Constraining the Dark Matter Distribution With
Large-Scale Structure Observations

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Abstract. We discuss the use of galaxies to trace the large-scale structure of the universe and thereby to make cosmological inferences. We put special emphasis on our lack of knowledge about the relative distribution of galaxies and the dynamically important dark matter. We end with a discussion of the increasing importance of infrared astronomy to large-scale structure studies.

1. Introduction

Modern observational cosmology is done within a standard paradigm that has been in development since the invention of the concept of the expanding universe. It is worth reminding ourselves what the basic tenets of the paradigm are.

- We live in a uniformly expanding universe, which originated in a Hot Big Bang. The evidence for the uniform expansion is overwhelming: independent measurements of redshift and distance show that the two are proportional to impressive accuracy. This has been most spectacularly demonstrated recently with observations of high-redshift supernovae (e.g., Schmidt et al. 1998), which are found to obey the Hubble Law from $z = 0.003$ to $z \approx 1$.

- The universe is homogeneous and isotropic on large scales, and thus is described in General Relativity by the Friedman-Robertson-Walker (FRW) metric. This is a statement of the Cosmological Principle, and is dramatically demonstrated by the isotropy of the Cosmic Microwave Background (CMB) to one part in $10^5$.

- The large-scale distribution of matter grew via gravitational instability from initially low-amplitude fluctuations. The CMB indeed does show deviations from isotropy, which are interpreted to be due to tiny fluctuations in the initial density field. Gravity amplifies the contrast between overdensities and underdensities, eventually leading to the structures that we see today.

1 Of course, the supernovae are showing evidence of deviations from the linear relation, which is interpreted to be due to the curvature of the Universe, but that is a different story.
• Dark matter dominates the mass density of the universe. There is strong evidence that most of the mass density of the universe is in a form that is not directly visible, manifesting itself only through its gravitational influence, and that the baryonic material makes up of order 10% or less of the mass density of the universe. This paradigm leaves many important questions unanswered.

• The FRW metric is described by a number of parameters (not all independent), which we might hope to measure: \( \Omega \), the mass density of the universe relative to the critical density; \( H_0 \), the Hubble Constant; \( \Lambda \), the contribution to the curvature by vacuum energy; \( q_0 \), the deceleration parameter; and \( t_0 \), the current age of the universe. The quantity \( \Omega \) can be further divided into the contributions from different mass constituents: baryons, and hot and cold dark matter. Our model will not be complete until we have estimates of these parameters, and show that they are mutually consistent within the model.

• We must characterize the initial perturbations from which the present-day large-scale structure grew. To the extent that the Fourier modes of the initial perturbations had random phases, as expected in inflationary models, the power spectrum gives a complete statistical description of the perturbations. If the fluctuations were seeded by discrete structures, as one expects in models involving phase transitions in the early universe, then the phases are correlated, and one needs higher-order statistics to describe the density field.

• The physical nature of the dark matter remains unknown. We have good indirect evidence that most of it is non-baryonic, and because it is dark, we know that it does not interact strongly with photons. Its detailed nature will affect the shape of the power spectrum of fluctuations, so measurements of the power spectrum can shed light on the nature of dark matter.

• Dark matter may dominate the mass density of the universe, but it is galaxies that we see. A complete model must describe how and when they formed, and how their formation is tied to the distribution of dark matter. Our theories can most easily predict the statistics of the distribution of dark matter; the relative distribution of galaxies and dark matter remains an important unknown in interpreting the observed large-scale structure of galaxies.

In this paper, we do not attempt to answer all these rather broad and important questions; rather, we discuss how to get a handle on all of them by measuring the large-scale distribution and motions of galaxies, with special emphasis on the last problem mentioned above: the relative distribution of galaxies and dark matter. We will end with a brief description of the impact of infrared astronomy on the study of large-scale structure.
2. Large-Scale Structure Data

Imperfect though they may be, galaxies are the tracers that we use to learn about the distribution of mass on large scales.

The NGC was the first substantial catalog of galaxies compiled; it was apparent even from maps of these few thousand objects on the sky that they are not distributed uniformly. In particular, the plane of what we now call the Local Supercluster is quite apparent in the NGC, with a particular concentration in the Virgo Cluster. Although we can learn a great deal from the projected distribution of galaxies on the sky, including the power spectrum and other clustering statistics, we need to know the distance of the objects in a galaxy catalog to quantify all the properties of the large-scale distribution of galaxies. The Hubble Law, which relates the redshift of a galaxy to its distance, allows us to tease out the all-important third dimension of the galaxy distribution. Since the first substantial redshift surveys for the study of large-scale structure in the late 1970s, surveys have grown in size and completeness; currently, the largest single redshift survey is that of Schechtman et al. (1996), which contains roughly 25,000 galaxies.

