LOCAL PANCAKE DEFEATS AXIS OF EVIL

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ABSTRACT

Among the biggest surprises revealed by COBE and confirmed by WMAP measurements of the temperature anisotropy of the CMB are the anomalous features in the 2-point angular correlation function on very large angular scales. In particular, the $\ell = 2$ quadrupole and $\ell = 3$ octopole terms are surprisingly planar and aligned with one another, which is highly unlikely for a statistically isotropic Gaussian random field, and the axis of the combined low-$\ell$ signal is perpendicular to the ecliptic plane and the plane defined by the dipole direction. Although this < 0.1% 3-axis alignment might be explained as a statistical fluke, it is certainly an uncomfortable one, which has prompted numerous exotic explanations as well as the now well known “Axis of Evil” (AOE) nickname. Here, we present a novel explanation for the AOE as the result of weak lensing of the CMB dipole by large scale structures in the local universe, and demonstrate that the effect is qualitatively correct and of a magnitude sufficient to fully explain the anomaly.

Subject headings: cosmology: Lensing — cosmology: large-scale structure

1. INTRODUCTION

The full-sky maps obtained by the Wilkinson Microwave Anisotropy Probe (WMAP) in its first year of observation have revolutionized the study of the CMB sky (Bennett et al. 2003a,b; Hinshaw et al. 2003; Spergel et al. 2003). One of the many exciting uses of these maps is the window they offer us on the physics of the early universe (Peiris et al. 2003) and the standard inflationary model. This picture predicts a statistically isotropic Gaussian random CMB temperature anisotropy to an excellent approximation, so that WMAP has enabled considerable study of non-Gaussianity and statistical anisotropy of the CMB (see e.g. Copi et al. 2005 and references therein).

Although WMAP data has largely been consistent with the standard cosmological picture, some challenges to the standard model have emerged. Among the most interesting occur on the largest angular scales, and are therefore called the “low-$\ell$ anomalies”. The first of these, the surprisingly small quadrupole moment, was noted a decade ago in the COBE data (Hinshaw et al. 1996) and has recently been confirmed by WMAP (Spergel et al. 2003). In addition, it is now known that the octopole is highly planar and aligned with the quadrupole (Schwarz et al. 2004; de Oliveira-Costa et al. 2004), and that the planes defined by these multi-poles is perpendicular to both the dipole and the ecliptic.

The original low quadrupole anomaly has long been dismissed as either the result of some residual systematic error or as a statistical fluke. However, the higher quality of data now available from WMAP strongly challenge the residual systematic explanation (Tegmark et al. 2003), and while a statistical fluke cannot be ruled out, the odds against are uncomfortably long. In one recent study, Copi et al. (2003) have used the multi-pole vector formalism to show that a purely accidental alignment is unlikely in excess of 99.9%. They have also shown that most of the $\ell = 2$ and $\ell = 3$ multi-pole vectors of known Galactic foregrounds are located far away from those observed in WMAP data, strongly suggesting that residual contamination by foregrounds which are currently included in the analysis is not a viable explanation. It is precisely this combination of a complete lack of any known systematic error, and long odds against random alignment that has earned the low-$\ell$ alignment anomaly the nickname “Axis of Evil” (AOE; Land & Magueijo 2005). The axis appears to possess mirror symmetric properties (Land & Magueijo 2005), and may be related to the north-south asymmetry in the angular power spectrum Eriksen et al. (2004).

The fact that the AOE alignment includes sources of both cosmological and local origin suggests that the explanation might be found in some sort of interaction with local structure which is not already included in the foreground analysis. If this is the case, then the fact that the AOE points in the direction of the Virgo cluster (de Oliveira-Costa et al. 2004) is certainly intriguing, and has led some to suggest (Abramo & Sodre 2003) that the SZ (Sunyaev & Zeldovich 1972) imprint of the local supercluster might help explain at least some of the AOE. Although this idea is initially attractive, the SZ is probably 3 or 4 orders of magnitude too small to do the trick (Dolag et al. 2003).

Local effects remain an attractive option, especially since the mass distribution is so highly anisotropic. The observed motions of galaxies in the local universe have revealed a bulk flow in the direction of the “Great Attractor” region (Lynden-Bell et al. 1988). The Local Supercluster, in which galaxies lie preferentially in the supergalactic plane (de Vaucouleurs 1955), dominates as we move closer to the Earth, and of course the Milky Way itself dominates on still smaller scales.

