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Observed Anisotropy in the Universe's Expansion Rate

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Abstract

We present all-sky maps of the variation in H_0 as observed from our locale in the universe. These are obtained by using the final results of the *HST* Extragalactic Distance Scale Key Project for H_0 and using H_0 values obtained in the CMB frame. Smearing the H_0 values (which are associated with specific lines of sight) across the sky according to a Gaussian profile, all-sky contour maps are constructed. Various Monte Carlo methods are used to test the likelihood of achieving as much variation as is observed in the maps, and statistically significant variation is found. By comparing maps of the sky for different distances, it appears to indicate two sets of variations that are distinct from one another. Within our supercluster, differences as great as $\sim$35 km s^{-1} Mpc^{-1} are observed, and these tend to occur near the supergalactic plane with a minimum near ($\alpha = 9^h30^m$, $\delta = +70°$) and a maximum near ($\alpha = 19^h30^m$, $\delta = -70°$). Beyond our supercluster, differences as great as $\sim$20 km s^{-1} Mpc^{-1} are observed, and these tend to occur away from the supergalactic plane with a minimum near ($\alpha = 18^h$, $\delta = +15°$) and a maximum near ($\alpha = 5^h30^m$, $\delta = +5°$). The approximate directional uncertainty is 10°–20°. Comparison with bulk flow studies shows some concordance, but the structure in the maps may also demonstrate where the differences stem from in reported bulk flow directions.

1.1 Introduction

The first study of an anisotropy in H_0 appears to have been that of Rubin et al. (1976a) in an attempt to determine the velocity of our Galaxy from the dipole anisotropy created by its motion. With a sample volume in the recessional velocity range of 3500 to 6000 km s^{-1}, the velocity of our Galaxy was determined to be 454 ± 125 km s^{-1} toward ($l = 163° \pm 15°$, $b = -11° \pm 14°$) (Rubin et al. 1976b).

The first use of anisotropy in observed H_0 values to study intrinsic variation in H_0 appears to have been carried out by Fennelly (1977). This work involved the use of empirical values obtained for H_0 to fit the model of a mass overdensity 120 Mpc distant at ($\alpha = 12^h42^m$, $\delta = +20°$).

Conventionally, the Hubble flow is thought of as uniform and isotropic. Deviations from the Hubble flow are eliminated by imparting objects' observed residual recessional velocities into peculiar velocities, such that objects move around randomly or fall into mass overdensities while space expands uniformly. Bulk flow studies (e.g. Hudson et al. 1999) have sampled objects over reasonably large volumes of space to study net peculiar velocities (with respect to the CMB). Thus far, no matter what the sample size, bulk flows continue to be found, which suggests a uniform Hubble flow might not be the best paradigm to use in thinking about the universe's expansion.

Since there is no ether, alternatively one may say that objects remain fixed in space while space expands nonuniformly due to its nonuniform distribution of mass, which slows the universe's expansion by different amounts in different places. We will use this latter paradigm and study variations in the universe's expansion rate that can be observed using H_0 values measured on different lines of sight.

Historically, the errors in H_0 have been too great for the study of real variation in the universe's expansion rate. The most accurate work to date to study H_0 is the *HST* Extragalactic Distance Scale Key Project (hereafter the Key Distance Project), which has finally (Ferrarese et al. 2000; Gibson et al. 2000; Kelson et al. 2000; Mould et al. 2000; Sakai et al. 2000; Freedman et al. 2001) yielded distances accurate enough for a meaningful study of real variation in H_0.

1.2 Mapping Method

The mapping method involves making all-sky maps from a set of H_0 values (in the CMB frame) associated with specific directions on the sky. The values are smeared on the sky by laying down a fine grid and calculating weighted values of H_0 at each grid point, where the weighting for each actual data point falls off as a Gaussian based on the angular separation between the data point and the grid point. Typically, the Gaussian profile is set with a sigma of 25°, as this is roughly the spacing of the data points on the sky. The positions of contours of constant H_0 are then interpolated between the grid points. Finally, the maps are plotted using a sinusoidal projection of the sky in Galactic coordinates.