Even at low redshift, where cosmological curvature effects are unimportant, the Hubble Law holds exactly only in the case of a perfectly homogeneous universe. The over- and under-densities we are concerned with here exert a gravitational pull on the adjacent galaxies. This gives galaxies a peculiar velocity, above and beyond the pure Hubble flow. The radial component of these velocities enters into the redshift:

$$cz = H_0 r + \hat{r} \cdot [v(r) - v(0)].$$

One can thus estimate the radial component of these peculiar velocities using independent measurements of the redshifts $cz$, and distances, $H_0 r$, of galaxies. Of course, the measurement of distances is inherently difficult, especially for extragalactic objects; the standard candles one uses (such as the Tully-Fisher relation, which allows one to estimate the absolute magnitude of a spiral galaxy, given its rotation speed) have substantial scatter. Nevertheless, peculiar velocity studies have been done for large samples of galaxies, which are starting to yield a picture of the large-scale velocity field.

With these redshift and peculiar velocity data, one can carry out a number of studies:

- We can ask for the large-scale topology of the galaxy distribution. Even if the initial density field satisfied the random-phase hypothesis, nonlinear gravitational growth will cause coherent structures to form. People have described the galaxy distribution as being in sheets, filaments, the walls of bubbles, and so on. Interestingly, there still is not a satisfying statistical method of describing the features that are so apparent to our pattern-seeking eyes.

- We can calculate the power spectrum of the galaxy distribution. This has been distorted in various complicated ways from the initial power spectrum of the early universe due to nonlinear growth, the effects of peculiar velocities, and so on, but still has much to teach us about the
initial fluctuations, and by inference, the nature of dark matter, and the values of cosmological parameters.

- We can calculate higher-order statistics of the clustering as well. As we have mentioned several times above, the nonlinear growth of clustering can take an initially random-phase distribution, and generate coherent structures, for which the power spectrum does not give the entire statistical description of the density field. One can calculate the growth of the higher-order clustering measures with time using perturbation theory, which can then be checked against observations; to the extent they agree, one has a consistency check on the hypotheses of an initially random-phase field and the growth of structure via gravitational instability.

- We can relate the large-scale distribution of galaxies to the peculiar velocities. We believe that it is the gravitational influence of the density inhomogeneities in the galaxy distribution that causes the peculiar velocities. In fact, to linear order in the fluctuations, gravitational instability predicts a simple relationship between the velocity field $v$ and the mass density field $\delta$:

$$\nabla \cdot v(r) = -\Omega_0^{0.6} \delta(r). \tag{2}$$

The status of all these analyses has been reviewed extensively in the literature (for example, Strauss & Willick 1995 and Strauss 1998a, b); here we want to stress the limitations of existing data and analyses. First, for many of the analyses that one would like to do in large-scale structure, existing datasets survey too small a volume. An obvious example is the power spectrum on large scales. On sufficiently large scales, one expects the power spectrum to have the same shape as a function of wavenumber (albeit with a much greater amplitude) as the initial power spectrum; moreover, the features in the power spectrum that are diagnostics of the cosmological parameters and the nature of the dark matter manifest themselves on large scales, above $50 h^{-1}$ Mpc or so. However, in order to measure the clustering signal on these scales, one needs a substantial number of independent volumes of this size. Existing redshift surveys simply do not cover a large enough volume to get a high signal-to-noise measurement of the shape of the power spectrum on these scales and larger.

Second, these data are generically affected by systematic errors. Many of the state-of-the-art large-scale structure studies are based on galaxy catalogs selected by eye off of photographic plates in the 1970s and earlier. As the clustering on large scales is weak, it takes only small inhomogeneities in the selection of the catalog to swamp the cosmological signal one is looking for.

New and larger redshift surveys, such as the Sloan Digital Sky Survey (Gunn & Weinberg 1995; cf., \url{http://www.astro.princeton.edu/BBOOK/}) and the Two-degree Field redshift survey (Colless 1998; cf., \url{http://mso.anu.edu.au/~colless/2dF/}), will be able to address these problems. But there is another problem, astrophysical in nature, which places a more fundamental limitation on the interpretation of large-scale structure, namely our lack of knowledge of the relative distribution of galaxies and dark matter.
3. How are Galaxies Distributed Relative to Dark Matter?

