Chapter 1

Introduction

1.1 Constraining the Universe

Human beings have always been fascinated by the subject of how we got to where we are and how we will get to where we are going – not just the history of human events, but also the history of the world and the universe. On the largest scales and longest time-scales this is the subject of cosmology. Many of the cosmological questions have been answered in a general way. However, there are many questions which are (seemingly) open. Specifically, the history of the universe is beginning to be generally agreed upon. It seems that the universe began, some 13 ± 2 billion years ago, much smaller, denser, and hotter than today. The present data also suggest that the expansion of the universe will not only continue indefinitely but could also accelerate.

Many lines of research have come together to bring this picture into focus, including the study of galaxy redshift surveys. To understand the relevance of galaxy redshift surveys, it is instructive to look at the the parameters that describe the universe and how they have been measured.

1.1.1 Parameters

Maybe the most interesting parameter to the lay-person is the ultimate fate of the universe. An expanding universe can have two ultimate conclusions. The first is a forever expanding and cooling universe. The second possibility is that the mass in the universe is sufficient to cause the expansion to end and the universe to collapse upon itself. The parameters of chief importance in determining the fate of the universe are the omegas: Ω_Λ, Ω_m. The omegas are ratios of the density of a particular type of matter to the critical density:

$$\Omega_a = \frac{\rho_a}{\rho_{\rm crit}}. \tag{1.1}$$

The critical density is that density which gives an exactly flat universe. The sum of the omegas gives the shape of the universe. If the sum is greater than one, the universe is closed. If the sum, is less than one the universe is open. The universe will continue to expand indefinitely if Ω_Λ is positive and Ω_m is not significantly greater than 1 or if $\Omega_\Lambda = 0$ and $\Omega_m < 1$ (Carroll et al., 1992).

In addition to knowing the end result, many people are interested in how long the universe has been around. The parameter of primary importance in the question of the age of the universe is the Hubble constant (H_0). The Hubble constant is a measure of how fast the universe is expanding. The age of the universe is given by

$$t_{\rm universe} = \frac{1}{H_0} f(\Omega_m, \Omega_\Lambda). \tag{1.2}$$

The function f is of order unity.

Once the age of the universe and the ultimate fate of the universe are known, other cosmological parameters become interesting. For example, Ω_b, the amount of baryons in the universe is interesting. A significant fraction of the matter in the universe is invisible, or dark. Also one would like to know what fraction of that matter is normal matter and what fraction is non-baryonic dark matter.

Studies of the universe may also yield information about the formation of galaxies. It is clear that gravity plays the largest role in galaxy formation; however, it is not clear when galaxies form and how sensitive galaxy formation is to the local environment. It is also not clear how large the “local environment” is.

Power Spectra

The power spectrum of matter density fluctuations (P_k) is one of the most important measurable quantities. The theory of how the power spectrum relates to the other (perhaps more interesting) parameters is quite sophisticated (Eisenstein and Hu, 1999). It allows one to measure several basic parameters (*e.g.,* Ω_m, Ω_b, Ω_Λ, H_0, etc.) from measurements of the power.

1.1.2 Progress on Measuring the Parameters

Before setting out to measure any parameter of the universe, it is important to note which parameters have already been constrained and by which methods.

Big Bang Nucleosynthesis

Big Bang nucleosynthesis is the study of which elements are produced and in what amounts from the nuclear reactions that take place in the first few minutes of the universe. The fractions of baryons in each of the light elements (H, D, ^{3}He, ^{4}He and ^{7}Li) are sensitive to the density of baryonic matter. Current results have uncertainties in the measurement of $\Omega_b h^2$ at the 10 per cent level (*e.g.,* Tytler et al., 2000) at $\Omega_b h^2 = 0.019 \pm 0.0024$ (h is the Hubble constant in units of 100 km/s/Mpc). These estimates have tightened considerably in the last few years. Maybe more importantly, there are no aspects of the theory that are discrepant with observational measurements. Big Bang nucleosynthesis is one of the success stories of modern cosmology.

Type 1a Supernovae

In the last 2 to 3 years, the study of type 1a supernovae has yielded some of the most interesting results. Type 1a supernovae are a useful measure for cosmologists because they are believed to be extremely uniform. This means that the physics between local and more distant type 1a supernovae are the same. This allows the distance to the supernova to be measured accurately. The redshift of the object can also be measured. Having the redshift and distance to several objects allows measurements of H_0 and a combination of Ω_Λ and Ω_m. Both teams trying to measure the combination of omegas concluded that $\Omega_\Lambda \neq 0$ (Riess et al., 1998; Perlmutter et al., 1999). In his review, Riess (2000) concludes that the supernova evidence does not yet compel us to accept an accelerating universe ($\Omega_\Lambda > \Omega_m/2$); however, the accelerating universe is the most likely solution.

