THE KINEMATICS OF THE LOCAL SUPERCLUSTER

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The spatial distribution of galaxies in the Local Supercluster, as described at this meeting, together with the measured anisotropy in the microwave background suggest that there exist significant deviations from a uniform Hubble flow in the velocity field of galaxies within a few thousand km/s. In principle, it is not too hard to improve on the uniform flow model: one simply needs to examine the spatial distribution of the radial velocity residuals for many nearby galaxies. In practice, the problem is non-trivial because of the coupling of velocity and distance, and the lack of a distance indicator of high precision, and the "thermal" noise in the velocity field. Our recent efforts in this direction are described in more detail in a paper in a current *Astrophysical Journal* (Aaronson *et al.* 1982*a*).

The model we fit to the local velocity field is analogous to that used to describe the motion of the Sun in the Milky Way galaxy. In both cases one decomposes the solar motion into a systematic motion of the Local Standard of Rest and a peculiar velocity with respect to the LSR. However, in the present case (in the first instance) we take the systematic motion to be a radial deceleration rather than circular motion. For an assumed spherical density enhancement centered on the Virgo cluster, it is a simple matter to predict the pattern of velocity perturbations in the Supercluster (i) assuming they are proportional to the present density distribution (the "linear model", Peebles 1976) or (ii) integrating the flow through the whole course of the expansion (the "non-linear model", Schechter 1980). We fit this model to a data set consisting of velocities and 21-cm velocity-widths for 306 spiral galaxies within 3000 km/s (Aaronson *et al.* 1982*b*). The velocity-widths are used as luminosity indicators, following Aaronson, Huchra and Mould (1979) and Tully and Fisher (1977), but it should be noted that *the current problem is totally independent of the absolute distances of galaxies*.

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The model is fitted by a careful χ^2 minimization technique, but as in any problem where a signal is being extracted from considerable noise, it is necessary to guard against biases in the fit. If one uses velocity-widths to predict absolute magnitude, it is possible, of course, to either underestimate or overestimate the distance to any particular galaxy, and these errors occur in a volume limited sample in a normally distributed way. However, in a magnitude limited sample, which to some extent the present sample is, this technique, in which one minimizes the *redshift* residuals, is biassed, because the galaxies with underestimated distances come from a larger volume. The problem is known as "Malmquist bias", and can be formally corrected if one knows the sample selection criteria and the true spatial distribution.

We chose to invert the problem to avoid this bias, following Schechter (1980). If one takes the distance of each galaxy from its redshift and the (iterated) flow model and uses it to predict velocity-width, there is no such volume effect. The solution is in principle unbiassed, if one minimizes *width* residuals. However, even this method is not uinbiassed, as we rapidly discovered from numerical simulations. This can be seen from the distribution of residuals in a nearby subsample in Figure 1. Suppose one is a galaxy in the "redshift plateau" in Figure 1 just "above" the Virgo cluster. Suppose also one has a redshift one or two hundred km/s different from the canonical value required by the flow model. Distance changes very rapidly with redshift in this region, and depending on the sign of the noise term, one tends to be seriously mislocated in the model either on the near or the far side of the plateau. The consequent residual, however, also enters χ^2, and the fitting routine compensates by artifically decreasing the amplitude of the flow pattern. The result is a bias in which the infall velocity is underestimated.

There is no single strategy for overcoming this bias, and we elected to (i) exclude a cone within 25° of the Virgo cluster and (ii) correct the remaining bias using Monte Carlo simulations. The one fringe benefit from this problem is that we obtain an estimate of the noise in the local velocity field of approximately 150 km/s. The local infall velocity determined by this method is 250 ± 64 km/s, and, as we shall see, there are significant peculiar motions. This value is dependent principally on the assumed power-law index of the radial density distribution. We adopted $\rho = r^{-2}$ (Yahil, Sandage and Tammann 1980*a*), and we find a change of approximately -/+65 km/s, if that index is changed by +/-0.5. We find negligible sensitivity of our result, however, to hypothesised "second parameters" in the Tully-Fisher relation, such as surface-brightness or Hubble type.

In seeking to minimize χ^2 still further, however, we did achieve a real measure of success by adding a rotational term to the flow model. We tested a rotation curve of the form $W_{rot}(r) = W_r r \exp(1-r^2)$ (de Vaucouleurs 1958). Distance (r) is in units of our distance from Virgo. We found W_r (the local rotational velocity) to be 191 ± 49 km/s, and have incorporated that in our final solution given in Table 1.

