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Status of Cosmology on the Occasion of the Carnegie Centennial

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Abstract

Cosmology today is free of serious controversies, though not of exciting discoveries and puzzles. Many controversies have been settled: there is agreement about the Hubble constant (72 ± 7 km s^{-1} Mpc^{-1}), a consistent age (13 ± 1.5 Gyr), consensus that the cold dark matter paradigm provides a successful explanation for how structure formed, and evidence for an early period of inflation. The basic features of the Universe are now quantified: it is spatially flat and has the critical density; ordinary matter accounts for $4 \pm 1\%$ of the total mass/energy content with dark matter and dark energy accounting for the other 96%; and the expansion is accelerating not decelerating. This remarkable picture is supported by an interlocking web of increasingly more precise observations. It also raises profound questions: What is the dark matter? What is the mysterious dark energy whose repulsive gravity is causing the Universe to speed up? Did the early Universe undergo a rapid acceleration (inflation)? An ambitious program of new observations, experiments and theoretical investigations is being launched, with the aim of elucidating our understanding of this new cosmology.

1.1 Introduction

Cosmology has attracted more than its share of attention and controversies over the years. They include: Big Bang versus Steady State; expansion age versus age of astrophysical objects; the nature of quasars; the value of the Hubble constant; isothermal versus adiabatic density perturbations; hot versus cold dark matter (CDM); flat versus non-flat; CDM versus topological defects and nonbaryonic dark matter models versus baryons-only models. Today cosmology is attracting attention not for its controversies—currently there are none—but rather for the remarkable progress toward a consistent cosmological model that describes our Universe and the compelling questions now being asked (NRC 2003).

It has always been a challenge to find ideas expansive enough to describe the Universe and to create instruments powerful enough to explore the Universe. This explains at least in part the uneven progress in cosmology as well as the propensity for controversy (without definitive observations it can be difficult to settle issues). It also is at the root of the current boom: we have both powerful ideas, many motivated by advances in elementary particle physics, and powerful probes of the Universe. The latter include a new generation of astronomical instruments, from the *Hubble Space Telescope* (*HST*) and numerous 6 to 10-meter ground-based optical telescopes, to satellite-borne instruments that probe the Uni-

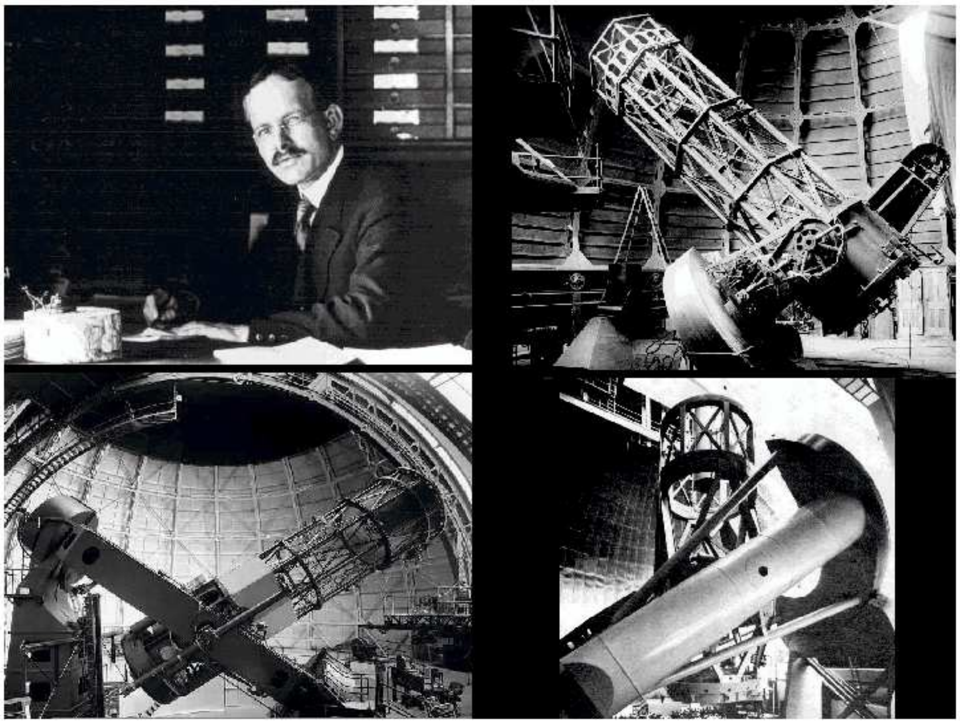

Fig. 1.1. George Ellery Hale and three of the four telescopes he built, which were the world's largest at the time: the 60-inch and 100-inch telescopes at Mount Wilson and the 200-inch Hale telescope at Mount Palomar.

verse across the electromagnetic spectrum, as well as laboratory probes, from accelerator experiments to specialized, ultrasensitive detectors searching for dark matter particles.

In 1902, Andrew Carnegie donated a gift of $10 million to the Carnegie Institution of Washington to "encourage investigation, research and discovery in the broadest and most liberal manner, and the application of knowledge to the improvement of mankind." Under the energetic guidance and vision of the solar astronomer and first Carnegie Observatories Director, George Ellery Hale, 60-inch and 100-inch telescopes were built on Mount Wilson, and soon thereafter the construction of the 200-inch Hale telescope on Mount Palomar was initiated (see Fig. 1.1).

The Carnegie Institution and its scientists have made and are continuing to make seminal contributions to our understanding of the origin and evolution of the Universe. In the early part of the century, while at Carnegie, Harlow Shapley studied the distribution of globular clusters in the Milky Way, and displaced the Sun and Solar System from the center of the Universe. Hubble's discovery of Cepheid variables within nebulae led first to the recognition that there were galaxies outside of our Milky Way, and then in 1929, to the discovery of the expansion of the Universe. Walter Baade's bold concept of stellar populations revolutionized the study of stellar and galactic evolution as well as impacting the cosmological distance scale. Allan Sandage has made seminal contributions to measurements of the Hubble constant and the ages of globular clusters. Vera Rubin's optical spectroscopy of galaxies was pivotal in establishing the presence and importance of dark matter in the Universe. With the twin Magellan telescopes now in full operation and even bolder plans for a 20-meter telescope, prospects for future discoveries and breakthroughs remain just as bright.

In this paper we discuss the current status of cosmology. The outline of this review follows from this three-sentence summary of cosmology today:

- We have delineated the basic features of the Universe (*The Cosmological Model*).
- There is still much to understand about the Universe (*The Big Questions*).
- We have excellent prospects for deepening our understanding (*Looking Forward*).

1.2 The Cosmological Model

On the large scales today ($> 100\,\mathrm{Mpc}$) and on all scales at early times ($t < 10^6\,\mathrm{yr}$), our Universe is well described by the isotropic and homogeneous Friedmann-Robertson-Walker (FRW) models of general relativity. The features of the FRW model that well describes our Universe are summarized as follows:

- Spatially flat with the critical density ($\Omega_0 = 1 \pm 0.03$), expanding at a current rate of $H_0 \equiv (\dot{R}/R)_0 = 72 \pm 7\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, and accelerating with a deceleration parameter of $q_0 \equiv -\ddot{R}/RH_0^2 = -0.67 \pm 0.25$.
- Age $t_0 = 13 \pm 1.5\,\mathrm{Gyr}$.
- Composition: Baryons $\Omega_b = 0.04 \pm 0.01$, with stars contributing $\Omega_* \approx 0.005$; nonbaryonic dark matter $\Omega_{\rm DM} = 0.29 \pm 0.04$ with massive neutrinos contributing $\Omega_\nu = 0.001 - 0.05$; dark energy (something with very negative pressure, $w \equiv p/\rho < -0.6$) $\Omega_{\rm DE} = 0.67 \pm 0.06$; cosmic microwave background (CMB) photons $\Omega_\gamma \approx 10^{-4}$ with temperature $T_0 = 2.725 \pm 0.001\,\mathrm{K}$.
- Early, hot, dense primordial soup phase.
- Large-scale structure build up through the gravitational attraction of CDM.
- Evidence for an early phase of accelerated expansion (inflation), which produced seed density perturbations from quantum fluctuations.

