Bulk flows in inflation and in Lemaître-Tolman-Bondi models

F Atrio-Barandela$^1$, A Kashlinsky$^2$, H Ebeling$^3$ and D Kocevski$^4$

$^1$Universidad de Salamanca, Spain.
$^2$Goddard Space Flight Center, Maryland.
$^3$Institute of Astronomy, University of Hawai'i.
$^4$Dpt of Physics, UC Davis.

E-mail: atrio@usal.es, Alexander.Kashlinsky@nasa.gov, ebeling@ifa.hawaii.edu, kocevski@physics.ucdavis.edu

Abstract. We describe the recent measurements of bulk flows of unprecedented scale and amplitude. These results are not easily accommodate in the standard ΛCDM cosmology. We study two possible solutions: preinflationary superhorizon sized perturbation and void models of the Lemaître-Tolman-Bondi type and discuss their viability.

1. Introduction

In standard gravitational instability picture, peculiar velocities are departures from the Hubble flow due to local inhomogeneities. Gravitational instability states that the present large scale structure of the Universe originates from the growth of small density perturbations on an initially weakly inhomogeneous Friedmann-Robertson-Walker model. Then, they trace directly the matter density field. Peculiar velocities of individual galaxies are very difficult to measure and only moments of the velocity field have been derived from the data. One such moment is the bulk flow, the centre of mass motion of the matter contained on a given volume. For all scales larger than Matter-Radiation equality $\sim 100 \text{ Mpc}/h$, bulk flows probe the primordial power spectrum of matter density perturbations. The expected amplitude is

$$P(k) \propto k \quad \Rightarrow \quad V_{\text{rms}} \simeq \left( \frac{r}{100 \text{ Mpc}/h} \right)^{-1} 250 \text{ km/s}$$

Measuring peculiar velocities on scales larger than 100Mpc/h offers a test of inflation and of the gravitational instability paradigm.

Determination of peculiar velocity using galaxies requires to subtract the velocity due to the Hubble expansion. Since uncertainties on distance estimators increase with distance, measurement of peculiar velocities has been limited to scales $\leq 100 \text{ Mpc}/h$. In [1] we proposed to use clusters as tracers of the velocity field using the temperature anisotropies induced on the Cosmic Microwave Background (CMB). The proposed method, based on the Sunyaev-Zel’dovich (SZ) effect [2], has systematics that are very different from those of galaxy distance estimators. Physically, the hot intracluster gas distorts the black body spectrum of the CMB photons due to the thermal motion of electrons in the potential wells of clusters and to the
kinematic motion of the cluster as a whole with respect to the matter rest frame [2]. The CMB temperature anisotropies generated by the thermal SZ effect are proportional to the electron pressure integrated along the line of sight $\hat{n}$. The anisotropies produced by kinematic SZ effect depend on the electron density $n_e$ and the projection of the peculiar velocity $\vec{v}_d$ of the cluster along the line of sight. If clusters are isothermal, then

$$\left(\frac{\Delta T}{T}\right)_{tSZ}(\hat{n}) = G(\nu)\frac{k_B T_x}{m_e c^2}, \quad \left(\frac{\Delta T}{T}\right)_{kSZ}(\hat{n}) = \frac{\tau}{c} \hat{n} \cdot \vec{v}_d. \quad \text{(2)}$$

In eq. (2) $k_B T_x$ is the cluster X-ray temperature, $m_e c^2$ the electron annihilation temperature and $\tau = \int n_e(\vec{r})dl$ is the optical thickness of the cluster along the line of sight, integrated over the cluster volume. $G(\nu)$ gives the frequency dependence of tSZ effect. The SZ effect is very useful to identify clusters at high redshifts since, being a distortion of the CMB black body spectrum, it is independent of distance. In the Rayleigh-Jeans part of the spectrum, $G(\nu) \sim -2$ and clusters appear as temperature decrements in CMB maps and can be distinguished from other foreground contributions.

Since clusters can be detected with the SZ effect and its effect is redshift independent, the kSZ effect is a very promising tool to trace the velocity field to very high redshifts. But, similarly to the case of galaxies, measurements of the peculiar velocity of a single cluster are dominated by the cosmological CMB anisotropy. The peculiar velocity of a sample of clusters can be measured with much better accuracy. In [1] we proposed that by measuring the dipole components $a_{1m}$ on CMB maps at the position of clusters one would determine the bulk flow of the cluster sample. The signal is:

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

The error bar on the measurement contains contributions that do not have a dipole pattern: noise, that integrates with the number of pixels and frequency bands, and intrinsic CMB and thermal SZ, that integrate as the number of clusters. The error bar is dominated by the sampling variance of the CMB cosmological signal, resulting from evaluating a dipole on the fraction of the sky occupied by clusters. To reduce this contribution, in [1] we also proposed to filter the intrinsic cosmological anisotropy. We showed how the velocity field could be probed using the Wilkinson Microwave Anisotropy Probe (WMAP) and PLANCK satellites data.