The physics of dark matter is relatively simple: being collisionless (as we infer, given its lack of interaction with baryons or photons), gravitational physics describes its evolution and its large-scale distribution in the context of any specific model. However, it is galaxies which we observe directly, and it is not at all obvious a priori whether the large-scale structure we observe in the galaxy distribution mirrors that in the underlying, and presumably dynamically dominant, dark matter.

Let us define the density field $\rho(r)$ of either galaxies or dark matter, smoothed on a scale $R$. The Cosmological Principle states that the universe is homogeneous on large scales; it makes sense to speak of a mean density $\langle \rho \rangle$ of the universe. Thus we find it useful to define the density fluctuation field relative to this mean density:

$$\delta(r) = \frac{\rho(r) - \langle \rho \rangle}{\langle \rho \rangle}.$$  

(3)

The simplest relation one could imagine between the galaxy and mass distribution is that they are the same:

$$\delta_{\text{galaxies}} = \delta_{\text{dark matter}}.$$  

(4)

However, it was realized in the early 1980s that this assumption was quite simplistic. In particular, if galaxies form preferentially in the regions of greatest dark matter density, one generically expects the galaxies to be more clustered than the dark matter (Kaiser 1984; Bardeen et al. 1986). This idea gave theorists a new free parameter, the biasing parameter $b$, with which to fit their models; it was particularly valuable, for example, in reconciling the $\Omega = 1$ CDM models with observations (Davis et al. 1985). (In retrospect, the value of $b$ needed to fit the CDM model is quite unrealistic, but that is another story). In particular, in the appropriate limit of Kaiser’s original formulation of bias, one expects that the galaxy and mass density fields should be proportional to one another:

$$\delta_{\text{galaxies}} = b \delta_{\text{dark matter}}.$$  

(5)

This linear bias model has been the default for most analyses of large-scale structure. For example, people have used Equation (2) (e.g., Sigad et al. 1998) or its integral equivalent (e.g., Willick et al. 1997) to compare redshift and peculiar velocity data; assuming the linear bias relation, it can be phrased:

$$\nabla \cdot \mathbf{v}(r) = -\frac{\Omega}{b} \delta_{\text{galaxies}}(r).$$  

(6)

Thus, one ends up not measuring the really interesting quantity $\Omega$, but the somewhat awkward combination $\beta \equiv \Omega^{0.6}/b$.

The linear bias model is just a parameterization of our ignorance, and is certainly over-simplistic, at least on small to moderate scales (say, less than 20 $h^{-1}$ Mpc). It has been known for a long time that the bias parameter must be a function of galaxy type. After all, one sees a preponderance of spiral galaxies in the field, but they are completely absent in the cores of rich clusters (e.g.,
Dressler 1980). The large-scale distributions of galaxies of different types are not identical. Moreover, the bias relationship must be nonlinear at some level; the morphology-density relation in clusters shows that the density of spirals is a non-monotonic function of the density of ellipticals; therefore they cannot both be linear functions of the underlying dark matter! The bias relationship is almost certainly not completely deterministic; the detailed physics that determines whether a galaxy forms in a given place is not a function purely of the present-day dark matter density, and thus the galaxy density field depends also on additional physical quantities. The bias relationship must also be a function of smoothing scale $R$; on small scales, the rms density fluctuations are large, $\sigma \equiv \langle \delta^2 \rangle^{1/2} \gg 1$, and there are regions in which $\delta = -1$, devoid of matter. But if $b > 1$ in Equation (5) (as models would suggest), one would have the unphysical situation of $\delta_{\text{galaxies}} < -1$. Finally the bias relationship is a function of redshift: as gravity pulls galaxies and dark matter alike into deep potential wells, one expects $b$ to approach unity with time. Indeed, Adelberger et al. (1998; see also Steidel, this conference) observe clustering at $z \approx 3$ which is as strong as clustering today. Clustering of matter grows with time, so the underlying dark matter distribution should be appreciably weaker back then, implying that the effective galaxy bias was quite a bit stronger at $z \approx 3$ than it is today.

One way to get a handle on all these complications is to turn to cosmological simulations. In particular, Blanton et al. (1998) have examined the relative distribution of galaxies and dark matter in a simulation which models both the gravitational physics of dark matter and the gas physics of the baryons. The simulation handles star formation by converting gas into collisionless particles in regions with infalling gas, with cooling times below the local dynamical time, and masses above the Jeans mass. One can then look at the relationship between the density field of these collisionless particles (which we take as a proxy for the galaxy density field) and the dark matter density field.

