Effects of sedimented helium on the X–ray properties of galaxy clusters

S. Ettori1 and A.C. Fabian2

1 INAF, Osservatorio Astronomico di Bologna, via Ranzani 1, I-40127 Bologna, Italy (stefano.ettori@oabo.inaf.it)
2 Institute of Astronomy, Madingley Road, Cambridge CB3 0HA

Accepted 2006 March 13. Received 2006 March 13; in original form 2005 December 6

ABSTRACT

In this Letter, we consider the role played by the sedimentation of helium nuclei on the emissivity and metallicity distribution of the X-ray emitting plasma in the cores of relaxed galaxy clusters. We model the gas density and temperature profiles of nearby cooling core clusters to estimate the gravitational acceleration acting on the helium and show that its sedimentation time scale is too long with respect to the present age of these objects to play a significant role. However, we argue that these time scales have to be definitely lower in the past allowing the helium to settle in the cluster cooling cores and raise its abundance to values higher than the solar one. A direct consequence of this speculation is that the helium, by increasing the total X-ray emissivity, reduces the measured metal abundance in the inner ($r \lesssim 20$ kpc) cluster regions.

Key words: cosmology: theory - dark matter – galaxies: clusters: general - cooling flows – X-ray: galaxies: clusters

1 INTRODUCTION

The plasma in X-ray emitting clusters of galaxies is composed by hydrogen (H), helium (He) and various ionized metals of which iron (Fe) is the most interesting from the astrophysical point of view owing to its connection to the star formation activity (e.g. Renzini 2003). In an X-ray emitting plasma with solar abundance, for each atom of hydrogen a number density of $9.77 \times 10^{-2}$ ions of He and $4.68 \times 10^{-5}$ ions of Fe is expected (as in Anders & Grevesse 1989; for the most recent determinations in Grevesse & Sauval 1998 and Asplund, Grevesse & Sauval 2005). In a multicomponent plasma that is generally assumed with a fixed solar abundance of elements, He in particular, on the description of the X-ray emitting plasma the atomic weight $A$ of (H, He, Fe) = (1, 4, 56), the mass fraction on the total is 0.75 for the hydrogen (generally labeled as $X$), 0.24 for helium (called $Y$) and the rest ($Z = 1 - X - Y \approx 0.017$) for heavier elements.

Diffusion of helium and other metals can occur in the core regions of the intracluster plasma under the attractive action of the central gravitational potential, enhancing their abundances on time scales comparable to the cluster age. Qin & Wu (2000) and Chuzhoy & Nusser (2003), following the work by Fabian & Pringle (1977), Rephaeli (1978), Abramopoulos et al. (1981), Gilfanov & Syunyaev (1984) on the sedimentation of elements in clusters, studied the concentration of helium in cores concluding that it can gravitationally settle within a Hubble time. Abramopoulos et al. (1981) obtained the same results of Qin & Wu assuming a global thermal equilibrium and the Boltzmann equation, while Gilfanov & Syunyaev (1984) applied the diffusion equation to the light elements (atomic number $Z_{i} < 16$) where the changes are more efficient. Therefore, in a H-He plasma, the helium tends to be more centrally peaked than the hydrogen.

More recently, Chuzhoy & Loeb (2004) solved the full diffusion equations derived by Burgers (1969) for a multicomponent fluid, finding that the diffusion, if the suppression due to magnetic fields is modest, can alter X-ray properties as the steepening inward of the baryon distribution as well as the spectrum and evolution of stars forming out from helium-rich gas. However, all these studies assume a gas temperature constant in time and space in evaluating the gravitational acceleration in the cluster core, where instead steep spatial gradients are observed in cool core clusters.

In the present work, we analyze the effects of sedimented elements, He in particular, on the description of the X-ray emitting plasma that is generally assumed with a fixed solar abundance of helium (as tabulated in, e.g., Anders & Grevesse 1989; on more recent estimates of the solar chemical composition see, for example, Asplund, Grevesse & Sauval 2005) and a relative contribution from metals determined through the equivalent width of the detected emission lines in X-ray spectra. We model properly the central steepening of the observed gas temperature and density profiles to estimate the gravitation potential in the inner cluster regions where the effect of the gravitational sedimentation is expected to be more relevant. In these regions, we prove that the underestimation of the amount of helium can propagate to inaccurate measurements of the total X-ray emissivity, gas density and metallicity.
2 Joint best-fit of the gas density and temperature profile with a modified NFW gas profile of the deprojected data of Centaurus (left, Sanders et al. 2002), A2199, (right, Johnstone et al. 2002) and A1795 (center, Ettori et al. 2002). The density profile presents a mean relative uncertainty of about 2 per cent that is 5 times lower than the value associated with the estimates of the temperature profile.

