PROSPECTS FOR DETECTION OF INTRACLUSTER GAS BULK VELOCITIES THROUGH THE SUNYAEV-ZELDOVICH EFFECT

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ABSTRACT

Intracluster gas velocity gradients have been recently detected by the authors in the Centaurus Cluster (A3526) using the Doppler shift of X-ray spectral lines with ASCA Solid-State Imaging Spectrometers. The velocity gradient was found to be maximum along a line roughly perpendicular to the direction of the incoming subgroup Cen 45 and has a correspondent velocity difference of \( \sim (3.4 \pm 1.1) \times 10^3 \) km s\(^{-1}\) within a \( \sim 10' \) diameter region centered on the cD galaxy NGC 4696. Such bulk velocities should Comptonize the cosmic microwave background radiation (CMBR) producing variations of intensity and temperature that can be detectable in the near future with bolometers such as BOLOCAM. In this paper we realistically estimate the expected CMBR Comptonization for the central region of A3526, using ASCA and ROSAT data to constrain the Sunyaev-Zeldovich parameter expectations.

Subject headings: cooling flows — cosmic microwave background — galaxies: clusters: individual (Abell 3526) — intergalactic medium — X-rays: galaxies: clusters

1. INTRODUCTION

Clusters of galaxies are believed to form from the infall/merging of smaller scale systems. Memory of the formation process may be probed through the X-ray analysis of the intracluster medium (ICM), where most of the cluster’s visible mass resides. This is because the merging of subunits is predicted to create gas substructures such as temperature and density inhomogeneities, destruction of cooling flows and metal abundance gradients, and generation of gas bulk velocities. The comparison of observed structures to numerical hydrodynamic+\( N \)-body simulations can then provide clues as to the cluster’s evolutionary stage (e.g., Evrard 1990; Katz & White 1993; Navarro, Frenk, & White 1995; Evrard, Metzler, & Navarro 1996; Roettiger, Burns, & Loken 1993, 1996; Schindler & Muller 1993; Pearce, Thomas, & Couchman 1994; Gomez et al. 2002 and references therein).

Until very recently the physical characteristics of the ICM had been derived almost exclusively by the analysis of distributions of electron temperature \( (T_e) \) and surface brightness \( (S_X) \) (or gas density), even though in the last few years various numerical simulations of off-center cluster mergers have been published predicting the presence of long-lasting residual intracluster gas velocities approaching a few thousand kilometers per second (e.g., Roettiger, Loken, & Burns 1997; Ricker 1998; Roettiger, Stone, & Mushotzky 1998; Takizawa & Mineshige 1998; Takizawa 1999, 2000; Roettiger & Flores 2000; Burns et al. 2002). Furthermore, since we are always looking at two-dimensional projections, velocity maps will be a crucial addition, necessary to break the degeneracies associated with analyses based solely on \( T_e \) and \( S_X \) distributions.

Recently, Dupke & Bregman (2001a, 2001b) detected ICM bulk motions in two galaxy clusters using ASCA data: Perseus (A426) and Centaurus (A3526). The intracluster gas velocity distributions detected in these two clusters are roughly consistent with systematic gas bulk rotation with correspondent circular velocities greater than \( 1000 \) km s\(^{-1}\), implying that a significant fraction of the intracluster gas energy can be kinetic. Since X-ray measurements are haunted by the need for precise knowledge of instrumental gain,1 these detections are significant only at the 2–4 \( \sigma \) level. Realistically, the significance of these measurements are not expected to improve substantially within the next several years, even with Chandra and XMM-Newton, since the spectral resolution of the imaging spectrometers on board these satellites, ACIS and the European Photon Imaging Cameras,2 is only slightly better than that of the Solid-State Imaging Spectrometers on board ASCA. Furthermore, it will take a few years before detailed gain variations across those detectors are known well enough for reliable ICM velocity measurements. To compensate for the lack of knowledge of the gain variations in X-ray spectrometers, it is necessary to take several consecutive off-center long-exposure observations of a cluster so that sky regions with discrepant radial velocities can be observed at the same CCD position. However, this kind of measurement is very time consuming if one does not have prior knowledge of the best orientations for velocity measurements.

