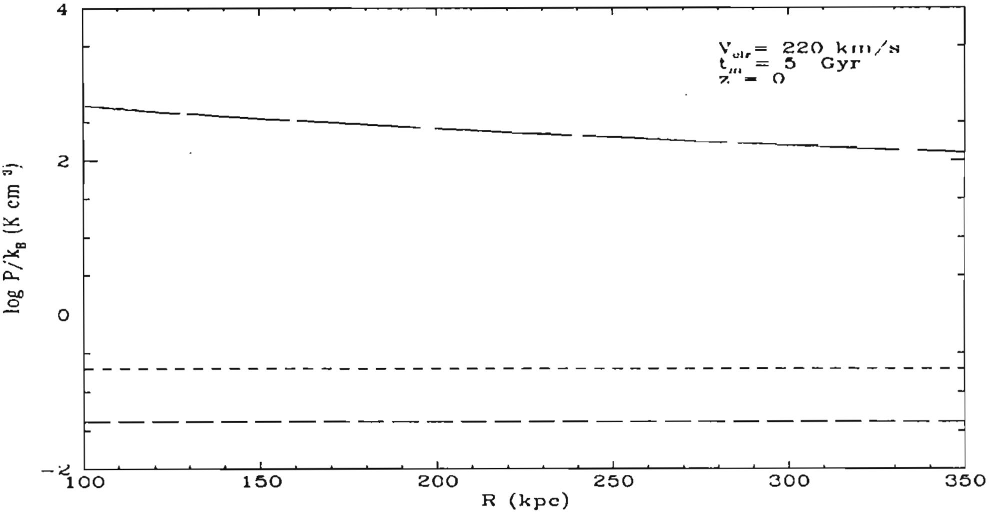

Fig. 1. Thermal pressure of the hot halo corresponding to an L_* galaxy as a function of galactocentric distance in the two-phase model, with other parameters: $f_g = 0.05$, $z = 0$ (present epoch) and $t_m = 5$ Gyr. Horizontal lines represent the *maximal* ambiental IGM pressure for $\Omega_{\rm IGM} = 0.1$ (short-dashed) and $\Omega_{\rm IGM} = 0.01$ (long-dashed line). Vertical tick denotes the LBTW low-redshift absorption radius for $h = 0.5$.

3. RAM-PRESSURE CONFINEMENT BY IGM

Ram-pressure stripping of gas from gravitationally bound astrophysical systems was discussed by many authors in the last quarter of century (Gunn & Gott 1972; Gisler 1979; Farouki & Shapiro 1980; Sarazin 1986; Sofue & Wakamatsu 1993; Sofue 1994) mainly in the context of stripping of the gas in cluster galaxies by dense ICM, but also in the context of depletion of globular cluster gas (Frank & Gisler 1976; Ninković 1985), and mass stripping of Lyα clouds in the minihalo model (Murakami & Ikeuchi 1994). The mechanism of the sweeping of gas by the ram pressure is well-established, although detailed results require sophisticated numerical modeling. We shall hereby limit ourselves to a very simple approach, and relegate more serious discussion to a later work.

The force law for the cloud of gas of size R at the galactocentric distance r in the scalar form is (see, for example, Sofue & Wakamatsu 1993):

$$m\frac{d^2r}{dt^2} = m\frac{\partial\Phi(r)}{\partial r} - \pi R^2 \rho(r)(\Delta v)^2, \tag{8}$$

where Δv is the relative velocity of a cloud with respect to the galaxy. In further discussion we shall approximate $\Delta v = v_{\rm pec}$, where $v_{\rm pec}$ is the peculiar velocity of the galaxy with respect to the CMBR. this need not necessarily represent actual differential velocity of the galaxy in comparison to the local IGM. Still, we shall use this approximation in the present discussion, and relegating more detailed treatment to a later work. From the eq. (8) follows the Gunn & Gott (1972) criterion for the sweeping of the gas by ram pressure; in our notation we can write it as