Figure 2. (Left panel) Equipartition time between H and He (thick dotted line) and between H and Fe (thin dotted line) in the Centaurus cluster; sedimentation times, \( t_{\text{sed}} = \int_{r_{\text{in}}}^{r_{\text{out}}} dr/v_{\text{sed}}(r) \), of He (solid line). The dots mark the radius \( r_{\text{in}} \) at which the material is accumulated from the regions beyond with a sedimentation time represented by the line. (Right panel) Sedimentation times of He for the three objects under examination (from thickest to thinnest line: Centaurus, A2199, A1795). The cluster potentials are described by equation 4 given the best-fit values in Table 1. A flat temperature profile is assumed (see text at the end of Section 2). The shaded region ranges between \( 2 \times 10^7 \) years, which is about the cooling time associated with a gas with solar abundance of helium and proton density of \( 0.2 \, \text{cm}^{-3} \) at \( \sim 1 \, \text{keV} \) and the age of the Universe for the assumed cosmology, \( 1.3 \times 10^{10} \) years.

2 SEDIMENTATION OF HELIUM

Spitzer (1956) presents the physics of fully ionized gases that we adopt in the following discussion. In general, the time of equipartition between H and He (Fe) ions is low when it is compared to the cluster age, whereas the sedimentation time is comparable to it. Hereafter, we assume a cosmology \((H_0, \Omega_m, \Omega_\Lambda) = (70 \, \text{km s}^{-1}\text{Mpc}^{-1}, 0.3, 0.7)\) that implies an age of the Universe of \( 1.3 \times 10^{10} \) years.

To describe the action of the gravitational acceleration in drifting inward the plasma elements, we consider an intracluster gas in hydrostatic equilibrium with a Navarro, Frenk & White (1995, hereafter NFW) potential

\[
\frac{d\phi}{dr} = 4\pi G \rho_s r_s \left( \frac{\ln(1 + x)}{x^2} - \frac{1}{x(1 + x)} \right) = 4\pi G \rho_s r_s f(x), (1)
\]

with \( x = r/r_s \). We are interested to measure such potential in the inner regions of a cluster, where a steep gradient in temperature is generally observed. A model for the gas density profile obtained analytically from the hydrostatic equilibrium equation (HEE) with a NFW potential is available in literature (e.g. Makino, Sasaki & Suto 1998, Ettori & Fabian 1999), but it assumes an isothermal gas. We relax this assumption to accommodate the observed gradients and modify accordingly the model of the gas density profile. We assume a temperature profile with the functional form
that is just the rearranged expression of the equation that Allen, Schmidt & Fabian (2001) show to be able to reproduce the temperature profiles of relaxed clusters (see Vikhlinin et al. 2005). We use then this model in the HEE with a NFW potential to recover a numerical expression of the gas density profile:

\[ n_{\text{gas}}(x) = n_{\text{gas}}(0) \frac{1}{t(x)} \exp \left( -\eta \int_0^x \frac{f(x)}{t(x)} dx \right), \]  

with \( \eta = 4\pi G \rho_o r_s^2 \mu m_p / T_{\text{max}} \).

These functional forms of the temperature and density profiles are then joint-fitted with a \( x^2 \) minimization to the deprojected data of Centaurus (Sanders et al. 2002), A2199 (Johnstone et al. 2002) and A1795 (Ettori et al. 2002). The best-fit results are presented in Table 1 and plotted in Fig.1.

A proper fit of the gas density and temperature gradient allows us to define accurately the cluster gravitational acceleration \( g \) by using the NFW potential in equation 1

\[ g(r) = \frac{d\phi}{dr} = \frac{\eta T_{\text{max}}}{\mu m_p r_s^2} f(r), \]  

with the parameters \( \eta, T_{\text{max}} \) and \( r_s = r/x \) obtained as best-fit results of the deprojected gas density and temperature profiles. By using, instead, the best-fit parameters from an isothermal NFW gas density profile, as generally done for this kind of analysis, one would infer a potential in the inner regions that is larger than the adopted value by a factor of \( \sim 4 \), mainly owing to the assumed higher temperature value that propagates linearly to the gravitational acceleration.

