Can the Local Supercluster explain the low CMB multipoles?

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We show that the thermal Sunyaev-Zeldovich effect caused by hot electrons in the Local Supercluster (LSC) can explain the abnormal quadrupole and octopole of the cosmic microwave background (CMB) that were measured by WMAP and COBE. The distortion needed to account for the low observed quadrupole is a spot in the direction of the LSC with a temperature decrease of order $\Delta T \approx -7\,\mu$K for $\nu \sim 20$ — 90 Ghz photons. The temperature and density of the hot gas which can generate such an effect are consistent with observations of the X-ray background. If this hypothetic foreground is subtracted from the WMAP data, we find that the amplitude of the quadrupole ($\ell = 2$) is substantially increased, and that the "planarity" of both the quadrupole and the octopole ($\ell = 3$) are weakened. For smaller scales the effect decays and, at least in our simplified model, it does not affect the angular power spectrum at $\ell > 10$. Moreover, since the Sunyaev-Zeldovich effect increases the temperature of photons with frequencies above 218 GHz, observations sensitive in that range (such as PLANCK's HFI) will be able to confirm whether the LSC indeed affects the CMB.

Introduction

The cosmic microwave background (CMB) anisotropies have now been measured with exquisite accuracy by WMAP [1]. Such a barrage of new data seldom brings only confirmation of known theories and mechanisms, and WMAP is no exception: early reionization [1], lack of higher correlations [2] and a curious supression of power at the largest observable scales [3, 4] are some of the most intriguing questions that have been raised by the WMAP data. In this letter we focus on the problem of the CMB multipoles corresponding to the largest scales, and show that at least these anomalies can be explained by ordinary physics.

The CMB temperature anisotropies on very large scales were first measured by COBE [6]. WMAP [1] confirmed those observations and showed moreover a nearly flat curve of the angular power spectrum C_ℓ at large scales (spherical harmonic indices $\ell < 100$) and a pattern of acoustic oscillations at smaller scales ($\ell > 150$). This is consistent with the inflationary picture of a nearly-scale invariant spectrum of adiabatic density perturbations.

However, the data is not entirely devoid of its quirks: there are a few "sticky" points in the observed angular power spectrum, in particular those around $\ell = 200$, $\ell = 40$ and $\ell = 20$, all with statistically significant deviations from the expected (smooth) curve. In addition to

those points, WMAP confirmed the COBE observation that showed that the quadrupole ($\ell = 2$) appears to be supressed by a factor $\sim 80\%$ with respect to nearby multipoles. Furthermore, an analysis of the components $a_{\ell m}$ for the quadrupole and octopole reveals that both have an unusual degree of symmetry ("planarity") [3].

The actual relevance of the deviant data points seems to be still under debate: different estimates for the chance that the low value of the quadrupole can be explained by a purely statistical fluctuation vary, from 0.15% [7] to 5% [3, 4] to 30% [5] — incidentally, these are much less significant factors than obtained for the "sticky" points at ℓ=40 and ℓ=200. This lack of power at large scales has motivated many ingenious explanations, such as compact topologies [8], a broken or supressed spectrum at large scales [9] and oscillations superimposed on the primordial spectrum of density fluctuations [10].

However, when the low value of the quadrupole is combined with the unusual symmetry of the quadrupole and octopole ($\ell = 3$), and with the alignment of the directions defined by these two multipoles, the overall chance of such a statistical fluctuation falls to 0.004% [3]. As noted by de Oliveira-Costa *et al.* [3], the directions preferred by the quadrupole and the octopole point roughly towards the Virgo cluster — which is, of course, the direction of the dipole as well. Add to this indications that the polarization of radio and optical sources also have a tendency to point in that same direction [11], and the reported differences in the CMB maps between the northern/western galactic hemispheres (where lie Virgo and most of the LSC) and the southern/eastern hemispheres [2], and the string of coincidences becomes rather too long to ignore.