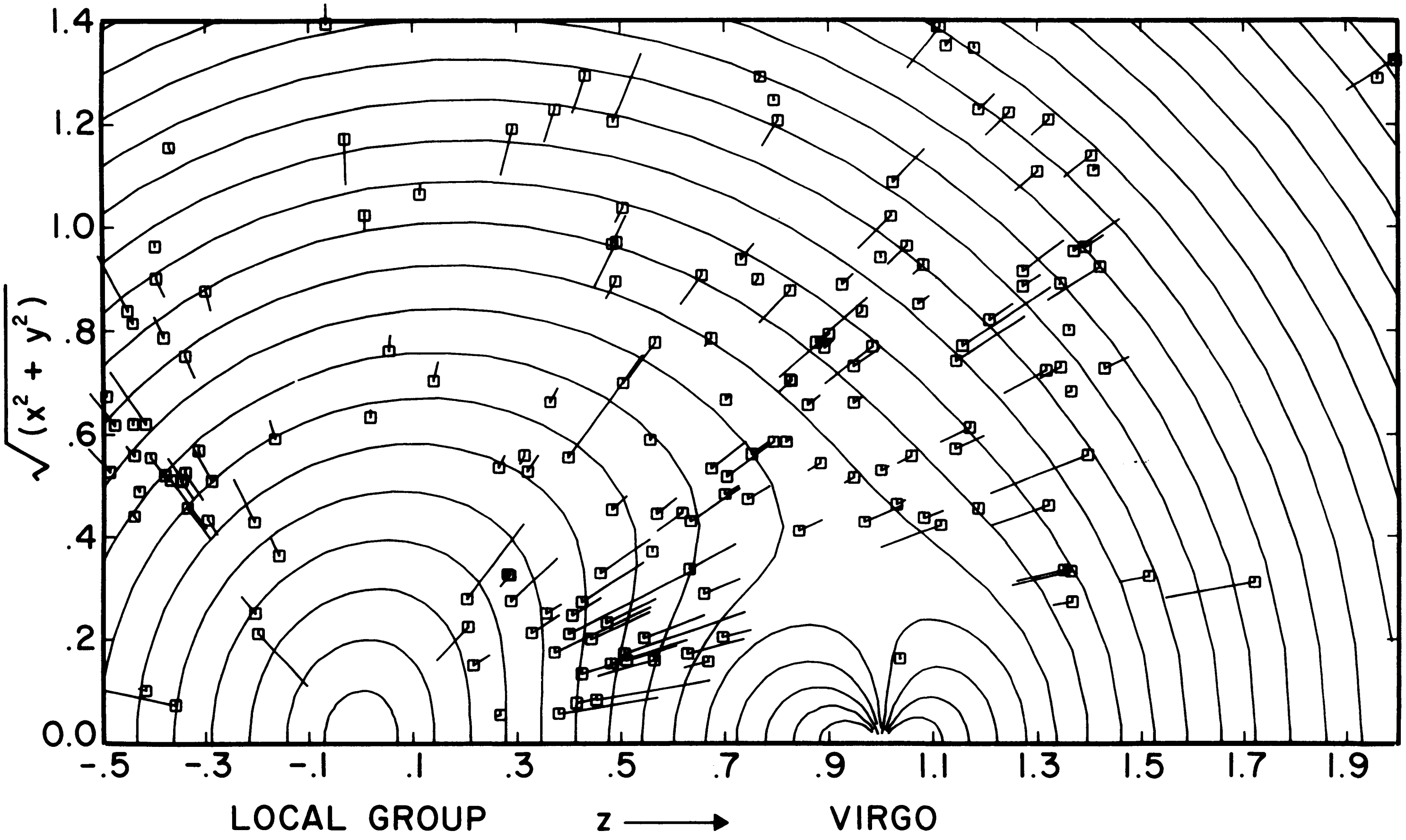

FIG. 1 - H I velocity width residuals for a solution obtained from our data, fixing W_i at 257 km/s and $W_x = W_y = W_z \equiv 0$. Tails point away from the Local Group when the observed is greater than the predicted velocity width. Contours of redshift are shown, spaced at intervals 1/10th the Virgo redshift.

Table 1 allows comparison of the present result with those of other workers. This is complicated by the assumption of different models by different groups. The second and third lines represent the most recent results from the microwave background. Here one should compare the vectors (W_x^{tot}, W_y, W_z^{tot}), where the z axis points at M87 and the x axis is in the supergalactic plane (see Aaronson *et al.* 1982*a*). The magnitude of the velocity difference is 250 ± 150 km/s. The difference appears to be significant: it is unclear to what extent it represents an additional motion relative to a distant frame or an intrinsic microwave anisotropy. The next three entries in Table 1 are pure infall solutions, and W_z^{tot} should be compared with the present result. Our value is bracketed by previous determinations. A number of other recent results are also included for comparison. It is interesting to note a significant component of our peculiar velocity (W_y) towards the south Supergalactic pole. Conceivably, this could be a result of acceleration towards the Supergalactic plane, as discussed by White & Silk (1979).

It is clear, however, that the dominant component is the infall velocity, W_i. If our kinematical model is a dynamical (gravitational) reality, and if the density contrast (ratio of interior to background densities) is 4, then the ratio of that (local) background density to the critical density in Friedmann cosmological models is approximately 0.1.

