Measuring Galaxy Cluster Polarization with Microwave Background Observations

Kevin M. Huffenberger
University of Miami, Coral Gables, Florida 33146

Abstract

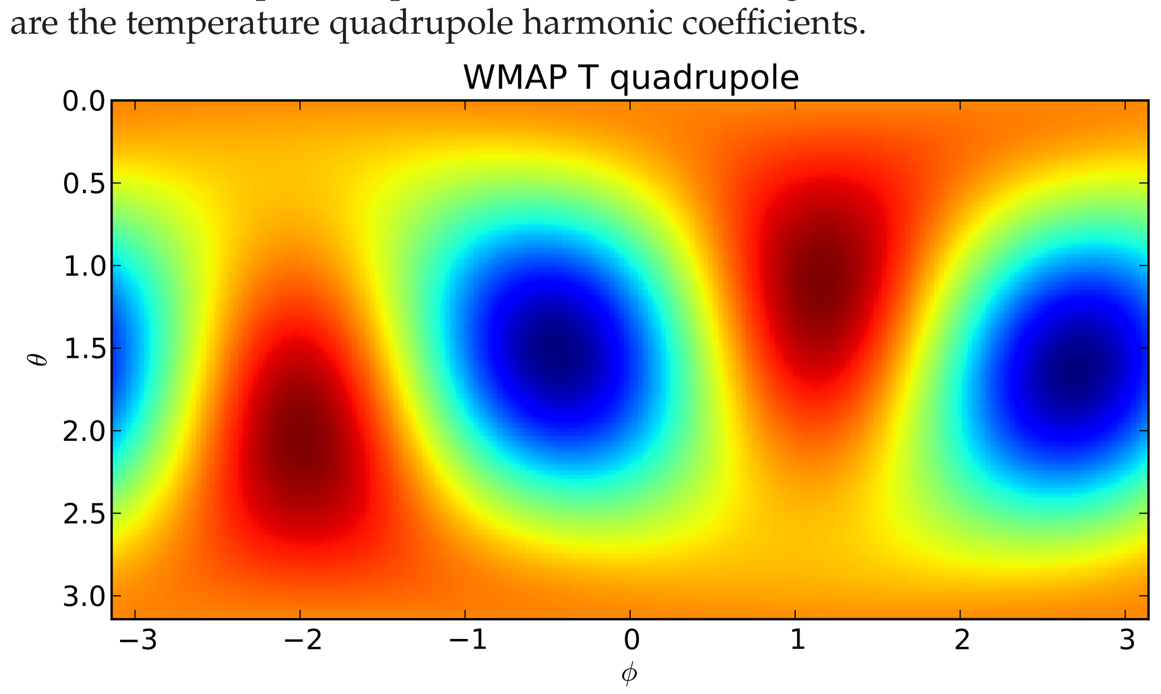
The temperature quadrupole of the Cosmic Microwave Background (CMB) is one of the largest observable structures in the universe. In galaxy clusters, the quadrupole induces linear polarization of the microwave photons scattered by the free electrons in the hot gas. Kamionkowski & Loeb (1997) noted that this polarization presents the opportunity to measure the quadrupoles of last scattering surfaces that are centered around other points in the Universe. Here I begin to examine the prospects that upcoming ground-based CMB polarization experiments can measure this effect, using the Croston et al. (2008) profile for cluster electron density and the Meta-Catalogue of X-ray Clusters (MCXC, Piffaretti et al., 2011).