Galaxy Clusters

Galaxy clusters can be used to measure Ω_m. The method is to measure the mass-to-light ratio (M/L) and the background luminosity density (j) at the same redshift. This allows

$$\Omega_m = \frac{M}{L} \times \frac{j}{\rho_{\rm crit}}. \tag{1.3}$$

Measurements of this kind (*e.g.*, Carlberg et al., 1998) yield $\Omega_m \sim 0.2$ with errors at the 20 per cent level. There are two interesting points to be made about this result. First of all, it implies that a majority of the matter in the universe is non-baryonic. Second, it suggests that the density in matter is significantly lower than the critical density.

Also using galaxy clusters to probe cosmological quantities Donahue et al. (1998) observed cluster MS 1054-0321 and calculated that the probability that $\Omega_m = 1$ is less than a few $\times 10^{-5}$.

Cosmic Microwave Background

Measurements of the cosmic microwave background (CMB) are likely to answer most of the current cosmological questions definitively. The CMB is a great place to make a clean measurement of the power spectrum. The fluctuations in the CMB are small enough to be thoroughly treated in a linear approximation; most of the foreground contamination is small or at least removable (Tegmark et al., 2000); and the Gaussian nature of the fluctuations allows them to be completely characterized by their angular spectrum (Hu, 2000). The upcoming MAP and Planck missions should yield power spectra with sufficient resolution to measure all of the omegas, H_0 and several other parameters to the accuracy of a few percent (Bond et al., 1997). A glimpse of this future was afforded to us by the BOOMERANG results. de Bernardis et al.

(2000) gives the results of the BOOMERANG experiment. The BOOMERANG experiment measured approximately 18000 pixels 14 arc-minutes in size in four frequencies. The resulting maps were then analyzed and an angular power spectrum was calculated. Their result was that $0.88 < \Omega_0 < 1.12$ with 95 per cent confidence. Their best fit to the power spectrum had parameters $(\Omega_b, \Omega_m, \Omega_\Lambda, n_s, h) = (0.05, 0.31, 0.75, 0.95, 0.70)$. Already the CMB has constrained the universe to be (nearly) flat. Expect much more to come.

Galaxy Redshift Surveys

After seeing what other methods for measuring the parameters have done, and will do soon, it is important to ask what galaxy redshift surveys can contribute. Galaxy redshift surveys are also used to measure power spectra. Unfortunately, the results are not as clean as those of the CMB. The measurement one would like is that of the matter power spectrum. Galaxy redshift surveys only yield the galaxy-galaxy power spectrum. On large scales, these power spectra differ by the square of the bias parameter (b). On small scales, non-linearities cause more complicated departures from the matter power spectrum. Redshift surveys are also complicated by redshift distortions. Because the radial distance to an object is measured by the redshift rather than a "true" distance, local "peculiar" velocities cause errors in the distance to galaxies. At linear scales, the amplitude of redshift distortions, however, can be used as a measure of the quantity β. β is a function of the omega divided by the bias parameter:

$$\beta \approx \frac{1}{b}\left[\Omega_m^{\frac{4}{7}} + \frac{\Omega_\Lambda}{70}\left(1 + \frac{\Omega_m}{2}\right)\right] \qquad (1.4)$$

(*e.g.,* Lahav et al., 1991).

The information extracted from the galaxy survey can be used in two ways. One way would be to make an independent measurement of the parameters. The second way is to use the parameters measured by some other technique to measure the bias parameter on all scales. The advantage that the galaxy survey has over, say, the CMB is that the power spectrum can be measured on smaller scales. However, particularly on the smallest scales, non-linearities make parameter extraction difficult. However, using the measurements to constrain the non-linear models will yield information about how galaxies form and cluster.

1.2 Pair Weight Compression Method

This thesis focuses on the use of a new method, the pair weight compression method, to extract the power spectrum and measure β from galaxy surveys. The advantage of the pair weight compression method is that it is able to give accurate weights to each galaxy pair and accurate error bars to the results, even in the presence of redshift distortions, non-linearities and difficult data sets.

Currently favored extraction methods fall into one of two categories: the brute force methods and the classical methods. Brute force methods are the methods of choice when dealing with the largest scales (scales where the fluctuations can be treated as Gaussian). On the smallest scales, brute force techniques are too computationally expensive. Furthermore, with non-Gaussian fluctuations brute force techniques fail.

On the other hand, at small scales classical methods work the best. Classical methods rely on the selection function (expected density of galaxies contained within the catalog at a given location given the selection criteria of the survey) being slowly varying over the range of the measurement. This means that on the largest scales, classical methods are no longer ideal.

Depending on the observational procedures for a given catalog, there may be a region where both brute force and classical methods work well or there may be a region where neither technique works well at all. The pair weight method works on all size scales. Therefore, the pair weight method looks like the ideal method.

However, the pair weight method has serious disadvantages. The biggest problem with the pair weight method is that it is computationally expensive even for simple catalogs. Either of the other types of extraction method, if viable, will probably be less computationally expensive than is the pair weight method. This means that the pair weight method is likely to be the method of choice only in situations where the catalog or the prior model is complicated. In this thesis we chose the Las Campanas Redshift Survey as an example of a catalog which has the property of being complicated enough that both brute force methods and classical methods will have a difficult time in extracting the relevant parameters (Matsubara et al., 2000).