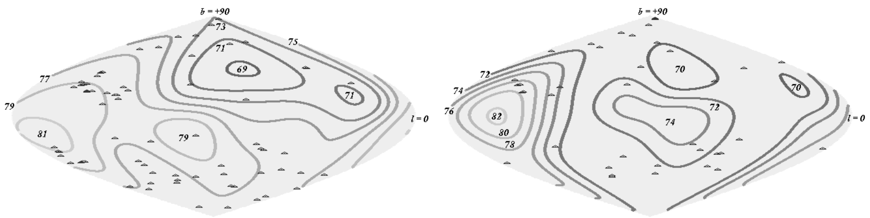

Fig. 1.1. Hubble constant contour maps (in Galactic coordinates) for (left) the Key Distance Project H_0 values and (right) an independent set of H_0 values. The positions of the actual data points are indicated by markers, and the contours range from low (dark) to high (light) values of H_0 (in km s^{-1}Mpc^{-1}) as indicated.

For comparison, Figure **??** shows the map produced using the final H_0 values of the Key Distance Project along with a map produced using a mixed bag of data taken from the literature (which are more riddled with error but are useful in that they are essentially independent of the Key Distance Project—there isn't space to reference these here, but a database is available upon request). Both maps pick out four extrema. The Key Distance Project map yields minima near ($\alpha = 9^h30^m$, $\delta = +70°$) and ($\alpha = 18^h$, $\delta = +15°$) as well as maxima near ($\alpha = 19^h30^m$, $\delta = -70°$) and ($\alpha = 5^h30^m$, $\delta = +5°$). While the maps aren't identical (and shouldn't be considering their errors), the fact that both maps pick out essentially the same four extrema locations suggests these extrema exist independent of errors in the data. Also, the residual of the difference between the maps only has two-thirds the range of variation in it that each map has: if the features in the maps were solely due to error, the residual should have a greater magnitude of variation than either map, so this also suggests the extrema aren't just due to errors in the data.

1.3 Statistical Significance and Magnitude of Variation

While the Gaussian sigma is typically set at 25°, with larger values, noise in the data is averaged out better (but any true variation is smoothed down more). With smaller values of sigma, the variation is less blunted out by the smearing (but noise is more prominent). Thus, larger and smaller values of sigma yield complementary information: confidence that the variation is more than just noise, versus seeing just how great the magnitude of variation may be across the map.

The statistical significance of the variation in the Key Distance Project map is found using a Monte Carlo technique that involves calculating fake H_0 values. Ideal H_0 values are varied by adding Gaussian deviates based on the uncertainties of the real data. A map and its magnitude of variation is calculated for each set of fake values. Repeating this for 10,000 randomizations shows what fraction of the fake maps possess as much variation as the real map and, thus, the probability of getting as much variation in the maps due to the errors alone. The results are that the magnitude of variation is only as great as in the real map 3.82% of the time for a sigma of 45° (which yields a range of variation of 6.3 km s^{-1} Mpc^{-1} in the real map), 4.93% of the time for a sigma of 35° (which yields a range of 8.8 km s^{-1} Mpc^{-1}), or 13.08% of the time for a sigma of 25° (which yields a range of 12.9 km s^{-1} Mpc^{-1}).

A second method for testing the statistical significance is to take the combined Key Distance Project data and independent data and randomly swap H_0 values and their coordinate pairings to see if as much variation can occur in the map with the data randomized on the sky. For 10,000 randomizations the results are that the variation is only as great 1.16% of the time for a sigma of 45° (which yields a range of 6.6 km s^{-1} Mpc^{-1} in the map of the combined data), 2.60% of the time for a sigma of 35° (which yields a range of 8.9 km s^{-1} Mpc^{-1}), or 19.29% of the time for a sigma of 25° (which yields a range of 12.6 km s^{-1} Mpc^{-1}). Thus, it can be concluded that a variation of about 6–9 km s^{-1} Mpc^{-1} is statistically significant.

To explore the affect of distance on the mapping, the Key Distance Project data and the independent data are combined and divided (at 80 Mpc) into near and far groups to produce separate maps (see Figure **??**). The nearer map picks out the primary extrema and the farther map picks out the secondary extrema from the original maps of Figure **??**, which may imply these extrema are associated with deviations in the universe's expansion that occur at different distances. Applying the H_0-coordinate pairing swapping technique to test the statistical significance of these maps, the result is that as much variation occurs only 0.16% of the time for a sigma of 35° (which yields a range of 18.8 km s^{-1} Mpc^{-1}) in the nearer map or 23.05% (corresponding to a range of 11.1 km s^{-1} Mpc^{-1}) in the farther map. Thus, while the extrema in the nearby map are certainly significant, the extrema in the more distant map cannot be said to be significant. Applying smaller values of sigma, to try to determine the possible degree of variation in H_0 across the sky, yields the result that differences as great as

