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Reconstruction of Gas Temperature and Density Profiles of the Galaxy Cluster RX J1347.5–1145 *

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Abstract We use observations of Sunyaev-Zel'dovich effect and X-ray surface brightness to reconstruct the radial profiles of gas temperature and density under the assumption of a spherically symmetric distribution of the gas. The method of reconstruction, first raised by Silk & White, depends directly on the observations of the Sunyaev-Zel'dovich effect and the X-ray surface brightness, without involving additional assumptions such as the equation of state of the gas or the conditions of hydrostatic equilibrium. We applied this method to the cluster RX J1347.5–1145, which has both the Sunyaev-Zel'dovich effect and X-ray observations with relative high precision. It is shown that it will be an effective method to obtain the gas distribution in galaxy clusters. Statistical errors of the derived temperature and density profiles of gas were estimated according to the observational uncertainties.

Key words: X-rays: galaxies: clusters — cosmology: theory — cosmic microwave background — galaxies: clusters: individual (RX J1347.5–1145)

1 INTRODUCTION

Galaxy cluster is known to be the largest virial gravitational bound system in the universe. The strong gravitational potential heats the gas (Hydrogen and Helium) to be fully ionized with a very high temperature $\sim 10^7 - 10^8$K. The thermal electrons collide with ions and emit bremsstrahlung radiation, which is mainly in X-ray band, making galaxy clusters strong X-ray sources. The intensity of thermal bremsstrahlung radiation is approximately proportional to $T_{\rm e}^{1/2} n_{\rm e}^2$ (Birkinshaw 1999). So by measuring the X-ray surface brightness, we can obtain information about the gas temperature and density distributions of the galaxy cluster. One of the most popular models is the so-called isothermal β model (Cavaliere & Fusco-Femiano 1976), in which the temperature distribution as a function of radius is assumed to be constant and the density profile takes the form $n_{\rm e}(R) = n_{\rm e0}(1 + R^2/R_c^2)^{-3\beta/2}$. This simple model gives good approximations to many galaxy clusters. However, more and more observations indicate that the temperature distribution may not be a constant over the whole galaxy. Hughes et al. (1988) introduced a revised model with a constant temperature in a range $r < r_{\rm iso}$ and a decrease at large radius, while the electron density has a truncation at a radius $r_{\rm lim}$. This form provides an adequate description for some of the clusters. Further modification on the β model has been proposed to deal with the existence of cooling flow in the center of the cluster (Fabian et al. 1984).

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In order to get rid of the degeneracy between $T_{\rm e}$ and $n_{\rm e}$, further assumptions like the hydrostatic equilibrium condition or the polytropic equation of state (EOS) of the electron gas (Cowie et al. 1987; Xue & Wu 2000; Wu & Chiueh 2001), or the spectrometric analysis (Jia et al. 2006) are needed. However, the results are still model dependent. A realistic reconstruction is expected to come directly from the observations.

The inverse Compton scattering between the electrons in clusters and the cosmic microwave background (CMB) photons, namely the Sunyaev-Zel'dovich (SZ) effect (Zeldovich & Sunyaev 1969; Sunyaev & Zeldovich 1970a, b), provides a possible way to achieve this goal. The distortion of the CMB spectrum is related to the electron temperature and density, and will provide another equation of $T_{\rm e}$ and $n_{\rm e}$. Combining the SZ effect and the X-ray observations, one can obtain the electron temperature and density profiles. This method was first suggested by Silk & White (1978), but has not yet been put into practice due to the limited instrumental sensitivity and resolution in the detection of the temperature fluctuation of CMB. Up to the 1990s some preliminary observational results of the radial temperature distribution were obtained for a few clusters (Birkinshaw et al. 1991; Birkinshaw & Hughes 1994), but it was still difficult to obtain precise reconstructions of the temperature and density profiles because the data points were too sparse and uncertain (Wu 2003).

In this paper, we try with this method to acquire some preliminary information about the gas temperature and density distribution. For simplicity, we assume a spherically symmetric distribution of the gas in the clusters. We adopt the ΛCDM model with $\Omega_M = 0.27$, $\Omega_\Lambda = 0.73$, and Hubble constant $H_0 = 71\,{\rm km\ s^{-1}\ Mpc^{-1}}$ (Spergel et al. 2003). This paper is organized as follows: we describe the method of reconstruction in Section 2. In Section 3 we apply this method to the galaxy cluster RX J1347.5–1145 to reconstruct its of temperature and density profiles, together with an estimate of the uncertainties. The conclusions and discussion are presented in Section 4.