This new cosmology builds and extends upon the highly successful hot Big Bang model (standard cosmology), which emerged in the 1970s and describes the evolution of the Universe from the beginning of Big Bang nucleosynthesis (BBN) ($t \approx 10^{-2}\,\mathrm{s}$) until the present ($t \simeq 14\,\mathrm{Gyr}$) (see, e.g., Weinberg 1972; Peebles 1993; or Kolb & Turner 1990). A striking success of cosmology today is a set of cosmological parameters with reliable error bars, shown in Table 1.1 from a recent review (Freedman & Turner 2004). The quantity and quality of cosmological data have advanced to the point where essentially all of the parameters are supported by an interlocking web of independent measurements. To illustrate this, we discuss in detail the measurements underlying some of the parameters.

1.2.1 The Hubble Constant

Hubble's discovery of a deceptively simple correlation between galaxy distance and recession velocity 74 years ago did not foreshadow the challenge of obtaining an accurate value for the Hubble constant. The most difficult aspect lies in establishing accurate distances over cosmologically large scales. The importance of pinning down H_0 has only grown with time: not only does it set the scale for all cosmological distances and times,

Table 1.1. *Our 16 Cosmological Parameters*

Parameter	Value*	Description	*WMAP*†
		Ten Global Parameters	
h	0.72 ± 0.07	Present expansion rate[a]	$0.71^{+0.04}_{-0.03}$
q_0	-0.67 ± 0.25	Deceleration parameter[b]	-0.66 ± 0.10[c]
t_0	$13 \pm 1.5\,\mathrm{Gyr}$	Age of the Universe[d]	$13.7 \pm 0.2\,\mathrm{Gyr}$
T_0	$2.725 \pm 0.001\,\mathrm{K}$	CMB temperature[e]	
Ω_0	1.03 ± 0.03	Density parameter[f]	1.02 ± 0.02
Ω_b	0.039 ± 0.008	Baryon density[g]	0.044 ± 0.004
Ω_CDM	0.29 ± 0.04	Cold dark matter density[g]	0.23 ± 0.04
Ω_ν	$0.001 - 0.05$	Massive neutrino density[h]	
Ω_X	0.67 ± 0.06	Dark energy density[g]	0.73 ± 0.04
w	-1 ± 0.2	Dark energy equation of state[i]	< -0.8 (95% cl)
		Six Fluctuation Parameters	
$\sqrt{S}$	$5.6^{+1.5}_{-1.0} \times 10^{-6}$	Density perturbation amplitude[j]	
$\sqrt{T}$	$< \sqrt{S}$	Gravity wave amplitude[k]	$T < 0.90S$ (95% cl)
σ_8	0.9 ± 0.1	Mass fluctuations on 8 Mpc[l]	0.84 ± 0.04
n	1.05 ± 0.09	Scalar index[f]	0.93 ± 0.03
n_T	—	Tensor index	
$dn/d\ln k$	-0.02 ± 0.04	Running of scalar index[m]	-0.03 ± 0.02

*The 1-σ uncertainties quoted in this table represent our combined analysis of published data.
†Bennett et al. 2003.
[a]Freedman et al. 2001; note: $H_0 = 100h\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$.
[b]Supernova results combined with measurements of the total matter density, $\Omega_\mathrm{m} = \Omega_\nu + \Omega_\mathrm{b} + \Omega_\mathrm{CDM}$ and Ω_0, assuming $w = -1$ (Riess et al. 1998; Perlmutter et al. 1999a).
[c]*WMAP* results combined with Tonry et al. 2003.
[d]Value based upon CMB, globular cluster ages, and current expansion rate (Oswald et al. 1996; Knox, Christensen, & Skordis 2001; Krauss & Chaboyer 2003).
[e]Mather et al. 1999.
[f]Combined analysis of four CMB measurements (Sievers et al. 2003).
[g]Combined analysis of CMB, BBN, H_0, and cluster baryon fraction (Turner 2002).
[h]Lower limit from SuperKamiokande measurements (Fukuda et al. 1998); upper limit from structure formation (Elgarøy et al. 2002).
[i]Supernova measurements, CMB, and large-scale structure (Perlmutter, Turner, & White 1999b).
[j]Contribution of density perturbations to the variance of the CMB quadrupole (with $T = 0$) (Gorski et al. 1996).
[k]Contribution of gravity waves to the variance of the CMB quadrupole (upper limit) (Kinney, Melchiorri, & Riotto 2001).
[l]Variance in values reported is larger than the estimated errors; adopted error reflects this (Lahav et al. 2002).
[m]Deviation of the scalar perturbations from a pure power law (Lewis & Bridle 2002).

but also its accurate determination is needed to take full advantage of increasingly precise measurements of other cosmological quantities.

Determining an accurate value for H_0 was one of the motivating reasons for building the *HST*, and the goal of 10% accuracy for H_0 was designated as one of three “Key Projects.”

Determining H_0 accurately requires the measurement of distances far enough away that both the small- and large-scale motions of galaxies can be neglected compared to the overall Hubble expansion. The H_0 Key Project provided a Cepheid calibration of a several distance methods, averaging over the systematics of any one method (Freedman et al. 2001).*

Calibrating five secondary methods with Cepheid distances, Freedman et al. (2001) determined a value of $H_0 = 72 \pm 3\,(\mathrm{stat}) \pm 7\,(\mathrm{sys})$ km s^{-1} Mpc^{-1}. Four of the methods yield a value of H_0 between 70 and 72 km s^{-1} Mpc^{-1}, while the fundamental plane gives $H_0 = 82$ km s^{-1} Mpc^{-1}. Type Ia supernovae are the secondary method, which currently extends out to the greatest distances, about 400 Mpc. The measurements are shown in Figure 1.2.

The largest remaining sources of error result from uncertainties in the distance to the Large Magellanic Cloud, photometric calibration of the *HST* Wide Field and Planetary Camera 2, metallicity calibration of the Cepheid period-luminosity relation, and cosmic scatter in the density (and therefore, velocity) field that could lead to observed variations in H_0 on very large scales. These sources of error are what contribute to the systematic uncertainty quoted above.

An external check of the Cepheid distance scale is provided by a distance independently measured to the NGC 4258, a nearby spiral galaxy with an inner disk containing H_2O masers (Herrnstein et al. 1999). Both radial and transverse motions of the maser system have been measured. Assuming a circular, Keplerian model for the disk, Herrnstein et al. (1999) derive a distance to the galaxy of 7.2 ± 0.3 Mpc, with the error increasing to ± 0.5 Mpc allowing for systematic uncertainties in the model. Maoz et al. (1999) used *HST* to discover a sample of 15 Cepheids in NGC 4258. The maser distance is in very good agreement with the Cepheid distance of $7.8 \pm 0.3\,(\mathrm{stat}) \pm 0.5\,(\mathrm{sys})$ Mpc (Newman et al. 2001), and the metallicity-corrected distance of 8.0 Mpc.

At present, to within the uncertainties, there is broad agreement about the value of the Hubble constant, using completely independent techniques. The most recent applications of the Sunyaev-Zel'dovich (SZ) technique, based on two-dimensional interferometry SZ data for 41 well-observed clusters, as discussed by Reese (2004), yield $H_0 = 61 \pm 3\,(\mathrm{stat}) \pm 18\,(\mathrm{sys})$ km s^{-1} Mpc^{-1}. The systematic uncertainties are still large, but the near-term prospects for this method are improving rapidly as additional clusters are being observed, and higher-resolution X-ray and SZ data are becoming available.