These all contribute to the velocity of the Earth relative to the background, which gives rise to the CMB dipole term. The dipole is more than two orders of magnitude larger than the quadrupole and octopole, and is
by far the largest of the temperature anisotropies; however, since the dipole arises from the peculiar motion of the observer with respect to the background, it is clearly of non-cosmological origin, and is therefore measured and subtracted from maps of the CMB. Here, we show that this subtraction is imperfect. Weak gravitational lensing by local large scale structures will coherently deform the initially perfect dipole, causing a leakage of power at the sub-percent level into other low-$\ell$ moments.

We suggest, to our knowledge for the first time, that it is this lensing induced mixing of power from the CMB dipole that is the root cause of the AOE. We will introduce the basic idea, along with some relevant background in Section 2, where we will show that the explanation is natural and qualitatively correct. In Section 3, we will present the results of a toy model simulation which demonstrate the effect to be of the right order of magnitude, and we will conclude in Section 4 with some discussion of the cosmological implications of the reinterpreted large scale CMB sky in the event that the lensed dipole ultimately proves to be the right answer.

2. WEAK LENSING OF THE CMB DIPOLE

Weak lensing of the CMB has long been a topic of interest to cosmologists (e.g. Seljak 1996, Zaldarriaga & Seljak 1998, Hu 2000, Challinor & Lewis 2005). The effect is both simple and inescapable; all light which reaches us from the surface of last scattering (or any other source, for that matter) is deflected from its original path by the weak gravitational lensing interaction with the matter distribution along the line of sight (see Bartelmann & Schneider 2001, for a comprehensive review), and no exceptions are made for photons from the CMB dipole. Although the dipole owes its existence to the motion of the observer with respect to the background, this makes no difference from the perspective of someone in the same frame of reference as the observer; one side of the universe is simply hotter than the other, and this anisotropy will be lensed. For the case of an observer comoving with the Earth, the observed dipole term will be that measured by WMAP (Bennett et al. 2003), which is more than two orders of magnitude larger than the quadrupole term (and is by far the largest anisotropy in the CMB), so that even sub percent level scalar will strongly affect the low-$\ell$ moments. Also, because the dipole is coherent over the whole sky, it will couple best to lensing effects that are also coherent over much of the sky, so that local structures will be the dominant lenses.

This cannot be accounted for by simply subtracting the observed dipole; lensing will scatter the initially pristine dipole into something that is only almost a perfect dipole, so that if we fit a dipole to the measured sky and subtract it, we are going to be stuck with a residual. It is this residual which we believe is a likely culprit to explain the AOE, as we will now explain. In the following, we will adopt a frame of reference that moves with the lens and observer, work in comoving coordinates $\chi$, set $c = 1$, and assume a flat universe.

2.1. Lensing and the CMB

The notion that gravitational lensing by large scale structure will scatter power between $\ell$-modes of the CMB is certainly not a new one (Seljak 1996), and while we will consider effects on much larger than usual angular scales, we will begin our discussion in the usual way. While en route to us, the photons of the primary CMB are gravitationally lensed (see e.g. Challinor & Lewis 2005, for a recent discussion of CMB lensing) by the mass distribution along the line of sight all the way from the epoch of last scattering to the present, so that the photons we see have been displaced from their original position on the sky by an angle

$$\hat{a}(\hat{n}) = 2 \int_0^\chi d\chi \frac{\chi' - \chi}{\chi'} \nabla_\perp \Phi$$

where $\hat{n} = (\theta, \phi)$ is the angular position on the sky, $\nabla \Phi$ is the spatial gradient of the gravitational potential perpendicular to the path $d\chi$ of a given light ray, and $\chi'$ is the distance to the surface of last scattering. The scattering can be well described as the angular gradient of an effective projected potential $\Psi$. The observed temperature $T$ is a simple re-mapping of the primordial value $T'$

$$T(\hat{n}) = T'(\hat{n} - \hat{a})$$

If we expand equation (2) to linear order, then the observed temperature is simply approximated as

$$T(\hat{n}) = T'(\hat{n}) - \nabla T \cdot \nabla \Psi$$

where for our purposes $\nabla T$ is dipole as seen by a given lens. Equations (2) and (3) highlight some important points about CMB lensing. First, the lensing deflection falls off slowly, as $\alpha \sim 1/\theta$, so that the deflection effect of large concentrations of mass extends much further on the sky than lensing induced shear and magnification (e.g. Bartelmann & Schneider 2001). Second, the magnitude of the deflection from a given overdensity is weighted as $\alpha \sim M/\chi$, so that the relatively local universe will contribute substantially to the overall deflection field; points one and two are crucial given our need for deflections which are coherent over huge fractions of the sky. Third, since $\nabla T$ and $\nabla \Psi$ are proportional to the velocity and mass, respectively, the scatter will be maximized around large momentum overdensities. Finally, power which is scattered from the CMB dipole will be locally perpendicular to its gradient, establishing a preferred axis.