2. Uncovering the ‘Dark Flow’.

The technique proposed by us in [1] was used in [3] to uncover a large scale flow of clusters of galaxies on the unprecedented scale $\sim 300\text{Mpc/h}$. To carry out the measurement we assembled a catalogue of $\sim 1000$ clusters with well measured redshifts, X-ray luminosities and electron densities. To remove the intrinsic CMB signal, a filter was constructed that minimized the difference $\langle (\delta T - \delta T_{\Lambda CDM})^2 \rangle$. The filter effectively removed the CMB signal down to the limit imposed by cosmic variance [4]. By evaluating the dipole contribution at cluster locations, we measured a flow of amplitude $600 - 1000\text{km/s}$ in the direction $(l, b) = (283^\circ; 11^\circ) \pm 30^\circ$ in galactic coordinates, coincident with the direction of the Local Group with respect to Isotropic CMB frame: $(276^\circ \pm 3^\circ; 30^\circ \pm 3^\circ)$ [5].

In Figure 1 we plot the amplitude of the bulk flow for different scales. We selected cluster subsamples of our main catalogue, containing all clusters with redshift $z \leq [0.04, 0.08, 0.12, 0.16, 0.2, 0.3]$. The data correspond to the analysis of WMAP 3 year data. The error has two main contributions: noise and intrinsic CMB residuals. In [4] we showed that the error bars of the analysis of WMAP 3-year data were dominated by CMB residuals, correlated
Figure 1. Amplitude of the bulk flow on the given scale. Vertical lines give the error bars on the measured amplitude and horizontal error bars join the mean and median redshift of the cluster sample. The solid line represents the expected amplitude on the standard ΛCDM model.

between the 8 WMAP Differencing Assemblies, and not by noise. The errors in Figure 1 have been corrected accordingly.

At present, our formalism does not allow us to determine the scale length of the flow. As an order of magnitude estimate in Figure 1 we took the middle point between the mean and the median redshift of the cluster subsample. The horizontal error bar, stretching from the mean to the median redshift, provides an estimate of the uncertainty on the scale of the flow. The solid line represents the prediction of the concordance ΛCDM model. Even though the measurement has large errors, it is clear that the measured amplitude, at the largest scale probed by our cluster sample, is much larger than the concordance model prediction.

Let us summarize the different pieces of evidence that support the idea of a large scale flow:

(a) The motion is found at cluster positions. The error bars in Figure 1 are computed by placing clusters at random positions on the filtered data excising the pixels occupied by real clusters and by the mask. A more extensive discussion can be found in [4].

(b) The signal is persistent when we include all clusters with redshifts \( z \leq 0.12 \) to \( z \leq 0.3 \), where the number of clusters varies from \( \sim 150 \) clusters to \( \sim 700 \). Any undiagnosed systematic effect present in the data would dilute the signal when more clusters were added.

(c) The dipole kSZ signal is measured when the thermal SZ monopole is effectively zero. The thermal and kinematic components are both generated by the X-ray gas. We demonstrated that the dipole contribution was not generated by the thermal motion of the intra cluster gas: If clusters were isothermal, the kinematic and thermal SZ effects would be proportional to each other (see eq. 2). It was believed that the kinematic SZ effect could only be measured in experiments with extensive frequency coverage [6]. But in [7] we showed that clusters are not isothermal. Rather, they follow a Navarro, Frenk and White profile, with temperature and electron density falling with increasing distance from the centre. Then, on the cluster outskirts the kinematic component dominates over the thermal and the former signal is present when the latter is effectively zero.

(d) Since the motion of clusters induces secondary anisotropies on the CMB, if all clusters in a sample move at a similar speed then the more massive clusters would generate larger anisotropies, larger dipoles. This prediction was confirmed in [8] where we showed that the thermal SZ monopole of a cluster sample correlates with the dipole. Larger tSZ signal, i.e. more
massive clusters, have systematically larger dipoles indicating that all the clusters in the sample share the same motion.

Briefly, (a-d) are strong indications that the flow is real and affects all the clusters of our sample. The main limitation of the method is the conversion from the measured signal in units of temperature to a velocity. This conversion factor can be uncertain by up to a 50% and could lead to an overestimate of the amplitude of the flow but would not affect the direction. In Figure 2, we superposed two circular shaded region on WMAP Q1 Differencing Assembly 3-year data. The outer circle gives the direction of the measured bulk flow and its $1\sigma$ uncertainty. The inner circle gives the direction of the CMB dipole derived from the Dipole anisotropy of COBE Differential Microwave Radiometers [5].