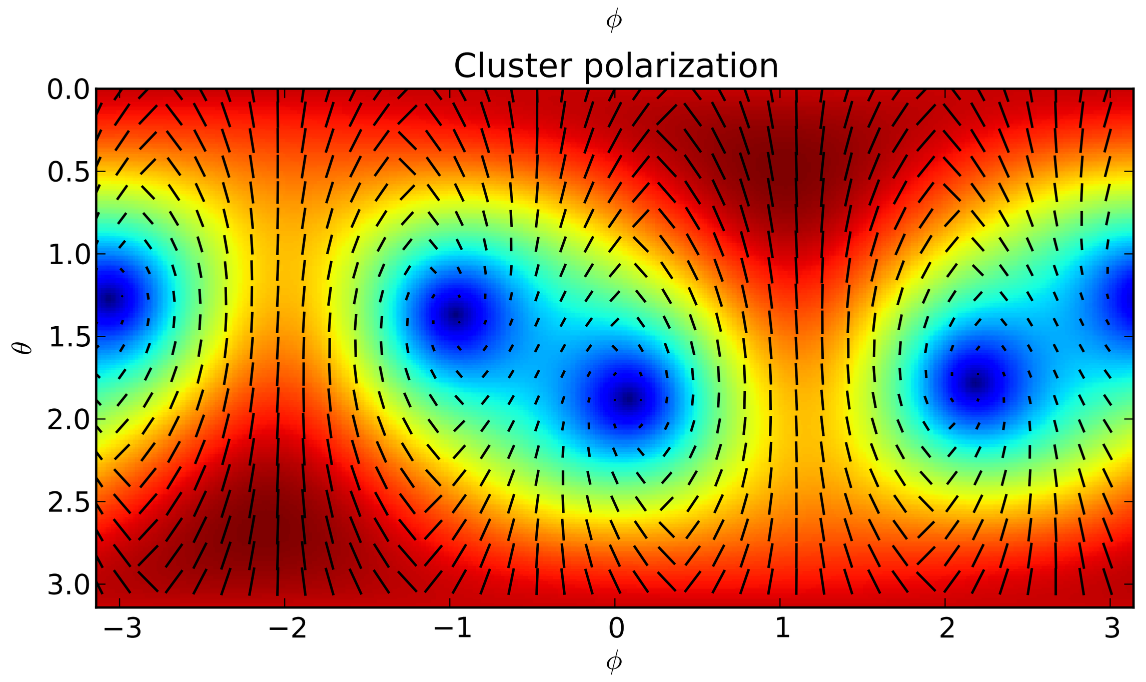
Polarization signal

For CMB polarization, Portsmouth (2004) gives the Stokes parameters due to this effect:

$$Q(\hat{\mathbf{x}}) + iU(\hat{\mathbf{x}}) = F(\hat{\mathbf{x}}) = -\frac{6}{20}\sqrt{\frac{2}{3}}\tau(\hat{\mathbf{x}})\sum_m {}_{\pm 2}Y_{2m}(\hat{\mathbf{x}})a_{2m}, \tag{1}$$

where τ is the optical depth to Thomson scattering (in the cluster) and the a_{2m} are the temperature quadrupole harmonic coefficients.





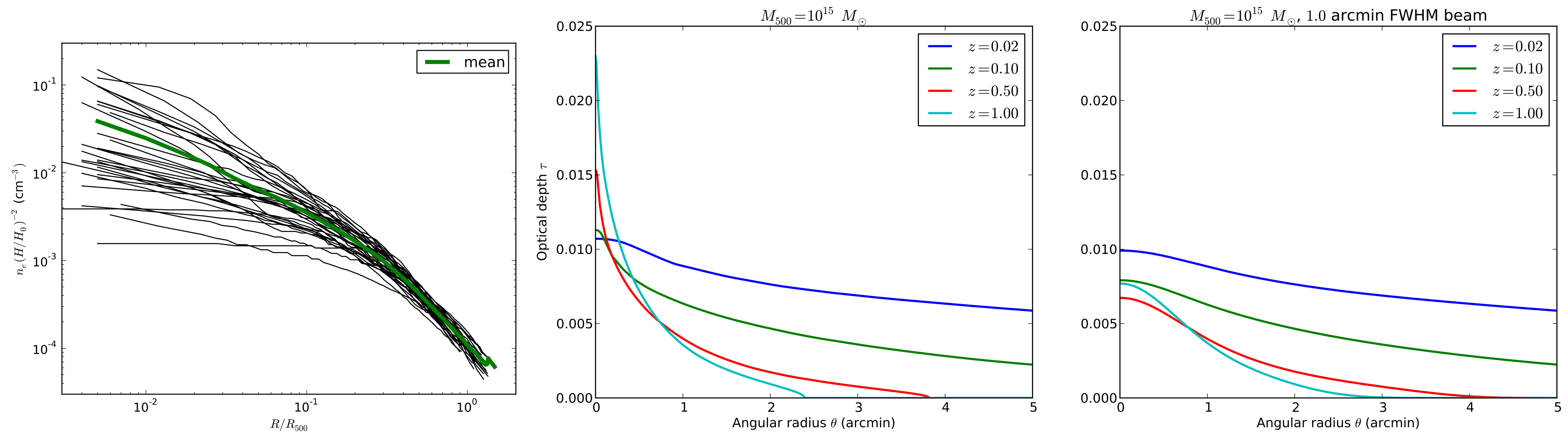
Plots show the WMAP temperature quadrupole (Bennett et al., 2011) and the predicted polarization pattern. The temperature range is -21 to 16 μK. The maximum $P = (Q^2 + U^2)^{1/2}$ is 3.8τ μK, the rms P is 2.8τ μK, and the minimum P is zero.