$$\rho_{IGM}(\Delta v)^2 > \rho(r) v_0(r), \tag{9}$$

where $v_0(r)$ is the escape velocity at the considered point. On the right-hand side of the eq. (9), we have physical quantities dependent on galactocentric distance r. The critical case for which this inequality becomes equality (i.e. the forces on a volume element of gas are exactly balanced) can be described by $f(r_{\rm crit}) = 1$, where the dimensionless function f is given by

$$f(r) = \frac{\rho_{\rm IGM}}{\rho(r)} \frac{(\Delta v)^2 r}{2GM(r)} = 8.02 \times 10^{-6} \frac{m_{\rm H} \mu \Omega_{\rm IGM} h^2 (1+z)^3 (\Delta v)^2 r}{2GM\rho(r_c)\left(1 - 0.8 \ln \frac{r}{r_c}\right)^{3/2}}, \tag{10}$$

where $m_{\rm H}$ is the mass of hydrogen atom, and we approximated the total mass enclosed in radius r with the mass of entire L_* galaxy $M(r) \equiv M \approx 5 \times 10^{11}\ M_\odot$ (since we are dealing here with very large galactocentric distances $r \gtrsim 10^2$ kpc, it is reasonable to assume that the dark matter distribution is truncated at some smaller radius). We have also used the relation (eq. (2)) for the density of the hot halo gas.

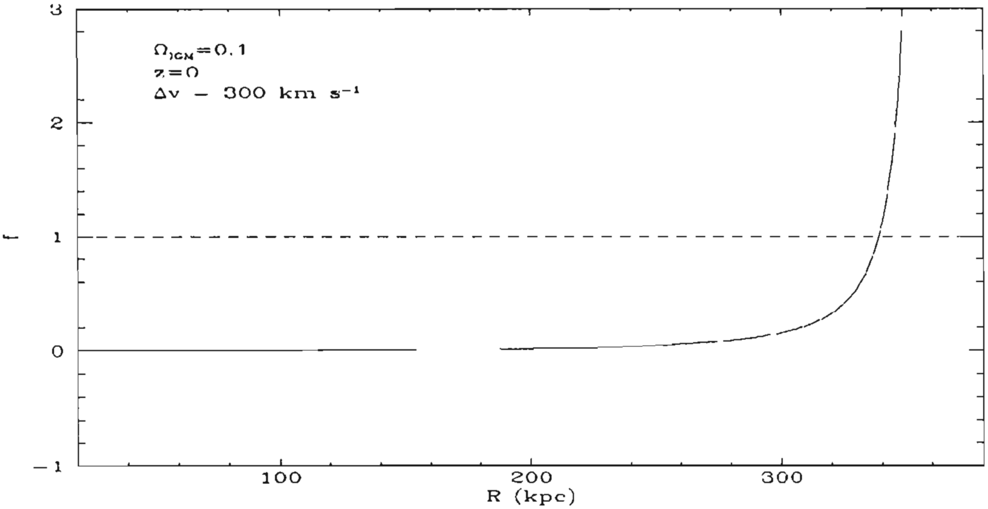

Fig. 2. Ratio of the ram-pressure force to the restoring force acting on a volume element of the halo gas shown as a function of galactocentric distance. Halo parameters are as in Fig. 1, and a differential velocity $\Delta v = v_{\rm pec} = 300$ km s^{-1} is assumed. Above the horizontal dashed line, gas is swept by the intergalactic ram-pressure, and after reaching steady-state can not be associated with the galactic halo.

