New, large, ground and space telescopes are contributing to an exciting and rapid period of growth in observational cosmology. The subject is now far from its earlier days of being data-starved and unconstrained, and new data are fueling a healthy interplay between observations and experiment and theory. I report here on the status of measurements of a number of quantities of interest in cosmology: the expansion rate or Hubble constant, the total mass-energy density, the matter density, the cosmological constant or dark energy component, and the total optical background light.

1 General Background Cosmology and Assumptions

Based on the assumption that the universe is homogeneous and isotropic on large scales, the framework for modern cosmology rests on Einstein’s general theory of relativity, leading to the very successful hot big bang or Friedmann–Robertson–Walker cosmological model. The dynamics of the expanding universe are described by the Friedmann equation, relating the expansion rate to the density and curvature of the universe:

\[ H^2 = \frac{8\pi G \rho_m}{3} - \frac{k}{R^2} + \frac{\Lambda}{3} \]

where \( R(t) \) is the scale factor, \( H = \frac{\dot{R}}{R} \) is the Hubble parameter (and \( H_0 \) is the Hubble ‘constant’, the expansion rate at the present epoch), \( \rho_m \) is the average mass density, \( k \) is the curvature term, and \( \Lambda \) is the cosmological constant, a term which represents the energy density of the vacuum. However, as described in Section 3, the last term of the Friedmann equation may arise from a different form of dark energy parameterized by \( \Omega_X \), rather than a cosmological constant. Generally, the matter density is expressed as \( \Omega_m = \frac{8\pi G \rho_m}{3H_0^2} \) and the vacuum energy density as \( \Omega_\Lambda = \frac{\Lambda}{3H_0^2} \). The values of these parameters are not specified by the model, but must be determined experimentally.

Measurements of the cosmic microwave background (CMB) spectrum have provided evidence of isotropy on large scales at the thousandths of a percent level. But, until very recently, questions about the homogeneity of the universe on large scales have remained, primarily because of the discovery, in the 1980s, of unexpectedly large filaments, giant walls and voids – features having
dimensions up to the sizes of the survey volumes themselves (~200 Mpc). However, in the most recent generation of galaxy surveys (LCRS, SDSS, and 2DFGRS), which now extend six to more than an order of magnitude greater distances, out to redshifts of z~0.3, the largest observed structures no longer rival the observed survey volumes. What were for Einstein two convenient mathematical approximations, homogeneity and isotropy, are also apparently very good approximations to the real universe.

Preliminary results from 2DFGRS and SDSS are beginning to provide improved statistics on the shape of the galaxy power spectrum. The power spectrum, P(k), is the Fourier transform of the correlation function (which represents the probability of finding a pair of galaxies over a random distribution); k is the wave number. The power spectrum can be parameterized by the shape parameter, Γ ∼ Ω_m h, which characterizes the horizon scale at the time of matter and radiation equality. On small to intermediate scales, the observed power spectrum is well represented by a power law, but then turns over at larger scales. These recent, as well as earlier, surveys are consistent with a value of Γ ∼ 0.15–0.20. An important advance resulting from these new large surveys is that the scale range of the observed galaxy power spectrum is now beginning to overlap that in the CMB anisotropy measurements, which will offer an increasingly precise means of constraining a number of cosmological parameters.

2 The Total Matter/Energy Density

Currently, the determination of the total matter/energy density of the universe is most accurately achieved from measurements of the angular power spectrum of microwave background temperature anisotropies. Recent results from a number of independent groups working with either balloon or high-altitude mountain experiments are finding that the first acoustic peak in the angular power spectrum is located at a multipole value of l ∼ 210. This result is consistent with a value of Ω_{total} very near unity:

