The first measurement of temperature standard deviation along the line-of-sight in galaxy clusters

D. A. Prokhorov1*, S. Colafrancesco2,3

1 W. W. Hansen Experimental Physics Laboratory, Stanford University, Stanford, CA 94305, USA
2 University of the Witwatersrand, School of Physics, Private Bag 3 - Wits 2050, Johannesburg, South Africa
3 INAF - Osservatorio Astronomico di Roma, via Frascati 33, I-00040 Monteporzio, Italy.

ABSTRACT

Clusters of galaxies are mainly formed by merging of smaller structures, according to the standard cosmological scenario. If the mass of a substructure is \( \gtrsim 10\% \) of that of a galaxy cluster, the temperature distribution of the intracluster medium (ICM) in a merging cluster becomes inhomogeneous. Various methods have been used to derive the two-dimensional projected temperature distribution of the ICM. However, methods for studying temperature distribution along the line-of-sight through the cluster were absent. In this paper, we present the first measurement of the temperature standard deviation along the line-of-sight, using as a reference case the multifrequency SZ measurements of the Bullet Cluster. We find that the value of the temperature standard deviation is high and equals to \((10.6 \pm 3.8)\) keV in the Bullet Cluster. This result shows that the temperature distribution in the Bullet Cluster is strongly inhomogeneous along the line-of-sight and provides a new method for studying galaxy clusters in depth.

Key words: galaxies:clusters:general– cosmic background radiation

1 INTRODUCTION

Clusters of galaxies are the largest gravitationally bound structures with size \( \sim 1 \div 3 \) Mpc (\( \approx (3 \div 10) \times 10^{24} \) cm) containing a hot diffuse plasma (the intracluster medium or ICM) which eventually sets in equilibrium in the potential wells of the cluster. The plasma is hence heated to high temperatures during the cluster gravitational collapse and the subsequent virialization by the gravitational energy released by the cluster formation from the assembly of smaller structures. The temperature of the ICM in its equilibrium stage can be as high as \( 10 \div 15 \) keV in the most massive clusters and ensures that the elements present in the ICM are highly ionized. Abundant light elements (such as hydrogen, helium, and oxygen) in the ICM have all the electrons removed from their nuclei. The free hot electrons in the ICM cause X-ray bremsstrahlung emission due to the interaction with protons (see, e.g., Rybicki & Lightman 1979) and also cause a distortion of the CMB radiation towards galaxy clusters due to the Inverse Compton (IC) scattering off CMB photons (the Sunyaev-Zel’dovich effect, hereafter the SZ effect; see, e.g., Sunyaev-Zel’dovich 1980). The typical number density of free electrons in the ICM is \( 10^{-3} \div 10^{-2} \) cm\(^{-3}\).

Mergers of sub-clusters occurring during cluster evolution cause an additional significant and non-uniform heating of the ICM due to the conversion of kinetic energy of gravitationally accelerated sub-clusters into thermal energy released into the ICM by shock waves. Shocks have been found, in fact, by the Chandra X-ray observatory in various systems, from galaxy groups with temperature of \( \approx 1 \) keV to the most massive galaxy clusters with temperature of \( \approx 15 \) keV (for a review, see Markevitch & Vikhlinin 2007). The cluster 1ES0657-558 (known as the Bullet Cluster) is a “textbook” example of a hot, merging cluster which has a bullet-like substructure in the ambient ICM, a strong shock wave driven by the bullet substructure, and very high and non uniform values of temperature (Markevitch et al. 2002). Thanks to deep Chandra observations, the Bullet Cluster is one of the best-studied galaxy clusters in X-rays. The analysis of the X-ray data from Chandra (see, e.g., Million & Allen 2008) shows that a single temperature model (i.e., a single temperature value observed along the line-of-sight through the cluster) does not properly describe the observed its X-ray spectrum. The temperature distribution along the...
line-of-sight in this cluster is then presumably strongly inhomogeneous.