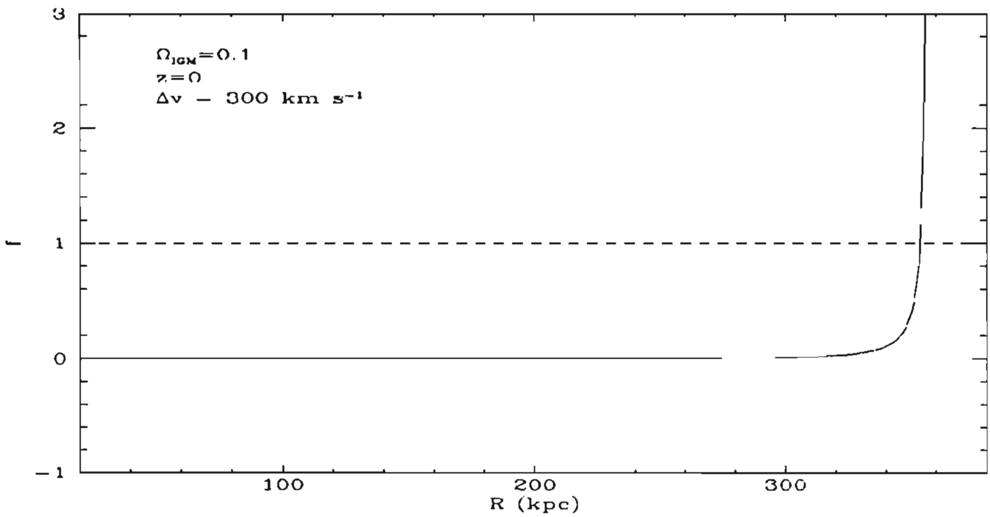

Fig. 3. The same as in Fig. 2, with the cosmological density parameter in IGM set to a "conservative" value of $\Omega_{\rm IGM} = 0.01$.

The resulting plot of function f vs. galactocentric distance at present epoch is shown in Figures 2 (for $\Omega_{\rm IGM} = 0.1$) and 3 (for $\Omega_{\rm IGM} = 0.01$). A typical peculiar velocity is assumed to be $\Delta v \approx 300$ km s^{-1} (e.g. Gavazzi *et al.* 1991; Courteau *et al.* 1993). We notice that, as expected, at small galactocentric distances, restoring force acting on a volume element of gas is completely dominant, and ram-pressure is completely negligible. It steeply increases when we consider distances $\gtrsim$300 kpc and after reaching equilibrium at critical radius of $\sim$ 318 kpc ($\Omega_{\rm IGM} = 0.1$) or $\sim$ 325 kpc ($\Omega_{\rm IGM} = 0.1$), continues to increase rapidly toward infinity (i.e. point where restoring force associated with the galaxy becomes negligible). In both Fig. 2 and Fig. 3, we see that gas at every point for which f is below the dashed horizontal line can be associated with galaxy, but the gas at points above the $f = 1$ line will be stripped on a short time-scale (as indicated by the large slope of f). It is essential to note that the critical radius for the ram-pressure stripping is intriguingly similar to the characteristic absorption radius R_0 in the eq. (1), as indicated by the absorption statistics of LBTW and Chen *et al.* (1998).

4. CONCLUSIONS AND PROSPECTS

Hot halo medium in a simple, two-phase model represents natural transition between the ISM and the IGM. We have hereby shown that pressure considerations quite agree with this picture. Ram-pressure stripping of the hot gas by the ambiental IGM seems to be a viable mechanism for confining the galactic halos. Typical critical radii of ram-pressure stripping ($\sim$ 320 kpc) are quite near to those values obtained from the absorption line studies for L_* galaxies. That does not, of course, proves that this is actually dominant mechanism for confinement of the hot halos. Other effects, thermal and gasdynamical instabilities may play very significant or dominant roles. Other difficulties involved with ram-pressure mechanism are sharp anisotropies and resulting flattening of the hot halos. Although there are some indications that ensembles of QSO absorbers may actually be flattened (Rauch & Haehnelt 1995), the question is far from clear. However, we may hope that the results presented here will encourage more sophisticated models of the same type to be investigated.

Model of ram-pressure confinement predicts an anticorrelation between the size of the halo and differential velocity of the galaxy with respect to the local IGM (peculiar velocity in our approximation). With plausible assumptions about thermal instabilities in the hot halo, this gives rise to a similar anticorrelation between peculiar velocity and maximal extent of the cold, photoionized phase, which can be, in principle, empirically established through the studies of the QSO absorption line systems. Unfortunately, the magnitude of this effect is still too small to be observationally checked, and there are as yet no peculiar velocity surveys in the absorption-selected samples of galaxies. But, looking back at the dynamic development of the absorption studies, we may hope that the enormously improved statistics of the near future will be able to resolve this question.

