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Measuring velocities using the CMB and LSS

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Abstract

Here is discussed various ways by which the cosmic microwave background (CMB) radiation can be use to measure the velocities of matter in the universe. We include some new statistical techniques for using the kinetic Sunyaev–Zel'dovich (kSZ) effect and integrated Sachs–Wolfe (ISW) effect to determine velocities by correlating wide area CMB maps with overlapping large-scale structure (LSS) surveys.

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1. Why measure velocities

Much of cosmological observations involve the measurement of the (relative) positions of things: e.g., the clustering of galaxies, the angular structure of the CMB temperature and polarization anisotropies. It is also interesting to concentrate on the measurements of the motion of things, i.e., (relative) velocities. The reasons for this are many:

- *Because they are there:* Often velocity information is encoded in measurements one makes for position information (e.g. redshift space distortions) so one gets velocities nearly for free.
- *Self Consistency*: The observed position of matter in the universe is obtained by the motion of the matter from its (presumed) uniformly distributed initial condition. By comparing velocities and positions we can see if we get a self consistent picture for the formation of structure in the universe.
- *Forces*: The motion of matter in the universe is generated by forces acting upon the matter. By measuring velocities we can check if we understand the forces which cause the formation of structure. The forces are mostly gravitational and this provides another test of gravity on cosmological length- and time-scales.

2. Traditional approaches to velocity using the CMB

Many of the major contributions to CMB anisotropies are fairly direct measurements of velocities (combined with other quantities). One has always expected velocity information from the CMB, so much so that the peak structure of the CMB angular power spectrum was, in the past and somewhat misleadingly, often called the "Doppler peaks".

2.1. The Integrated Sachs–Wolfe (ISW) effect

An important contribution to the standard model of anisotropies is the integrated Sachs–Wolfe (ISW) effect (Sachs and Wolfe, 1967). This is usually written in terms of a line-of-sight integral of the time varying gravitational potential

$$\frac{\Delta T_{\mathrm{ISW}}}{T} = \frac{2}{c^3}\int dl\,\mathrm{e}^{-\tau}\dot{\Phi}, \tag{1}$$

where dl is the path length, τ the Thompson optical depth (see below), and Φ the peculiar gravitational potential (i.e. deviation of the potential from it is value in a homogeneous cosmology). Of course, the reason for the time-varying potential is that matter is moving around, i.e. because of velocities. This is evident from the expression[1]

$$\frac{1}{4\pi G}\nabla^2\dot{\Phi} = \frac{\partial(a^2(\rho_{\mathrm{m}}-\overline{\rho_{\mathrm{m}}}))}{\partial t} = -a^2H(\rho_{\mathrm{m}}-\overline{\rho_{\mathrm{m}}}) - a\nabla\cdot(\rho_{\mathrm{m}}\mathbf{v}) \tag{2}$$

where a is the cosmic scale factor, ∇ the comoving gradient, ρ_{m} the matter density, $\overline{\rho_{\mathrm{m}}}$ its mean, $\mathbf{v}$ the peculiar velocity (i.e. wrt the cosmic rest frame), and H the Hubble parameter. Note that even the first term, $\propto H$, can be interpreted in terms of velocities since H is the mean cosmological velocity gradient. Thus we can say that the ISW anisotropies are caused by velocities.

For small growing mode inhomogeneities $\nabla\cdot\mathbf{v} = -a\,H f\,\delta_{\mathrm{m}}$, where $\delta_{\mathrm{m}} = \frac{\rho_{\mathrm{m}}}{\overline{\rho}_{\mathrm{m}}} - 1$, $f = \frac{\mathrm{d}\ln[g]}{\mathrm{d}\ln[a]}$, $g[a]$ is the linear growth function, and $\Omega_{\mathrm{m}} = \frac{8\pi G\overline{\rho}_{\mathrm{m}}}{3H^2}$. Using $\mathrm{d}l = c\ \mathrm{d}\ln[a]/H$ the ISW integral becomes

$$\frac{\Delta T_{\mathrm{ISW,linear}}}{T} = -3\int \mathrm{d}\ln[a]\mathrm{e}^{-\tau}\Omega_{\mathrm{m}}(1-f)\left(\frac{c\nabla}{aH}\right)^{-2}\delta_{\mathrm{m}}. \tag{3}$$

The factor $1-f \propto a\ H - \nabla\cdot\mathbf{v}/\delta_{\mathrm{m}}$ is a weighted difference of cosmic velocity gradients (H) and peculiar velocity gradients ($\nabla\cdot\mathbf{v}$). For pressureless growth $f \approx \Omega_{\mathrm{m}}^{0.6}$ so the two cancel when $\Omega_{\mathrm{m}} = 1$ in which case the ISW effect is zero. In the now standard flat ΛCDM model Ω_{m} deviates significantly from unity at $z \lesssim 1$ and $z \gtrsim 10^3$. Also before recombination ($z \approx 1100$) pressure forces become important for growth. So at both early times and late times we expect a significant ISW contributions to the CMB anisotropy.

2.1.1. ISW from CMB alone

The standard ΛCDM model gives an extremely accurate description of the CMB anisotropy data, as is best illustrated in the 3-year WMAP data (see Fig. 1) (Hinshaw et al., 2006; Spergel et al., 2006). The early-time ISW must

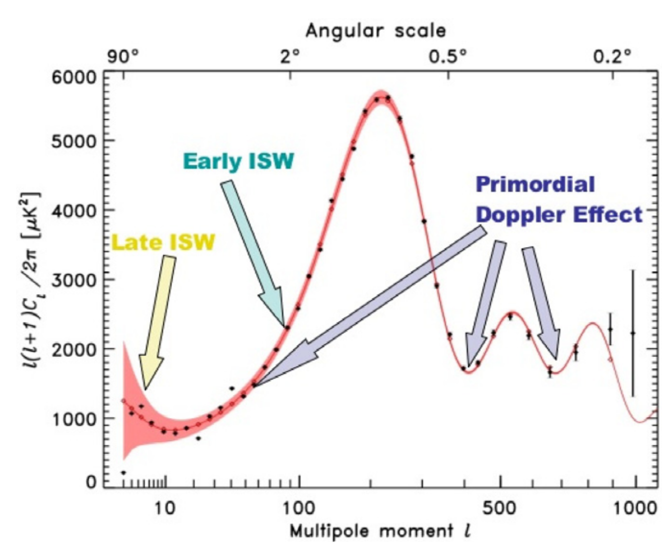

Fig. 1. Taken from (Hinshaw et al., 2006) with annotations. The dots represent the WMAP three year anisotropy angular power spectrum while the shaded band give the best fit ΛCDM predictions with sample variance. While most of the power is from the Sachs–Wolfe effect on large-scale, and adiabatic heating on small scales, the arrows indicate regions most sensitive the early- and late-time ISW effect as well as the primordial Doppler effect. We argue in the text that these effects are fairly direct indicators of velocity flows of the dark matter and gas. The fact that the model fits so well is indicative that the velocities are just as expected.

[1] This is an expression for non-relativistic matter but may include a Λ.