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TABLE 1
Comparison with Selected Previous Results

Reference	W_x	W_y	W_z	W_i	W_r	W_z^{tot}	W_x^{tot}	remarks
Present	-106	-141	22	281	180	303	74	
work	±41	±47	±54	±63	±58	±39	±71	
Boughn	318	-341	411	≡0	≡0	411	318	quadrupole
et al.	±≈30	±≈30	±≈30			±≈30	±≈30	dipole; 3°K
Smoot &	178	-311	373	≡0	≡0	373	178	dipole fit
Lubin	±≈25	±≈25	±≈25			±≈25	±≈25	3°K
Yahil	≡0	≡0	≡0	230	≡0	230	≡0	V_{Virgo} = 979
et al.				±75		±75		nearby galaxies
Tonry &	≡0	≡0	≡0	440	≡0	440	≡0	V_{Virgo} = 979
Davis				±75		±75		ellipticals+S0
AMHS^{2}B	≡0	≡0	≡0	480	≡0	480	≡0	IR/H I
				±75		±75		cluster sample
de Vaucouleurs	≡0?	-250	≡0?	727	400	727	400	
(1972)		±50		±50	±50	±50	±50	
Stewart	≡0	≡0	≡0	-207	253	-207	253	
& Sciama			±230	±92				
de Vaucouleurs	-83	-106	153	≡0	≡0	153	-83	optical/H I
et al. 1981	±≈50	±≈50	±≈30			±≈30	±≈50	
Rubin	-367	-210	-138	≡0	≡0	-138	-367	ScI's
et al.								
Hoffman	≡0	≡0	≡0	250	≡0	250	≡0	2nd moment
et al.				±50		±50		
Hart &	105	-197	375	≡0	≡0	375	105	
Davies	±≈30	±≈30	±≈30			±≈30	±≈30	

Discussion

Occhionero: Does your evaluation of Ω_0 have any implication on the amount of dark matter?

Mould: I've talked about only the kinematics of the supercluster in this paper, without inquiring into the dynamics. But if one uses the linear model, for example, to determine the mass responsible for the deceleration, one obtains a mass within the Local Group radius of 10^{14} to 10^{15} $M_\odot$, and, as the others have shown, a mass-to-light ratio of the order of 500.

Dressler: I'd like to ask Tully and Mould to clarify their conclusions about the random component, the noise, of the Hubble flow. Tully quoted a value of 50 km/sec, and Mould gave 150 km/sec, based on different analyses of similar, if not common, data. Is this difference significant?

Mould: The estimate of 150 km/s was a coarse value for the thermal noise in the Hubble flow required to produce observed systematic residuals in a very sensitive region of the supercluster. One would need a very precise distance indicator to measure the quantity Brent would like to know, namely, σ_y in the present coordinate system. The Local Group motion of 140 km/s towards the South Supergalactic Pole, seen not only in our kinematic model but also in other determinations, does give a hint about motions perpendicular to the plane, however.

Szalay: The value of Ω as inferred from the galaxy distribution is based upon two assumptions: 1) the mass distribution is spherical; 2) the galaxies represent the distribution of all matter.

It is likely that neither of these assumptions is exactly fulfilled. What deviations would you expect, were these effects taken into account?

Mould: The present work does indeed assume a spherical mass distribution in the spirit of a zeroth-order approximation to the true mass distribution in the supercluster. To test this assumption, it would be of interest to fit: 1) a flattened distribution, and 2) a clumpy or cloud model (see Tully, this meeting) to see if an improved description of the kinematics could be obtained.

Gott: We appear to be on the edge of the local supercluster.

Since a flattened disk of radius r and mass m produces a stronger acceleration at its edge than a sphere of radius r and mass m, a flattened model for the local supercluster should require somewhat less mass-to-light ratio to produce a given infall velocity. Thus, models including this refinement should lead to somewhat lower estimates of Ω than those that assume spherical symmetry.

Dekel: Dr. Gott's conclusion is valid at the post-collapse stages. If, however, we are not at the very edge of the Local Supercluster, the effect on the determined value of Ω is reversed during the one-dimensional collapse, as the density contrast interior to us grows faster due to incoming material while the dynamical effect of the flattening on the deceleration is still unimportant.

Segal: Although the motions of the Local Group estimated from CBR measurements on the one hand and by you and your colleagues by an entirely different technique on the other are in somewhat similar directions, the motion towards Virgo has the effect of impairing the fit of the theoretical (m, z) relation to, for example, the Visvanathan complete sample of E and SO galaxies, while the former improves it. The analysis is based on an optimal nonparametric method for removal of the observational cutoff bias, and the comparative results are the same whether the Hubble or Lundmark law is used. Is your estimate of the motion of the Local Group towards Virgo at all dependent on the assumption that the galaxies in Virgo are approximately at its center and, if so, isn't this assumption fundamentally model-dependent?

Mould: In principle, we could add three further parameters to the present analysis and determine the inflow center. In practice, we have not attempted this. Davis and Huchra have, of course, considered the local "luminosity vector" from the CfA redshift survey, and we have been guided by this and the natural assumption that the mass distribution is like the light distribution.

In response to the first part of your question, I should point out that an infall field plus a local peculiar velocity is a significantly better fit to the present data than a peculiar velocity alone.