Gas temperature in galaxy clusters can be derived by using different techniques, such as analyzing the X-ray spectra or the spectral form of the CMB distortion owing to the SZ effect. The derived X-ray spectroscopic temperature for a multitemperature electron population is weighted with a factor that is proportional to the squared number density and to the gas temperature to the power $\approx 3/4$ (Mazzotta et al. 2004). Therefore, due to the non-linear combination of density and temperature there is no simple way to interpret the X-ray spectroscopic temperature as the actual gas temperature and to obtain direct information about the temperature distribution along the line-of-sight. Additional assumptions about the gas density and temperature profiles along the line-of-sight, which are a priori unknown in merging galaxy clusters, are required for the X-ray analysis (see, e.g., Samsing et al. 2012). The temperature derived through the SZ technique is the mass-weighted temperature (Hansen 2004; Prokhorov et al. 2010, see also Colafrancesco & Marchegiani 2010 for a discussion on the spectroscopic SZ temperature derivation) and, therefore, it has a more explicit interpretation. Below, we will use this fact to obtain the information about the temperature distribution along the line-of-sight.

The SZ effect is an important tool for studying of galaxy clusters, since both the amplitude and spectral form of the CMB distortion (caused by the IC scattering of CMB photons off free electrons) depend on the ICM physical parameters (e.g., the plasma pressure and temperature). Relativistic corrections to the SZ effect are significant for high-temperature plasmas in massive clusters of galaxies (see Rephaeli 1995). The contribution from the relativistic corrections becomes stronger at high frequencies. The first detection of the SZ effect brightness increment from the Bullet Cluster at frequencies above 600 GHz has been obtained with the Herschel-SPIRE instrument (Zemcov et al. 2010). These high-frequency SZ observations have been used by Colafrancesco et al. (2011) to demonstrate that plasma models with several electron components provide a better fit than that with a single thermal component. This means that a substantial temperature variance (or standard deviation) $\sigma$ is expected along the line of sight through this cluster. The method of measurements of the temperature standard deviation, $\sigma$, along the line-of-sight has been proposed by Prokhorov et al. (2011). The use of the temperature standard deviation, which is a measure of the plasma inhomogeneity along the line of sight, provides us hence with a model-independent approach to characterize the amount of the temperature inhomogeneity in the ICM.

In this paper, we present the first measurement of the temperature standard deviation $\sigma$ along the line-of-sight in galaxy clusters. We use the method of Prokhorov et al. (2011) and SZ effect intensity data for the Bullet Cluster measured at four frequencies (150, 275, 600, and 857 GHz) to derive the temperature standard deviation. Using this method, we demonstrate that the temperature distribution along the line of sight through this cluster is very inhomogeneous and we quantify such an inhomogeneity by using the value of the standard temperature deviation.

## 2 THE TEMPERATURE STANDARD DEVIATION OF THE BULLET CLUSTER

In this section, we calculate the temperature standard deviation for the Bullet Cluster. This high temperature, merging galaxy cluster is a good target for measuring the standard temperature deviation because the contributions of high order corrections to the SZ effect are strong and because the gas temperature distribution is expected to be inhomogeneous along the line of sight owing to the cluster merger effects. In the following, we first describe the method to calculate the temperature standard deviation along the line of sight that takes into account SZ measurements at different frequencies and then apply this method to the Bullet Cluster.