One of further interesting issues to be addressed in subsequent work is the question of redshift evolution of the galaxy-IGM interface. The thermal intergalactic pressure evolves very strongly with redshift: $P_{\rm IGM} \propto (1+z)^5$ in the simplest model (e.g. Peebles 1993). Thus, although it is unlikely, as we have shown, that it represents a major influence today, its enhancement for the factor of $\sim 10^3$ by the redshift $z = 3$ could change the situation. Parameters of the halo also change for $z > 0$, as shown in MM96, and further work is necessary to disentagle all these interconnected influences. On the other hand, the ram-pressure mechanism is subject to additional uncertainty in redshift evolution of peculiar velocities (which will partially offset the density increase). An attractive speculation is that these evolutionary effects might play some role in the transition between two distinct populations of Lyα absorption systems - a rapidly evolving intergalactic population dominating at high z, and a slowly evolving, strongly clustered galactic population dominating at $z < 1$ - as suggested by recent observations (e.g. Bahcall *et al.* 1996) as well as the investigations of the absorber autocorrelation function (Fernández-Soto *et al.* 1996; Cristiani *et al.* 1996). Obviously, much theoretical work remains to be done in this exciting field.

Acknowledgements

The author thanks Prof. Kenneth M. Lanzetta, Prof. Phil Solomon and Dr. Hou Jun Mo for useful discussions and great encouragement. Technical help of Dr. Luka Č. Popović and Mr. Srdjan Samurović is greatly appreciated, as well as their advice and friendly support.

References

Aldcroft, T., Elvis, M., McDowell, J., & Fiore, F.: 1994, *Astrophys. J.* **437**, 584.

Babul, A. & Katz, N.: 1993, *Astrophys. J.* **406**, L51.

Bahcall, J. N., & Spitzer. L.: 1969, *Astrophys. J.* **156**, L63.

Bahcall, J. N. *et al.*: 1996, *Astrophys. J.* **457**, 19.

Barcons, X., Fabian, A. C. & Ress, M. J.: 1991, *Nature*, **350**, 685 (BFR).

Bechtold, J. & Ellingson, E.: 1992, *Astrophys. J.* **396**, 20.

Böhringer, H. & Hensler, G.: 1989, *Astron. Astrophys.*, **215**, 147.

Bregman, J.N.: 1981, *Astrophys. J.* **250**, 7.

Cen, R. & Ostriker, J.P.: 1993, *Astrophys. J.* **417**, 404.

Chen, H.-W., Lanzetta, K. M., Webb, J. K. & Barcons, X.: 1998, *Astrophys. J.* in press.

Chiba, M. & Nath, B.B.: 1997, *Astrophys. J.* **483**, 638.

Courteau, S., Faber, S.M., Dressler, A. & Willick, J.A.: 1993, *Astrophys. J.* **412**, L51.

Cristiani, S., D'Odorico, S., D'Odorico, V., Fontana, A., Giallongo, E. & Savaglio, S.: 1997, *MNRAS*, **285**, 209.

Ćirković, M.M.: 1998, *Bull. Astr. Belgrade*, submitted.

Dalcanton, J., Canizares, C.R., Granados, A., Steidel, C. C. & Stocke, J.T.: 1994, *Astrophys. J.* **550**, 568.

Davidsen, A.F., Kriss, G.A. & Zheng, W.: 1996, *Nature*, **380**, 47.

Farouki, R. & Shapiro, S.L.: 1980, *Astrophys. J.* **241**, 928.

Fernandez-Soto, A., Lanzetta, K.M., Barcons, X., Carswell, R.F., Webb, J. K. & Yahil, A.: 1996, *Astrophys. J.* **460**, L85.

Flynn, C., Gould, A. & Bahcall, J. N.: 1996, *Astrophys. J.* **466**, L55.

Frank, J. & Gisler, G.: 1976, *MNRAS*, **176**, 533.

Gavazzi, G., Scodeggio, M., Boselli, A. & Trinchieri, G.: 1991, *Astrophys. J.* **382**, 19.

Gerhard, O. & Silk, J.: 1996, *Astrophys. J.* **472**, 34.