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We propose here that the explanation for the properties of the quadrupole and octopole is a chance alignment of a hot spot of the primordial temperature fluctuations with the region of the sky occupied by the local supercluster (LSC) — which is centered roughly around Virgo cluster. The thermal Sunyaev-Zeldovich effect (SZe) due to hot electrons in the intra-supercluster (ISC) medium causes, for the range of frequencies observed by WMAP and COBE, an apparent decrease in the temperature of the CMB photons in the direction of the LSC, with an amplitude which we have estimated, using a simple model, as being of order $|\Delta \hat{T}_{\ell=2}|_{rms} \approx 7 \ \mu K$ for the quadrupole, and similar (but smaller) values for $\ell > 2$.

This means that the primary anisotropies of the CMB could actually be interfering with the SZe caused by the LSC, so that the observed low multipoles of the CMB are significantly distorted with respect to their true (primordial) values. This distortion would supress the quadrupole and introduce a preferred direction in the components of the low multipoles — which would, of course, point towards Virgo.

Sunyaev-Zeldovich effect in the LSC?

The SZe is caused by the inverse Compton scattering of CMB photons by hot electrons in the intra-cluster medium [12]. It is a *nonthermal*, frequency-dependent effect: the upscattering causes an incident blackbody spectrum of photons to become distorted in such a way that the resulting higher abundance of high-energy photons is compensated by a shortage of low-energy photons. The frequency at which photons are neither depleted nor overproduced is $\nu_0 = 218$ GHz [13] (COBE DMR and WMAP work in the range $20 - 90$ GHz). Therefore, for frequencies below ν_0 the effect is a reduction in the temperature of the photons, and for frequencies above that the effect is the opposite. This means that measurements over a range of frequencies around ν_0 (such as PLANCK's LFI and HFI [14]) can pick up the signal of the SZe and distinguish it from the primary anisotropies.

For low-frequency photons, the SZe is given by:

$$\frac{\Delta \hat{T}(\theta, \phi)}{T_0} = -2y(\theta, \phi) \ , \tag{1}$$

where $T_0 = 2.726$ K is the CMB temperature and y is the comptonization parameter in the direction (θ, ϕ). The comptonization parameter y measures an optical depth for the CMB photons created by the hot electrons, and its value is given by the product of the Thomson cross-section $\sigma_T = 6.65 \times 10^{-25}$ cm^2 by the temperature-averaged density of photons along the line of sight [13]:

$$y = \int \sigma_T \frac{kT_e}{m_e c^2} n_e dl \ , \tag{2}$$

where T_e is the electron temperature, m_e is the electron mass and $dl = dl(\theta, \phi)$ is the line-of-sight distance element along the direction (θ, ϕ).
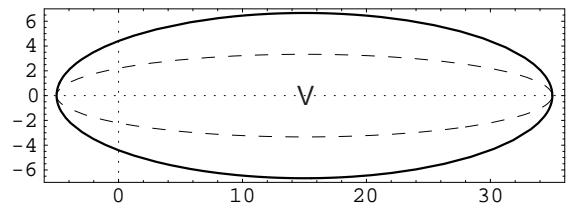

FIG. 1: Assumed shape of the LSC (solid and dotted ellipsoids denote different cross-sections of the spheroid.) Distances are in Mpc. The Sun is located at the origin and Virgo (V) is at the center of the LSC.

The SZe has been observed over the past few years in many clusters, but its weak strength means that it could only be detected in the central parts of clusters, where column densities of hot gas are sufficiently high [13, 15]. It is evident that some amount of SZ will take place also in the LSC, but the question is, how much? The answer depends on the gas density in the ISC medium, its temperature distribution, the morphology of the LSC and our position inside it.

The morphology of the LSC is relatively well known [16]: it is a flattened collection of groups and clouds of galaxies centered at the Virgo Cluster, which contains $\sim$20% of its bright galaxies. The Local Group is dynamically linked to the LSC, and lies $\sim$15 Mpc from Virgo, at the border of the LSC. Notice that the LSC itself is not a virialized structure, hence the gas in its midst is not necessarily in equilibrium.