For a Boltzmann distribution of particles labeled \( 1 \) with density \( n_1 \) and thermal velocity \( v_{\text{th}} = (2kT/A_1 n_1)^{1/2} \) in a plasma with temperature \( kT \) in hydrostatic equilibrium with a NFW potential \( g(r) \), the drift velocity of the heavier ions 2 with respect to 1 is given by (e.g. Spitzer 1956)

\[ v_{\text{sed}}(r) = 3 m_2 v_{\text{th}}^2 A_1 A_2 v_{\text{th}}^2 g(r) \frac{3m_2^2 A_1 A_2 v_{\text{th}}^2}{16 \pi n_1 \lambda Z_1 Z_2 n_1 \ln \Lambda}, \]  

where \( \ln \Lambda \) is the Coulomb logarithm equals to 37.9 + \ln \left( (kT/10\, \text{keV}) (n_1/10^{-3}\, \text{cm}^{-3})^{-1/2} \right). \) Typical velocities of about 2 kpc Gyr\(^{-1} \) are expected which can make reasonable the sedimentation of helium in the inner 10 kpc or so. The time elapsed in drifting from \( r_{\text{inn}} \) and \( r_{\text{out}} \) is the sedimentation time, \( t_{\text{sed}} = \int_{r_{\text{inn}}}^{r_{\text{out}}} dr / v_{\text{sed}}(r) \), that is therefore proportional to \( n_1 g^{-1} kT^{-3/2} \).

The time required to sediment helium in the inner cluster regions is in the order of few Giga-years (see also Chuzhoy & Loeb 2004). Owing to the competing drag forces from the protons moving upwards and the helium diffusion inwards, heavier elements can sediment with similar velocity, as discussed in Chuzooy & Nasser (2003). We conclude that sedimentation of helium is not an efficient process, given the present condition of the cluster plasma.

However, the intracluster medium evolved to a well-defined cool core during its formation history. We can assume that the gas started originally with a flat temperature distribution equal to the value measured in the outskirts and a gas density profile obtained from the equation 2 by fixing \( t(x) = 1 \) and by requiring that the outer pressure remains unchanged as the overall gravitational potential. While the evolution of a cool core from an initially isothermal plasma is the natural consequence of the radiative processes taking place in the central regions at higher density, there is not yet detailed studies from, e.g., cosmological simulations of structure formation that discuss the evolution of cool cores owing to the still unknown balance of energetic losses and feedbacks that rules the X-ray emitting plasma in the cluster cores (for example, the temperature profiles are expected to be flatter and density higher at \( z = 1 \) with respect to the local measurements in Ettori et al. 2004, but Burns et al. 2004 suggest an alternative scenario in which cool cores in massive clusters are formed through the merging of subclumps with its own cool core). These assumptions imply that the gas temperature increases in the inner regions by a factor of \( \sim 3 \) and the density decreases in the center by about an order of magnitude. As shown in Fig.2 these changes in gas temperature and density values cause the sedimentation time to be shorter. This makes reasonable the scenario in which (i) the helium sedimented during the initial collapse and subsequent relaxation of the cluster plasma and (ii) it resides nowadays in super-solar abundance in cluster cores.

### 3 EFFECTS OF THE SEDIMENTED HELIUM

Intracluster plasma emits mainly by X-rays through bremsstrahlung with a typical emissivity,

\[ \epsilon \sim \Lambda(T_{\text{gas}}) n_e \sum Z_i M_i Z_i^2 n_i, \]

where \( \Lambda(T_{\text{gas}}) \) is the cooling function of a plasma with temperature \( T_{\text{gas}} \), \( Z_i \) is the electric charge (e.g. 1 for H, 2 for He, 24 for Fe), \( M_i \) is the element abundance relative to the solar value and \( n_i \) is the density of the species in exam. It is thus evident that any metal enhancement of its relative abundance with respect to the hydrogen, as occurs when sedimentation is relevant, affect the total X-ray emission. It is important to note that the X-ray emissivity is generally measured under the assumption that the helium abundance is fixed to the solar value relatively to hydrogen, i.e. \( \epsilon \sim 1.85 n_e^2 \). In the extreme case of a plasma composed by pure helium \( (X = 0, Y = 1) \), \( n_e = 0 \) He and \( \epsilon \propto 8 n_e^2 \), with the direct implication that if this plasma is assumed with solar abundance, the total density is overestimated by a factor of 2, Moreover, the change in the relative abundance of H and He induces variation in the number of electrons and ions present in the plasma