- **Boomerang**: 1.02 ± 0.06
- **DASI**: 1.04 ± 0.06
- **MAXIMA**: 0.94 ± 0.18

Under the assumption that the initial density fluctuations that gave rise to these temperature fluctuations are Gaussian and adiabatic, these results provide the most compelling evidence to date that we live in a flat (Ω_{total} = 1.0) universe. The data are no longer restricted to the first peak alone; there is solid evidence for additional peaks located at l ∼ 540 and 840. CBI has provided coverage over the range l = 400 to 1500, showing a predicted sharp
decrease in power at higher multipoles. All of these experiments are consistent with an adiabatic, cold dark matter (CDM) inflationary model with a power law initial perturbation spectrum index, $n_s$, close to 1. The next generation of polarization experiments will test this hypothesis further and yield information on the gravitational wave spectrum predicted by inflation.

3 The Cosmological Constant / Dark Energy

For several years, something has not been quite right in the state of cosmology. Until a few years ago, the “standard” cold dark matter (sCDM) model with $\Omega_m = 1$, $h (= H_0 / 100) = 0.5$, $\Omega_\Lambda = 0$ was the favored model. However, this model has been found to fall short in a number of very different ways. In numerical simulations, sCDM fails to produce the large-scale distribution of galaxies, producing too little power on large scales. The expansion ages derived for Hubble constants of 60 or more (most estimates in the recent literature) yield ages of less than 11 Gyr for $\Omega_m = 1$; these ages are lower than most estimates for the Galaxy, which range from 12 to 15 Gyr. And finally, measurements of the matter density (Section 4) have tended to yield values of only about 1/3 of the critical density.

All of these inconsistencies are removed by allowing a non-zero value for the cosmological constant, or more precisely, by having a flat universe with a contribution from some form of dark energy. Direct evidence for a current acceleration of the universe has come with the observation that supernovae at high redshifts are fainter than predicted by their redshifts, in comparison to their local counterparts. Although systematic effects due dust or differing chemical compositions could produce an observed difference between the high and low redshift supernovae, several tests have failed to turn up any such systematics. The resulting implication is that the universe is now undergoing an acceleration, and the data are consistent with $\Omega_m = 0.3$, $\Omega_X = 0.7$, assuming a flat universe, where $\Omega_X$ represents some form of dark energy having a large, negative pressure.

Although the CMB angular power spectrum contains information on $\Omega_X$, a direct determination of $\Omega_X$ is not possible from CMB measurements alone. This is due to intrinsic degeneracies among the cosmological parameters which allow models with the same matter content, but very different geometries. However, the position of the first peak in the CMB angular power spectrum, combined with large-scale structure data, can be used to break these degeneracies and are also consistent with $\Omega_X \sim 0.75$.

In future, it may be possible to measure the expansion rate as a function of redshift directly by measuring the displacement of individual Lyman α lines.
Figure 1: Predicted velocity shift in units of meters/second/century as a function of redshift for different cosmologies. Based on the calculations of Loeb (dashed: $\Omega_m = 1$, dotted: $\Omega_m = 0.3$, solid: $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$) for a value of $H_0$ of 70 km/sec/Mpc.

in quasar absorption spectra over a time baseline of a decade or so. The velocity shift is predicted to be at the level of only $\sim 2$ m/sec/century (see Figure 1), beyond current technical reach, but of interest for the next generation of 30–meter–class ground–based telescopes being planned for the next decade.

4 The Matter Density / Dark Matter

There are several completely independent routes to measuring the average matter density of the universe. In the past decade, increasingly strong evidence for dark matter has emerged, from a wide variety of independent studies. Only about 5% of the universe appears to be made of ordinary baryons. However, there is a strong consensus that the amount of dark matter falls well short of the critical density.