This is the largest of several effects that imprint a polarization on CMB photons that scatter from electrons in clusters (Sazonov & Sunyaev, 1999; Shimon et al., 2006).

The Kamionkowski-Loeb effect is also useful because (1) the CMB quadrupole for nearby clusters correlates strongly to our own quadrupole; and (2) the value our quadrupole is difficult to measure due to Galactic emission, and its somewhat low variance is the subject of some controversy. In the past, several authors have examined this effect (Cooray & Baumann, 2003; Baumann & Cooray, 2003; Portsmouth, 2004; Seto & Pierpaoli, 2005; Bunn, 2006).

Cluster optical depth template

The unique feature of this work is that we based our template for optical depth on recent X-ray observations of the electron density distribution in clusters. Croston et al. (2008) presents the e^- distributions for the REXCESS cluster sample (reproduced, below left). We integrate the mean profile along lines-of-sight to produce optical depth templates, scaling R_{500} as a function of mass and redshift, convolving with an instrument beam (middle, right).



Because the optical depth is proportional to the electron density, the cluster profile for τ is broader than for X-ray or SZ observations, falling over a few arcminutes for distant clusters, or even tens of arcminutes for nearby clusters.

Estimating the signal

X-ray and SZ cluster measurements can provide a template for τ. In the next few years, ACTPol (Niemack et al., 2010) and SPTpol (McMahon et al., 2009) expect to measure CMB polarization at arcminute scales with a few μK arcmin noise. Their proposed deep-survey regions comprise a few hundred square degrees. We can model the pixelized microwave polarization data as a scaled template plus pixelized noise:

$$d_i = AF_i + n_i \tag{2}$$

where the template F_i is for pixel i. Writing the noise covariance as $N_{ij} = \langle n_i n_j \rangle$, for the scale ($A$) we can make an optimal linear estimate, $\tilde{A} = Wd$, by minimizing the error ($\sigma_A^2 = WN^{-1}W^\dagger$) subject to the unbiased constraint ($\langle \tilde{A} \rangle = A$). This yields the filter:

$$W = (F^\dagger N^{-1} F)^{-1} F^\dagger N^{-1}. \tag{3}$$

Axisymmetric, white noise approximation. For homogeneous, uncorrelated noise with $\sigma_Q = \sigma_U$ per pixel, we have $\sigma_A^2 = \sigma_Q^2/(F^\dagger F)$. If F is approximately symmetric around the cluster center, then

$$F^\dagger F = \frac{2\pi}{\Delta\Omega}\int d\theta\, \theta\, [F_Q^2(\theta) + F_U^2(\theta)] \tag{4}$$

in an aperture with solid angle $\Delta\Omega$.

Distant clusters and groups

For a 1-arcminute beam in the white noise approximation, using as a rule-of-thumb the signal from a collection of clusters at $z = 0.5$, we find the signal:

