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Probing the missing baryons around Virgo with Planck

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Abstract

We study the largest cluster in the sky (in terms of solid angle) with Planck through the SZ effect. Virgo is well resolved by Planck, and shows an elongated structure. Good agreement between the SZ signal and the expected signal inferred from X-ray observations is found. We study the gas beyond the virial radius in Virgo and find that significant amounts of low-density plasma surround Virgo, out to twice the virial radius. The observed signal is consistent with simulations and points to a shallow pressure profile in the outskirts of the cluster that can be linked with the hottest phase of the elusive warm/hot intergalactic medium. After comparing the integrated SZ and X-ray signal, we find that a prolate model is favoured, in agreement with predictions.

1 Introduction

The Virgo cluster is the dominant cluster in our environment and is located ≈ 18 Mpc from our Galaxy. Virgo is a moderate cluster in terms of its mass, $M \approx (4\text{–}8) \times 10^{14} \mathrm{M}_\odot$ but it is the biggest cluster in terms of angular size (tens of square degrees). The combination of moderate mass and large angular size makes this cluster the largest single source for the Sunyaev-Zeldovich (SZ) effect in the sky in terms of integrated flux as shown in [4]. The Coma cluster, on the other hand, is the most prominent cluster in terms of signal-to-noise but subtends a significantly smaller solid angle than Virgo. Despite its proximity to us, the strength of the SZ signal (or more specifically the surface brightness) is expected to be low for this moderate mass cluster, as shown by [2], making it a challenging object to study.

The angular size of the virial radius, $R_{\rm vir}$, of Virgo is 4 deg corresponding to 1 Mpc (for a distance of $D = 15\,\mathrm{Mpc}$). The area enclosed between $R_{\rm vir}$ and $1.25R_{\rm vir}$ is an impressive 30 deg^2. No other cluster offers such a large area, enabling us to average the SZ signal and increase the sensitivity to an unprecedented level. Hence, the Virgo cluster offers a

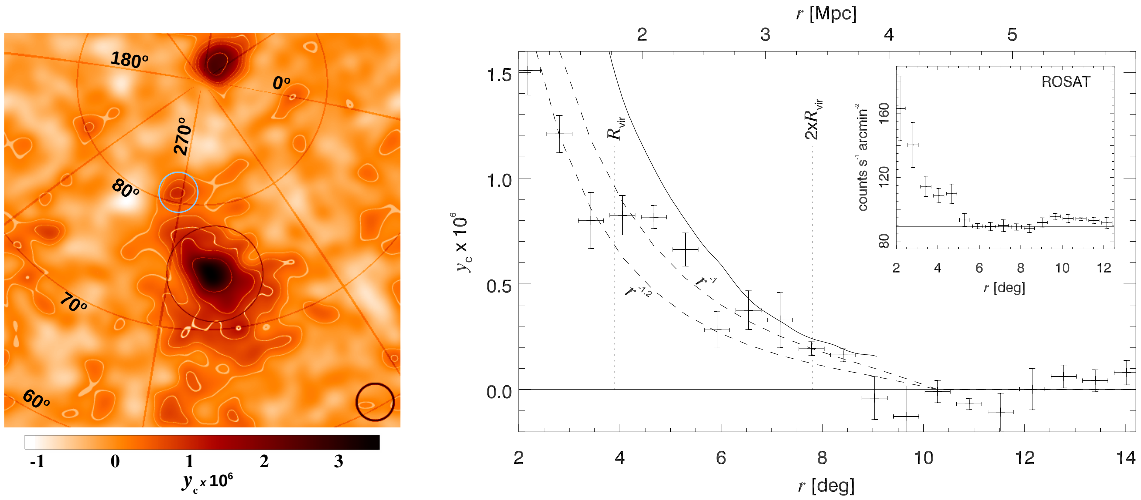

Figure 1: SZ effect map around Virgo cluster (left) and profile of the SZ effect at large radii (right).

unique opportunity to study the elusive warm/hot intergalactic medium (or WHIM), which is believed to exist around clusters and has, so far, evaded a clear detection. WHIM gas is expected to have temperatures of 10^5–10^7 K and densities of 10–30 times the mean density of the Universe (see e.g [1]). The strength of the SZ signal around Virgo owing to the WHIM is expected to be of the order of a microkelvin at the relevant Planck frequencies as shown by [2]. This level of sensitivity in the outskirts of clusters can be reached with Planck only after averaging big areas of the sky. This, in turn, is possible only in the Virgo cluster, which subtends such a sizable solid angle (tens of $\deg^2$) while other clusters subtend areas of the order of 1 $\deg^2$ at most (with Coma a little above this number).

2 Results

We combine the bands in Planck data to produce a map of the SZ effect around Virgo. The combination of different bands allows us to subtract the dominant CMB contribution as well as contributions from our Galaxy and a fraction of the CIB. The brightest point sources are also masked out. We produce an estimation of the SZ map at three different frequencies (70 GHz, 100 GHz and 143 GHz). These three maps are combined to produce a map of the Compton parameter which directly traces the plasma. Finally, the map of the Compton parameter is processed in the Fourier domain to reduce the negative impact of stripes still present in the data. The stripes are a consequence of imperfect baseline removal in the map-making process. The final map of the Compton parameter is shown in Fig. 1. The left panel shows SZ effect map around the Virgo cluster. The contours are proportional to 1, 2, 3, 4, and 7 times the dispersion of the background. We only show the contours for the positive (negative in the map) fluctuations of the Compton parameter. Virgo's centre (M87) is 4 deg south of the centre of the image and the Coma cluster is clearly seen at the top (i.e,