One of the most fundamental outstanding questions in cosmology is the nature of the dark matter. No one simple explanation is sufficient to explain all of the available data - that is, there appears to be more than one type of dark matter. There is dark matter in galaxies thought to be in the form of ordinary baryons whose form has not yet been identified, perhaps warm (100,000°K) gas or faint stellar remnants; there is cold, dark matter in clusters whose form has also not been identified, but which must be non–baryonic or else it would
violate big bang nucleosynthesis constraints; atmospheric neutrino experiments yield evidence for hot, non–baryonic dark matter in the form of neutrinos with a total mass density about equal to that in luminous stars ($\lesssim 1\%$ of the critical density); perhaps there is warm or self–interacting dark matter that might explain some of the observed properties of galaxies on small (galaxy) scales. And there is also the evidence that $70\%$ of the total mass/energy density of the universe is in a form of dark (vacuum) energy (Section 3).

Most recent estimates of the global matter density have used clusters of galaxies as probes of the matter distribution, assuming that clusters are large enough that they are representative of the overall average mass density. A number of independent techniques have been used for $\Omega_m$ estimates: cluster mass–to–light ratios, the baryon density in clusters both from x-ray and Sunyaev-Zeldovich measurements, the distortion of background galaxies behind clusters or weak lensing (also on supercluster scales of $\sim 3 \, h^{-1} \, \text{Mpc}$), and the existence of very massive clusters at high redshift. A widespread consensus has emerged that the apparent matter density appears to fall in the range $\Omega_m \sim 0.2-0.4$, at least on scales up to about $2h^{-1} \, \text{Mpc}$; i.e., only $\sim 20-40\%$ of the critical density required for a flat, $\Omega_{\text{total}} = 1$ universe.

5 The Hubble Constant

The Hubble constant, the current expansion rate of the universe, is one of the most critical parameters in big bang cosmology. Together with the energy density of the Universe, it sets the age, $t$, and the size of the observable Universe ($R_{\text{obs}} = ct$). The square of the Hubble constant relates the total energy density of the Universe to its geometry. The density of light elements (H, D, $^3\text{He}$, $^4\text{He}$, and Li) synthesized after the Big Bang also depends on the expansion rate. Determinations of mass, luminosity, energy density and other properties of galaxies and quasars require knowledge of the Hubble constant. In addition, the Hubble constant defines the critical density of the Universe ($\rho_{\text{crit}} = \frac{3H^2}{8\pi G}$). The critical density (and therefore $H$) further determines the epoch in the Universe at which the density of matter and radiation were equal. Hence, the growth of structure in the Universe is also dependent on the expansion rate. During the radiation era, growth of matter on small scales is suppressed – the turnover in the power spectrum corresponds to the point at which the Universe changes from radiation to matter dominated. This feature, set by the critical density, is used to normalize cosmic structure formation models.

For several decades, over a factor of two discrepancy has persisted in measurements of the Hubble constant spanning a range of about 40 to 100 km/sec/Mpc. Why has the measurement of $H_0$ been so difficult? It requires
Figure 2: Velocity versus distance for galaxies within 400 Mpc calibrated by the Cepheid distance scale. Distances for five secondary methods are plotted: the Tully–Fisher relation for spiral galaxies (filled circles), type Ia supernovae (filled squares), the fundamental plane for elliptical galaxies (filled triangles), type II supernovae (open squares) and surface brightness fluctuations (filled diamonds). A correction for metallicity has been applied to the Cepheid calibration. A fit to the slope yields a value of \( H_0 = 72 \text{ km/sec/Mpc} \). One-sigma error bars are also indicated. The bottom panel plots \( H_0 \) versus distance and the horizontal line corresponds to \( H_0 = 72 \text{ km/sec/Mpc} \).

Measurements of recession velocities and the distances to galaxies at large distances (where deviations from the smooth Hubble expansion are small). Progress in measuring \( H_0 \) has been limited by the fact that measuring accurate distances presents an enormous challenge. Primarily as a result of new instrumentation at ground-based telescopes, and with the availability of the Hubble Space Telescope (HST), the precision with which \( H_0 \) can be measured has evolved at a rapid pace.