The relativistically correct SZ effect can be described in the formalism based on the extension of the Kompaneets equation which allows relativistic effects to be included (e.g., Challinor & Lasenby 1998; Itoh et al. 1998) Analytical forms for the spectral changes due to the SZ effect, that are correct to second order in the expansion parameter $\Theta = k_b T_e/(\rho m_e c^2)$, can be written as

$$\frac{\Delta I(x)}{I_0} \approx \sigma_T \int \nu \Theta x \left[ (g_0(x) + \Theta g_1(x) + \Theta^2 g_2(x)) dl \right],$$

where $I_0 = 2(k_b T_{cmb})^3/(hc)^2$, $x = \nu/k_b T_{cmb}$, $T_e$ is the electron temperature, $\rho_{gas}$ is the number density of the ICM, $\sigma_T$ is the Thomson cross-section, $m_e$ the electron mass, $c$ the speed of light, $k_b$ the Boltzmann constant, and $h$ the Planck constant. The spectral functions of $g_0(x)$, $g_1(x)$, and $g_2(x)$ are taken from Eqs. (28) and (33) of Challinor & Lasenby (1998) and are given by

$$g_0(x) = \frac{x^4 \exp(x)}{(\exp(x) - 1)^2} \left( \frac{\exp(x) + 1}{\exp(x) - 1} - 4 \right),$$

$$g_1(x) = \frac{x^4 \exp(x)}{(\exp(x) - 1)^2} \left( -10 + \frac{47}{2} C(x) - \frac{42}{5} C^2(x) + \frac{7}{10} C^3(x) + \frac{7x^2}{5 \sinh^2(x/2)} (C(x) - 3) \right),$$

$$g_2(x) = \frac{x^4 \exp(x)}{(\exp(x) - 1)^2} \left[ \frac{-152}{8} C(x) - \frac{868}{5} C^2(x) + \frac{329}{5} C^3(x) - \frac{44}{5} C^4(x) + \frac{11}{30} C^5(x) + \frac{x^2}{30 \sinh^2(x/2)} \times \left( -2604 + 3948 C(x) - 1452 C^2(x) + 143 C^3(x) \right) + \frac{x^4}{60 \sinh^4(x/2)} \left( -528 + 187 C(x) \right) \right),$$

where $C(x) = x \coth(x/2)$.

The spectral function, $g_0(x)$, corresponds to the spectral function derived from the Kompaneets approximation (Zel’dovich & Sunyaev 1969). Both the first-order and second-order relativistic effects make significant contributions to the spectral distortion for $k_b T_e \gtrsim 10$ keV. We verified that, for a plasma with the temperature of $k_b T_e = 13.9$ keV and optical depth $\tau = 1.3 \times 10^{-3}$, as used by Zemcov et al. (2010), the second-order corrections in $\tau$ to the spectral shape (see Colafrancesco et al. 2003, for technical details) do
not produce appreciable variations in the SZ spectrum and, therefore, their contribution will be neglected in our paper.

The CMB intensity change produced by the SZ effect from a galaxy cluster with inhomogeneous density and temperature distributions in the formalism based on an extension of the Kompaneets equation, that is correct to second order in the expansion parameter \( \Theta \), is given by

\[
\frac{\Delta I(x)}{I_0} \approx \tau \left( \frac{\langle k_b T_e \rangle}{m_e c^2} x g_0(x) + \frac{\langle (k_b T_e)^2 \rangle}{m_e^2 c^4} x g_1(x) + \frac{\langle (k_b T_e)^3 \rangle}{m_e^3 c^6} x g_2(x) \right),
\]

(5)

where \( \langle k_b T_e \rangle = \int n_e k_b T_e \, dl / \int n_e \, dl \) is the temperature averaged along the line-of-sight and \( \langle (k_b T_e)^2 \rangle = \int n_e (k_b T_e)^2 \, dl / \int n_e \, dl \) is the squared temperature averaged along the line-of-sight. Note that the optical depth of the electron plasma, \( \tau \), can be derived from X-ray observations.