Alternatively, ICM velocity measurements can be, in principle, corroborated/detected by the use of the kinetic Sunyaev-Zeldovich (SZ) effect (Sunyaev & Zeldovich 1970, 1972, 1980). Intracluster gas bulk velocities as high as those detected in A3526 should generate significantly different levels of Comptonization of the cosmic microwave background radiation (CMBR) toward different directions of the cluster (redshifted and blueshifted sides). This effect could be detected with current (or in development) instruments, such as the BOLOCAM,3 or, with smaller spatial res-

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1 Conversion between pulse height and incoming photon energy.
2 We are not considering the gratings since they are less suited for this kind of spatially resolved spectroscopy.
3 Information is available at http://www.astro.caltech.edu/~lgg/bolocam/bolocam.html.
olution, ACBAR\textsuperscript{4} and the High Frequency Instrument on board the Planck Surveyor.\textsuperscript{5}

In this paper we realistically predict differential variation of the CMBR temperature as it passes through the intracluster gas of the central regions of the Centaurus Cluster, \((\Delta T / T)_{\text{CMBR}} \sim 10^{-4}\). We propose that this effect can soon be observed in cool clusters, such as Centaurus, at frequencies that minimize the thermal component \((\sim 214 \, \text{GHz})\). We suggest that differential SZ measurements of clusters, coupled with X-ray spatially resolved spectroscopy can provide information crucial not just to cosmology but also to the study of intracluster gas dynamics.

2. THE MECHANISM

The CMBR intensity and temperature variations with respect to the background toward the direction of a rotating cluster has two components; a thermal and a kinetic component. The latter can be associated with some global peculiar velocity and also with internal bulk motions, which is the one in which we are interested in this work. If the resulting radial velocity associated with the kinetic SZ component at some projected radius \(b\) is denoted by \(V_r\), then the thermal and kinetic variation of intensity \((\Delta I)\) and temperature \((\Delta T)\) of the CMB in the nonrelativistic approximation can be can be given by (for reviews see, e.g., Rephaeli 1995; Birkinshaw 1999)

\[
\Delta I \approx 2 \left( \frac{kT}{\hbar c} \right)^3 \frac{x^4 e^x}{(e^x - 1)^2} \left[ K(T_e, \nu) - \beta(b) \right] \tau(b), \tag{1}
\]

\[
\left( \frac{\Delta I}{T} \right)_{\nu} \approx \frac{xe^x}{e^x - 1} \left[ K(T_e, \nu) - \beta(b) \right] \tau(b), \tag{2}
\]

\[
\left( \frac{\Delta T}{T} \right)_{\nu} \approx K(T_e, \nu) - \beta(b) \tau(b), \tag{3}
\]

where

\[
K(T_e, \nu) = \frac{kT_e}{m_e c^2} \left( x e^x + 1 \right), \tag{4}
\]

\[
\beta(b) = \frac{V_r(b)}{c}, \quad x = \frac{h\nu}{kT}, \tag{5}
\]

where \(T_e\) and \(T\) are the ICM and CMB temperatures, respectively, and the other parameters have their usual meanings. If the gas number density \(n(r)\) follows a King-like profile \(n(r) = n_0 \left[ 1 + (r/r_c)^2 \right]^{-3/2}\), where \(r_c\) and \(n_0\) are the core radius and the central density, respectively, then the optical depth is given as a function of the projected radius \(b\) by

\[
\tau(b) = \sigma T n_0 r_c B \left( \frac{1}{2}, \frac{3}{2} \right) \left[ 1 + \left( \frac{b}{r_c} \right)^2 \right]^{-3/2} \left[ 1 + \left( \frac{b}{r_c} \right)^2 \right]^{-1/2} \tag{6}
\]

where \(B(p, q) = \int_0^\infty x^{p-1}(1 + x)^{q-p}dx\) is the beta function of \((p, q)\).