We are interested in an analytic approach at this point, hence we will make a radical simplification by approximating the shape of the LSC by an oblate spheroid of maximal radius 20 Mpc with approximate axial ratios 6:3:1 [16]. Therefore, our simple model assumes that the LSC is a collection of objects (clouds, groups and the Virgo cluster) which are distributed smoothly across the spheroid. The Sun stands at the margin of the spheroid (which looks like a flattened pumpkin), approximately 15 Mpc away from Virgo (see Fig. 1.)

Much less known than the shape of the LSC, however, are the density and temperature distribution of the hot gas of the ISC medium. Unfortunately, X-ray and microwave observations have not yet reached the level of sensitivity required to detect directly the very smooth, diffuse columns of hot gas in the outer regions of clusters. It seems, however, obvious that there must be a great amount of ionized gas in the ISC medium, among other reasons because the absence of the Gunn-Peterson effect means that most of the hydrogen that we know must exist is not in neutral form. The gas is thought to have been shock-heated at the time of galaxy formation, and now it is probably distributed in many phases, including filaments and a more homogeneous component [17, 18, 19]. Phillips, Ostriker and Cen [20] have constrained the amount of gas in filaments using numerical simulations and the X-ray background, and argued that this "warm-hot" ($kT \approx 100$ eV – 10 keV) gas can account

for only 5–15 % of the "missing baryons". It is therefore quite possible that much of this gas is in the ISC medium. The question is then, how hot is this ionized gas, and how is it distributed?

Hogan was the first to propose that superclusters (and the LSC) could impact the CMB anisotropies through the thermal and kinetic Sunyaev-Zeldovich effects [21]. Molnar and Birkinshaw used HEAO 1 A2 [22] and COBE DMR data to analyze the Shapley supercluster and found no evidence of hot ($> 10^7$K) gas in the ISC medium [23]. Boughn [24], on the other hand, used the HEAO 1 A2 X-ray map and a simple "pillbox" model of nearly constant electron density in the LSC to argue that the SZe could be as high as $|\delta T| \sim (17 \pm 5)\,\mu$K — although he assumed a gas temperature in the high end of the range 10^5–10^8 K. Kneissl *et al.* [25] did study the correlation of COBE DMR and ROSAT X-ray data away from the galactic plane, but it is not clear that the X-ray data has enough sensitivity to detect the diffuse hot gas of the LSC, and in any case the authors analyzed a region which misses a large chunk of the LSC.

Much work has been done to study the impact of the SZe from *distant* clusters on the CMB [26, 27, 28, 29]. It has been found that the largest contribution to the angular power spectrum from the SZe comes from the most massive clusters ($M \sim 10^{15} h^{-1} M_\odot$), at scales $\ell \sim 3000$, with amplitudes $\ell(\ell+1)C_\ell/2\pi \approx 10 - 100\,\mu$K^2.

Angular power spectrum of the LSC SZe

The overall number of free electrons in the LSC can be computed given its mass: $N_e = M_{LSC} f_g / \mu_e m_p$, where M_{LSC} is the LSC mass, f_g is the gas fraction, μ_e is the molecular weight per electron and m_p is the proton mass. We may assume that the mass of the LSC is $\sim 7 \times 10^{15}$ M$_\odot$ [30]. Assuming that the Hydrogen is fully ionized and that the helium mass fraction is $Y = 0.24$, then $\mu_e = 1/(1 - Y/2) \simeq 1.14$. The gas fraction is not very well known, but X-ray observations of clusters indicate that $f_g \approx 0.06 h^{-3/2}$ [32]. Using $h = 0.7$ we get finally that the total number of electrons in the LSC should be of order $N_e \sim 7 \times 10^{71}$. We assume that the volume of the LSC is $V_{LSC} = 4\pi/3 \times ABC$, where $A = 20$ Mpc, $B = 6.7$ Mpc and $C = 3.3$ Mpc are the principal semi-axes of the spheroid, the average density of electrons in the LSC is $n_e = N_e/V_{LSC} \sim 1.4 \times 10^{-5}$ cm^{-3}.