3. Origin of the ‘Dark Flow’

The amplitude and coherence of the flow has strong implications for the present gravitational instability picture. Several explanations have been put forward. The flow could be an indication of a tilt created by the pre-inflationary inhomogeneous structure of space-time [9] that might provide an indirect probe of the landscape produced in certain variants of string cosmology [10, 11] or be an indication of a higher dimensional structure of gravity [12].

Alternatively, it could have a ‘local’ origin, due to a void or large scale overdensity [13]. Large scale voids of $\sim 1Gpc$ with an underdensity of $\delta \sim -0.3$ have been advocated to explain the cold spot on the cosmic microwave background on scales of $\sim 5^\circ$. An order of magnitude of the effect can be easily calculated. At a distance $R$ from the centre of a Lemaître-Tolman-Bondi void:

$$v_p = \frac{1}{6} \Omega_0^{0.6} H_0 R \delta = 600 \text{km/s} \left(\frac{R}{1Gpc}\right) \left(\frac{\delta}{0.1}\right)$$

Such voids will generate a peculiar velocity field with a measurable shear. At present, our results have not enough statistical power to determine the shear of the flow. However, our latest results [8] indicate the flow extends out to $\sim 750$Mpc, without showing signs of convergence, which cast doubts on this type of explanation.

The scale and coherence of the flow supports a different and more radical solution requiring ‘global’ motion: the dipole anisotropy of the CMB is intrinsic. The observers at rest with the matter distribution in the Universe do not coincide with the observers where the CMB is isotropic. If the CMB dipole anisotropy is intrinsic, then viewed from the isotropic CMB frame
the Universe appears to be tilted, with galaxies moving from one side of our Hubble volume to the other with speeds of the order of 600 km s\(^{-1}\).

An intrinsic anisotropy on the last scattering surface requires a superhorizon isocurvature perturbations of wavelength \(L\) much larger than the Hubble radius \(cH_o^{-1}\). First, the perturbation can not be adiabatic since it would produce the same dipole on all energy densities. Second, this perturbation must be a preinflationary remnant since its amplitude is not given by the Harrison-Zel’dovich prescription. The amplitude \(\delta_L\) of this primordial perturbation could be of order unity. It will generate a horizon flow \(D\), also reflected in the quadrupole \(Q\) and higher order multipoles [10, 14]:

\[
D \sim \frac{u}{c} \sim \left(\frac{cH_o^{-1}}{L}\right) \delta_L \sim 2 \times 10^{-3} \quad Q \sim \left(\frac{cH_o^{-1}}{L}\right)^2 \delta_L \sim 4 \times 10^{-6}
\]  (5)

A pre-inflationary remnant of \(\delta_L \sim 1\) would produce a dipole of the required amplitude if \(L \sim 500cH_o^{-1}\) [3]. However, it will also generate a quadrupole of similar magnitude to the one measured [10]. Higher order multipoles are strongly suppressed and are subdominant with respect to the anisotropies generated during inflation.

The quadrupole estimate of eq. (5) would add linearly to the quadrupole generated by perturbations on horizon scales and this could be a testable prediction. As is well known, the quadrupole in COBE and WMAP data is smaller than the ΛCDM predicted value. Depending on the exact structure of the superhorizon isocurvature perturbation, the intrinsic and inflation generated quadrupoles could add or subtract, preferentially along the direction of the motion, aligning the quadrupole with the dipole and removing power, bringing the measured quadrupole in better agreement with the ΛCDM model.

4. Conclusions.
We have developed a new method to measure the bulk flow velocity of clusters of galaxies. The method is based on measuring the dipole anisotropy at cluster locations generated by the kinematic SZ effect. These measurements have very different systematics than peculiar velocity surveys. We have determined a coherent bulk flow on the direction of the CMB dipole on a scale of \(\sim 300\text{Mpc}/h\), with amplitude of \(600 \sim 1000\text{km/s}\). The amplitude of the flow is almost one order of magnitude larger than the prediction of the standard cosmological model. This flow could be generated by \(\sim 1\text{Gpc}\) void or by density perturbations on superhorizon scales. Measuring the shear and other higher order moments could discriminate between a 'local' or a 'global' origin of the flow.

Other observational results are consistent with the measurements presented here, although at a much smaller scale. The dipole anisotropy of the all sky X-ray selected clusters of galaxies indicates that an important contribution to the velocity of the Local Group is due to overdensities \(> 150\text{Mpc}/h\) [15]. Measurements using galaxy peculiar velocities or reconstructions of the density field suggest similar flows on scales of \(50 \sim 100\text{Mpc}/h\) [16]. A more recent analysis suggest the source of the flow to be an effective distance larger than \(200\text{Mpc}/h\) [17], providing evidence in favour of a superhorizon perturbation.

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