A second method for measuring H_0 at very large distances, also independent of the need for any local calibration, comes from the measurement of time delays in gravitational lenses. As noted by Schechter (2001), the small numbers of well-determined time delays leave open dangers in making decisions about which lenses to include in an analysis or not. Based on three lenses, Schechter finds $H_0 = 62$ km s^{-1} Mpc^{-1}, dominated by a systematic error estimated to be of order 20 km s^{-1} Mpc^{-1}. Kochanek (2002), in an analysis of five lenses (one of which overlaps the sample of Schechter) finds $H_0 = 51 \pm 5$(stat) km s^{-1} Mpc^{-1} for models with flat rotation curves, and $H_0 = 73 \pm 8$(stat) km s^{-1} Mpc^{-1} for models with constant mass-to-light ratios. Kochanek & Schechter (2004) report values of $H_0 = 48 \pm 3$(stat) km s^{-1} Mpc^{-1}, and $H_0 = 71 \pm 3$(stat) km s^{-1} Mpc^{-1} for the same two classes of models, based on four lenses that can be modeled by a single galaxy (and are not members of groups or clusters). The numbers of suitable lenses for this kind of analysis should increase in the near future. A

* The Cepheid positions, magnitudes, and periods for each of the 18 galaxies observed as part of the Key Project are available at: `http://www.ipac.caltech.edu/H0kp/H0KeyProj.html`.

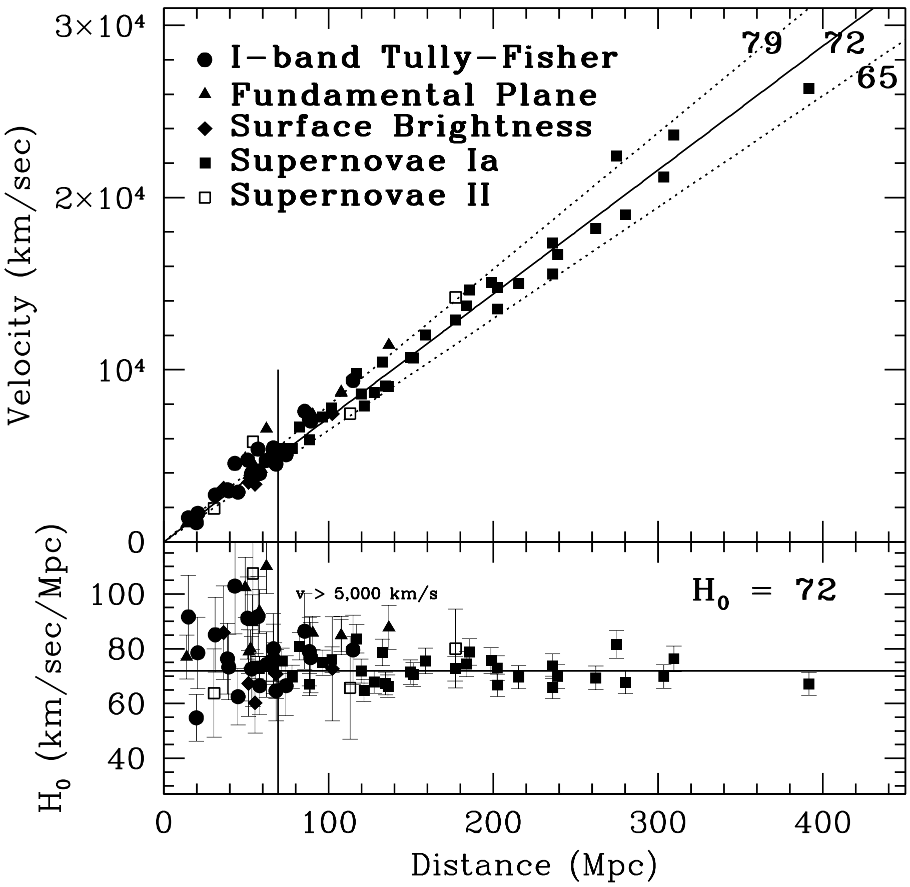

Fig. 1.2. Composite Hubble diagram of velocity versus distance. The Cepheid distances are calibrated relative to a distance to the Large Magellanic Cloud of 50 kpc. The consistency of the five different distance indicators is shown. The lower panel shows the value of the Hubble constant object by object and the convergence to 72 km s^{-1} Mpc^{-1}. The scatter at distances less than 100 Mpc arises due to gravitationally induced "peculiar velocities" that arise from the inhomogeneous distribution of matter.

long-term monitoring program is being undertaken by the Magellan consortium, using the 6.5-meter telescopes at Las Campanas.

1.2.2 Age

The time back to the Big Bang depends upon H_0 and the expansion history, which itself depends upon the composition:

$$t_0 = \int_0^\infty \frac{dz}{(1+z)H(z)} = H_0^{-1} \int_0^\infty \frac{dz}{(1+z)[\Omega_m(1+z)^3 + \Omega_{DE}(1+z)^{3(1+w)}]^{1/2}} \quad , \qquad (1.1)$$

where $\Omega_m = \Omega_{CDM} + \Omega_b + \Omega_\nu$ is the total mass density. For a Universe with a Hubble constant of 72 km s^{-1} Mpc^{-1}, $\Omega_m = 1/3$, and $\Omega_{DE} = 2/3$, the time back to the Big Bang is 13 Gyr. Taking account of the uncertainties in H_0 and in the composition, the uncertainty in the age of the Universe is estimated to be about ± 1.5 Gyr. The expansion age can also be determined from CMB anisotropy, but without recourse to H_0, and it gives a consistent age, $t_0 = 14 \pm 0.5$ Gyr (Knox et al. 2001).

The expansion age can also be checked for consistency against other cosmic clocks. For example, the best estimates of the age of the oldest stars in the Universe are obtained from globular clusters. Detailed computer models of stellar evolution matched to observations of globular cluster stars yield ages of about 12.5 billion years, with an uncertainty of about 1.5 Gyr (Krauss & Chaboyer 2002). These estimates are also in good agreement with other methods that independently measure the rates of cooling of the oldest white dwarf stars, and techniques that use various radioactive elements as cosmic chronometers (Oswald et al. 1996). Finally, with the assumption that $w = -1$, the Type Ia supernova data can constrain the product of the age and Hubble constant independent of either quantity, $H_0 t_0 = 0.96 \pm 0.04$ (Tonry et al. 2003). This is consistent with the product of the two quantities, $(H_0 = 72 \pm 7\,\mathrm{km\,s^{-1}\,Mpc^{-1}}) \times (t_0 = 13 \pm 1.5\,\mathrm{Gyr}) = 0.96 \pm 0.16$.

In summary, all the ages are consistent with a consensus age of 13 ± 1.5 Gyr.

1.2.3 Baryon Density

Both the CMB and BBN provide the means for a high-precision measurement of the baryon density. However, they are based upon very different physics: nuclear reactions occurring when the Universe was seconds old (BBN) and gravity-driven acoustic oscillations in the baryon-photon fluid when the Universe was 400,000 yr old (CMB).

The amount of deuterium synthesized in the Big Bang is very sensitive to the baryon density, $(\mathrm{D/H})_p \propto \rho_b^{-1.7}$, and thus a measurement of its primordial abundance can accurately pin down ρ_b. The detection of deuterium Lyman absorption features in six high-redshift ($z \approx 2-4$) quasars (O'Meara et al. 2001; Kirkman et al. 2004) has led to a consistent estimate for the primeval deuterium abundance of $(\mathrm{D/H})_p = 3.0 \pm 0.2 \times 10^{-5}$. Using the most up-to-date calculations of the light-element abundances, this deuterium abundance implies a baryon density, $\rho_b = 3.8 \pm 0.2 \times 10^{-31}\,\mathrm{g\,cm^{-3}}$, or equivalently, $\Omega_b h^2 = 0.02 \pm 0.001$ (Burles, Nollett, & Turner 2001).

The ratio of the heights of the odd to even acoustic peaks in the CMB angular power spectrum depends upon the baryon density. This is a distinctive feature in the CMB power spectrum: the dependence upon peak heights of most other parameters is monotonic. Four experiments—two using microwave interferometers and two using bolometric receivers—have now resolved the first three acoustic peaks (BOOMERanG, MAXIMA, DASI, and CBI). The combined measurements from these experiments are consistent with a baryon density of $\Omega_b h^2 = 0.022 \pm 0.003$ (Sievers et al. 2003).

