Bulk flows from clusters of galaxies.

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Abstract. The kinematic Sunyaev-Zeldovich effect produces a measurable temperature anisotropy in the cosmic microwave background that can be used to measure the bulk motion of clusters of galaxies. We discuss our recent measurement of motions on scales of \( \sim 300 - 800 \) Mpc with amplitude and direction similar to the cosmological dipole, its systematics, uncertainties and the correlation with X-ray luminosity. The latter is a crucial test that supports the existence of the flow. We discuss the cosmological implications if the flow extends out to the cosmological horizon.

1. Introduction
In the local matter rest frame, the recession velocity of a galaxy of redshift \( z \) is: \( cz = H_0 r + v_r \). The peculiar velocity \( \vec{v} \) is a local departure from the Hubble expansion \( H_0 r \). From redshift and distance measurements we can determine only its projection along the line of sight, \( v_r \). Peculiar velocities play important role in understanding the large scale matter distribution in the Universe and have been subject of intense research. Uncertainties on distance indicators makes it difficult to measure peculiar velocities of individual galaxies. An alternative statistic is to measure the center of mass motion of galaxies within a given region, known as bulk flow. Even this statistic is difficult to determine from galaxy surveys beyond a scale of 50Mpc/h (see Strauss & Willick 1995 for a review). Nevertheless, the motion of the Local Group is well known. It has an amplitude of \( 627 \pm 22 \) km/s and direction \( (273^0 \pm 3^0, 30^0 \pm 3^0) \) in galactic coordinates. It has been determined from the Cosmic Microwave Background (CMB) dipole. This motion is supposed to be generated by local inhomogeneities but due to the lack of reliable distance estimators, is not clear what scales contribute. Kocevski & Ebeling (2006) found that most of the peculiar velocity of the Local Group was due to over-densities at \( > 150h^{-1} \)Mpc, a result difficult to accommodate in the standard \( \Lambda \)CDM model.

2. Peculiar velocities from the kinematic Sunyaev-Zeldovich effect.
Alternative methods to measure peculiar velocities was proposed in Kashlinsky and Atrio-Barandela (2000) and Atrio-Barandela, Kashlinsky and Mücket (2004). Clusters of galaxies
are the largest astronomical objects bound gravitationally. The hot Intra Cluster gas is highly ionized and the free electrons scatter the CMB radiation. When the cluster moves in the isotropic CMB frame, the Doppler shift of the radiation produces a dipole pattern in the cluster rest frame. When the CMB photons cross the cluster, they get thermalize through Compton scattering with the electrons within the potential well. This effect produces a secondary anisotropy of amplitude \( \Delta T / T_0 (\hat{n}) = -\tau (\hat{n} \cdot \vec{v}_{cl}) / c \). This component, termed kinematic Sunyaev-Zeldovich (kSZ), depends on the cluster velocity \( v_{cl} \), the electron density along the line of sight \( \tau \) and the direction of observation \( \hat{n} \). This signal is subdominant in most clusters with respect to the anisotropy generated by the thermal motion of the electrons within the potential well of the cluster. This effect is known as thermal Sunyaev-Zeldovich (tSZ) effect. In the Rayleigh-Jeans regime, frequencies at which the WMAP satellite operates, it produces a decrement in the CMB temperature.

Kashlinsky and Atrio-Barandela (2000) showed that a bulk flow motion of \( N_{cl} \) clusters will produce a dipole pattern on the CMB at cluster locations with amplitude:

\[
a_{1m} = 1 \mu K \frac{v_{bulk}}{300 \text{km/s}} \pm 3 \mu K \left[ \frac{N_{cl}}{1000} \right]^{1/2} \pm 0.6 \mu K \left[ \frac{N_{pixels}}{10000} \right]^{1/2} \pm 0.2 \mu K \left[ \frac{N_{cl}}{1000} \right]^{1/2}
\]

The signal will be overshadowed by three competing effects: intrinsic CMB, noise and tSZ dipole due to the inhomogeneous cluster distribution on the sky. For typical cluster parameters, the expected signal of \( \sim 1 \mu K \) would be dominated by the sampling variance of the intrinsic CMB signal at the cluster positions. Since the CMB signal is spatially correlated, Kashlinsky and Atrio-Barandela (2000) suggested to filter the data to remove the intrinsic CMB signal.

Figure 1. WMAP W1 Differencing Assembly. The three overlapping circles show the direction and 1\( \sigma \) uncertainty in the direction of the dark flow for three subsets of the scout cluster catalog: all clusters have X-ray luminosities in the Rossat broadband larger than \( 2 \times 10^{44} \text{erg/s} \), and redshifts smaller than 0.16 (dark blue) and 0.2 (blue) and 0.25 (cyan). The red spot indicates the direction of the CMB dipole.