\[ \frac{n_e}{n_p} = c_M = \sum M_i Z_i N_i + 1 + 2 M_{\text{He}} N_{\text{He}} + \sum_{i \neq \text{He}} M_i Z_i N_i. \]

| Centaurus | A2199 | A1795 |
|-----------|-------|-------|
| \( z \)   | 0.0104| 0.0309| 0.0632|
| \( r_s \) (kpc) | 16    | 33    | 246   |
| \( n_e(0) \) \((\text{cm}^{-3})\) | 0.264 | 0.133 | 0.089 |
| \( T_0 \) (keV) | 0.48  | 1.36  | 2.25  |
| \( T_{\text{max}} \) (keV) | 3.92  | 5.22  | 12.24 |
| \( b \) | 0.91  | 0.94  | 0.86  |
| \( \eta \) | 12.1 | 7.6   | 15.9  |
| \( \chi^2/\text{dof} \) | 212/10 | 12/20 | 29/10 |
| \( \chi^2(T) \) | 453  | 20    | 10    |
| \( \chi^2/n_e \) | 665/10 | 32/10 | 39/12 |
where $M_i$ is the element metallicity and $N_i$ is the particle number density according to Anders & Grevesse (1989), and affects the measurements of the mean molecular weight,

$$
\mu = \left( \sum_i X_i (1 + Z_i) / A_i \right)^{-1} \approx \frac{1}{2X + (3/4)Y + (1/2)Z},
$$

that is generally fixed to a value of $\sim 0.6$ appropriate for solar abundance. When $c_M$ and $\mu$ are quite independent of the metal component of the plasma (e.g. $\mu = 0.618$ and $c_M = 1.209$ for a solar abundance, $\mu = 0.613$ and $c_M = 1.200$ for a metallicity of $0.3Z_{\odot}$ for the reference values in Anders and Grevesse; note that, on the basis of the compilation in Grevesse & Sauval, $\mu = 0.605$ and 0.600 and $c_M = 1.182$ and 1.174, for a solar and 0.3 times solar abundance, respectively), their values are highly sensitive to the variation in the helium abundance: for $M_{\text{He}}$ of, e.g., 2 and 10, $\mu = 0.699$ and 1, respectively, $c_M = 1.405$ and 2.968.

Through these quantities, several other cluster measured properties are affected, like, e.g., the cooling time $t_{\text{cool}} \approx n_e T_e / \epsilon \approx (1 + 1/c_M) T_{\text{gas}} / (n_e \Lambda_{\text{cool}})$, the gas mass density $\rho_g = \mu (n_e + n_p) m_p = \mu (1 + c_M) n_e m_p$, the total gravitational mass measured through the hydrostatic equilibrium equation, $M_{\text{tot}} \propto \mu^{-1}$, the gas mass fraction, $f_{\text{gas}} = M_{\text{gas}} / M_{\text{tot}} \propto \mu^2 (1 + c_M)$. The gas fraction, in particular, increases by a factor from 1.4 to 4.8 for 2 and 10 times the solar abundance of helium, respectively. To quantify the effect of sedimented helium on, e.g., the cooling time we have first used the model vmekal in XSPEC (Arnaud 1996) to estimate the cooling function $\Lambda_{\text{cool}} = \epsilon / (n_e t_{\text{cool}})$ for a range of gas temperatures, $kT_{\text{gas}}$, and He abundances, $M_{\text{He}}$, in the interval 1 and 10 with respect to the solar chemical compilation in Anders & Grevesse (1989; see command abund in XSPEC: $n_{\text{He}} = 9.77 \times 10^{-2} n_{\text{H}}$). As expected, higher helium abundance induces larger emission and shorter cooling time of the emitting plasma, with a cooling function that raises for, e.g., a gas at 2 keV and proton density of 0.2 cm$^{-3}$ by a factor of 1.2 ($M_{\text{He}} = 2$) and 2.6 ($M_{\text{He}} = 10$) and a cooling time that decreases from $7 \times 10^7$ years to $5.6 \times 10^7$ ($M_{\text{He}} = 2$) and $2 \times 10^7$ ($M_{\text{He}} = 10$) years. Under the assumption that bremsstrahlung dominates, $t_{\text{cool}} / t_{\text{cool}} \propto n_{\text{gas}}^2 / T_{\text{gas}}^2$ which makes evident how the formation of a cool core, with the central gas that becomes progressively higher in density and lower in temperature, reduces significantly any process of sedimentation.