2.2. Lensing and the integrated Sachs-Wolfe effect

We have so far considered the gravitational interaction of the CMB with lenses that are comoving with the observer, and we will now generalize this result. We will start by considering the effect in the rest frame of the CMB, where it is known as the integrated Sachs-Wolfe (ISW) effect. We note that a number of people have commented to the author that the ISW is in some ways a more intuitive description. While we do not share this view, it’s certainly worth pointing out the relation, dictated by the equivalence principal, between the two (in our opinion) equally valid descriptions.
Let us consider a photon with a 4-momentum $p' = E_0(1, \mathbf{n})$ traversing a potential which is changing in time, so that the energy a photon gains when falling into the well is not equal in magnitude to that lost when climbing out. The observed potential will be described by a metric with $\Phi(\mathbf{x} - (V_{\text{lens}} - V_{\text{obs}})t)$, so that (working to first order) the observed change in energy is

$$dE_{\text{ISW}} = 2 \, d\chi \, E_0 (\mathbf{V}_{\text{lens}} - \mathbf{V}_{\text{obs}}) \cdot \nabla_{\perp} \Phi_{\text{lens}}$$

(5)

where $\mathbf{V}_{\text{obs}}$ is the observer’s velocity and $\nabla_{\perp}$ implies the direction perpendicular to the path of the photon. To compute the dipole lensing term, we take the dot product of the change in 4-momentum of the photon with the 4-velocity the observer, so that $dE_{\text{lens}} = E_0 \mathbf{V}_{\text{obs}} \cdot d\mathbf{n}$, and

$$dE_{\text{lens}} = 2 \, d\chi \, E_0 \mathbf{V}_{\text{obs}} \cdot \nabla_{\perp} \Phi_{\text{lens}}$$

(6)

Adding equations 5 and 6, integrating, and noting that $E_0 V_{\text{lens}}$ is the dipole magnitude seen by the lens, we arrive at

$$\Delta E = 2 \, \nabla T_{\text{dipole}} \cdot \hat{\alpha}$$

(7)

3. RESULTS FROM A TOY MODEL

We compute the lensing distortion of the CMB dipole in two steps. First, for a given mass distribution, we compute the deflection field $\hat{\alpha}(\mathbf{n})$ using the 3-d ray-tracing method described in Vale & White (2003) over the whole sky. This method first computes the 3-d gradient of the gravitational potential on a 3-d grid, maps the result onto the points of a 3-d spherical grid, and selects the components which are locally perpendicular to the line of sight. This gives us $\nabla_{\perp} \Phi(\mathbf{x}, \mathbf{n})$ from equation 2 so that $\hat{\alpha}$ is given by a sum over $\chi$ at each position on the spherical surface $\mathbf{n} = (\theta, \phi)$. We then generate the temperature map for the lensed dipole on the 2-d spherical grid by following the prescription of equation 3 in which we compute the dipole temperature at position $(\mathbf{n} - \hat{\alpha})$ and apply it to position $\mathbf{n}$. The spherical harmonic coefficients $a_{\ell m}$’s of the new field are then computed, and the $\ell > 1$ terms are observed to no longer be zero.

However, before we can employ this technique, we must first decide on a mass distribution from which to derive the lensing deflection. This is a challenging proposition given the current level of uncertainty in the local distribution of dark matter. The closest superclusters such as the Local Supercluster, the Centaurus Wall, the Perseus-Pisces chain, and the Great Attractor, all intersect the Milky Way “Zone of Avoidance”, so that Galactic extinction makes a full probe of their properties currently problematic (see e.g. Kraan-Korteweg 2005, for a recent discussion). Furthermore, even if this obstacle were somehow overcome, our ability to probe the dark matter distribution, using optical tracers or any other method, is highly uncertain. We are at present unable to confidently state even the source of the mass dipole moment responsible for the bulk flow of galaxies in the local universe, with opinions divided between the so called Great Attractor region (centered on the ultra-massive Norma cluster ACO 3627), which is roughly $45h^{-1}\text{Mpc}$ from us, and the Shapley Supercluster, which is $100h^{-1}\text{Mpc}$ further.