A convenient approximation is to assume a constant electron density across the LSC. If the gas has an *average* temperature of 2 keV then $\langle kT_e\rangle/m_e c^2 \simeq 0.004$, and with a line-of-sight distance of 30 Mpc we obtain that the comptonization parameter is of order $\Delta y \approx \sigma_T \langle kT_e\rangle/(m_e c^2) \times n_e \times 30\text{Mpc} \approx 3.5 \times 10^{-6}$.

The amplitude that is needed to explain the quadrupole is of order $\Delta y \approx 10^{-5}$. Therefore, if that is the case then either the gas is hotter than 2 keV, or the density of electrons is higher than 10^{-5} cm^{-3}, or both.

The main constraint on the density and temperature of the ISC medium comes from the X-ray background. A compilation of observations [20] gives a background flux for energies $h\nu \sim 1$ keV of approximately 10^{-25} erg s^{-1} cm^{-2} sr^{-1} Hz^{-1}. On the other hand, the expected flux at this energy due to thermal bremsstrahlung emission in the center of a uniform sphere of radius 30 Mpc with $n_e = 1.4 \times 10^{-5}$ cm^{-3} and $T_e = 2$ keV is $\sim 2 \times 10^{-26}$ erg s^{-1} cm^{-2} sr^{-1} Hz^{-1}. Since the X-ray flux is proportional to the square of the electron density, if the gas temperature is indeed 2 keV, the upper bound for the electronic density is of order $n_e \approx 5 \times 10^{-5}$ cm^{-3}.

The comptonization parameter can be exactly computed from Eq. (2) for our "pumpkin model". The assumed ionized gas distribution is uniform inside the oblate spheroid defined by $(6x)^2 + (3y)^2 + z^2 = A^2$, and zero outside it. The angular power spectrum for the SZe of the LSC is given in Fig. 2. The amplitude of the SZe quadrupole is:

$$\Delta \hat{T}_2^2 \;\equiv\; \frac{6}{2\pi}\hat{C}_2 \approx 50\,\alpha^2\,\mu\text{K}^2\,, \qquad (3)$$
$$\alpha \;=\; \frac{n_e}{5 \times 10^{-5}\text{cm}^{-3}} \times \frac{\langle kT_e\rangle}{2\,\text{keV}}\,.$$

This level of temperature distortion agrees with the COBE FIRAS limit on deviations from the blackbody spectrum on large angular scales [31].

Compare the results in Fig. 2 with the WMAP data points for $\ell < 20$, for which $\ell(\ell+1)C_\ell/2\pi \approx 800\ \mu$K^2 [1]. The SZe quadrupole has almost the same order of magnitude as the expected primary CMB quadrupole. The SZe octopole ($\ell = 3$) appears to be very small, but the multipoles $\ell > 2$ are more sensitive to the assumed symmetry. Nevertheless, the fall-off with ℓ is expected, given our assumption of a homogeneous gas distribution. Hence, even if the SZe from the LSC contributes at the largest scales, that effect becomes irrelevant as ℓ grows, as long as the ISC gas is diffuse enough. Another interesting result of our calculations is the fact that the amplitude of the $m = 0$ components seem to be higher than the amplitudes of the $m \neq 0$ components. However, a more precise statement concerning the decomposition of the SZe from the LSC into components $\hat{a}_{\ell m}$ is evidently not possible until we consider a more realistic approach to the gas density and temperature distributions in the LSC.