We derive the value of the temperature standard deviation by using the available multifrequency SZ observations of the Bullet Cluster: these have been obtained by ACBAR at frequencies of 150 GHz and 275 GHz (Gomez et al. 2004) and by Herschel-SPIRE at frequencies of 600 GHz and 857 GHz (Zemcov et al. 2011). This set of SZ observations have been used by Colafrancesco et al. (2011) in their studies of plasma models with different thermal and non-thermal components. The central SZ intensity values, \( \Delta I/I_0 \), measured by ACBAR and Herschel-SPIRE are shown with errorbars in Fig. 1 and listed in Table 1 (in units of MJy sr\(^{-1}\)). Note that the central SZ intensity values have been derived by using the radial profiles with an isothermal \( \beta \) model (for a review, see Birkinshaw 1999) taking the core radius and \( \beta \) parameter from Tucker et al. (1998) for the ACBAR data (Gomez et al. 2004), and the density profile given by Halverson et al. (2009) for the analysis of the Herschel-SPIRE data (Zemcov et al. 2010). We checked the consistence between the central SZ intensity values derived from these models and found that the difference in the central values is \( \approx 10\% \). However, the gas temperature distribution should be inhomogeneous along the line of sight and isothermal \( \beta \) models are just an approximation used to fit the data. With that caveat in mind, we will take the central SZ intensities from the papers by Gomez et al. (2004) and Zemcov et al. (2010) as it has been done in Colafrancesco et al. (2011).

The SZ intensity at each frequency is given by the sum of zero-th, first, and second order contributions in \( \Theta \) and can be written as

\[
\frac{\Delta I(x_i)}{I_0} \approx A_0 \times g_0(x_i) + A_1 \times g_1(x_i) + A_2 \times g_2(x_i)
\]

(7)

Table 1. The central values of the SZ effect at the various frequencies as obtained by ACBAR and HERCSHEL-SPIRE

| Frequency (GHz) | \( \Delta I_0 \) (MJy sr\(^{-1}\)) | Error (MJy sr\(^{-1}\)) |
|----------------|-------------------------------|-------------------|
| 150            | -0.325                        | 0.015             |
| 275            | 0.21                          | 0.077             |
| 600            | 0.268                         | 0.031             |
| 857            | 0.097                         | 0.019             |

where the dimensionless frequencies \( x_1, x_2, x_3, \) and \( x_4 \) equal to 2.64 (\( \nu = 150 \) GHz), 4.84 (\( \nu = 275 \) GHz), 10.57 (\( \nu = 600 \) GHz), and 15.09 (\( \nu = 857 \) GHz), respectively. We use the function “MPFITEPR”\(^1\) to find the best set of model parameters \( (A_0, A_1, A_2) \) which match the data performing Levenberg-Marquardt least-squares fit. We also apply the same method to find the best set of parameters in the models based on the Kompaneets approximation and on the expression including the zero and first order terms from Eq. 5, respectively. We denote these models as M1, M2, and M3, accordingly to the used number of terms proportional to \( \Theta \) for calculating the SZ effect (i.e., the model M1 corresponds to the Kompaneets approximation). The best-fit sets of parameters \( (A_0, A_1, A_2) \) and 1-sigma errors on these parameters \( (\delta A_0, \delta A_1, \delta A_2) \) derived from the SZ data are shown in Table 2 for the models of M1, M2, and M3. The values of \( \chi^2 \) for these models used to fit the observed SZ spectrum of the Bullet Cluster are also shown in Table 2. Comparing the values of \( \chi^2 \) from Table 2 with those from the \( \chi^2 \) table, we conclude that the model M3 agrees with the observed SZ data much better than the models M1 and M2. The model M3 is consistent with the SZ data and the \( \chi^2 \) value in this case is 0.3706 with 1 degree of freedom (d.o.f.). The SZ spectra derived from the models M1, M2, and M3 are shown in Fig. 1 by the dotted, dashed, and solid lines, respectively. Comparing the SZ spectra derived from the models with the observed SZ data, we find that the high-frequency observations provided by