The BBN and CMB numbers are consistent and point strongly to a low baryon density. The agreement of these two numbers not only makes the case for a low baryon density (inserting the Hubble constant implies $\Omega_b = 0.04 \pm 0.008$), but also speaks to the consistency of the entire cosmological framework, from general relativity and the FRW model to nuclear physics in the early Universe.

Finally, the net absorption of light emitted from very distant quasars by intervening gas, which exists largely in the Lyα forest, provides a third independent accounting of baryons, at a much lower redshift, $z \approx 3-4$ vs. $z \approx 10^{10}$ for BBN and $z \approx 10^{3}$ for CMB. While additional assumptions must be made (the CDM paradigm to simulate the distribution of clouds, and a lower limit to the flux of ionizing radiation), the result is consistent (McDonald et al. 2001):

$$\Omega_{\mathrm{b}} h^2 > 0.017 \left[\Omega_{\mathrm{m}} h^2/(0.3)(0.65)^2\right]^{1/4} \Gamma_{-12}^{1/2} \quad , \tag{1.2}$$

where Γ_{-12} is the photoionization rate in units of $10^{-12}\,\mathrm{s}^{-1}$.

What is still lacking is a robust accounting of baryons today; only a small fraction of the baryons are "visible" in the form of stars (about 15%); most are unaccounted for, most likely existing in the form of hot gas somewhere—the intergalactic medium, extended halos, small groups (see, e.g., Fukugita, Hogan, & Peebles 1998).

1.2.4 Matter Density

Determining the mean density of matter in the Universe is a formidable task that has challenged astronomers for almost as long as the Hubble constant has. Because there is inhomogeneity in the distribution of matter on scales approaching 30 Mpc, the matter density must be probed on scales larger than this, for example, using the mass-to-light ratio technique:

$$\langle \rho_{\mathrm{m}} \rangle = \langle M/L \rangle \, \mathcal{L} \tag{1.3}$$

(see Bahcall, Lubin, & Dorman 1995). However, there remain a number of difficulties inherent in this approach. (1) Mass-to-light ratios for field spirals, which are more representative of the mean galaxy, provide only a lower limit to the mean density because halo mass measurements have yet to converge. (2) While cluster mass-to-light ratios do not suffer from this problem, the typical galaxy is not found in a cluster. And (3) determining the mean luminosity density is difficult and subject to evolutionary effects.

The recent consensus for a value for the matter density and a lower uncertainty, $\Omega_{\mathrm{m}} = 0.3 \pm 0.04$, has resulted from a new approach (Turner 2002; Sievers et al. 2003). The new and previous results agree quite well within their quoted uncertainties. In this new approach, the key inputs are physical parameters that do not depend upon any assumed relationship between mass and light: $\Omega_{\mathrm{m}} h^2$ and $\Omega_{\mathrm{b}} h^2$, deduced from CMB anisotropy measurements; $\Omega_{\mathrm{b}} h^2$, determined from BBN; $\Omega_{\mathrm{m}} h$, determined from the shape of the power spectrum of matter inhomogeneity; and $\Omega_{\mathrm{m}}/\Omega_{\mathrm{b}}$, determined from cluster measurements assuming that they provide a fair sample of baryonic and nonbaryonic matter.

It is straightforward to see how these measurements determine Ω_{m} and Ω_{b}. The CMB and cluster measurements fix the matter-to-baryon ratio, $\Omega_{\mathrm{m}}/\Omega_{\mathrm{b}} = 7.2 \pm 2$ (CMB, pre-*WMAP*) and 9 ± 1.5 (clusters). The value for $\Omega_{\mathrm{b}} h^2$ (from CMB and BBN) and H_0 fixes $\Omega_{\mathrm{b}} = 0.04 \pm 0.008$; Ω_{b}, together with the matter-to-baryon ratio, then fixes $\Omega_{\mathrm{m}} = 0.3 \pm 0.04$.

The reliability of this determination of the matter density is tied to the consistency of the input values for $\Omega_{\mathrm{m}}/\Omega_{\mathrm{b}}$ (CMB and clusters), $\Omega_{\mathrm{b}} h^2$ (BBN and CMB), and H_0 (the various methods discussed above). This simple chain of reasoning and consistent set of measurements of physical parameters make the case that the mean matter density has finally been determined.

1.2.5 CMB Anisotropy

The anisotropy of the CMB arises due to the inhomogeneous distribution of matter and provides a snapshot of the Universe at an earlier, simpler time (redshift 1100 and

400,000 yr after the Big Bang). The temperature is determined to four significant figures, 2.725 ± 0.001 K, and deviations from a Planckian spectrum are constrained to be less than 0.01% (Mather et al. 1999). Encoded in the small (0.001%) variations in temperature across the sky (anisotropy) is a wealth of information about the Universe, past, present, and future. Since the discovery of CMB anisotropy in 1992 by the DMR instrument on the *COBE* satellite (Smoot et al. 1992) with its 7° angular resolution and signal-to-noise ratio per pixel of order unity, a host of ground- and balloon-based experiments have been improving both the precision and angular resolution of CMB measurements. The angular (spherical harmonic multipole) power spectrum now extends to $\ell \approx 3000$ (*COBE* probed to $\ell \approx 20$), with each multipole region measured by two or more independent experiments with consistent results; see Figure 1.3. Not only are the same regions of the spectrum probed by different experiments, but also by different techniques (microwave interferometers operating at 30 GHz vs. bolometric receivers operating at frequencies above 100 GHz).

Among the conclusions inferred from the CMB are:

- Spatial flatness of the Universe as indicated by the position of the first acoustic peak ($\ell \simeq 220$), $\Omega_0 = 1.03 \pm 0.03$.
- Low baryon density as indicated by the ratio of the first to second acoustic peaks, $\Omega_b h^2 = 0.022^{+0.004}_{-0.003}$.
- Total matter density, $\Omega_m h^2 = 0.16 \pm 0.04$, as indicated by the heights of the acoustic peaks, which exceeds the baryon density by a factor of 7.
- Independent evidence for dark energy based upon the factor of 3 discrepancy between Ω_m and Ω_0.
- Adiabatic density perturbations, as indicated by the existence of acoustic peaks, with near scale invariance, $n = 1.05 \pm 0.09$.
- Hubble constant ($h = 0.71^{+0.04}_{-0.03}$) and age (13.7 ± 0.2 Gyr) consistent with other independent measurements (these are both *WMAP* results).

1.2.6 Inflationary Beginning

Inflation has been the single most important idea in cosmology for the past 20 years. Twenty years ago there was skepticism about testing inflation, especially in the absence of a standard model. However, over the past five years evidence for inflation has mounted.

While there is no standard model of inflation, inflation makes three basic predictions (Turner 1997):

- Spatially flat Universe (i.e., $\Omega_0 = 1$).
- Nearly scale-invariant spectrum of Gaussian, adiabatic density perturbations.
- Nearly scale-invariant spectrum of gravitational waves.

The evidence for flatness comes from the measurements of CMB anisotropy mentioned above ($\Omega_0 = 1.03 \pm 0.03$) and an independent cosmic inventory of material that adds to the critical density: $(\Omega_m \simeq 1/3) + (\Omega_{DE} \simeq 2/3) = 1$. The discovery of cosmic acceleration provided an important (and successful) test of inflation: before that time, firm estimates for the matter density were falling a factor of 3 short of the critical density, and dark energy suddenly filled the gap.

