Angular Averages

- Monopole variation of average expansion is determined in 11 independent spherical shells of minimum width 12.5\,h^{-1}\,Mpc, for two separate choices of shell boundaries. The Hubble constant \( H_0 \) for a linear expansion law, computed for the 4th shell is

\[
H_4 = \left( \frac{\sum (\bar{r}_i^2 + \sigma_i^2)}{N} \right)^{-1}
\]

where distances \( r_i \) and their uncertainties \( \sigma_i \) are in \( h^{-1}\,\text{Mpc} \).

- The difference of \( H_4 \) for each shell relative to the asymptotic value \( H_0 \) (at \( r > 156h^{-1}\,\text{Mpc} \)) is determined as a relative fraction \( \Delta H_4 = (H_4 - H_0)/H_0 \).

- The analysis is carried out in the CMB, Local Group and Local Sheet frames.

- We find with extremely strong Bayesian evidence (in \( H \leq 5 \)) that the Hubble constant, when averaged in these spherical shells, is closer to its asymptotic value when referred to the rest frame of the LG, rather than the CMB.

Systematic Boost Offset

- The variance observed in the CMB frame can be almost entirely explained as a systematic boost effect. If \( H_a \) is the value of the Hubble constant in the 4th shell in a frame in which the spherical Hubble variance is minimized, and \( H_b \) is the value in any frame with relative velocity \( v \), then the difference is found to be

\[
\Delta H = H_a - H_b \approx \frac{v^2}{H^2} \left( \sum \left( \bar{r}_i^2 + \sigma_i^2 \right) \right)^{-1} - \frac{v^2}{H^2} \left( \sum \sigma_i^2 \right)^{-1}
\]

Fitting a power law, \( \Delta H = v^2 \beta \), \( \beta \approx 1 \), gives a value of \( \beta = 1.0 \pm 0.2 \) as expected.

Frame of Minimum \( H_0 \) Variance (with J.H. McKay)

- In which frame of reference is spherically averaged linear Hubble law the "most uniform"?

- There is a degeneracy of possible minimum variance frames, all boosted from the Local Group in the plane of the galaxy. The magnitude of this boost from the LG is consistent with zero, thus not ruling out the LG frame. The lack of a systematic boost effect between these degenerate frames further supports this claim. Correlation between the CMB temperature dipole and the Hubble variance is also considered as an independent test.

Further analysis will test the hypothesis that the lack of data in the Zone of Avoidance is responsible for the large uncertainty in this boost velocity and trim the cause of the degeneracy.

Angular Averages

- In order to associate variance in the Hubble law with foreground structures angular information is also required.

- Angular averages were studied by two methods: (1) Gaussian window averages, (4) fitting a simple linear dipole law

\[
\frac{\sigma_i^2}{H_i} = H_a + \beta v_i \phi
\]

in the same spherical shells, in LG and CMB rest frames. In each case \( \phi \) is the angle on the sky between each galaxy and the direction of the best fit dipole axis, \( \phi_0, H_0, \beta_0, \beta \) and \( \phi_0 \) are determined using a least squares fit. Figure 2 shows the value of \( \beta \) for each shell.

- The dipole magnitudes coincide at \( r = 39.2h^{-1}\,\text{Mpc} \) and \( r = 63.7h^{-1}\,\text{Mpc} \), yet exhibit very different behaviors in close-by shell.

- Analysis of this phenomena leads to the conclusion that the boost from the LG to the CMB frame is compressing for structures in the range 30\,h^{-1} < \( L_{\text{asym}} < 63h^{-1}\,\text{Mpc} \.

- The transition occurs in the same range in which the angular average also produces a better fit in the CMB than LG frame; i.e., the differential expansion almost (but not exactly) has the character of a local boost.

The CMB dipole and differential expansion

- Does the Hubble law dipole correlate with the component of the CMB temperature dipole that is usually attributed to the motion of the Local Group? (455 km/s towards (4.6°, -26.4°, 29.3°).

- We compute the correlation of the residual CMB temperature skymap with a Gaussian window averaged skymap (on scales > 159\,h^{-1}\,Mpc). Figure 3 shows these sky maps with the dipole clearly evident.

- A Pearson correlation coefficient of \( -0.92 \) is found, indicating a strong anti-correlation.

- Calculations show that a 0.5% differential expansion of space on scales > 50h^{-1}\,Mpc is what is required to account for all the putative 65 km/s "local motion" of the Local Group.

- In every exact general relativistic model cosmology (other than the FLRW model) differential expansion, which cannot be reduced to a local boost, is the norm.

- Realistic CMB spectra for dipole, quadrupole, have been produced by ray-tracing in non-linear foreground inhomogeneities using the Lemaitre-Tolman and Bondes models (K. Bolejko, M.A. Nazer, D.L. Wiltshire, in preparation).

To boost or not to boost?: CMB anomalies

- Since data is intrinsically transformed to the CMB, our result has obvious implications for all observational cosmology.

- A differential expansion dipole can differ subtly from a boost dipole. Dipole subtraction and foreground galaxy cleaning require reanalysis (and it is hard).

References