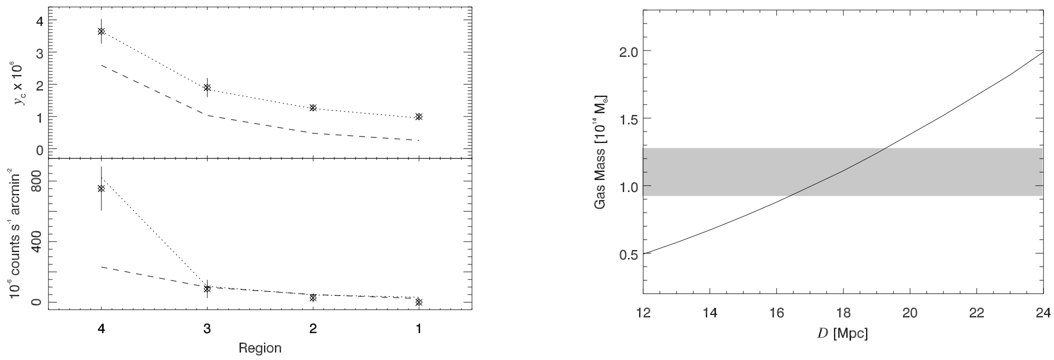

Figure 2: The left panel shows the mean signal in four different regions that trace the SZ signal. The right panel shows the estimated gas mass as a function of distance. The grey region shows an independent estimate based on the cosmic value.

north). Other clusters like the Leo cluster (or group) can also be appreciated near the east edge of the image (in the middle). The big black circle around Virgo marks the area enclosed within the virial radius (3.9). The small circle at the bottom right has a diameter equal to the FWHM of the Gaussian kernel used to smooth the image (1.5). The small light-blue circle at $\ell \approx 270°, b \approx 80°$ marks the position of a feature in the SZ map that is possibly due to Galactic contamination. The field of view is 31.9 degrees. The right panel shows the binned radial y_c profile of Virgo outskirts. The bins are 33' (or 230 kpc) wide. The two dashed lines correspond to the expected signal from two analytical models where the electron density beyond 0.5 Mpc falls as r^{-1} or $r^{-1.2}$. At $r = 0.5$ Mpc the model is normalized to the electron density given by [3] (G04) at that distance. At distances smaller than 0.5 Mpc the electron density follows the model of G04. The solid line shows the profile of the simulated Virgo cluster. The inset shows the corresponding profile in the ROSAT map using the same bins. We find an excess in our SZ map reaching out to twice the virial radius. The observed signal is consistent with expectations from models based on an extrapolation of the electron density beyond the virial radius, with a power law $n_e \propto r^{-1.2}$. The observed signal is also consistent with the expectation derived from a constrained simulation of Virgo. We observe that in order to reproduce the observed signal between R_{vir} and $2R_{vir}$ with this power law, the temperature needs to be in the range of 1 keV beyond 1 Mpc from the cluster centre. The properties of this rarefied medium coincide with those expected for the hottest phase of the WHIM.

The strong dependence of X-rays on the electron density is particularly useful to constrain the gas density. However, in order to constrain the gas properties several assumptions have to be made. One common assumption is that the gas distribution is smooth, that is, there is no significant clumpiness. When comparing the X-ray-derived profiles in rings from previous models with the Planck SZ circular profile, we observe that the X-ray-derived profiles predict reasonably well the right amount of SZ signal without invoking the need for clumpiness to explain possible deviations. Another common assumption is that the cluster has spherical symmetry. We find that models derived from sparse XMM data and a spherical deprojection are able to reproduce the ring-averaged signal relatively well, both in X-rays and in the SZ effect within the virial radius (however, we note that in the X-ray domain the coverage of the outer regions with XMM and CHANDRA is sparse, limiting the diagnostic power of the X-ray/SZ comparison.) However, when the irregular geometry of Virgo is taken into account, the spherical model predicts significantly less SZ signal than observed beyond the virial radius. A model that breaks the spherical symmetry and concentrates the gas closer to the cluster plane (where the temperature should be higher) produces a better fit, suggesting an ellipsoidal distribution for Virgo. A prolate-like distribution with the longest axis (or axis of symmetry) in the image plane, (i.e., perpendicular to the line of sight) would be consistent with our model. This is shown in the left panel of Fig. 2 where we plot the mean signal (SZ and X-rays) in four different regions (asterisks with error bars) compared with the predicted signal from analytical models in the same regions (lines). Each region is defined by having a similar value of the projected Compton parameter and follows closely the contours shown in Fig. 1. We consider two models. A spherical model shown as dashed line and an ellipsoidal model shown as a dotted line. The error bars are the dispersion in each region. The ellipsoidal model is able to reproduce both, SZ and X-ray data simultaneously while the spherical model can not produce a good fit to both data sets.

Finally, using the estimated total gas mass inferred from the combination of SZ and X-ray data and under the assumption that the total baryon fraction of Virgo is representative of the cosmic value, we infer a distance to Virgo of approximately 18 Mpc. In the right panel of Fig. 2 we show the estimated gas mass as a function of distance (solid line). The shaded region corresponds to the gas mass derived assuming the total mass of the cluster can take values from $5 \times 10^{14}\,\mathrm{M}_\odot$ to $7 \times 10^{14}\,\mathrm{M}_\odot$ (consistent with actual constraints) and that the fraction of mass corresponding to the gas equals the cosmic value, $f_\mathrm{b} = \Omega_\mathrm{b}/\Omega_\mathrm{m} = 0.1834$. The shaded region assumes also that different estimates of the total mass are independent of the distance.

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