The second prediction leads to a series of tests: the existence of the harmonically spaced

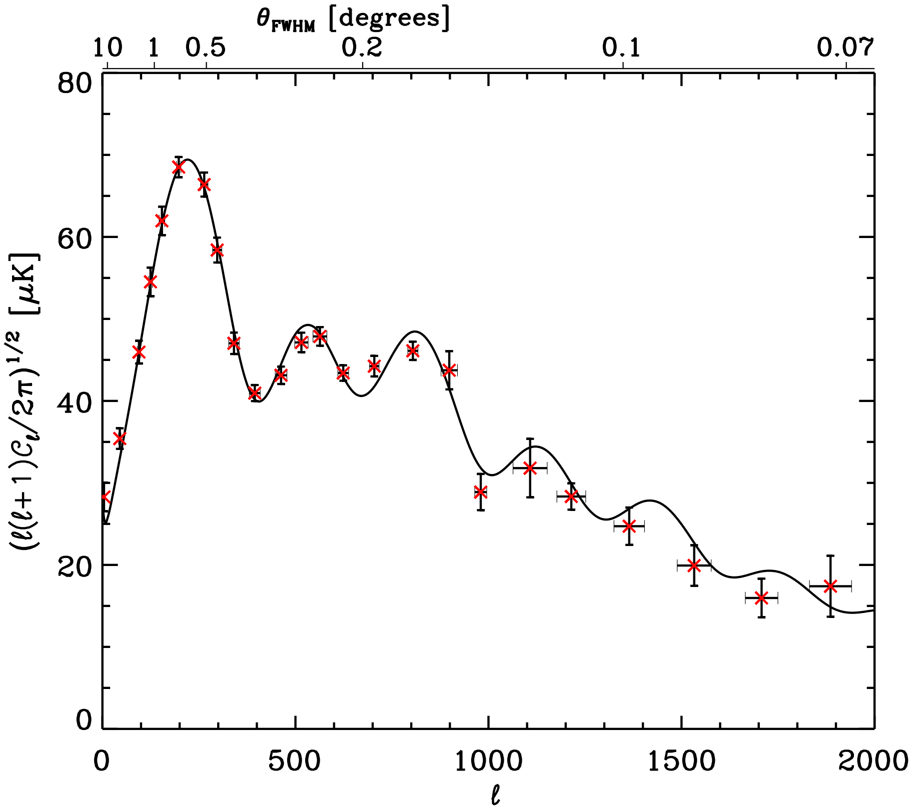

Fig. 1.3. Angular power spectrum of the CMB, incorporating all the pre-*WMAP* data (*COBE*, BOOMERanG, MAXIMA, DASI, CBI, ACBAR, FIRS, VSA, and other experiments). Variance of the multipole amplitude is plotted against multiple number; as indicated by the top scale, multipole ℓ measures the fluctuations on angular scale $\theta \approx 200°/\ell$. Evidence of the baryon-photon oscillations can be seen as the distinct "acoustic peaks." The theoretical curve is the consensus cosmological model. (Figure courtesy of C. Lineweaver.)

acoustic peaks associated with adiabatic perturbations; spectrum characterized by power-law index $n = 1 \pm \mathcal{O}(0.1)$ and slow variation $dn/d\ln k \approx \mathcal{O}(10^{-3})$; and density perturbations with Gaussian statistics. The angular power spectrum of CMB anisotropy (discussed above) provides evidence for at least three acoustic peaks, has determined $n = 1.05 \pm 0.09$ and $dn/d\ln k = -0.02 \pm 0.04$, and shown that the underlying density perturbations are consistent with being Gaussian. The data are consistent with the four tests of inflation associated with the prediction of density perturbations produced from quantum fluctuations (see Fig. 1.4).

In addition, the density perturbations predicted by inflation, together with the prediction of a flat Universe, gave rise to the CDM scenario for structure formation (see, e.g., Blumenthal et al. 1984). A host of cosmological observations, from measurements of large-scale

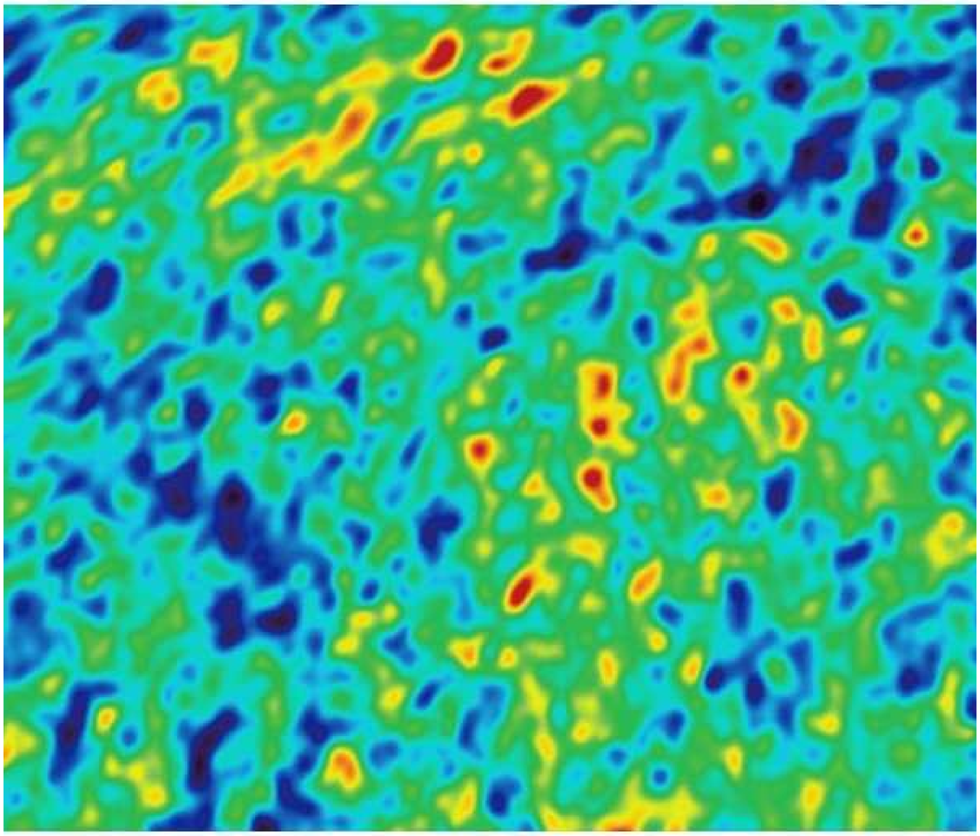

Fig. 1.4. Small portion of the CMB sky as measured by *WMAP*; for reference, the size of the typical hot/cold spots is of order 1°. According to inflation, this image is quantum noise on length scales $\ll 10^{-17}$ cm blown up in size by the expansion of the Universe during inflation and thereafter.

structure to the sequence of structure formation (galaxies first, clusters next, etc.) to the distribution of the masses of clusters and galaxies, have tested the CDM scenario (see, e.g., Primack 2001). CDM is consistent with a large body of diverse observations, and today most would agree that it plays an important role in structure formation. Shown in Figure 1.5 is a comparison of the predicted CDM power spectrum of density inhomogeneity today with that determined from a variety of observations.

The third basic inflationary prediction—an almost scale-invariant spectrum of gravitational waves—remains untested, and is one of the biggest challenges in cosmology. Like the amplitude of the density perturbations, there is no firm prediction for the amplitude of the gravitational wave spectrum. However, unlike density perturbations, where the existence of structure today leads to a prediction for the required amplitude, there is no phenomenologi-