\(^1\) http://cow.physics.wisc.edu/~craigm/idl/idl.html

Figure 1. The SZ spectrum of the Bullet Cluster fitted with the zero-order term (dotted), with the zero plus first order terms (dashed), and with the zero, first, and second order terms (solid).
Herschel-SPIRE allow us to constrain the contributions of the first-order and second-order relativistic SZ corrections to the thermal SZ effect. We calculate the covariance matrix for the parameters, \( A_0 \), \( A_1 \), and \( A_2 \), in the model M3 using the function of "MPFITEXPR". The calculated covariance matrix is

\[
\text{cov}_{ij} = \begin{pmatrix}
2.44800E-10 & 1.42381E-11 & 1.67978E-13 \\
1.42381E-11 & 7.15626E-12 & 2.68991E-13 \\
1.67978E-13 & 2.68991E-13 & 3.38113E-14
\end{pmatrix}
\]

where \( i, j = 0, 1, 2 \). The square root of the diagonal elements of the covariant matrix gives the 1-sigma statistic errors on the parameters \( A_0 \), \( A_1 \), and \( A_2 \).

Using the definitions of the parameters of \( A_0 \) and \( A_1 \), we rewrite Eq.(9) as

\[
\sigma = m_c c^2 \sqrt{\frac{A_1}{\tau} - \left(\frac{A_0}{\tau}\right)^2}
\]

We derive the value of the optical depth, \( \tau \), using the X-ray observations of the Bullet Cluster by ROSAT those have been analyzed by Tucker et al. (1998). The surface brightness profile of the primary cluster was obtained by extracting the net counts in concentric annuli about the primary X-ray peak after excluding the western quadrant (which contains the secondary peak) and all point sources. Tucker et al. (1998) fitted the observed X-ray surface brightness profile to the standard hydrostatic-isothermal/\( \beta \) model and obtained the values of a core radius, a central electron number density, and a beta parameter for the best fit. We re-scale the values of a core radius, a central electron number density using the present-day Hubble constant value, \( H_0 = 74 \) km s\(^{-1}\) Mpc\(^{-1}\). Using the parameters of the beta model and Monte-Carlo simulations, we find that the value of the optical depth is \( \tau = 0.0138 \pm 0.0016 \).

To calculate the temperature standard deviation along the line of sight in the Bullet Cluster, we use the derived values of parameters \( (A_0, A_1, \text{and } A_2) \), 1-sigma errors on these parameters, covariance matrix (\text{cov}), and optical depth (\( \tau = 0.0138 \pm 0.0016 \)). The 1-sigma error on the standard temperature deviation is given by

\[
\sigma = \sqrt{\sum_{i=0}^{1} \left( \frac{\partial \sigma}{\partial A_i} \right)^2 A_i^2 + 2 \sum_{i=0}^{1} \sum_{j=0}^{2} \frac{\partial \sigma}{\partial A_i} \frac{\partial \sigma}{\partial A_j} \text{cov}_{ij} + \left( \frac{\partial \sigma}{\partial \tau} \right)^2 \tau^2}.
\]

We consider the value of the optical depth as derived from X-ray observations, while the parameters \( (A_0, A_1, \text{and } A_2) \) are derived from SZ observations. Thus, the optical depth is an uncorrelated variable with other parameters in Eq.(8).

Using Eqs.(5) and (8), we find that the value of temperature standard deviation in the Bullet Cluster equals to \( \sigma = 9.5 \pm 2.6 \) keV. This value of standard temperature deviation is high although somewhat lower than the average plasma temperature, \( k_b T_e \approx 14.5 \) keV, derived from the Chandra X-ray observations of the Bullet Cluster (see, e.g., Million & Allen (2009)).

Since the derived value of temperature standard deviation is high and the contribution of higher order terms in the expansion parameter \( \Theta \) is significant at high frequencies for temperatures \( \gtrsim 15 \) keV, we recalculate the values of the temperature standard deviation and 1-sigma error on this quantity considering the spectral changes due to the SZ effect correct to third order in \( \Theta \). We estimate the uncertainty of the technique comparing the SZ intensity value derived in the extended Kompaneets formalism with that is derived from the Wright formalism (1979) and take them into account as systematic errors in the analysis. In this analysis, we consider electron temperatures in the range 5 keV - 30 keV that agree with that was found in the recent hydrodynamic simulations of the Bullet Cluster (Akahori & Yoshikawa 2011). We find that the values of the temperature standard deviation and 1-sigma error, \( \sigma = 10.6 \pm 3.8 \) keV, are consistent with those derived above.