3. THE CASE FOR A3526

Centaurus (A3526) is a BM type I, nearby \((z \sim 0.0104)\), X-ray–bright cooling flow \((\text{accretion rate } < 30 - 50 \, M_\odot \, \text{yr}^{-1})\), cold \((kT_e \sim 3 - 5 \, \text{keV})\) cluster. Its X-ray emission is relatively smooth except for the central \(1\), where Chandra found a large amount of X-ray substructure (Sanders & Fabian 2002), and it is peaked on the cD galaxy NGC 4696. The existence of galaxy velocity bi-modality in Centaurus had been shown by Lucey, Currie, & Dickens (1986a, 1986b) and was more recently confirmed by Stein, Jerjen, & Federspiel (1997). Two galaxy groups are clearly separated: the main group (Cen 30), which is centered on the cD galaxy (NGC 4696) shows an average radial velocity of \(3397 \pm 139\) km s\(^{-1}\) and a velocity dispersion of \(933 \pm 118\) km s\(^{-1}\). The second group (Cen 45) is associated with the galaxy NGC 4709 at \(\sim 15\) from NGC 4696. It has an average radial velocity of \(4746 \pm 43\) km s\(^{-1}\) and a velocity dispersion of \(131 \pm 43\) km s\(^{-1}\). One arcminute at Centaurus distance corresponds to \(\sim 19\) kpc. The general interpretation for this bi-modality is that Cen 45 is being accreted by the Centaurus Cluster. This explanation has been further strengthened by (1) the discovery of higher gas temperatures \((\geq 5 \, \text{keV})\) associated with Cen 45 by Churazov et al. (1999) and (2) a marginally significant intracluster gas velocity difference of \(\sim 1800\) km s\(^{-1}\) between Cen 45 and Cen 30 detected by Dupke & Bregman (2001b, hereafter DB01).

More interestingly, DB01 found a small-scale (within the central \(10\)) significant \((\geq 99.8\%\) confidence) intracluster gas velocity gradient more or less symmetric with respect to the cluster’s center, consistent with bulk gas rotation with a corresponding circular velocity of \((1.59 \pm 0.32) \times 10^3\) km s\(^{-1}\). The nature of this velocity gradient is likely to be related to some previous merger on the main body of the Centaurus Cluster (Cen 30). The maximum velocity difference is found roughly along an axis at a position angle of \(\sim 40^\circ\) (Fig. 1). Therefore, velocity measurements by means of the kinetic SZ effect on CMBR temperature and intensity variations could be optimized along that axis (e.g., by choosing symmetric subregions for source/background along that position angle, such as the extremes of the box in Fig. 1).

In Figure 2 we show the absolute and relative variations of intensity and CMBR temperature toward the directions of maximum (dotted line) and minimum (dashed line) velocities as observed by ASCA, i.e., \(5\) away from the cluster’s core (regions P3 and P7 in Fig. 1), as a function of wavelength. Both kinetic and thermal effects are added. The gas density profile used was obtained taking into account that we are looking at spatial regions with the same scale as (or smaller than) the cluster’s core radius. Therefore, it is more appropriate to choose surface brightness profile fittings that realistically take into account the cluster’s central region, where the surface brightness is enhanced and single \(\beta\) models diverge significantly from the observed profiles. We believe that the double \(\beta\) fitting profiles used in the extensive ROSAT analysis of Mohr, Mathiesen, & Evrard (1999, hereafter MME99) are the most reliable for that purpose, and we use them in our calculations.\textsuperscript{6}

\textsuperscript{4}Arcminute Cosmology Bolometer Array Receiver; information is available at http://www.astrophysics.phys.cmu.edu/research/viper.

\textsuperscript{5}Information is available at http://astro.estec.esa.nl/Planck.