Because we are interested in a proof of concept analysis, we avoid the painstaking complexities involved in modeling the local universe, which cannot in any case be done with any more certainty than current observations allow. Instead, we employ a toy model motivated by the flow of mass in the local universe. We begin by placing an overdensity near the Shapley concentration at a distance of $200h^{-1}\text{Mpc}$, with a fwhm of $100h^{-1}\text{Mpc}$ and a peak density five times the mean density of the universe, which is consistent with the observed galaxy overdensity in the region (Drinkwater et al. 2004). The overdensity is sufficient to induce a peculiar velocity at the Milky Way of roughly $600\,\text{km/s}$, which increases to over $2000\,\text{km/s}$ near the peak of the mass; remarkably, this is also consistent with recent observations (Kocevski & Ebeling 2005). The magnitude of the induced quadrupole and octopole are similar to those found in the WMAP data, about equal for the former and one third for the latter, while the orientation of these (Figure 1) is also remarkably close given the simple model employed.
As a demonstration (Figure 1), the author has attempted to recreate the observed \( \ell = 2, 3 \) modes “by hand” by placing several overdensities and voids at a distance of \( 200 h^{-1}\)Mpc, smoothed now on a \( 150 h^{-1} \) Mpc scale, with no net mass added. The resulting density field peaks at three times the mean density in the direction of the Shapley concentration, where the velocity of the flow also peaks at just over 2000 km/s, and the induced peculiar velocity at the Galaxy is 700 km/s. Although this toy is clearly not meant to be taken seriously, it is instructive that no particularly unrealistic mass concentrations are required to reproduce the observed modes. It is also instructive to note that most of the signal comes from structures located far away from any overdensities; the velocity field effects a huge volume of space, which is typically at the mean density, and it is this extended region that contributes the lion’s share of the effect.

We note that it is also relatively simple to create distributions which contribute power to alternating modes; for example, a dumbbell configuration, with the Galaxy at the center, contributes power to the \( \ell = 2, 4, 6 \ldots \) modes, and none at all to the odd modes. We also note that because power is preferentially added in the direction of the flow, this may fully or partially explain the north-south power asymmetry [Eriksen et al. 2004]. However, these effects depend strongly on the specific distribution of mass, so we have not attempted to quantify them here.

4. DISCUSSION

We have introduced a novel explanation for the alignment of the axes defined by the planes of the CMB quadrupole and octopole, with each other and with the CMB dipole, which has become known as the “Axis of Evil”. We find that the CMB dipole induced by the flow of local structures is scattered by gravitational interaction into the higher moments, and that although the effect on the dipole is at the sub-percent level, it is of order one for the higher moments, whose measured values are roughly two orders of magnitude smaller than the typical dipole seen by local structure. We have shown that dipole lensing is a natural mechanism to align axes and create an asymmetric distribution of power, and have explicitly demonstrated that it is not out of bounds to attribute the entire measured CMB quadrupole to dipole lensing. Consequently, it is highly unlikely that dipole lensing can be safely ignored in attempts to measure the large angle power in the CMB.

While we may have mitigated the alignment problem, the mechanism will on average add power to the low-\( \ell \) moments, so that the low quadrupole anomaly is stronger than ever. Low-\( \ell \) modes are profoundly affected by the influence of Dark Energy (DE) through the integrated Sachs-Wolfe effect. At late times, most models predict an epoch of equality between DE and Dark Matter (DM), after which DE causes an accelerated expansion. This expansion causes potential wells on scales not yet virialized to decay, causing a differential in the blue and red-shift photons experience as they traverse in and out of the wells. Overestimating the low-\( \ell \) power will lead to an overestimation of this differential, and lead to erroneous conclusions about the epoch of DE-DM equality, and therefor about dark energy parameters.

Overestimation of the low-\( \ell \) modes of the temperature may cause still other problems. One of the many important observations in the WMAP data is that there is more than the expected amount of power in the low-\( \ell \) modes of the cross correlation, \( C_{\ell}^{TT} \), between E-polarized modes and temperature, which has been used to infer a higher than expected re-ionization depth [Bennett et al. 2003b]. If much of the power in the observed data is due to the dipole and lensing, then it may be that the measured \( C_{\ell}^{TT} \) is biased high, which would alter the predicted ionization depth.

Whatever their cause ultimately proves to be, the low-\( \ell \) anomalies in the CMB temperature remain one of the fertile areas of research beyond the standard cosmological model, and just might prove to be the right window to look through to glimpse the physics driving the expansion of the universe.

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