The resulting bias relationship is nonlinear, stochastic, and is a strong function of galaxy age. These properties are revealed in Figure 1, which shows as a greyscale the conditional probability $P(1+\delta)|1+\delta|$ and as the solid line the conditional mean $\langle 1+\delta \rangle|1+\delta|$, where all quantities are defined with a top hat filter of radius $1 \ h^{-1} \ \text{Mpc}$. Each panel shows the results at $z = 0$ for galaxies formed at different epochs, as labeled. Note that the oldest galaxies are the cleanest tracers of the dark matter distribution, in that the scatter around the mean galaxy-dark matter density relation is small. However, the youngest galaxies show a very nonlinear, even non-monotonic, relation with the dark matter; they are underrepresented in the very densest regions of the dark matter map (reminiscent, indeed, of spirals in the cores of clusters, although in the real universe clusters still represent appreciable overdensities in the distribution of late-type galaxies; Strauss et al. 1992a). In addition, the scatter around the mean density relation for the youngest galaxies is quite sizeable.

In these simulations, the relationship between galaxies and mass also depends on scale. In Figure 2, we show the bias $b \equiv \sigma_g/\sigma$ calculated on various scales. The obvious scale-dependence of $b$ is due to the dependence of the galaxy formation process on temperature. The temperature sets the local Jeans mass, which partly determines whether star-formation occurs: the higher the temperature, the greater the overdensity needed to form stars. On small scales
the temperature is proportional to the gravitational potential $\phi$. Note that in Fourier space, $\tilde{\phi}(k) \propto \tilde{\delta}(k)/k^2$. For high $k$, then, there is little power in the potential or temperature fields; i.e. these fields are smoother than the density field. Thus, temperature correlates over large scales; furthermore, on these large scales it correlates with density as well. Thus the dependence of galaxy formation on temperature can couple the galaxy density on small scales with the dark matter density on larger scales. As Blanton et al. (1998) show, this coupling causes scale-dependence of the bias relation. The dependence of galaxy formation on local gas temperature is likely to be important in any galaxy formation scenario; thus, this scale-dependence may be generic.

The work ahead is evaluate the consequences of this rather complicated bias relationship for interpretations of statistical measures of large-scale structure. It is known, for example, that stochasticity in the bias relation will systematically affect analyses comparing peculiar velocity and density fields based on Equation (2) (Dekel & Lahav 1998); it may turn out that this effect is large enough to explain the discrepancy various workers are finding in analyses of existing datasets in the inferred value of $\beta$.

4. The Impact of IR Astronomy on Large-Scale Structure Studies

What is the connection of all of this to the subject of this meeting? Infrared astronomy has had a large impact on the study of large-scale structure, and
Figure 2. The bias $b(R) \equiv \sigma_g(R)/\sigma(R)$, where $R$ refers to the top hat smoothing radius. Solid line indicates all galaxies. Dashed lines indicate each age quartile, with range of formation redshifts listed. Note the strong scale-dependence, and that old galaxies are more biased than young.

promises to have an increasing role, as we argue in these final remarks. In many ways, the near-infrared is an optimal wavelength regime in which to study galaxies for statistical and dynamical purposes. The problems with both foreground and internal extinction are minimized, and the SEDs of the red stars that make up the bulk of the stellar mass of galaxies peak in the near-IR. However, it has only been relatively recently that infrared instrumentation has advanced to the point that large-scale surveys are possible.