Giallongo, E., Cristiani, S. & Trevese, D.: 1992, *Astrophys. J.* **398**, L19.

Giallongo, E., D'Odorico, S., Fontana, A., McMahon, R. G., Savaglio, S., Cristiani, S., Molaro, P. & Trevese, D.: 1994, *Astrophys. J.* **425**, L1.

Gisler, G.: 1979, *Astrophys. J.* **228**, 385.

Guilbert, P.W. & Fabian, A.C.: 1986, *MNRAS*, **220**, 439.

Gunn, J.E. & Gott, J.R.: 1972, *Astrophys. J.* **176**, 1.

Hu, E.M., Huang, J.-S., Gilmore, G. & Cowie, L.L.: 1994, *Nature*, **371**, 493.

Jenkins, E.B., Jura, M. & Loewenstein, M.: 1983, *Astrophys. J.* **270**, 88.

Lanzetta, K.M., Bowen, D.V., Tytler, D. & Webb, J.K.: 1995, *Astrophys. J.* **442**, 538 (LBTW).

Lepp, S., McCray, R., Shull, J.M., Woods, D.T. & Kallman, T.: 1985, *Astrophys. J.* **288**, 58.

Lu, L. & Savage, B.D.: 1993, *Astrophys. J.* **403**, 127.

Marshall, F.J., Boldt, E.A., Holt, S.S., Miller, R.B., Mushotzky, R.F., Rose, L.A., Rothschild, R.E. & Serlemitsos, P.J.: 1980, *Astrophys. J.* **235**, 4.

Mo, H.J.: 1994, *MNRAS*, **269**, L49.

Mo, H.J. & Miralda-Escudé, J.: 1996, *Astrophys. J.* **469**, 589 (MM96).

Murakami, I. & Ikeuchi, S.: 1994, *Astrophys. J.* **420**, 68.

Ninković, S.: 1985, *Ap & SS*, **110**, 379.

Norman, C.A. & Ikeuchi, S.: 1989, *Astrophys. J.* **345**, 372.

Ostriker, J.P. & Ikeuchi, S.: 1983, *Astrophys. J.* **268**, L63.

Peebles, P.J.E.: 1993, "Principles of Physical Cosmology" (Princeton University Press, Princeton).

Petitjean, P. & Bergeron, J.: 1994, *Astron. Astrophys.*, **283**, 759.

Pfenniger, D., Combes, F. & Martinet, L.: 1994, *Astron. Astrophys.* **285**, 79.

Phillipps, S.: 1993, *MNRAS*, **263**, 86.

Rauch, M. & Haehnelt, M.G.: 1995, *MNRAS*, **275**, L76.

Richstone, D., Gould, A., Guhathakurta, & Flynn, C.: 1992, *Astrophys. J.* **388**, 354.

Sarazin, C.L.: 1986, *Rev. Mod. Phys.* **58**, 1.

Sargent, W.L.W., Young, P., Boksenberg, A. & Tytler, D.: 1980, *Astrophys. J. Suppl.* **42**, 41.

Sargent, W.L.W., Steidel, C.C. & Boksenberg, A.: 1988, *Astrophys. J.* **334**, 22.
Shapiro, P.R. & Field, G.B.: 1976, *Astrophys. J.* **205**, 762.
Sofue, Y.: 1994, *Astrophys. J.* **423**, 207.
Sofue, Y. & Wakamatsu, K.: 1993, *Astron. Astrophys.* **273**, 79.
Songaila, A., Hu, E.M. & Cowie, L.L.: 1995, *Nature*, **375**, 124.
Spitzer, L.: 1978, "Physical Processes in the Interstellar Medium" (John Wiley & Sons, New York).
Sutherland, R.S. & Dopita, M.A.: 1993, *Astrophys. J. Suppl.* **88**, 253.
Wang, B.: 1995, *Astrophys. J.* **444**, L17.
Wolfire, M.G., Hollenbach, D., McKee, C.F., Tielens, A.G.G.M. & Bakes, E.L.O.: 1995, *Astrophys. J.* **443**, 152.