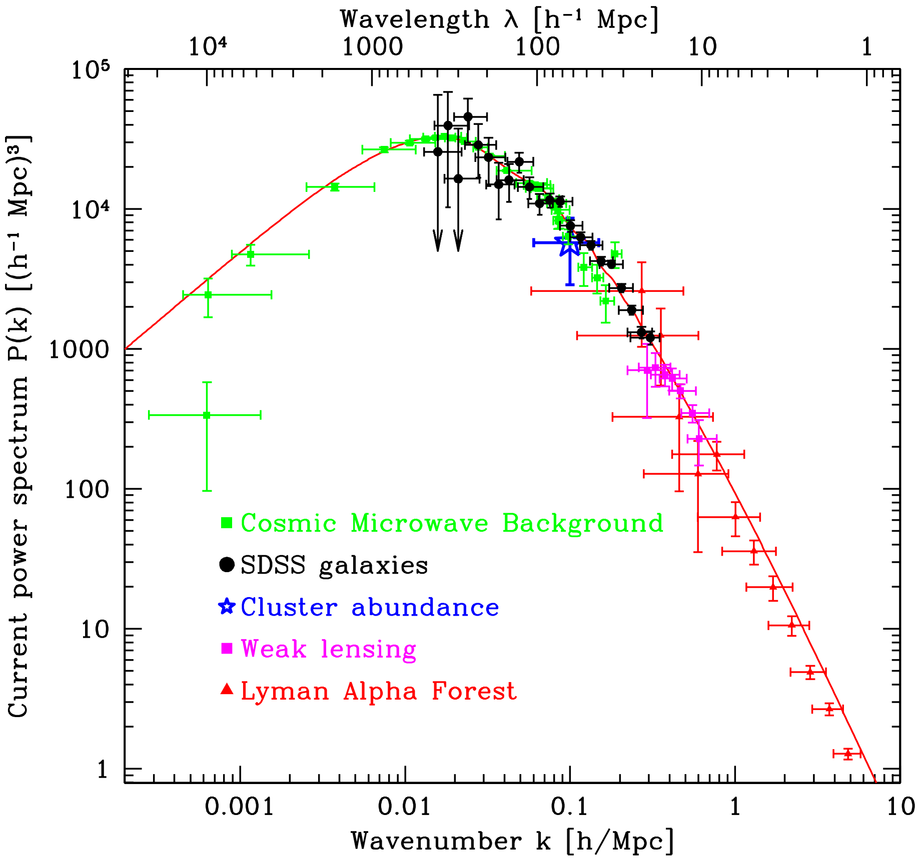

Fig. 1.5. Power spectrum of density inhomogeneity today obtained from a variety of measurements, including large-scale structure, CMB, weak lensing, rich clusters, and the Lyα forest. The curve is the theoretical prediction for the consensus cosmology model. (From Tegmark et al. 2004.)

cal prediction. Detecting the inflation-produced gravitational waves would not only confirm the third basic prediction, but would also reveal when inflation took place as the amplitude is tied directly to the energy scale of inflation.

1.2.7 Cosmic Acceleration and Dark Energy

Two independent lines of evidence lead to the remarkable conclusion that the expansion of the Universe is speeding up, not slowing down. The first, as reviewed by Filippenko (2004), is the direct evidence from Type Ia supernovae. That, too, involves two independent (and very competitive) groups whose results agree: the deceleration parameter is negative (Riess et al. 1998; Perlmutter et al. 1999a; Tonry et al. 2003). Megapixel CCDs

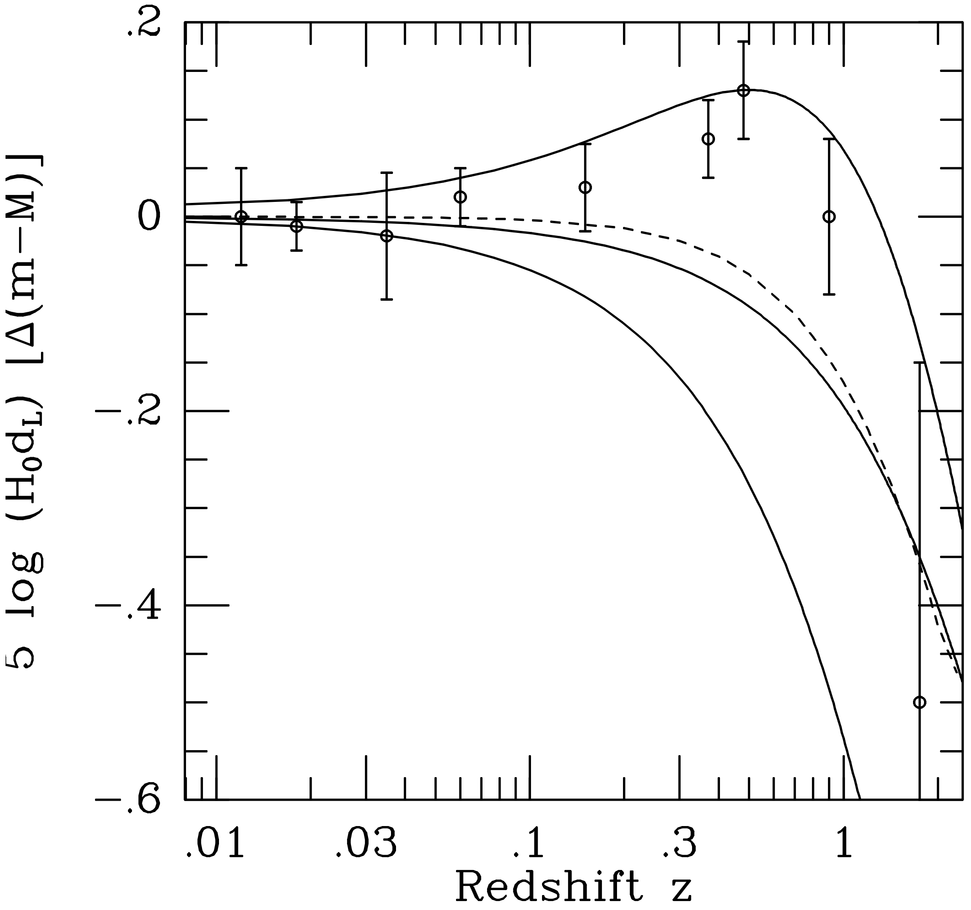

Fig. 1.6. Differential Hubble diagram adapted from Tonry et al. (2003). Data for 200 Type Ia supernovae are binned into 9 points, and shown relative to models with $\Omega_\Lambda = 0.7$, $\Omega_\mathrm{m} = 0.3$; $\Omega_\Lambda = 0$, $\Omega_\mathrm{m} = 0.3$; and $\Omega_\Lambda = 0$, $\Omega_\mathrm{m} = 1$ (top to bottom). The broken curve represents a flat, coasting universe, i.e., $q = 0$ for all z.

and pre-planned scheduling of telescopes for the discovery and follow-up spectroscopy have enabled the discovery of Type Ia supernovae over the redshift interval from zero to beyond one, and data for over 200 supernovae have now been published (see Fig.1.6), and a number of ambitious projects hope to increase this by a factor of a several over the next five years. No evidence for serious systematic effects (for example, the presence of grey dust or evolution of supernovae) has been uncovered, though numerous tests have been carried out. The most recent study indicates that if the equation of state of the dark energy is $w = -1$ (vacuum energy/cosmological constant), then $\Omega_\Lambda - 1.4\Omega_\mathrm{m} = 0.35 \pm 0.14$. Further, if a flat universe is assumed, this yields $\Omega_\mathrm{m} = 0.28 \pm 0.06$ and $\Omega_\Lambda = 0.72 \pm 0.06$ (Tonry et al. 2003).

As noted above, the second line of evidence involves the CMB. The position of the first acoustic peak indicates that the total amount of matter and energy is equal to the critical density ($\Omega_0 = 1.03 \pm 0.03$), while the CMB and (other methods) indicate that the amount of that in matter is only about 1/3, leaving 2/3 unaccounted for. In order not to have been "noticed" this additional component must be unclustered, and in order not to interfere with the formation of structure it must evolve much more slowly than matter, which implies a large negative pressure, $p \leq -\rho/2$ ($\rho \propto R^{-3(1+w)}$ where $w = p/\rho$) (Turner 2000). [The argument is a simple one: small density fluctuations only grow during the matter-dominated era; the ratio of dark matter to dark energy in the past grows as $(1+z)^{-3w}$; thus, the more negative the pressure is, the more recent the matter-dominated era ended.]

1.3 The Big Questions

While the new cosmology describes the basic features of the Universe, it does not provide a coherent picture complete with a physical basis. It does frame big questions for cosmologists to answer, questions that involve both astrophysics and particle physics and accelerators and telescopes.

What is the dark matter?