2 METHOD OF RECONSTRUCTION

The fluctuation of the temperature of CMB due to the thermal SZ effect is (Birkinshaw 1999)

$$\frac{\Delta T_{\rm CMB}(R)}{T_{\rm CMB}} = g(x)y(R), \tag{1}$$

where $g(x) = x\coth(x/2) - 4$ with $x = h\nu/k_{\rm B}T_{\rm CMB}$ the dimensionless frequency, $y(R)$ is the Comptonization parameter as a function of the two-dimensional skymap radius R. In the Rayleigh-Jeans limit, $x \ll 1$, $g(x) = -2$, so we have $\Delta T_{\rm CMB}(R)/T_{\rm CMB} = -2y(R)$. The Comptonization parameter is related to the electron temperature and density by

$$y(R) = 2A_y \int_R^\infty T_{\rm e}(r)n_{\rm e}(r)\frac{r{\rm d}r}{\sqrt{r^2-R^2}}, \tag{2}$$

where $A_y = k_{\rm B}\sigma_T/m_{\rm e}c^2$, $k_{\rm B}$ is the Boltzmann constant, σ_T the Thomson cross section, $m_{\rm e}$ the mass of electron and c the speed of light. r denotes the three-dimensional spatial radius from the center of the galaxy cluster, while $R = d_{\rm A}\theta$ with $d_{\rm A}$ the angular diameter distance from the Earth to the cluster and θ the (projected) angular separation. $T_{\rm e}(r)$ and $n_{\rm e}(r)$ represent the electron gas temperature and number density as functions of the radius r, respectively.

The X-ray surface brightness of thermal bremsstrahlung emission is

$$S_x(R) = \frac{1}{4\pi(1+z)^4}\cdot 2A_x \int_R^\infty T_{\rm e}^{1/2}(r)n_{\rm e}^2(r)C(T_{\rm e})\frac{r{\rm d}r}{\sqrt{r^2-R^2}}, \tag{3}$$

where $A_x = \frac{2^4e^6}{3\hbar m_{\rm e}c^2}(\frac{2\pi k_{\rm B}}{3m_{\rm e}c^2})^{1/2}\mu_{\rm e}\bar{g}$, $\mu_{\rm e} = 2/(1+X)$ with $X = 0.768$ the primordial Hydrogen mass fraction, $\bar{g} \approx 1.2$ the average Gaunt factor (this average leads to an uncertainty of $\sim 20\%$ in the bolometric emissivity, see e.g., Ettori 2000) and z the redshift of the cluster. $C(T_{\rm e}) = \exp[-E_{\rm min}(1+z)/k_{\rm B}T_{\rm e}] - \exp[-E_{\rm max}(1+z)/k_{\rm B}T_{\rm e}]$ is a correction factor from the whole band of thermal bremsstrahlung emission to the detector bands $[E_{\rm min}, E_{\rm max}]$ (e.g., for ROSAT, $E_{\rm min} = 0.1\,{\rm keV}$ and $E_{\rm max} = 2.4\,{\rm keV}$).

Table 1 Parameters used in Equations (6) and (7)

X-ray	S_{x0}(erg s^{-1} cm^{-2} arcmin^{-2})	θ_{cx}(arcsec)	β_{cx}
	$1.34 \times 10^{-10\,a}$	4.29 ± 0.10^{b}	0.535 ± 0.003
SZ	y_0	θ_{cy}(arcsec)	β_{cy}
	$4.1^{+1.7}_{-0.4} \times 10^{-4}$	$56.3^{+12.0}_{-19.1}$	$0.89^{+0.26}_{-0.61}$

[a] Derived from the *Chandra* ACIS-S detector counts, see *http://heasarc.nasa.gov/Tools/w3pimms.html.*

[b] Note that the angular diameter distance is different from Allen et al. (2002) due to different cosmological models.