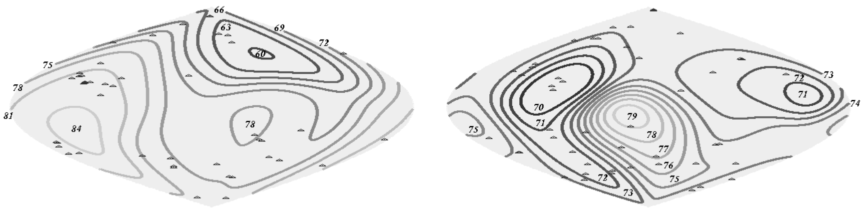

Fig. 1.2. Hubble constant contour maps (in Galactic coordinates) for (left) determinations between 13 Mpc and 80 Mpc and (right) determinations between 80 Mpc and 467 Mpc of a combination of the Key Distance Project H_0 values and an independent set of H_0 values. The positions of the actual data points are indicated by markers, and the contours range from low (dark) to high (light) values of H_0 (in km s^{-1} Mpc^{-1}) as indicated.

$\sim$35 km s^{-1} Mpc^{-1} occur in the nearby map and differences as great as $\sim$20 km s^{-1} Mpc^{-1} occur in the more distant map.

1.4 Discussion

Comparing the variation in the maps to the dust maps of Schlegel, Finkbeiner, & Davis (1998), the variation is not consistent. Thus, the possibility that the variation might be due to errors in correcting for dust extinction seems unlikely.

The nearby variation appears to coincide with the supergalactic plane, while the farther variation appears closer to the supergalactic poles. In the CMB frame, all the variation is perpendicular to the direction of the CMB dipole, while there is no variation along the dipole; thus, the CMB-frame H_0 values obviously aren't problematic—the correction seems too perfect in fact.

To get a sense of the directional uncertainty of the extrema in the maps, a Monte Carlo method is used to plot the extrema tweaked within uncertainties. Gaussian deviates are added to the data based on their uncertainties, maps are made for 500 randomizations, and the positions of the extrema from the randomized maps are plotted on the original map (see Figure **??**). While the uncertainty varies more in some directions than others, the plot appears to indicate an uncertainty of 10°–20°. The fact that the randomized extrema are well-constrained on the map as opposed to randomly fluctuating all over the map demonstrates that the extrema aren't generated simply from uncertainties in the data.

In Figure **??**, several bulk flow directions are also plotted. As expected, the bulk flows point in the direction of high H_0. However, the bulk flow directions are farther from the outskirts of the extrema error plot than expected. In some cases, it looks as though the bulk flow directions may suffer from confusion, pointing between the two maxima in the map. The distance dependence seen in the previous section implies bulk flow directions may be dependent on the sample volume used.

1.5 Conclusions

Errors in the maps are unquestionably large, yet there is sufficient evidence to say there is more than just error creating the variation in the maps. Thus, it appears the universe's expansion is not perfectly uniform, or alternatively (in the uniform Hubble flow paradigm)

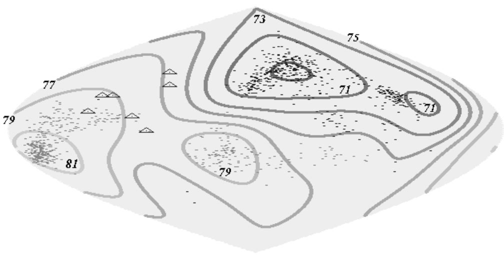

Fig. 1.3. Hubble constant contour map (in Galactic coordinates) for the Key Distance Project H_0 values with 500 randomized extrema (dots) and recent determinations of bulk flows (triangles). From high to low latitude, the bulk flows are those of Rauzy & Gurzadyan (1998), Dale et al. (1999), (right triangle) da Costa et al. (2000), (left triangle) Giovanelli et al. (1998), Dekel et al. (1999), Willick (1999), and Hudson et al. (1999). The positions of the randomized minima and maxima are indicated by dark and light dots respectively, and the contours range from low (dark) to high (light) values of H_0 (in km s^{-1} Mpc^{-1}) as indicated.

bulk flows exist and the lack of existence of a simple dipole in the map (independent of distance) may be evidence of shear.

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