An extremely solid case exists for the bulk of the dark matter not being made of neutrons and protons, but rather being made of a new form of stable (or long-lived) matter. Evidence for neutrino mass has validated this hypothesis, though neutrinos provide only a small fraction of the dark matter ($\Omega_\nu \simeq 0.001 - 0.05$). Finishing the neutrino story will involve laboratory and accelerator experiments. Identifying the nature of the bulk of the dark matter is not only of importance to cosmologists, but also to particle physicists as the two leading candidates, the neutralino and the axion, have deep implications for particle physics (see, e.g., Sadoulet 1999).

The neutralino is the lightest of a new class of particles, the supersymmetric partners of the ordinary particles. The existence of the axion would solve a nagging and profound problem with quantum chromodynamics, the theory of how quarks and gluons interact. Detection schemes for the neutralino illustrate how astrophysics and particles are deeply connected: production at an accelerator (Tevatron at FNAL or LHC at CERN); direct detection of neutralinos that comprise the halo of the Milky Way; detection of the annihilation products of neutralinos in the halo (positrons, gamma-rays, and antiprotons) or in the Sun and Earth (high-energy neutrinos).

What is dark energy and what is the destiny of the Universe?

At present there is no compelling explanation for cosmic acceleration. It could be due to a diffuse dark energy with large negative pressure ($p \leq -\rho/3$) or an indication of the breakdown of general relativity and evidence for new gravitational physics. The connections to fundamental physics are strong: the energy of the quantum vacuum has just the right property—large, negative pressure ($p = -\rho$)—to explain cosmic acceleration. However, at the same, it raises three questions:

- Why is the energy associated with the quantum vacuum at least 55 orders of magnitude smaller than any estimate for it?
- If it is vacuum energy, what is the explanation for the fact that its energy density is small, but not zero?
- If quantum vacuum energy is too small to explain cosmic acceleration, what does?

Then too there is the question of why the acceleration began so recently, and when and if it will end. Since the primary effect of dark energy is upon the expansion rate of the Universe, telescopes that probe the past expansion history by measuring supernova light curves, measuring the growth of structure, and counting galaxies and clusters will play the leading role in shedding light on dark energy.

Where did the baryons come from?

Even the origin of the matter we are made of is still a mystery. To ensure the existence of quark-based matter today, there must be an asymmetry between quarks and antiquarks of a few parts per billion at times earlier than about 10 microseconds (in a baryon symmetric universe, quarks and antiquarks annihilate to a negligible level when the Universe is 10 microseconds old). This asymmetry can arise through nonequilibrium baryon-number and CP-violating interactions in the early Universe (baryogenesis). One possibility is that the needed asymmetry begins as an excess of neutrinos over antineutrinos, which arises early on through neutrino interactions that involve neutrino mass and neutrino CP violation, and later, nonperturbative electroweak processes that violate both baryon and lepton number transmute the neutrino asymmetry into a baryon asymmetry. Further understanding of CP violation and physics beyond the standard model of particle physics is needed, for which accelerators are required.

When did inflation take place? What are future tests of inflation?

The CMB radiation has provided the first solid evidence for inflation and is consistent with its first two basic predictions, spatial flatness and almost scale-invariant, adiabatic density perturbations. Additional measurements of CMB anisotropy will sharpen these tests by a factor of 30 or so, for example by determining Ω_0 and n to 0.1% precision. The biggest test involves detecting the signature of the gravitational waves produced by inflation. Unfortunately, there is no firm prediction for the amplitude (though it has been argued that the contribution of gravity waves to the quadruple anisotropy of the CMB is at least 10^{-3} that of density perturbations; Hoffman & Turner 2001). However, if detected they would not only confirm the third basic prediction of inflation, but also immediately reveal the time when inflation took place. There are two basic ways of getting at the gravity waves: direct detection and through their imprint on CMB anisotropy, especially their polarization signature. Neither the LIGO nor *LISA* detectors will have sufficient sensitivity to reach the level predicted by standard inflationary models (Turner 1997)—but maybe we will be pleasantly surprised. For now, CMB anisotropy offers the most promise, especially the possibility of a satellite to follow *WMAP/Planck* dedicated to CMB polarization. Knox & Song (2002) estimate that the gravity wave polarization signature can be detected if its contribution to the CMB quadrupole is at least 5×10^{-4} that of density perturbations.

How did the Universe begin?

When inflation was proposed over 20 years ago it appeared revolutionary, solving the vexing horizon, flatness, and monopole problems, as well as explaining the origin of the perturbations that seeded all structure in the Universe. With the advent of superstring/M-theory, which holds the promise of unifying the forces and particles as well as a quantum description of gravity, expectations have risen. In particular, inflation does nothing to address the problem of the initial singularity of Big Bang cosmology. Addressing the Big Bang singularity is critical to both having a complete model of cosmology as well as getting at how the Universe began. There have been some small steps toward tackling this tall issue, such as the brane world scenarios now being studied (see, e.g., Lykken 2001; Rubakov 2001; or Steinhardt & Turok 2002).

Does general relativity provide an accurate description of the Universe?

One of the side benefits of a set of interlocking and precision cosmological measurements is that the consistency of the underlying assumptions can be tested. There is no bigger assumption in cosmology than that of the validity of general relativity to describe the Universe across billions of years in time and billions of light years in space. Over the next decade, precision measurements will create many opportunities to test general relativity in completely new ways.

The baryon density is an example of things to come. We now have two precision measurements: the first based on the abundance of deuterium and nuclear physics when the Universe was seconds old ($\Omega_b h^2 = 0.020 \pm 0.001$), and the second based upon the anisotropy of the CMB and gravitational physics when the Universe was 400,000 years old ($\Omega_b h^2 = 0.022^{+0.004}_{-0.003}$). Both measurements assume the validity of general relativity and its prediction for the expansion rate of the Universe. The agreement between these two numbers test general relativity in a completely new regime. We can expect more such tests of gravity theory as well as other physics.

1.4 Astrophysical Cosmology

While the connections between the largest and the smallest scales in Nature largely involve the underlying cosmological model and the earliest moments of creation, cosmology is more than simply determining and understanding the cosmological model. It also encompasses reconstructing the evolution that got us here and addressing the future. Once the cosmological model is fixed, the study of evolution, be it of galaxies or baryons, becomes simpler. Just a simple example; at fixed redshift, with fixed H_0, the age of a flat ($\Omega_\Lambda = 0.7$) Universe and an Einstein-de Sitter universe differ by almost a factor of 2. The emergence of a consistent set of accurate ($\pm 10\%$) cosmological parameters has greatly simplified the astrophysical cosmology problem by fixing the cosmology.

An important aspect of inflation is that it provides not only a means of resolving a number of cosmological issues, but also a natural framework for understanding the growth of structure in the Universe: the CDM paradigm. Numerical simulations, currently with billions of particles, yield power spectra for the large-scale distribution of galaxies that are quantitatively consistent with the SDSS and 2dF galaxy survey data (see, e.g., Dodelson et al. 2001; Tegmark, Hamilton, & Xu 2002). In these models, galaxy formation proceeds hierarchically, with baryons and CDM assembling into galaxies, and over time, the great walls and clusters and filaments we observe today. Deep *HST* observations, revealing the changing morphology of galaxies at different redshifts, and detailed kinematics and chemical abundance analyses of stars within the halo of the Milky Way are consistent with a picture of galaxies undergoing significant evolution, and with frequent mergers and larger galaxies accreting smaller galaxies over time.

