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Anisotropy in the Hubble constant as observed in the *HST* extragalactic distance scale key project results

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Abstract

Based on general relativity, it can be argued that deviations from a uniform Hubble flow should be thought of as variations in the Universe's expansion velocity field, rather than being thought of as peculiar velocities with respect to a uniformly expanding space. The aim of this paper is to use the observed motions of galaxies to map out variations in the Universe's expansion, and more importantly, to investigate whether real variations in the Hubble expansion are detectable given the observational uncertainties. All-sky maps of the observed variation in the expansion are produced using measurements obtained along specific lines-of-sight and smearing them across the sky using a Gaussian profile. A map is produced for the final results of the *HST* Extragalactic Distance Scale Key Project for the Hubble constant, a comparison map is produced from a set of essentially independent data, and Monte Carlo techniques are used to analyse the statistical significance of the variation in the maps. A statistically significant difference in expansion rate of 9 km s^{-1} Mpc^{-1} is found to occur across the sky. Comparing maps of the sky at different distances appears to indicate two distinct sets of extrema with even stronger statistically significant variations. Within our supercluster, variations tend to occur near the supergalactic plane, and beyond our supercluster, variations tend to occur away from the supergalactic plane. Comparison with bulk flow studies shows some concordance, yet also suggests the bulk flow studies may suffer confusion, failing to discern the influence of multiple perturbations.

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1. Introduction

Conventionally, the Hubble flow is thought of as being completely uniform and isotropic. Deviations from a uniform Hubble flow are eliminated by imparting objects' observed residual recessional velocities into peculiar velocities, such that objects are thought to move with respect to a uniformly expanding space. However, empirically it is only valid to consider the velocity field of the matter and how everything is moving relative to everything else in the Universe. It is not possible to infer the existence of an absolute space that expands uniformly and that objects have peculiar velocities with respect to. Thus, deviations from a uniform Hubble flow should properly be considered deviations in the Universe's expansion itself.

Interestingly, Raychaudhuri (1955) showed that (ignoring vorticity) if a velocity field has locally isotropic expansion, then the space is locally isotropic. Yet we know from examples such as gravitational lensing that inhomogeneities alter the curvature of space such that it is not locally

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isotropic. Thus, since space is not locally isotropic, then the Universe's expansion cannot be locally isotropic either. Whether to conceive of the Universe expanding non-uniformly or whether to conceive of it expanding uniformly with superimposed peculiar velocities is more than just a conceptual issue, however.

According to Raychaudhuri's equation (1955), the existence of shear in a velocity field will lead to a decrease in the volume expansion. Since inhomogeneities should introduce tidal forces and shear the velocity field, then the existence of overdensities and underdensities in the Universe should lead to shear throughout the Universe that decreases the Universe's volume expansion compared with that of a homogeneous universe. This effect should only be significant when measured locally in the vicinity of an inhomogeneity: the global influence should be quite small. Raychaudhuri's equation also shows that the existence of vorticity (and also velocity dispersion in the Newtonian version) will lead to an increase in the volume expansion. When structures start to collapse in the Universe and eventually become supported by vorticity or velocity dispersion, those regions of space cease shrinking, which can lead to an increase in the global expansion of the Universe. Thus, it is important to consider the influence inhomogeneities may have on the Universe's expansion.

The Cosmological Principle—that the Universe is homogeneous and isotropic—is generally assumed to hold, since averaged over large enough scales the Universe will appear homogeneous. However, general relativity is needed to understand not only small dense systems, but also large diffuse systems such as the Universe, and according to Einstein's field equations, the spacetime corresponding to a homogeneous universe cannot be used to represent a spatially-averaged inhomogeneous universe. This is because Einstein's field equations do not equate the spacetime to the mass-energy distribution directly. The energy–momentum tensor T_{ab} depends on the Ricci tensor R_{ab} and scalar R, which stem from taking derivatives of the metric tensor g_{ab}, with Einstein's equations equating

$$R_{ab} - \frac{1}{2} R g_{ab} = \kappa T_{ab}.$$

If the left-hand side of the field equations for a homogeneous universe is equated to the spatially-averaged mass-energy of an inhomogeneous universe, there will generally be a discrepancy between the two sides of the field equations, which will act like a cosmological constant and either accelerate or decelerate the universe's expansion from that expected for a homogeneous universe. Thus, even if the Universe may look homogeneous on large enough scales, assuming the Universe to expand uniformly is ultimately misleading. Several researchers have suggested this effect may even explain the Universe's apparent acceleration (reported by Perlmutter et al., 1999) as being due to structure formation—Bildhauer and Futamase, 1991; Bene et al., 2003; Kolb et al., 2005—although Russ et al. (1997) argue that the effect of inhomogeneities should be small.

Also, conceiving of the Universe's expansion as uniform and assigning the galaxies peculiar velocities, bulk flow studies such as that of Hudson et al. (2004) have continued to find that the peculiar velocities with respect to the Cosmic Microwave Background (CMB) frame are correlated such that volumes of space of order 100 Mpc in radius are moving with bulk velocities of approximately 300–700 km s^{-1}. This suggests inhomogeneities significantly perturb the velocity field of the Universe. The existence of the Universe's large-scale structure of voids and superclusters suggests the voids are underdense regions that have been decelerated less due to gravity so they have ballooned up into roughly spherical regions without undergoing structure formation, while the superclusters are overdense regions where gravity has overcome the Universe's expansion such that they have reached turnaround and collapsed in their densest regions.

Moffat and Tatarski (1995) looked at what observational effects we would theoretically observe if we were to inhabit a local void. Via comparison of their theoretical curves with a survey of redshift-distance determinations, they found the data were better fit by a model with a local void than by a homogeneous universe. Zehavi et al. (1998) used 44 type Ia supernova H_0 values to show that we may just inhabit an underdense region of the Universe (where the expansion in the velocity field has been slowed less due to gravity than in more dense regions of the Universe). Referring to Fig. 4 of Freedman et al. (2001), it appears that the H_0 values tend to fall off beyond a distance of 100 Mpc, which suggests the Universe may be expanding faster locally. A here–there difference in the Universe's expansion could be an alternative to the notion of a now–then difference, which is the assumption the Universe's supposed acceleration (Perlmutter et al., 1999) rests on, so it is important to account for the possible influence of inhomogeneities on the Universe's expansion if the cosmological parameters are to be properly determined.

Thus, in this paper we will not assume the existence of a uniform spatial expansion with peculiar velocities superimposed. We will use H_0 values measured along different lines-of-sight to see whether local variation in H_0 exists, and to produce all-sky maps of the observed variation across the sky. If more variation exists in the maps than should be expected due to measurement errors in the data, and if the high and low values of H_0 are correlated in position on the sky, then this will be taken as evidence that the expansion is indeed locally anisotropic across the sky. Since bulk flow studies find bulk flows of a few hundred km s^{-1} on 100 Mpc scales, which is predicted depending on the cosmological model (e.g. see Zaroubi, 2002), and bulk flows only show the net flow of a sample volume rather than the individual variations in the velocity field, then it would be expected that variations in H_0 observed on this scale should be at least a few km s^{-1} Mpc^{-1}.

While it is easy enough to measure how fast objects are expanding away from us via redshifts, it is the determination of accurate distances that is problematic in the deter-