Questions and Controversies in the Measurement and Interpretation of Large-Scale Flows

Michael A. Strauss
Princeton University Observatory, Princeton, NJ 08544

Abstract. This introductory talk to the 1999 Victoria Conference on Large-Scale Flows will present the “big questions” which will be discussed in the conference:

- Does the velocity field converge on the largest scales?
- Why can’t we agree on the value of $\beta$?
- How can we properly measure the small-scale velocity dispersion?
- Just how complicated can biasing be?
- How universal are the distance indicators we are using?
- How do we design our next generation of surveys to answer the above questions?

One of the great advantages of giving a review talk at the beginning of a conference is that I get to ask all the questions; it is up to the rest of the participants to come up with the answers. That being said, I will interject my own opinions here and there, occasionally colored by what I learned at the conference itself (a benefit of hindsight I of course did not have at the time I gave the talk itself!). However, I will resist the temptation to steal too much from Avishai Dekel’s conference summary.

1. The Large-scale Velocity Field

If the universe approaches homogeneity as one looks on ever-larger scales, then we expect the rms peculiar velocities to approach zero as we average over larger and larger spheres. With this basic notion in mind, astronomers since the path-breaking work of Vera Rubin and co-workers in the mid-1970’s have been trying to measure the scale on which the bulk flow approaches zero, or equivalently, on which the velocity field measured in the Local Group frame simply reflects the 600 km s$^{-1}$ motion of the Local Group with respect to the CMB. A definitive measurement of this scale would both confirm a fundamental prediction of the Cosmological Principle and the gravitational stability paradigm, and test our interpretation of the dipole moment in the CMB. Moreover, the measurement of the amplitude of the flow as a function of scale is a strong probe of the matter power spectrum on large scales; it is unaffected by bias, and is
less sensitive to non-linear effects, and more sensitive to the longest-wavelength modes, than is the measurement of galaxy fluctuations on equivalent scales (cf., Strauss 1997).

With that in mind, Table 1 qualitatively lists some of the important bulk flow measurements in the literature up to the time of this meeting; apologies to any surveys I may have left out. See Strauss & Willick (1995) for references to the older literature.

Table 1. Recent Measurements of Large-Scale Bulk Flows

| Reference                | Result                                                                 |
|--------------------------|------------------------------------------------------------------------|
| Aaronson et al. (1986)   | Convergence to Hubble flow at 6000 km s⁻¹                               |
| Lynden-Bell et al. (1988)| Flow towards the Great Attractor                                      |
| Courteau et al. (1993)   | Bulk flow of 300 km s⁻¹ at 6000 km s⁻¹                                 |
| Lauer & Postman (1994)   | Bulk flow of 600 km s⁻¹ at 15,000 km s⁻¹                               |
| Riess et al. (1996)      | SN are at rest with respect to the CMB                                  |
| Giovanelli et al. (1998) | No bulk flow at 6000 km s⁻¹                                            |
| Saglia et al. (1998; EFAR)| No bulk flow at 10,000 km s⁻¹                                          |
| Hudson et al. (1999; SMAC)| Bulk flow of 600 km s⁻¹ at 15,000 km s⁻¹, in a different direction from LP |
| Willick (1999; LP10K)    | Bulk flow of 600 km s⁻¹ at 15,000 km s⁻¹, in a different direction from LP |
| Dale et al. (1999)       | No bulk flow to 20,000 km s⁻¹                                          |

Theoretical prejudice would suggest that on large scales, the bulk flows should be of low amplitude, and a number of the analyses listed in Table 1 indicate this. The most direct challenge to this was that of Lauer & Postman (1994), who found a 6000 km s⁻¹ flow within a volume of 15,000 km s⁻¹, which was completely unexpected. Many of the more recent surveys listed above, and discussed in this conference, were carried out to test this startling result. Unfortunately, none have confirmed the LP bulk flow, but the SMAC and LP10K results of Hudson et al. (1999) and Willick (1999), respectively, seem to find a bulk flow of similar amplitude, on similar scale, in a different direction. It is worth emphasizing that despite many efforts, no-one has found any serious errors in the LP data or any methodological problem with their analysis.