Using Abel's integral equation, Equations (2) and (3) can be inverted to (Yoshikawa & Suto 1999)

$$T_{\rm e}(r)n_{\rm e}(r) \;=\; \frac{1}{\pi A_y}\int_{\infty}^{r}\frac{{\rm d}y(R)}{{\rm d}R}\frac{{\rm d}R}{\sqrt{R^2-r^2}}, \tag{4}$$

$$T_{\rm e}^{1/2}(r)n_{\rm e}^2(r)C(T_{\rm e}) \;=\; \frac{4(1+z)^4}{A_x}\int_{\infty}^{r}\frac{{\rm d}S_x(R)}{{\rm d}R}\frac{{\rm d}R}{\sqrt{R^2-r^2}}. \tag{5}$$

Thus, given the observational distributions of $y(R)$ and $S_x(R)$, we can easily find the electron temperature and number density distributions from Equations (4) and (5).

3 APPLICATION TO CLUSTER RX J1347.5–1145

RX J1347.5–1145 is a highly X-ray luminous and dynamically relaxed galaxy cluster with redshift $z = 0.451$. Both *ROSAT* and *Chandra* have measured the X-ray emission of this cluster with high precision (Schindler et al. 1997; Allen et al. 2002). The X-ray surface brightness profile can be parameterized following the conventional β model as

$$S_x(R) = S_0\left(1+\frac{R^2}{d_{\rm A}^2\theta_{cx}^2}\right)^{-3\beta_{cx}+1/2}, \tag{6}$$

where $d_{\rm A}$ is the angular diameter distance of the cluster. For our adopted cosmological model, we find $d_{\rm A} = 1185\,$Mpc. Using the $18.9\,$ks *Chandra* ACIS exposure, Allen et al. (2002) gave a detailed X-ray image of this cluster in the energy band $0.3-7.0\,$keV. After subtracting the south-east excess, the X-ray surface brightness can be well described by Equation (6).

Detections of the SZ effect at different frequencies in this cluster were published by several groups (Pointecouteau et al. 2001; Komatsu et al. 2001; Reese et al. 2002). An empirical formula similar to the β model can also be used to parameterize the observational Comptonization parameter of the SZ effect $y(R)$,

$$y(R) = y_0\left(1+\frac{R^2}{d_{\rm A}^2\theta_{cy}^2}\right)^{-3\beta_{cy}/2+1/2}. \tag{7}$$

We use the fitting parameters from Pointecouteau et al. (2001). The parameters in Equations (6) and (7) are listed in Table 1.

Substituting $y(R)$ and $S_x(R)$ in Equations (4) and (5) by Equations (6) and (7), we can obtain

$$\begin{aligned} T_{\rm e}(r)n_{\rm e}(r) \;&=\; \frac{1}{\sqrt{\pi}A_y}\frac{y_0(3\beta_{cy}/2-1/2)}{d_{\rm A}\theta_{cy}}\frac{\Gamma(3\beta_{cy}/2)}{\Gamma(3\beta_{cy}/2+1/2)}\left(1+\frac{r^2}{d_{\rm A}^2\theta_{cy}^2}\right)^{-3\beta_{cy}/2} \\ &=\; C_y, \end{aligned} \tag{8}$$

$$\begin{aligned} T_{\rm e}^{1/2}(r)n_{\rm e}^2(r)C(T_{\rm e}) \;&=\; \frac{4\sqrt{\pi}(1+z)^4}{A_x}\frac{S_{x0}(3\beta_{cx}-1/2)}{d_{\rm A}\theta_{cx}}\frac{\Gamma(3\beta_{cx})}{\Gamma(3\beta_{cx}+1/2)}\left(1+\frac{r^2}{d_{\rm A}^2\theta_{cx}^2}\right)^{-3\beta_{cx}} \\ &=\; C_x. \end{aligned} \tag{9}$$

Then

$$T_{\rm e}(r)^{3/2}/C(T_{\rm e}) \;=\; C_y^2/C_x, \tag{10}$$
$$n_{\rm e}(r) \;=\; C_y/T_{\rm e}(r). \tag{11}$$

From Equation (10) we know that, if $\theta_{cx} = \theta_{cy}$, $\beta_{cx} = \beta_{cy}$, the temperature should be independent of the radius, as expected from the isothermal β model. If $\beta_{cy} > \beta_{cx}$, the temperature will decrease at large radius; while for $\beta_{cy} < \beta_{cx}$, the temperature will increase in the outer region of the cluster, which seems to be unreasonable.