These simulations provide an excellent match for a flat universe in which most of the mass is cold and dark, and which today is dominated by a dark energy component; see Figure 1.7. More complicated than the dark matter particles, for which only gravity is important, is the incorporation of the additional astrophysics governing the baryons: gas dynamics,

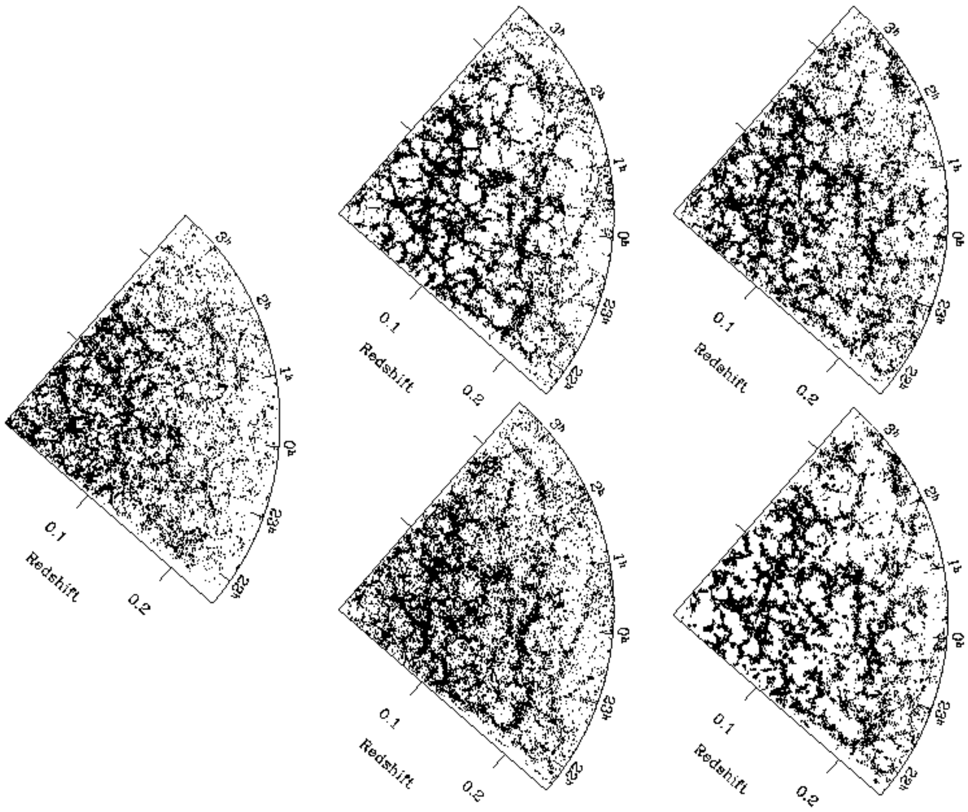

Fig. 1.7. The large-scale distribution of galaxies determined from the 2dF Galaxy Redshift Survey and mock catalogs from numerical simulations of CDM. (Figure courtesy of the 2dF collaboration.)

the formation of molecules, their destruction and cooling, radiative transfer, star formation, heating, and feedback. Models are becoming increasingly sophisticated in their treatment of these processes—and this must continue—because current and future observations are, and will continue to be, critical in providing constraints on these models.

At the moment, we know little empirically about the epoch between a redshift of about 1100, the surface of last scattering of the CMB, and a redshift of just greater than 6, where the most distant SDSS quasars have been discovered. Astrophysically speaking, much happened between then and now and a tremendous amount remains to be learned: What were the first stars to form and in what systems did they form? How did they affect their environment and the subsequent generation of stars? How did the billion-solar-mass black holes that power the high-redshift quasars form? How did the chemical elements build up? How did clusters form and evolve? Where are the bulk of the baryons? What processes led to the Hubble sequence of galaxies? What was the ionization history of the Universe? The list goes on.

Whether a fuller understanding of the cosmological framework and its connections to fundamental physics comes sooner or later, there is much still to be learned about the evolution of the astrophysical Universe.

1.5 Looking Forward: A Bright Future

The questions before us are grand and cut across both physics and astronomy. But so are the tools we have to answer them. An impressive array of new ground-based telescopes, space-based missions, and accelerator and laboratory-based experiments will soon be tackling today's big questions.

Accelerators and laboratory experiments will help solve the riddle of dark matter and the origin of ordinary matter. Advances in theory promise to put the whole picture together. The precision in cosmological parameters will improve as subsequent years of *WMAP* data are accumulated, as ground-based supernova, gravitational lens, and SZ surveys are expanded, and with the construction of the Large Synoptic Survey Telescope (LSST), the launch of ESA's *Planck* mission, and the launch of the *Supernova Acceleration Probe (SNAP)* satellite.

Our knowledge of astrophysical cosmology and insight into the reionization epoch and galaxy formation will increase dramatically with the building of the Atacama Large Millimeter Array (ALMA) and giant (20 to 30-meter class) optical telescopes, and in space as observations begin to be made by the *Space Infrared Telescope Facility (SIRTF)* and when the *James Webb Space Telescope (JWST)* is launched. *Constellation X* will open a window on the first clusters to form and on black holes. Much will be learned about the epoch of reionization from the LOw Frequency ARray (LOFAR) to measure inhomogeneities in the 21 cm neutral hydrogen density distribution at high redshift ($z > 10$), and from the Square Kilometer Array (SKA) at redshifts $z < 10$.

One hundred years ago the Carnegie Institution of Washington launched a revolution in cosmology by taking astronomy high into the mountains of California. Today, that revolution continues, with ground- and space-based telescopes operating across the electromagnetic spectrum; with neutrino, cosmic ray and gravity wave detectors monitoring the heavens; and with accelerators and laboratory experiments teaching us about cosmological physics. The future of cosmology on the occasion of the Carnegie Centennial appears very bright indeed.

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1.6 Addendum: *WMAP*

About two months after the Carnegie Symposium, the *Microwave Anisotropy Probe* team presented the results of the first year of data from their all-sky, five-channel CMB anisotropy measurements.* Details about *WMAP* are reported more extensively in by Ben-

* At the same time, NASA announced that the satellite had been renamed the *Wilkinson Microwave Anisotropy Probe* or *WMAP*, in honor of David Wilkinson, who spent his entire career designing and carrying out experiments to study the CMB, including both *COBE* and *MAP*, as well as training the majority of scientists working on the CMB.

nett et al. (2003) and Page (2004); we discuss the *WMAP* results here briefly in the context of this review.

The hallmarks of *WMAP* are all-sky coverage and control of systematics (at present, to better than 0.5%). The *WMAP* angular power spectrum is consistent with the composite compiled from previous experiments (BOOMERanG, DASI, VSA, CBI, ACBAR, and *COBE*), but with systematic uncertainties in the absolute temperature scale and much less sky coverage. The panoply of cosmological parameters determined by *WMAP* are consistent with previous determinations, but with smaller error bars. For example, $\Omega_0 = 1.02 \pm 0.02$, $\Omega_b h^2 = 0.0224 \pm 0.0009$, $n = 0.93 \pm 0.03$, and age $t_0 = 13.7 \pm 0.2\,\mathrm{Gyr}$ (assuming a flat universe and $w = -1$). The consistency speaks volumes about the maturing of cosmology and the robustness of the basic model, and the diminishing error bar and control over systematics bodes well for the future with *Planck* and other experiments on the horizon.

There were two new results from *WMAP*: (1) the ruling out of the first model of inflation, Linde's original model of chaotic inflation, $V(\phi) = \lambda\phi^4$; and (2) the first evidence for the beginning of the reionization of the Universe, at a redshift $z = 20 \pm 10$, in the cross correlation between polarization and temperature anisotropy. The former illustrates the promise of future CMB anisotropy measurements to test inflation and inform us about the underlying physics. The latter result, consistent with what was expected for CDM, combined with the observation of the Gunn-Petersen trough in $z > 6$ quasars implies that the epoch of reionization began (ionized fraction of order 50% or so) around $z \approx 20$ and was complete (ionization fraction of 99.999%) by around $z \approx 6$.

As several cosmologists put it, the most surprising result from *WMAP* was the absence of a surprising result. This is further testimony to the fact that cosmology has reached a level of maturity where the basic features and parameters of the underlying model are supported by several measurements, each with different systematics and a reliable error estimate. However, this era of boring consistency probably will not last for long. Precision measurements raise the stakes as the opportunities for discrepancies increase. In the *WMAP* data there are some intriguing deviations: Both the quadrupole and octupole anisotropies are lower than expected (though the statistical significance is only about 2σ) and at higher values of ℓ there are low points and high points. With precision data, cosmological theories will be increasingly in danger!