We also calculated the temperature standard deviation using the optical depth derived by using the radial density profiles given by Halverson et al. (2009) and Ota & Mitsuda (2004). We obtained the values of the temperature standard deviation and of the associated errors that are within 10% and 30%, respectively, of those derived above. Therefore, the temperature standard deviation is high compared to the value of the gas temperature also assuming these models for the radial density distribution.

Based on our results, we conclude that the plasma temperature distribution is very inhomogeneous along the line of sight in the Bullet Cluster. This result confirms the presence of additional electron components previously revealed by Million & Allen (2009) by means of X-ray observations and by Colafrancesco et al. (2011) by means of SZ observations. Note that the method of Prokhorov et al. (2011), that we use in this paper, can be also applied to other merging massive galaxy clusters as soon as high-frequency SZ observations of other clusters become available.

### 3 CONCLUSIONS

We have derived the value of temperature standard deviation, \( \sigma \), along the line of sight in the Bullet Cluster using SZ effect observations at frequencies of 150, 275, 600, and 857 GHz. The measured value, \( \sigma = 9.5 \pm 2.6 \) keV, is obtained from the analysis taking into account the three first terms in the expansion parameter \( \Theta = k_b T_e / m_c^2 \) of the SZ effect (see Eq.(1)), and the analysis including the four first terms in \( \Theta \) and taking into account the uncertainty of the technique gives a consistent value, \( \sigma = 10.6 \pm 3.8 \) keV. The derived value of \( \sigma \) is of the order of the average plasma temperature, \( k_b T_e = 14.5 \) keV, in this cluster. Such a high value of
σ suggests hence that the gas temperature distribution is strongly inhomogeneous along the line of sight.

The high plasma temperature inhomogeneity along the line of sight in the Bullet Cluster is likely caused by its past merger activity. The presence of the strong shock wave and “bullet” cold substructure in this galaxy cluster is strong evidence in favor of a recent major merger of subclusters. Our result shows that the value of temperature standard deviation along the line of sight can be quite high in massive clusters undergoing strong merging and, therefore, that the plasma in such clusters should be strongly disturbed. This agrees with the fact that a single temperature model does not provide a good fit to X-ray observations (see Million & Allen 2009) and to SZ effect measurements (see Colafrancesco et al. 2011). By comparing the derived temperature standard deviation for the different models of a radial density distribution, we verified that our results are insensitive to the choice of the radial density profile. However, note that our results can be subject to additional possible systematic errors that come from: i) the uncertainties in the flux scales between the different frequency bands; ii) incomplete knowledge of the radial gas density distribution; iii) the subtraction of the bright sub-mm sources that can cause confusion in the ACBAR as well as the SPIRE data (see Johansson et al. 2010). The first two of these issues will be considered in a following paper (Prokhorov et al. 2012) where a joint analysis of the X-ray and SZ data for the Bullet Cluster will be presented.

The technique we present here does not require any specific assumptions about temperature profile. Therefore, the advantage of using the temperature standard deviation is that this quantity provides a model-independent information of the plasma temperature inhomogeneity along the line of sight.

There are several astrophysical and cosmological consequences of having large values of temperature standard deviation, σ, in galaxy clusters: i) measuring σ in different clusters of galaxies will tell us the relevance of merging and shocks in the evolution of these systems, especially those undergoing a collision along the line-of-sight; ii) the specific value of σ will allow us to constrain the possible non-gravitational effects in clusters and their evolution with the mass and redshift of the system. In addition it will tell us how much of the energy density of the cluster is due to non-gravitational effects with respect to pure gravitational effects; iii) the value of σ will tell us how confidently we can use galaxy clusters as cosmological probes (e.g., those are based on using of a mass-temperature relation) assuming simple models for the ICM, such a single temperature model.