\textsuperscript{6}The choice of MME99 is also a conservative one since other surface brightness–derived density profiles available in the literature, e.g., Jones & Forman (1999), typically produce higher values for the optical depth within the spatial regions considered, thus enhancing the magnitude of \((\Delta T / T)\).
Fig. 1.—Radial velocity distribution in Centaurus. Top: ASCA GIS X-ray surface brightness overlaid by the regions analyzed by Dupke & Bregman (2001b). The values in parentheses indicate the 1σ confidence limits for one interesting parameter (radial velocities). The box shows the region of maximum velocity gradient. “N” denotes north. Bottom: Azimuthal velocity distribution. Curve shows a solid-body rotation fit with an associated circular velocity of 1600 km s⁻¹. The vertical lines indicate the direction of the incoming subgroup Cen 45. The two horizontal lines show the 1σ confidence limits for the velocity measured in the central region P0.
we use the following integral for our \( \tau(b) \):

\[
\tau(b) = 2 \sigma_T \frac{n_e}{f(0)} \int_b^\infty \left[ 1 + \left( \frac{r}{r_c} \right)^2 \right]^{(3/2)\beta} \frac{f(r) r \, dr}{\sqrt{r^2 - b^2}},
\]

instead of equation (6). In equation (7) \( n_e \) and \( f(0) \) are the number density and the “fudge” function \( f(r) \) at the cluster’s center (MME99). For the functional form of \( f(r) \) we use an inverse polynomial given as \( f(r > r') \equiv \text{const}0 + (\text{const}1/r) + (\text{const}2/r^2) \), where the best-fit values within \( b < 190 \, h_{50}^{-1} \) kpc are \( \text{const}0 = 0.817 \), \( \text{const}1 = 1.05 \times 10^{23} \) cm, and \( \text{const}2 = 2.7 \times 10^{16} \) cm$^2$.

The surface brightness parameters used to derive the optical depth (eq. [7]) are \( T_e(r = 5') = 3.4 \) keV, \( V_{\text{circ}}(r = 5') = 1600 \) km s$^{-1}$ (DB01), \( \beta = 0.57 \), \( n_e = 0.068 \) cm$^{-3}$, and \( r_c = 7.3 \) (MME99). In all three plots the thick solid line shows the difference between the redshifted and blueshifted curves. It can be seen that the CMBR intensity variation difference (Fig. 2, top) is maximized at 214 GHz (\( \lambda = 0.14 \) cm). This is the optimal frequency to observe the relative kinetic SZ effect and, consequently, to determine a velocity map. At that frequency the difference between the relative variations of intensity and temperature are \( \Delta(I/I) \sim 5 \times 10^{-4} \) and \( \Delta(T/T) \sim 10^{-4} \) (Fig. 2, middle and bottom plots).

The magnitude of the parameters derived above are, naturally, a function of the projected radial distance from the cluster’s center. In order to determine the radial profile of the expected \( \Delta T/T \) at 214 GHz we make two assumptions: First, we assume that in the region from \( r' \) to \( 5' \) the cooling flow can be approximated by a linear function varying from 3.4 to 1 keV at the center. The flattening of the temperature profile at the cluster’s center has been observed with Chandra and XMM for some clusters, and it may be a common feature of cooling flows (Fabian 2001). In the case of Centaurus there is evidence that the minimum temperature derived from spectral fittings using cooling flow models is greater than 0.4–1.0 keV (Sanders & Fabian 2002). The central arcminute in Centaurus has an impressive amount of substructure (plumes), and this makes our estimation of the central densities more uncertain. Therefore, we exclude that region from our analysis (Fig 3). Second, we assume that the gas motion can be approximated by a solid body rotation. This functional form for the gas velocity cannot be supported for larger radii since the gas becomes gravitationally unbound, but it is a good observed first-order approximation for the inner regions (R. A. Dupke & J. N. Bregman 2002, in preparation). This assumption is supposed to break at \( \sim 5'–6' \), when the combined bulk kinetic and thermal energies become greater than the gravitational and the gas becomes unbound (e.g., see Allen & Fabian 1994). We show the results in Figure 3. Assuming that the velocity “freezes” at 1600 km s$^{-1}$, we also show in Figure 3 the predicted behavior of \( \Delta T/T \) at regions radially greater than that encompassed by ASCA velocity analysis, for illustration purposes.