It is easy to calculate $T_{\rm e}(r)$ and $n_{\rm e}(r)$ using the parameters given in Table 1. To obtain the uncertainties of the derived temperature and density profiles, we run a Monte-Carlo (MC) sampling of the parameters according to their uncertainties. The parameter is thought to be Gaussian distributed peaked at the central value with width of 1σ error-bar. However, we note that the 1σ error-bars are not the same in the "$+$" and "$-$" directions. So the distribution of a parameter is the combination of two Gaussian functions, connected at the peak point. For example, for a parameter $a = a_0{}^{+\sigma_1}_{-\sigma_2}$, the width of $a > a_0$ is σ_1 and $a < a_0$ is σ_2, with the connecting condition $k_1/\sigma_1 = k_2/\sigma_2$. The probability distribution function of parameter a can be written as

$$p(a) = \begin{cases} \frac{k_1}{\sigma_1}\exp(-\frac{(a-a_0)^2}{2\sigma_1^2}) & a > a_0, \\ \frac{k_2}{\sigma_2}\exp(-\frac{(a-a_0)^2}{2\sigma_2^2}) & a < a_0. \end{cases} \tag{12}$$

Here, k_1 and k_2 can be derived according to the normalization condition $\int p(a){\rm d}a = 1$. Some cut conditions are adopted in the MC sample. Equations (8) and (9) require $\beta_{cy} > 1/3$ and $\beta_{cx} > 1/6$; the other parameters are required to be greater than $zero$. Even so, some of the parameter combinations make Equation (10) unresolved. These cases were also discarded.

The average values and variances of the temperature and density of the MC sampling are shown in Figure 1. Shaded regions are the $1\times$ and $2\times$ sample variances as represented by the $\pm 1\sigma$ and $\pm 2\sigma$ errors. The results of previous authors are also shown for comparison. The solid crosses are the deprojected temperature profiles from the *Chandra* X-ray spectroscopy (Allen et al. 2002), the dotted crosses are the derived results from the SZ effect and X-ray data using a method slightly different from this work (Kitayama et al. 2004), and the dot-dashed line is the extrapolated result from the *Chandra* spectroscopy observations (Schmidt et al. 2004). It is shown in this figure that our derived results are roughly consistent with the other results at 2σ level. For the inner region of the cluster, our results show an under-estimation of the temperature. This might be due to the systematic errors of the observations (especially the SZ measurements). From Equations (10) and (11) we know that a larger y_0 or a smaller S_{x0} may result in a larger central temperature. From Pointecouteau et al. (2001) it was shown that different fitting models could indeed give different y_0. The density profile, as shown in the lower panel of Figure 1, is consistent with the results in Schmidt et al. (2004) for $r < 500$ kpc. As pointed out in Allen et al. (2002), the surface brightness showed a steepening with increasing radius, which means an increase of the β parameter. A broken power law with $\beta = 0.54$ changing to 0.78 at $r = 487$ kpc could well describe the observations. We adopt a uniform β parameter here, so for large radii our results are somewhat high. According to Equation (10), a larger β_{cx} will also lead to a higher temperature at large radius.

4 CONCLUSIONS AND DISCUSSION

Using the observational data of the SZ effect and X-ray surface brightness, we applied the method suggested by Silk & White (1978) to the galaxy cluster RX J1347.5–1145, to reconstruct its gas temperature and density profiles. This is a direct way to obtain the temperature and density profiles of galaxy clusters, without additional theoretical assumptions. However, the quality of the observational data strongly affect the reconstruction results. Our attempt on cluster RX J1347.5–1145, which has both the X-ray and SZ measurements with relative high precision, demonstrates the effectiveness of this method. The derived results show similar behaviors as the previous studies. It indicates that there is a cooling flow in the center of the cluster, but the central value we derived is lower than the others. Poor quality and possible systematic uncertainties of the SZ effect data might be responsible for this discrepancy. It should be noted that the model parameters of the X-ray surface brightness and SZ effect were derived from finite area images around the center of the cluster,