A key project of the Hubble Space Telescope (HST) was the measurement of distances to a sample of nearby galaxies using Cepheid variables. These intrinsically bright stars follow a well-defined relation between luminosity and period of variation, from which, given a measurement of apparent luminosity and period, their distances can be established by applying the inverse square law. The Cepheid distances may then be used to provide a calibration of several independent methods for measuring relative distances which can be extended further than Cepheids: for example, type Ia supernovae, the Tully–Fisher relation (a relation between the luminosity of a spiral galaxy and its rotational velocity), or the fundamental plane for elliptical galaxies (relating luminosity to velocity dispersion). A summary of the final results for the key project yields a value of \( H_0 = 72 \pm 3 \) (statistical) ± 7 (systematic).
km/sec/Mpc based on 5 different methods (see Figure 2).

These measurements are consistent with other recent measurements of the Hubble constant from the measurement of the Sunyaev–Zeldovich effect and time delays for gravitational lenses. These methods, currently with systematics at the ± 20–25% level are yielding values of $H_0 \sim 60$ km/sec/Mpc for cosmologies in which $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$.

6 The Optical Extragalactic Background Light (EBL)

The luminosity of stars falls off as $1/r^2$, but the surface area intercepted increases as $r^2$. In an infinite universe, the cancelling $r^2$ terms ought to result in a constant surface brightness, and the sky should be as bright as the surface of a star (Olber’s paradox). This paradox was resolved with the discovery of the expansion of the universe, and the finite lifetimes (and the universe itself). But the measurement of the actual value of the optical night sky brightness has remained elusive simply because of just how dark the sky actually is. And because the optical background light is swamped by both the foreground airglow of the Earth as well as the foreground zodiacal light in the ecliptic plane (at the level of two orders of magnitude), to date it has only been possible to place limits on the EBL contribution. With HST it has been possible for the first time to make a direct measurement of the total optical background light from extragalactic sources.

The total star formation history of the universe is recorded in the extragalactic background light. The EBL is a record of the baryonic mass processed in stars, and the formation of elements heavier than lithium (the metal production). The intensity of the EBL can be expressed:

$$I_{EBL} = \frac{c}{4\pi} \int_{t_f}^{t_0} \frac{\rho_{bol}(t)}{1+z} dt$$

where $t_f$ and $t_0$ represent the formation and current epochs respectively, $\rho_{bol}$ is the total bolometric luminosity, and the factor $(1+z)$ accounts for the expansion of the universe. The measured EBL also includes a contribution from active galactic nuclei (AGN) and accreting black holes in quasars; recent estimates suggest that this contribution could amount to about 15%.

An important lower bound to the optical luminosity in extragalactic sources can be obtained by integrating the luminosities from individually detected galaxies (for example, the Hubble Deep Field (HDF)). However, the total amount of light in galaxies cannot yet be determined directly from individual galaxy counts because cosmological surface–brightness dimming (which goes as $(1+z)^4$) is sufficiently severe that even intrinsically bright galaxies of $L^*$ (Milky
Figure 3: Ultraviolet images of M51 and M101 as they would appear at successive redshifts from Kuchinski et al. Top panel: (Left) Ground-based U-band (3500 Angstrom) image of M51. (Center) M51 artificially redshifted to z=0.6, corresponding to the HST WFPC2 606W filter. (Right) M51 artificially redshifted to z=1.2, corresponding to the HST WFPC2 814W filter. Bottom panel: (Left) UIT far-ultraviolet (1500 Angstrom) image of M101. (Right) Simulated images of M101 at redshifts where the rest-frame UIT filter bandpass would coincide with the four HST WFPC2 filters used to image the Hubble Deep Field.