The kinetic Comptonization of the spectrum that reaches us from a rotating cluster is roughly antisymmetric with respect to the center of the cluster from \( \sim 160–270 \) GHz. This suggests that larger variations of intensity and temperature of the CMBR can be observationally enhanced by comparing the measurements (in the same channel) "within" the cluster, rather than to a background region.
away from the cluster. We show the distribution of CMB temperature variations ($\Delta T/T$) as a function of radius at that frequency in Figure 3. The horizontal errors in Figure 3 show the FWHM of BOLOCAM. The solid lines represent the estimated 1σ errors of measurement associated to the X-ray–derived parameters and are dominated by X-ray velocity measurement errors. SZ measurements of radial velocities can be performed within these 1σ limits with a relatively short exposure time (see below).

Variations of CMB intensity or temperature of that magnitude can be relatively easily observed currently, or in the very near future, with the new generation of bolometers. A total variation of CMB temperature of ~0.3 mK between the “knees” in Figure 3 is equivalent to a flux density of $\Delta f_{\text{lim}} \sim 1.2$ mJy (FWHM)$^{-2}$. Such observations could be made with high significance in a relatively short amount of time with, for example, BOLOCAM, given that the FWHM for that instrument is 430 and the expected noise equivalent flux densities is 35 mJy Hz$^{-1/2}$ at the 1.4 mm band\(^7\) (Glenn et al. 1998).

4. SUMMARY

Direct indications of the presence of large bulk motions in clusters of galaxies have been recently obtained through X-ray spatially resolved spectroscopy. However, these observations are limited by detector’s gain fluctuations, and this will continue to be the case for the next several years. An alternative way of measuring intracluster gas bulk velocities is through the use of the kinetic SZ effect. The use of bolometers has significantly improved the precision of radio observations of the SZ effect, especially within the optimal frequency range for such measurements, i.e., ~214 GHz ($\lambda = 0.14$ cm), so that it will be possible in the near future to perform such velocity measurements with instruments such as BOLOCAM (Bock et al 1998) with relatively short exposure times. The combination of X-ray and radio measurements can provide us with independent/complementary information crucial to building ICM velocity maps and to determining the degree of evolution and the history of galaxy clusters.

So far, the best candidate for testing the proposed multiwavelength measurements of velocity gradients is the Centaurus Cluster. The symmetry of the gas velocity distribution and the low temperatures measured for this cluster should facilitate the separation of the rotational kinetic component from both thermal and peculiar velocity ones. By combining the analyses of intracluster gas velocity and temperature distributions with other relevant X-ray cluster characteristics, we predict that the variations of CMBR temperature between two regions symmetrically located 5’ from the clusters center along the line of maximal velocity gradient at $\lambda = 0.14$ cm is ~0.3 mK.

The magnitude of the SZ parameters observationally derived in this work, if typical, could significantly enhance possible halo-induced gas rotational contribution to the CMBR angular power spectrum (Cooray & Chen 2002). However, the limiting nature of the search for velocity gradients using current X-ray spectrometers tends to be biased toward clusters with high bulk velocities, so that the current data does not yet allow us to calculate precise velocity distributions and, consequently, to determine the deviations from the assumptions used in statistical analysis of CMB temperature anisotropies, such as those performed by Cooray & Chen (2002). Furthermore, if both “rotational” and “transient” bulk velocities are as common in the central regions of clusters as suggested by a more extended ASCA analysis (R. A. Dupke & J. N. Bregman 2002, in preparation), measurements of cluster peculiar velocities should be treated with extreme caution, given the potential confusion with an internal gas bulk motion component.

Multiple off-center long-exposure velocity measurements of intracluster gas with the Chandra and XMM-Newton satellites coupled with radio observations of the differential kinetic SZ effect will be crucial in determining precise intracluster velocities in the central and intermediate regions of galaxy clusters, improving significantly the determination of their evolutionary stage, and constraining biases related to the presence of coherent velocity fields in blind SZ surveys.

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