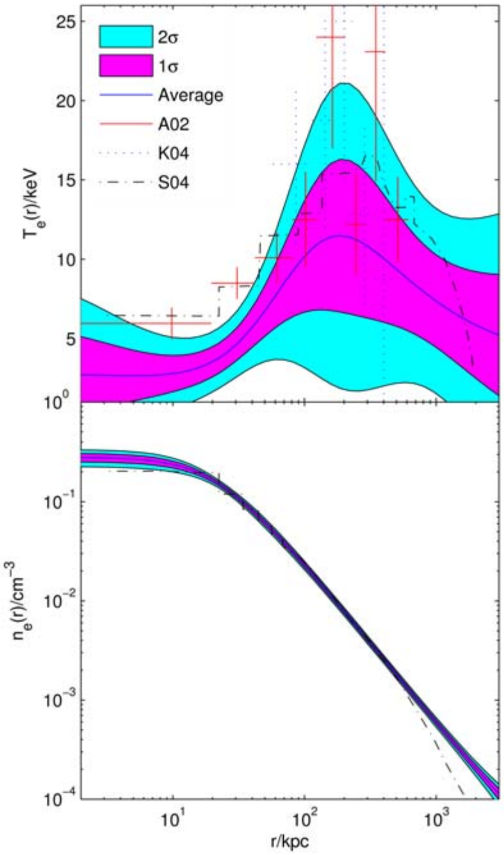

Fig. 1 Derived profiles of temperature (upper panel) and density (lower panel) together with their uncertainties. Also shown are the results of some previous studies, see the text for explanations.

then extrapolated to large radii. This may result in additional uncertainty (see the discussion in Section 3). When high quality measurements of the SZ effect become available in the future, it will be a powerful tool to study the intrinsic gas distribution independent of any theoretical arguments.

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References

Allen S. W., Schmidt R. W., Fabian A. C., 2002, MNRAS, 335, 256
Birkinshaw M., 1999, Phys. Rep., 310, 97
Birkinshaw M., Hughes J. P., 1994, ApJ, 420, 33
Birkinshaw M., Hughes J. P., Arnaud K. A., 1991, ApJ, 379, 466
Cavaliere A., Fusco-Femiano R., 1976, A&A, 49, 137
Cowie L. L., Henriksen M., Mushotzky R., 1987, ApJ, 317, 593
Ettori S., 2000, MNRAS, 311, 313
Fabian A. C., Nulsen P. E. J., Canizares C. R., 1984, Nature, 310, 733
Hughes J. P., Yamashita K., Okumura Y. et al., 1988, ApJ, 327, 615
Jia S. M., Chen Y., Chen L., 2006, Chin. J. Astron. Astrophys. (ChJAA), 6, 181

Kitayama T., Komatsu E., Ota N. et al., 2004, PASJ, 56, 17
Komatsu E., Matsuo H., Kitayama T. et al., 2001, PASJ, 53, 57
Pointecouteau E., Giard M., Benoit A. et al., ApJ, 552, 42
Reese E. D., Carlstrom J. E., Joy M. et al., 2002, ApJ, 581, 53
Schindler S., Hattori M., Neumann D. M. et al., 1997, A&A, 317, 646
Schmidt R. W., Allen S. W., Fabian A. C., 2004, MNRAS, 352, 1413
Silk J., White S. D. M., 1978, ApJ, 226, L103
Spergel D. N., Verde L., Peiris H. V. et al., 2003, ApJS, 148, 175
Sunyaev R. A., Zeldovich Y. B., 1970a, Ap&SS, 7, 3
Sunyaev R. A., Zeldovich Y. B., 1970b, Ap&SS, 7, 20
Wu X.-P., 2003, in Astronomical Society of the Pacific Conference Series, Vol. 301, Astronomical Society of the Pacific Conference Series, ed. S. Bowyer, C.-Y. Hwang, 365
Wu X.-P., Chiueh T., 2001, ApJ, 547, 82
Xue Y.-J., Wu X.-P., 2000, A&A, 360, L43
Yoshikawa K., Suto Y., 1999, ApJ, 513, 549
Zeldovich Y. B., Sunyaev R. A., 1969, Ap&SS, 4, 301