The results in this table are presented graphically in Figure 1, based on a similar figure in Postman (1995), which shows the dependence of these results on scale. Given the scatter in this diagram, we cannot yet claim as a community to have come to an agreement as to the nature of the flows on large scales. But keep in mind that Figure 1 (and its variants, which were presented throughout this meeting) is tremendously misleading. First, no single survey probes a given scale; the value of the scale assigned to each data point is usually some “typical”, or weighted mean distance. Second, the errors in the bulk flow are really characterized by a 3 × 3 covariance matrix, so the error bars given here leave out a substantial amount of information. Third, and most important, because the velocity field is more complex than just a bulk flow, any survey which is
Figure 1. A compilation of bulk flow measurements as a function of scale. The three panels give the components of the quoted bulk flows along the Galactic $X$, $Y$, and $Z$ directions in km s$^{-1}$, as a function of the depth of the various surveys. Error bars are as quoted by each paper, and do not take into account the covariance between the different directions (i.e., due to error ellipsoids whose principal axes are not aligned with the Galactic Cartesian directions). Adapted from Postman (1995).
not perfectly uniformly sampled across the sky with homogeneous errors will necessarily alias power from smaller wavelengths in its bulk flow determination, a point made most directly by Watkins & Feldman (1995). This means that one has to take into account this aliasing in asking whether the bulk flow results of two different surveys are in contradiction (see Hudson’s contribution to these proceedings).

Another warning, made by Marc Davis several times in this conference, was that the error bars in such analyses often only reflect statistical measurement errors (e.g., due to the known scatter of the distance indicator used), and ignore systematic errors, due, e.g., to the uncertainty in the calibration of the distance indicator relation itself. These systematic errors need to be properly quantified if we are to decide whether there are indeed serious discrepancies between different measurements, as Figure 1 appears to show.

2. The Value of $\beta \equiv \Omega_0^{0.6}/b_{\text{IRAS}}$

Linear perturbation theory gives a linear relation between the peculiar velocity and gravity fields; alternatively, it can be expressed as a linear relationship between the density field and the divergence of the velocity field. In the linear biasing paradigm (see the discussion in §4), the proportionality factor is the quantity $\beta \equiv \Omega_0^{0.6}/b$. There is a very extensive history of attempts to measure $\beta$ using a variety of techniques comparing peculiar velocity and redshift survey data (see, e.g., Strauss & Willick 1995 for a review of the earlier literature). I tabulate a rather incomplete list of such attempts in Table 2, with one representative entry per method used, apologizing to those whose results are left out. To keep things simple, I’ve restricted myself to recent analyses of IRAS galaxies, to avoid questions of the relative bias of IRAS and optical galaxies (e.g., Baker et al. 1998). I have translated the results from the measured cluster abundance to $\beta$ using the observed $\sigma_{8,g}$ of IRAS galaxies (Fisher et al. 1994).

Figure 2 plots each of these determinations of $\beta$ as a Gaussian with mean and standard deviation as given in the table. A qualitative sense of whether the community is in agreement is whether the sum of these curves (shown, rescaled, as the heavy curve) yields something sensible. The answer is not very convincing; the sum is far from a Gaussian, and is wide enough to include values to make cosmologists of all persuasions happy. It is interesting to compare this with the equivalent plot in Strauss & Willick (1995), based on the literature up to that point; they find a similarly broad sum, with the same mean (although not quite as bumpy), although only a few of the datapoints are shared between the two analyses.

Needless to say, this tells us that serious systematic effects are influencing at least some of these analyses, especially considering that many of them use the same underlying dataset, which means that the error bars are very far from independent. Among the likely important effects are:

- The fact that the effective smoothing scales of these different analyses are different;
- Nonlinear effects in the gravity;
Table 2. Methods for Determining $\beta$

| Method/reference | Result          |
|------------------|-----------------|
| $\delta_g$ versus $\nabla \cdot \mathbf{v}$ | $\beta = 0.89 \pm 0.12$ |
| Sigad et al. (1998) |                 |
| Maximum likelihood fit of velocity field model to TF data | $\beta = 0.50 \pm 0.07$ |
| Willick et al. (1997, 1998) |                 |
| Expansion of velocity field in spherical harmonics | $\beta = 0.6 \pm 0.1$ |
| da Costa et al. (1998) |                 |
| Maximum likelihood fit of $P(k)$ to TF data | $\beta = 1.2 \pm 0.2$ |
| Freudling et al. (1999) |                 |
| Anisotropy of redshift-space clustering | $\beta = 0.77 \pm 0.22$ |
| Hamilton (1998) |                 |
| Anisotropy of spherical harmonic expansion of $\delta_g$ | $\beta = 0.58 \pm 0.26$ |
| Tadros et al. (1999) |                 |
| Dipole moment of redshift surveys | $\beta = 0.6 \pm 0.15$ |
| Strauss et al. (1992) |                 |
| Cluster abundance | $\beta = 0.7 \pm 0.1$ |
| Eke et al. (1996) |                 |
| Depth of voids | $\Omega > 0.3$ |
| Dekel & Rees (1994) |                 |
| Gaussianity of velocity field | $\Omega = 1$ |
| Nusser & Dekel (1993) |                 |
Each of the values in Table 2 is represented as a Gaussian with mean and standard deviation as given. The rescaled sum is the heavy curve.