Finally, we have simulated typical thermal spectra of long-time exposed cluster cores with the ACIS-S configuration on the

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure3}
\caption{Deprojected metallicity profiles. An inverted gradient is present in the inner cluster regions.}
\end{figure}

Chandra X-ray satellite generally adopted to fully exploit the larger collecting area at low energies with respect to ACIS-I. We have used the vmekal model in XSPEC to fake spectra with helium abundance in the range 1–10 times the solar abundance as in Anders & Grevesse (1989). Then, we have fitted to the simulated data both mekal and vmekal models with fixed solar abundance of helium, leaving only the normalization, the temperature and the metal (one single parameter in mekal, 9 parameters –O, Mg, Al, Si, S, Ar, Ca, Fe, Ni– in vmekal) abundance free to vary. Our results, shown in Fig. 4 indicate how an unrecognized super-solar abundance of helium causes underestimates of the metal (iron) abundance and overestimates of the model normalization owing to the induced increase of the total bremsstrahlung emissivity (cf. equation 6). We do not measure any relevant variation in the gas temperature and do not find any significant dependence of these trends upon the assumed values of column density, normalization and temperature. An important implication of these results is that it can potentially explain the drops in metallicity observed through X-ray spectra extracted from the inner $\lesssim 20$ kpc regions of several nearby bright galaxy clusters (e.g. Centaurus, Sanders et al. 2002; A2199, Johnstone et al. 2002; A351, Johnstone et al. 2005; A2204, Sanders et al. 2005; note that also A1795 shows a flat, marginally decreasing metal abundance in the inner two bins as shown in Ettori et al. 2002; see few examples of this inverted gradient in Fig. 4. Figure 4 shows that an enhancement of a factor of few ($\sim 2$ to 4) in the helium abundance with respect to the assumed solar value in Anders & Grevesse (1989) is sufficient to explain the observed reduction of 20–50 per cent in the metallicity measurements.

\section{Discussion and Conclusions}

We have studied the effects of the sedimentation of helium nuclei on the X-ray properties of galaxy clusters. To this purpose, we have estimated the gravitational acceleration by adopting functional forms for gas density and temperature profiles that have been obtained under the assumption that the plasma is in the hydrostatic equilibrium with a NFW potential. These functional forms are fitted to the observed deprojected gas density and temperature profiles and the best-fit results are used to model properly in the inner cluster regions the gravitational acceleration. The observed gas density and temperature values do not allow the metal to settle down in cluster cores over timescales shorter than few $10^9$ years.
mass, abundance affects (i) the relative number of electron and ions place in cluster cores. Even modest enhancement in the helium $c_\epsilon$ sedimentation times are reduced by 1–2 order of magnitude within that is now describing a cool core was initially isothermal, the On the other hand, by assuming that in the same potential the gas $\epsilon$ times the solar metal composition as in Anders & Grevesse (1989). The results are independent of the input values of the absorbing column density, spectra normalization and metal abundance.

On the other hand, by assuming that in the same potential the gas that is now describing a cool core was initially isothermal, the sedimentation times are reduced by 1–2 order of magnitude within $0.5r_s \approx 0.2r_{200}$. The sedimentation of helium can then take place in cluster cores. Even modest enhancement in the helium abundance affects (i) the relative number of electron and ions $c_\epsilon$, (ii) the atomic mean molecular weight $\mu$ and all the X-ray quantities that depend on these values, such as the emissivity $\epsilon$, the gas mass density $\rho_\text{g}$ $\propto \mu(1 + c_\epsilon)$, the total gravitating mass, $M_\text{tot} \propto \mu^{-3}$, the gas mass fraction, $f_\text{gas} \propto \mu^{2}(1 + c_\epsilon)$.