We will discuss these and other consequences in more details elsewhere.

The first measurement of temperature standard deviation along the line-of-sight, that we have presented in this paper, demonstrates that existing microwave and mm. instruments provide us with a unique opportunity to derive this quantity in massive, merging clusters. Future multi-frequency SZ effect observations including high frequency observations of other merging galaxy clusters will allow us to study the plasma temperature distribution along the line of sight for many clusters of galaxies and will provide us with a better understanding of gas dynamical processes occurring in the ICM of merging clusters.

This is the first attempt in which we have been successful to measure σ, and we plan to provide a systematic analysis of the temperature standard deviation in all clusters with sensitive enough multi-frequency SZE observations. We believe that this new tool will provide a promising method to analyze the complex structure of cluster atmospheres.

4 ACKNOWLEDGEMENTS

We are grateful to Shigehiro Nagataki, Dmitry Malyshev, and Andrey Vladimirov for discussions and we thank the Referee for valuable suggestions.

REFERENCES

Akahori, T., Yoshikawa, K. 2011, PASJ, arXiv:1109.0826
Birkinshaw, M. 1999, Phys. Rep., 310, 97
Challinor, A., Lasenby, A. 1998, ApJ, 499, 1
Colafrancesco, S., Marchegiani, P., Palladino, E. 2003, A&A, 397, 27
Colafrancesco, S., and Marchegiani, P. 2010, A&A, 520, 31
Colafrancesco, S., Marchegiani, P., Buonanno, R. 2011, A&A, 527, L1
Hansen S. H., 2004, MNRAS, 351, L5
Gomez, P., Romer, A. K., Peterson, J. B. et al., 2004, AIPC, 703, 361
Kompaneets, A. S. 1957, Soviet Phys.-JETP, 4, 730
Itoh, N., Kohyama, Y., Nozawa, S. 1998, ApJ, 502, 7
Johansson, D.; Horellou, C.; Sommer, M. W.; Basu, K.; Bertoldi, F.; Birkinshaw, M.; Lancaster, K. et al. 2010, A&A, 514, A77
Markevitch, M., Gonzalez, A. H., David, L., Vikhlinin, A., Murray, S., Forman, W., Jones, C., Tucker, W. 2002, ApJ, 567, L27
Markevitch, M., Vikhlinin, A. 2007, Phys. Rep., 443, 1
Mazzotta, P., Rasia, E., Moscardini, L., Tormen, G. 2004, MNRAS, 354, 10
Million, E. T., Allen, S. W. 2009, MNRAS, 399, 1307
Ota, N., Mitsuda, K. 2004, A&A, 428, 757
Prokhorov, D. A., Dubois, Y., Nagataki, S. 2010, A&A, 524, A89
Prokhorov, D. A., Dubois, Y., Nagataki, S., Akahori, T., Yoshikawa, K. 2011, MNRAS, 415, 2505
Prokhorov, D. A., Million, E. T., Akahori, T., Zemcov, M. et al. 2012, in the preparation
Rephaeli, Y. 1995, ApJ, 445, 33
Rybicki, G. B., Lightman, A. P. 1979, New York, John Wiley & Sons, Inc.
Samsing, J., Skelboe, A., Hansen, S. H. 2012, ApJ, 748, 21
Sunyaev, R. A., Zel’dovich, Ya. B. 1980, ARA&A, 18, 537
Tucker, W., Blanco, P., Rappoport, S. et al. 1998, ApJ, 496, L5
Wright, E. L. 1979, ApJ, 232, 348
Zel’dovich, Ya. B., Sunyaev, R. A. 1969, ApSS, 4, 301
Zemcov, M., Rex, M., Rawle, T. D. et al. 2010, A&A, 518, L16