$\beta = 0.73 \pm 0.31$
• A bias relation more complicated than linear deterministic bias (see § 5);
• Possible correlated and systematic errors in the data.

These issues are discussed in more detail in the panel discussion on the value of $\beta$ (Willick et al., these proceedings).

3. The Coldness of the Velocity Field

Many workers over the past 15 years have remarked on the quietness of the velocity field on small scales. This result is tremendously important for constraining cosmological models. It was the smallness of the small-scale velocity dispersion that provided a first inkling to Davis et al. (1985) that the standard $\Omega = 1$ CDM model was in trouble, and motivated them to consider a model with $b = 2.5$ (which we now know to be in dramatic contradiction to COBE normalization). More generally, the Cosmic Virial Theorem tells us that a small velocity dispersion indicates a small value of $\Omega$.

There are a number of ways in which the quietness of the velocity field can be quantified:

• Measuring the small-scale velocity dispersion by the anisotropy of the galaxy correlation function in redshift space;
• Dividing up the observed bulk flow into large-scale and small-scale components;
• Quantifying the residuals that remain after fitting the large-scale flows to a smooth model.

The small-scale velocity dispersion as measured from the redshift-space correlation function is a pair-weighted statistic, and is therefore heavily weighted by the clusters in the survey volume. However, the small-scale velocity dispersion is a strong function of local density, being quite a bit higher in the cores of clusters than in the field (this is why redshift pie diagrams show dramatic fingers of God in dense clusters, and thin filaments elsewhere), which means that this statistic depends crucially on exactly how many clusters happen to enter your survey volume (e.g., Mo et al. 1993). A number of related statistics have been suggested: working in $k$-space (Szalay et al. 1998), measuring the small-scale velocity dispersion without the pair-weighting (Davis et al. 1997; see also Baker, this conference), and measuring the small-scale velocity dispersion as a function of local density (Strauss et al. 1998). The last two of these, at least, indicate that the small-scale velocity dispersion in the field is very small, less than 150 km s$^{-1}$, but not enough work has yet been done to confirm whether this is consistent with, e.g., currently popular cosmological models with $\Omega \approx 0.3$.

Measuring the coldness of the velocity field from a redshift survey is rather indirect; better is to work from a peculiar velocity survey directly. Sandage (1986), Brown & Peebles (1987), Burstein (1990) and others have remarked on how quiet the directly observed velocity field is; there seems to be little structure on scales smaller than the large-scale bulk flows. Groth et al. (1989) quantified this when they subtracted a bulk flow from the observed peculiar velocity field,
and found essentially vanishing residuals. More recently, the VELMOD technique directly measures the amplitude of velocity field residuals, after accounting for peculiar velocity measurement errors and the IRAS predicted velocity field model; Willick et al. (1997) and Willick & Strauss (1998) also find a small-scale noise below 150 km s$^{-1}$, and evidence that it is an increasing function of density. Tonry et al. (1999 and this conference) find similar results from their modeling of the flow field of the surface brightness fluctuation data.

Again, it is not yet clear to me that the models are doing an adequate job of matching this statistic, and and if not, what physical effects might we be missing? One important complicating effect is the nature of the galaxy bias, which is not going to be simple on small scales, and to which we now turn.

4. Galaxy Bias is Complicated, and Interesting

Galaxy bias exists. We know this from a number of observations: the relative density of elliptical and spiral galaxies is a strong function of environment (which tells us that it cannot be true that both are unbiased relative to the dark matter), and the strong clustering of Lyman-break galaxies at high redshift can only be understood if they are strongly biased.

Once upon a time, we parameterized our ignorance about the relative distribution of dark matter and galaxies with the linear bias model:

$$\delta_g(r) = b \delta(r),$$

where $b$ was implicitly assumed to be independent of the scale on which $\delta$ was defined. On small scales, where the characteristic fluctuations in $\delta$ are appreciably larger than unity, equation (1) cannot strictly hold true for $b > 1$, as both $\delta$ and $\delta_g$ are bounded from below by $-1$. More generally, we now believe that bias is quite a bit more complicated a beast than equation (1) would imply. On very large scales, there are compelling analytic arguments (e.g., Coles 1993; Scherrer & Weinberg 1998) that $b$ should be independent of scale. However, on smaller scales, things can be quite a bit more complicated. In particular,

- The galaxy density field can be a non-linear function of the galaxy density field.