Moreover, we show that if we model a super-solar abundance of helium with the solar value, we underestimate the metal (iron) abundance and overestimate the model normalization or emission measure. For example, with $M_{\text{He}} = 3$, the measured iron abundance and emission measure are $\sim 0.65$ and 1.5 times the input values, respectively. Therefore, increased helium abundance might explain the drops in metallicity observed in the core of some nearby systems. Other implications of the suspected and plausible super-solar abundance of helium in the cluster cores are: (i) the helium-rich gas will then cool out and form helium-rich stars that have a typical lifetime shorter and burn hotter than Sun-like objects by an order of magnitude (Chris Tout, priv. comm.); (ii) the central elliptical galaxies of cool core clusters might be then overabundant in helium (see speculation on this expected characteristic in Lynden-Bell 1967), (iii) the central infall of helium induces heating of the surrounding plasma by $\sim m_\text{He}n_\text{He}v_\text{esc}g \approx 6.5 \times 10^{-30} \text{erg/cm}^3$ that can offset the central cooling of about $n_\text{H}v_\Lambda(A) \approx 2 \times 10^{-27} \text{erg/cm}^3$ by a negligible amount. On the other hand, the diffusion of helium can be suppressed by the action of confinement due to reasonable magnetic fields, as recently pointed out from Chuzhoy & Loeb (2004), or limited to the very central region ($r < 20 \text{kpc}$) by the turbulent motion of the plasma.

ACNOWLEDGMENTS

ACF acknowledges the support of the Royal Society. We thank Jeremy Sanders and Roderick Johnstone for providing computer-readable tables of the gas density, temperature and metallicity profiles of Centaurus and A2199. We thank the referee, Eugene Churazov, for insightful comments.

REFERENCES

Abramopoulos F., Chana G.A., Ku W.H.-M., 1981, ApJ, 248, 429
Allen S.W., Schmidt R.W., Fabian A.C., 2001, MNRAS, 328, L37
Anders E., Grevesse N., 1989, Geochimica et Cosmochimica Acta, 53, 197
Arnaud K.A., 1996, “Astronomical Data Analysis Software and Systems V”, eds. Jacoby G. and Barnes J., ASP Conf. Series, 101, 17
Asplund M., Grevesse N., Sauval A.J., 2005, “Cosmic abundances as records of stellar evolution and nucleosynthesis”, eds. Bash F.N. and Barnes T.G., ASP Conf. Series, 336, 25
Burgers J.M., 1969, Flow Equations for Composite Gases, Academic Press, New York
Burns J.O., Motl P.M., Norman M.L., Bryan G.L., 2004, proc. of “The Riddle of Cooling Flows in Galaxies and Clusters of Galaxies”, eds. Reiprich T. Kempner J. and Soker N., URL http://www.astro.virginia.edu/coolflow/
Chuzhoy L., Nusser A., 2003, MNRAS, 342, L5
Chuzhoy L., Loeb A., 2004, MNRAS, 349, L13
Ettori S., Fabian A.C., Allen S.W., Johnstone R.M., 2002, MNRAS, 331, 635
Ettori S., Fabian A.C., 1999, MNRAS, 305, 834
Ettori S. et al., 2004, MNRAS, 354, 111
Fabian A.C., Pringle J.E., 1977, MNRAS, 181, 5p
Gilfanov M.R., Syunyaev R.A., 1984, Soviet Astron. Lett., 10, 137
Grevesse N., Sauval A.J., Space Science Rev., 85, 161
Johnstone R.M., Allen S.W., Fabian A.C., Sanders J.S., 2002, MNRAS, 336, 299
Johnstone R.M., Fabian A.C., Morris R.G., Taylor G.B., 2005, MNRAS, 356, 237
Lynden-Bell D., 1967, The Observatory, 87, 163
Makino N., Sasaki S., Suto Y., 1998, ApJ, 497, 555
Qin B., Wu X.P., 2000, ApJ, 529, L1
Renzini A., 2003, astro-ph/0307146
Rephaeli Y., 1978, ApJ, 225, 335
Sanders J.S., Fabian A.C., 2002, MNRAS, 331, 273
Sanders J.S., Fabian A.C., Taylor G.B., 2005, MNRAS, 356,1022
Sarazin, C.L., 1988, X-ray emission from clusters of galaxies, Cambridge University Press
Spitzer, L., 1956, Physics of Fully Ionized Gases, Interscience Publishers, New York
Vikhlinin A., Kravtsov A., Forman W., Jones C., Markevitch M., Murray S.S., Van Speybroeck L., 2005, ApJ, in press astro-ph/0507092