The interference between the SZe from the LSC and the primordial CMB can be estimated, if one rotates the axes of the CMB maps so that they coincide with ours. This task is facilitated because de Oliveira-Costa *et al.* [3] have computed the components of the quadrupole and octopole of the temperature fluctuations observed by WMAP, $a^O_{\ell m}$, in the rotated frame whose z-axis points in the direction of Virgo. If the x- and y-axis coincided as well, we could subtract the computed $\hat{a}_{\ell m}$ directly from the observed $a^O_{\ell m}$, to obtain the primordial multipoles. But since we do not know the precise angles between the two reference systems, the $m \neq 0$ components have unknown phases $\exp[im\Delta\phi]$ between them.
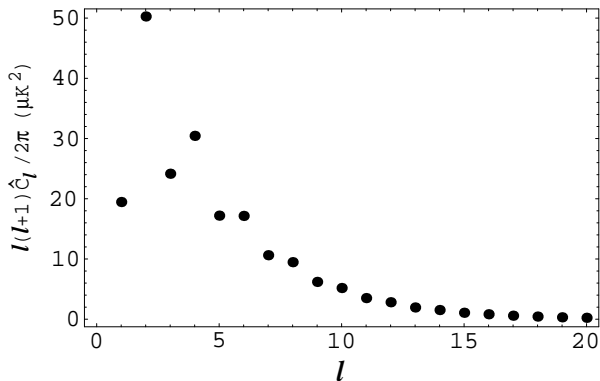
FIG. 2: Angular power spectrum of the LSC SZe (with $\alpha = 1$.)

For the quadrupole of the SZe we get:

$$\hat{a}_{20} \approx -15\,\alpha\,\mu\mathrm{K} \quad , \quad \hat{a}_{21} \approx 0 \quad , \quad |\hat{a}_{22}| \approx 4\,\alpha\,\mu\mathrm{K}\ . \quad (4)$$

Assuming $\alpha = 1$ and combining these components with those given in [3], we obtain an estimate for the amplitude of the primordial quadrupole:

$$\Delta T_2^2 = \frac{6}{2\pi}C_2 \approx (230 - 370)\,\mu\mathrm{K}^2\ , \qquad (5)$$

where the range corresponds to an unknown phase relating the $m = \pm 2$ components. If either the temperature or the density of electrons are higher than our fiducial values such that $\alpha = 4$, we would get that $\Delta T_2^2 \approx 340 - 640$ $\mu\mathrm{K}^2$. The amplitude of the octopole also grows after subtraction of the SZe foreground, but by a smaller factor which appears to be more model-dependent.

After subtraction of the SZe foreground, the levels of symmetry of the corrected quadrupole and octopole seem to be lower than those of the observed quadrupole and octopole. It should be possible to detect the same effect in the higher ℓ components as well, but the lower amplitude of the SZe and the larger number of components, which grow as $2\ell + 1$, can make such a distinction harder to establish. In any case, the precise way in which the SZe from the LSC breaks into harmonic components is evidently quite sensitive to the morphology of the LSC

and its spatial orientation. A more careful analysis is being carried out, combining the CMB maps with the observed LSC morphology, which will compute in detail the corrected CMB angular power spectrum.

Conclusions

We have argued that the SZe from the LSC can affect the low multipoles of the anisotropies of the CMB. The temperature and density of the hot LSC gas which causes the SZe obey the observational constraints on the X-ray background. After we subtract this hypothetical foreground, we obtain a greatly increased quadrupole and less symmetric components for the quadrupole and octopole. We can interpret the result for the quadrupole as meaning that there is a large-scale hot spot in the primordial CMB which roughly coincides with the position of the LSC. The probability that such an alignment happens by chance is of order 10-20%.

If the LSC indeed affects the temperature anisotropies through the thermal SZe, then it is conceivable that the *kinetic* SZe (caused by the anisotropic motion of gas), which has typical amplitudes one order of magnitude weaker than the thermal SZe, could be important as well [21]. Since the kinetic SZe polarizes the CMB photons, this might have interesting implications for the WMAP detection of polarization and reionization.

We should note that the evidence for hot gas in the ISC medium that can cause such effects is still weak. However, near-future X-ray and millimiter-band observations in the region of the North galactic plane will easily decide this issue. In particular, PLANCK's planned observations over a wide range of frequencies (30 – 900 GHz) will be able to clearly pick any SZe signal [14]. If the SZe is indeed observed in the LSC, it would have many interesting implications for the physical properties of hot gas in the ISC medium.

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