- There can be physical quantities other than the local density which affect the formation of galaxies, meaning that there will necessarily be some scatter (sometimes confusingly called “stochasticity”) around any mean relation between the galaxy and mass density field.

- The bias function can depend on scale, especially on small scales.

- The bias function is already known to depend on cosmological epoch. The continuity equation generically predicts that bias should approach unity with time (in the absence of galaxy formation and merging).

- The bias function is already known to depend on the sample of galaxies; clustering strength depends on surface brightness, luminosity (both optical and infrared), star-formation rate, and morphology, although we are still far from sorting out the dependencies.
Simulations are starting to give us some sense of the complexities involved (e.g., Blanton et al. 1999a,b; Frenk, these proceedings; Klypin, these proceedings), although they are not yet agreeing among themselves on the important physical mechanisms. The controversies are discussed further in the panel discussion on bias (Strauss et al. in these proceedings). I will simply bring up two points: first, we as a community have not thought enough about how the details of the bias relation in all its glory affect the various statistics we are interested in measuring. I’ve already hinted above that this may lie at the heart of both the current confusion about the value of $\beta$, and the small-scale velocity dispersion. Dekel & Lahav (1999) have given us a formalism which incorporates the complexities of bias in large-scale structure statistics, but we need analyses of how large these complicating effects are likely to be in practice. Second, when one has one’s eyes on basic cosmological parameters, the bias function is a nuisance parameter, which we wish to marginalize. But the bias relation itself encodes a large amount of information about galaxy formation itself, and I imagine that the study of large-scale flows and large-scale structure, even at zero redshift, will expand more and more to learn about how galaxies formed.

5. Understanding our Distance Indicators

To measure a peculiar velocity requires the use of distance indicators. There is a large literature on the searches for extra parameters on our two workhorse DI’s: Tully-Fisher and Fundamental Plane/$D_n - \sigma$; and there are somewhat controversial hints, e.g., that the TF relation has a small surface-brightness dependence, or that the Fundamental Plane has a small star formation history or environmental dependence. As we look on larger and larger scales, the signal-to-noise ratio per galaxy peculiar velocity drops, and we become susceptible to ever more subtle (and therefore difficult to discern) systematic effects. We must therefore continue to be vigilant in our search for problems in our data, and astrophysical effects, which can mimic the flows we are trying to measure. This meeting will discuss the next generation of substantially more accurate distance indicators, especially the use of Type Ia supernovae and the surface brightness fluctuation method, which should allow us to trace the velocity field in quite a bit more detail, which will presumably raise a whole new set of exciting questions.

As this happens, we have to think rather hard about the questions we actually want to ask. The best surveys are those that are specifically designed to ask pointed questions (even if, as is so often in astronomy, it ends up making completely unexpected discoveries that lead the observers in unplanned directions). One debate that started at this conference, but which we certainly have not seen the end of, is, what problems will we try to solve with the next generation of surveys? Until we have the answer to this question clearly in mind, we cannot effectively design these surveys and expect them to be scientifically relevant when they are completed.

6. Conclusions

I have unfortunately seen in recent conferences or general reviews on cosmology that the constraints that come from the large-scale peculiar velocity field and
from redshift surveys are being de-emphasized. This is perhaps partly due to the success of our CMB colleagues in convincing the community that MAP and Planck are going to measure all relevant parameters to the up to the twentieth decimal place (yes, I know they are not quite saying that), and partly due to the very real controversies on such basic issues as the value of $\beta$, the convergence of the velocity field, and the nature of bias, that give the impression that our field is in disarray. However, as Avishai Dekel pointed out during the meeting, this is the mark of a field at the cutting edge. Not everything need be clearcut at the frontline of our research. As we are discovering that different results are not as in perfect agreement with one another as we had hoped they would be, we are learning fundamentally new things about our distance indicators, the nature of bias, the effects of non-linearities, and so on. It may be frustrating that the large-scale flows community is not finding a clean set of results on all quantities we measure, but this should inspire us to work harder and learn more, not to give up in frustration.

After my talk, Tod Lauer told me about a conference on Dark Matter held in Princeton in the mid-1980’s. Martin Schwarzschild gave the introductory lecture, which was apparently quite brief. He listed, and succinctly described, a series of fundamental questions about the nature of dark matter and how it can be measured. He then said, in his familiar German accent: “These are the questions. You have the next five days to answer them!” The rest of this volume indicates how successful we as a community have been in answering the questions I’ve laid out in this introductory talk.

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