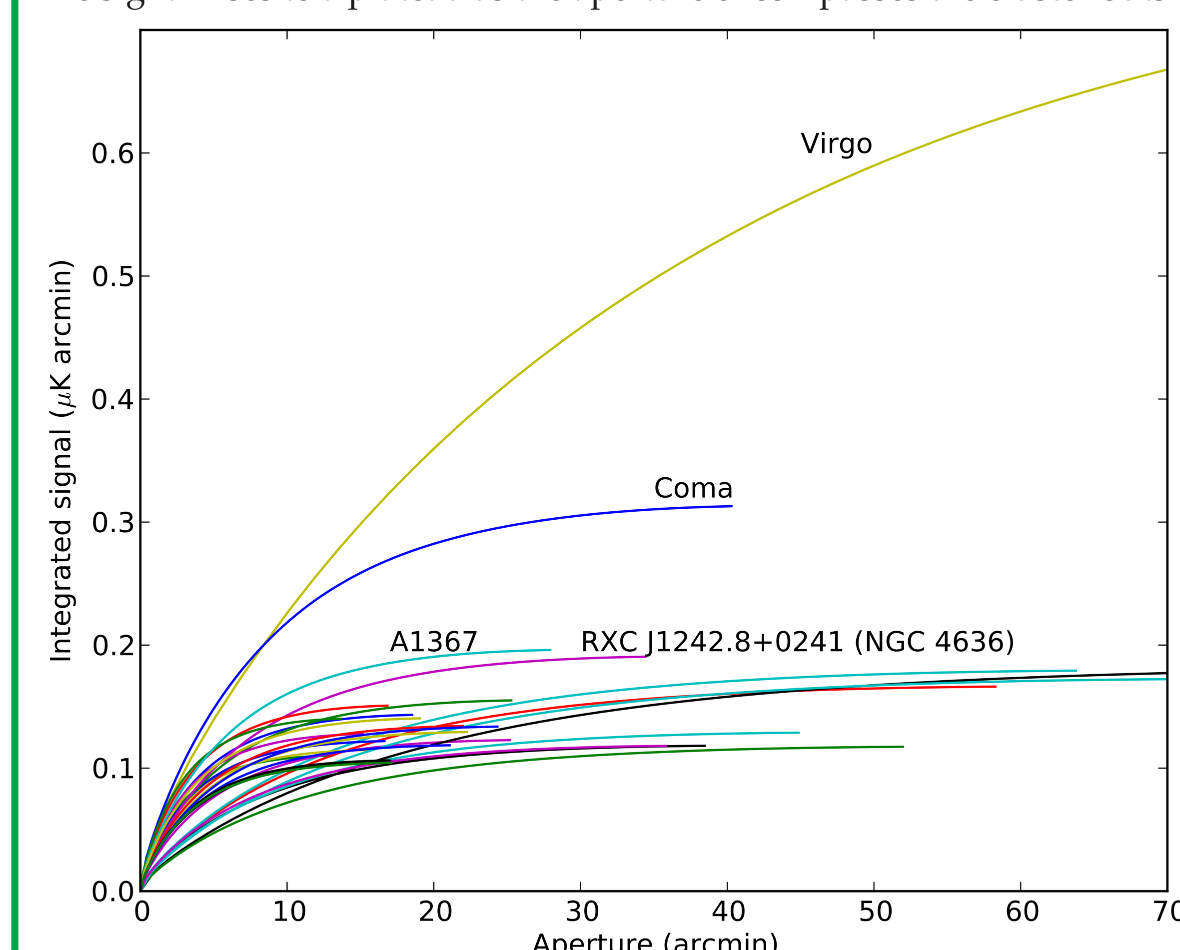
$$\sigma_A = 2.7 \frac{\sigma_Q \Omega_{\rm pix}^{1/2}}{1\ \mu\text{K arcmin}} \left(\frac{N_{\rm clust}}{1000}\right)^{-1/2} \quad (M = 2\times 10^{14}\ M_\odot) \tag{5}$$

$$\sigma_A = 31 \frac{\sigma_Q \Omega_{\rm pix}^{1/2}}{1\ \mu\text{K arcmin}} \left(\frac{N_{\rm clust}}{1000}\right)^{-1/2} \quad (M = 1\times 10^{13}\ M_\odot)$$

which are to be compared to the expected $A = 1$. Note that these estimates are not as reliable as considering the complete cluster mass function. For comparison, Sehgal et al. (2007) predict $\sim$ 7000 clusters at $z > 0.3$ and $M > 2\times 10^{14}\ M_\odot$ over the whole sky; the $z \sim 0.5$ BOSS sample from Hand et al. (2012) contained 27000 clusters in 10^{13}–$10^{14}\ M_\odot$.

Nearby clusters

We examine nearby clusters in the white noise approximation based on MCXC mass and redshift data (Piffaretti et al., 2011, containing $\sim$ 1700 clusters). Below we predict the signal for the 30 most significant clusters (based on their intrinsic properties and their position relative to the quadrupole). The signal rises to a plateau as the aperture encompasses the cluster outskirts.



The largest signals come from nearby clusters that subtend the largest areas of the sky. Combined, these 30 clusters have much higher signal-to-noise than the distant clusters in the previous example, but still are only at the level of $\sigma_A = 0.9(\sigma_Q \Omega_{\rm pix}^{1/2}/1\ \mu\text{K arcmin})$.

Future steps

The angular extents of the nearby clusters with the largest signals require that we account for the covariance from the CMB. Since these clusters are already known, their foreground and point source contamination can be evaluated. The transverse velocity of clusters also imparts a small polarization signal, which can also be accounted for in the covariance.

Conclusions

The signal from distant clusters appears very challenging. Even with thousands of clusters, the signal at a few $10^{14}\ M_\odot$ is very small.

Nearby clusters offer the best S/N, but are also faint. These clusters are well-studied and we have the best knowledge of their electron densities. Rather than taking microwave data from wide-field surveys, it may be advantageous to target these clusters specifically, with an strategy designed to build up signal-to-noise in half-degree-scale apertures around these clusters.

The four best cluster targets are in the Northern Hemisphere. This is significant because the sites of the major ground-based CMB observatories, the Atacama Desert (latitude $\sim 23°$ S) and the South Pole, are in the Southern Hemisphere. With respective declination at 12°, 27°, 19°, and 2°, the best nearby cluster targets are at least above the horizon from the Atacama.

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