Thus it was realized quite early on that the near-IR was a particularly good place to do galaxy photometry for the Tully-Fisher relation (Aaronson, Huchra, & Mould 1979), but the first large-scale survey of galaxies on the sky in the near-IR, the Two-Micron All Sky Survey, is only being carried out now (Skrutskie, this meeting). 2MASS will be invaluable for large-scale structure studies for a number of reasons. Having two identical telescopes observing in the two hemispheres with the same instrumentation, with data reduced identically, will result in a uniform galaxy catalog free from the headaches of trying to match disparate catalogs from different regions of the sky (cf., Santiago et al. 1996). This, coupled with the small effect of the Zone of Avoidance in the K Band, means that one can study galaxy clustering on large angular scales effectively with the 2MASS data. The galaxy catalogs generated from the IRAS database at 60µm (cf., Fisher et al. 1995) share many of these virtues, and indeed have been used for a large range of large-scale structure studies (as reviewed by Strauss & Willick 1995), but 2MASS will be sensitive to the early type galaxies that are mostly absent in IRAS, and it will go appreciably deeper, with far better sampling of the density field. In particular, the dipole moment of the galaxy
distribution can be compared with the peculiar velocity of the Local Group to infer the depth at which large-scale flows converge; Strauss et al. (1992b) find hints from the IRAS data of possible contributions to the flows on scales above 100 \( h^{-1} \) Mpc. 2MASS should be able to unambiguously nail this problem. The full analysis of large-scale structure with the 2MASS extragalactic database will require redshifts; the survey suffers from an embarrassment of riches, with of order \( 10^6 \) galaxies. John Huchra is leading a group with the ambitious goal of measuring redshifts for the brightest 250,000 2MASS galaxies in K; this should be an absolutely spectacular dataset for the study of large-scale structure, which will make the IRAS redshift surveys quite obsolete.

Most analyses of large-scale structure treat all galaxies as equal tracers of the density field. With our improved understanding of the messy problem of biasing, and in particular a realization that the bias of any given galaxy sample is a strong function of the way in which they were selected, we need to include galaxy properties explicitly in our analyses. Infrared astronomy is starting to give us a real understanding of where the bulk of the bolometric luminosity of galaxies is coming out; a real theme of this meeting was that SIRTF and other tools of infrared astronomy will finally give us a clear understanding of the full SEDs of galaxies of all different types. If we wish to have a real understanding of the distribution of galaxies in space, and in particular, its relation to the dark matter which dominates the dynamics, we need to have as unbiased (in both senses of the word!) a sample of galaxies as possible. We simply cannot learn how to do this properly until infrared astronomy gives us the tools to select galaxies and measure their simplest underlying physical properties.

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References

Aaronson, M., Huchra, J., & Mould, J. 1979, ApJ, 229, 1
Adelberger, K., Steidel, C., Giavalisco, M., Dickinson, M., Pettini, M., & Kellogg, M. 1998, ApJ, in press (astro-ph/9804236)
Bardeen, J., Bond, J. R., Kaiser, N., & Szalay, A. 1986, ApJ, 304, 15
Blanton, M., Cen, R., Ostriker, J.P., & Strauss, M.A. 1998, ApJ, submitted (astro-ph/9807023)
Colless, M. 1998, Phil. Trans. R. Soc. Lond. A, in press (astro-ph/9804079)
Davis, M., Efstathiou, G., Frenk, C. S., & White, S. D. M. 1985, ApJ, 292, 371
Dekel, A., & Lahav, O. 1998, preprint, astro-ph/9806193
Dressler, A. 1980, ApJ, 236, 351
Fisher, K. B., Huchra, J. P., Davis, M., Strauss, M. A., Yahil, A., & Schlegel, D. 1995, ApJS, 100, 69
Gunn, J. E., & Weinberg, D. H. 1995, in Wide-Field Spectroscopy and the Distant Universe, ed. S. J. Maddox and A. Aragón-Salamanca (Singapore: World Scientific), 3
Kaiser, N. 1984, ApJ, 284, L9
Santiago, B.X., Strauss, M.A., Lahav, O., Davis, M., Dressler, A., & Huchra, J.P. 1996, ApJ, 461, 38
Schmidt, B.P. et al. 1998, ApJ, in press astro-ph/9805200
Sheetman, S.A., Landy, S.D., Oemler, A., Tucker, D.L., Lin, H., Kirshner, R.P., & Schechter, P.L. 1996, ApJ, 470, 172
Sigad, Y., Eldar, A., Dekel, A., Strauss, M.A., & Yahil, A. 1998, ApJ, 495, 516
Strauss, M.A. 1998a, in Formation of Structure in the Universe, edited by Avishai Dekel and Jeremiah P. Ostriker (Cambridge: Cambridge University Press), 172
Strauss, M.A. 1998b, Nature, in press
Strauss, M. A., Davis, M., Yahil, A., & Huchra, J. P. 1992a, ApJ, 385, 421
Strauss, M. A., & Willick, J. A. 1995, Phys. Rep., 261, 271
Strauss, M. A., Yahil, A., Davis, M., Huchra, J. P., & Fisher, K. B. 1992b, ApJ, 397, 395
Willick, J.A., Strauss, M.A., Dekel, A., and Kolatt, T. 1997, ApJ, 486, 629