3. The Dark Flow.
To measure bulk flows using the kSZ effect as described in the previous section it is necessary to have a large cluster sample. We are currently using the SCOUT catalog, described in Kashlinsky
et al (2010). The same analysis could be also carried out using public data, as indicated in Kashlinsky, Atrio-Barandela and Ebeling (2010). The dipole evaluated on a CMB map at cluster positions would be dominated by the intrinsic CMB signal, as indicated in equation (1). In Kashlinsky et al (2008) and (2009) we showed this measurement could be carried out by adequately filtering the data. A description of the filter, the cluster catalog, the cosmological implications and a detailed description of the technical issues involved was also given. The dipole at cluster locations was measured at zero monopole, implying that the tSZ did not generate a significant dipole due to the inhomogeneous cluster distribution. As shown in Atrio-Barandela et al (2008), this is the result of clusters being well described by a Navarro, Frenk and White (1997) profile. If the baryons are in hydrostatic equilibrium, the temperature of the gas falls with distance from the core. When we integrate the signal including the cluster outskirts, the tSZ contribution drops and the kSZ signal becomes dominant.

Later, an improved analysis using WMAP 5yr data was carried out in Kashlinsky et al (2010). To summarize the results, in Figure 1 we represent the direction of the flow as derived for the most luminous clusters in the SCOUT catalog. The width of the circle corresponds to the 1σ error bar. The red spot indicates the direction of the CMB dipole. The direction is very consistent within the three subsamples and with the direction of the measured dipole.

In Atrio-Barandela et al (2010) we showed the filter to be optimal in the sense that its efficiency was limited by cosmic variance.

Figure 2. Y-component of the dipole evaluated at cluster positions on discs of size 30' versus the monopole evaluated on the original WMAP W-band on discs of size 10'. Clusters are bin by X-ray luminosity in three intervals: $L_X \in [1.0, 1.5], [1.5, 2.0]$ and $L_X > 2$ (in units of $10^{44}$erg/s). The blue triangles correspond to clusters with redshifts $z \leq 0.16$, the red squares to $z \leq 0.2$ and the full green circles to $z \leq 0.25$. The error bars are obtained from the dispersion within the 4 W Differencing Assemblies.

The evidence we have provided in favor of the measured dipole being associated with the kSZ effect can be summarized as follows: (a) the dipole originates at cluster locations, (b) it is present when the number of clusters grow from ~ 120 clusters to more than 700 and, as indicated above, (c) the dipole is measured when the tSZ monopole was effectively zero. In Figure 2 we
represent the measured y-component for clusters subsamples bin by X-ray luminosity, as a function of the measured tSZ monopole on the unfiltered four W Differencing Assemblies (DA). When computing the tSZ signal, all clusters are assigned an angular size of 10′. The dipole is computed on filtered W DA with apertures of 30′, where we have verified the tSZ monopole is close to zero. The error bars are computed from the dispersion within the W DA. Figure 2 shows a clear correlation between the measured dipole and the tSZ effect. The former is a proxy for X-ray luminosity, since a more luminous cluster produces a larger tSZ effect. Since our filtering does not use information about cluster positions or their luminosities, this correlation cannot be an artifact of our data processing or some unknown systematic effect present in WMAP data. It argues strongly in favor of the signal being real. The differences found between the subsamples are arguably due to clusters at higher redshifts having their tSZ and kSZ effects more strongly diluted by the beam.

4. Cosmological Implications.

As the data shows no signs of converging, one could assume that the scale of the flow extends all the way up to the observable horizon. Equivalently, seen from the matter rest frame the cosmological dipole is intrinsic, i.e., the matter and isotropic CMB frames do not coincide. An intrinsic dipole of amplitude $\Delta T/T_0 \sim 10^{-3}$ cannot be generated during inflation without generating a quadrupole of similar amplitude (Kashlinsky, Tkachev and Frieman 1994). However, an isocurvature pre-inflationary remnant of amplitude $\delta \sim 1$ and wavelength $L \sim 10^3 cH_o^{-1}$ could produce such anisotropy:

$$D \sim \frac{v}{c} \sim \left( \frac{cH_o^{-1}}{L} \right) \delta L \sim 10^{-3} \quad Q \sim \left( \frac{cH_o^{-1}}{L} \right)^2 \delta L \sim 10^{-6}$$

without generating a significant quadrupole. In this context, our local motion could be generated by a pre-inflation perturbation of wavelength much larger than the current horizon. In this respect, the concordance ΛCDM model would be valid on sub-horizon scales, but one could not longer assume that the matter rest frame and the isotropic CMB frame were equivalent.

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