Way) luminosities can be missed at high redshift in deep surveys, and the outer lower surface–brightness regions in galaxies can easily escape detection even in relatively nearby galaxies. Figure 3, from Kuchinski et al. illustrates directly how the well-known Messier objects, M51 and M101 would appear when observed at successively higher redshifts. Corrections for redshift and surface–brightness dimming are applied to rest–frame ultraviolet (U–band and 1500 Angstrom) images. Only the highest surface–brightness features remain visible at high redshift (see also the discussion by Colley et al.), and these reasonably bright (as well as all fainter) galaxies will be missed in deep galaxy surveys.

The optical HST EBL measurements are shown in Figure 4, from Bern-
EBL (0.1 to 1000 µm)

Figure 4: Background light in units of $\nu L_\nu$ from 0.1 to 1000 µm. The optical (UVI) EBL measurements are from Bernstein, Freedman & Madore (BFM) 37, along with EBL measurements and limits at near- and far-infrared, and submillimeter wavelengths; solid lines are theoretical predictions (see references cited in BFM).

stein, Freedman & Madore 37 in addition to measurements at longer wavelengths. The grey shaded band corresponds to the model of Dwek et al. 44 scaled to fit the HST data. This model is based on a star formation model including corrections for dust extinction and reradiation. From this figure, it can be seen that approximately 30% of the optical radiation (that produced in stars) is absorbed and then reradiated by dust at infrared wavelengths. The total EBL contribution from 0.1 to 1000 µm amounts to $100 \pm 20$ nW/m²/sr.

The measured optical EBL exceeds the light computed from counts in the Hubble Deep Field by a factor (depending on bandpass) ranging from two to three 35, 37. There are two major components to the missing light, the first being from the outer parts of detected galaxies (beyond the aperture used for photometry measurements), and the second being from galaxies below the surface brightness threshold of the HDF. Roughly 30% of the missing light comes from the outer parts of galaxies and 60% from galaxies below the detection threshold. This background light measurement is consistent with a star formation history of the universe characterized by a steep increase of star formation between redshifts of 0 and 1 (as observed in the CFRS survey 35) and a flat or slightly increasing star formation rate beyond in the redshift range 1-4, consistent with observations of star–forming galaxies at these redshifts (the
Lyman break galaxies\(^4\). Thus, much of the contribution to the background light may be due to normal galaxies at redshifts less than 4 that are missed because of cosmological surface–brightness dimming (and K-corrections due to band shifting with redshift). However, an earlier generation of stars, not yet detected, may also be contributing to the total background light\(^5\). The value measured for the optical EBL implies that the mass processed through stars contributes about 1% of the critical density (for h = 0.7); i.e., a small overall contribution, but a factor of two higher than previous estimates.

7 Concluding Remarks

At the current time, there is an impressive convergence on a new standard cosmological model: a flat \(\Omega_{\text{total}} = 1\) model with \(\Omega_m \sim 0.3\), \(\Omega_X \sim 0.7\), \(h = 0.7\), and an age of about 14 billion years. As the number of independent determinations of these parameters increases, so will our confidence in this overall picture. Importantly, this convergence does not depend on the results from a single experiment. For example, a non-zero value for a dark energy component, \(\Omega_X\), is implied not solely by the type Ia supernovae, but also by the combined CMB anisotropy and large–scale structure surveys. The position of the first acoustic CMB peak at a scale of about 1 degree strongly favors a flat universe, whereas several direct estimates of \(\Omega_m\) yield low values, again pointing to a missing energy component. Values of the Hubble constant exceeding 60 km/sec/Mpc lead to a conflict with the ages of the Milky Way globular clusters in an \(\Omega_X = 0\) universe. Many of the parameter measures would have to move beyond their current 2–\(\sigma\) error bounds for the cosmological model to change. Given the difficulty in eliminating systematic errors, such a possibility cannot be ruled out, but as more accurate data (from MAP, Planck, SDSS, Chandra, SIM, GAIA, LSST, GSMT and other ongoing or planned experiments) become available, the prospects for robustly constraining the cosmological parameters, ultimately leading to an understanding the physical basis of the underlying cosmological model, are looking extremely promising.

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