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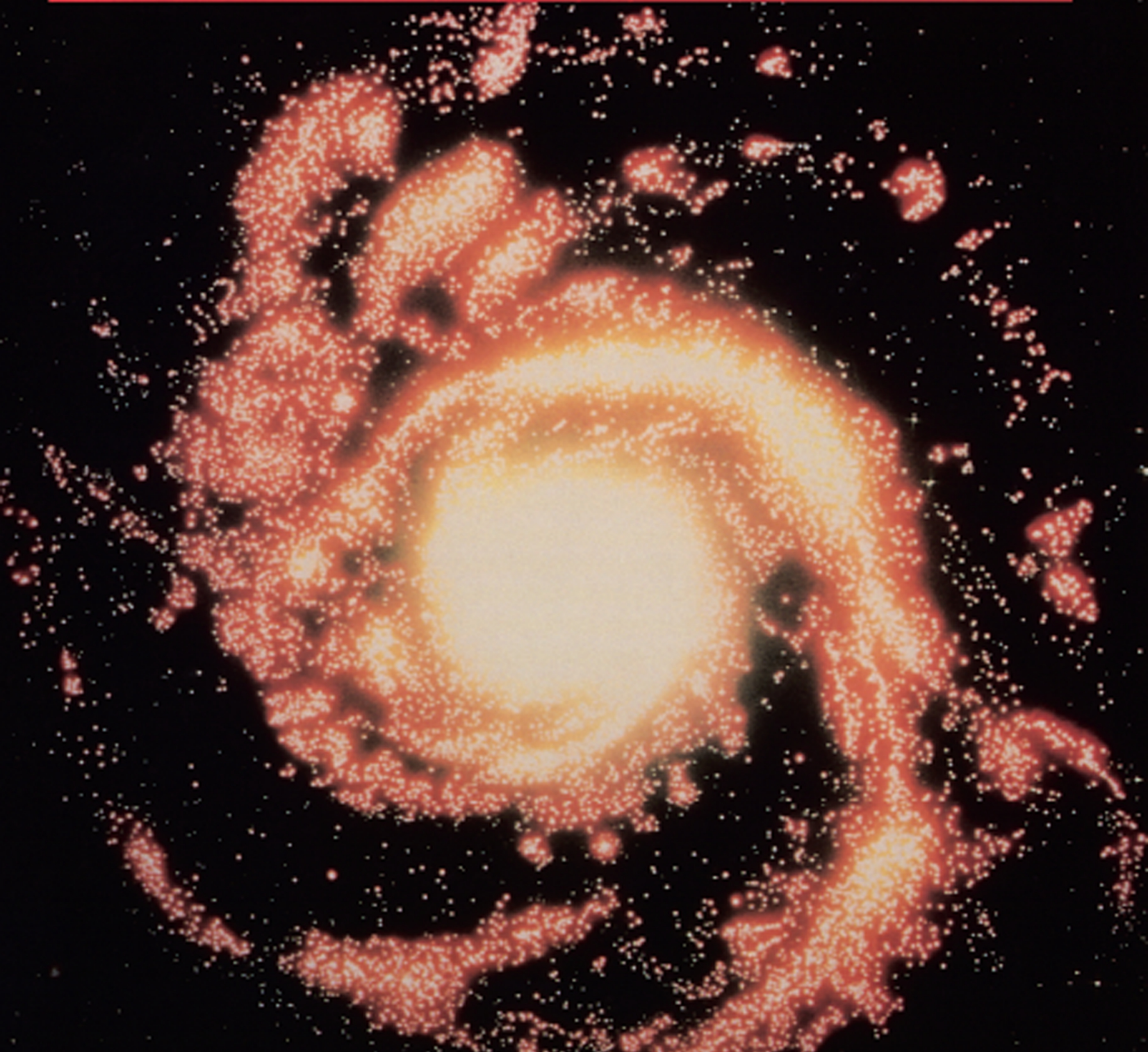

EDWARD W. KOLB ▪ MICHAEL S. TURNER

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FRONTIERS IN PHYSICS

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To

Adrienne and Barbara

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EDITOR'S FOREWORD

The problem of communicating in a coherent fashion recent developments in the most exciting and active fields of physics continues to be with us. The enormous growth in the number of physicists has tended to make the familiar channels of communication considerably less effective. It has become increasingly difficult for experts in a given field to keep up with the current literature; the novice can only be confused. What is needed is both a consistent account of a field and the presentation of a definite "point of view" concerning it. Formal monographs cannot meet such a need in a rapidly developing field, while the review article seems to have fallen into disfavor. Indeed, it would seem that the people most actively engaged in developing a given field are the people least likely to write at length about it.

FRONTIERS IN PHYSICS was conceived in 1961 in an effort to improve the situation in several ways. Leading physicists frequently give a series of lectures, a graduate seminar, or a graduate course in their special fields of interest. Such lectures serve to summarize the present status of a rapidly developing field and may well constitute the only coherent account available at the time. Often, notes on lectures exist (prepared by the lecturer himself, by graduate students, or by postdoctoral fellows) and are distributed on a limited basis. One of the principal purposes of the FRONTIERS IN PHYSICS Series is to make such notes available to a wider audience of physicists. A second principal purpose which has emerged is the concept of an *informal monograph*, in which authors would feel free to describe the present status of a rapidly developing field of research, in full knowledge, shared with the reader, that further developments might change aspects of that field in unexpected ways.

The Early Universe provides a fine example of what an informal monograph can accomplish in a frontier field of science. The authors, Edward W. Kolb and Michael S. Turner, are theoretical astrophysicists of great distinction who have made seminal contributions to our understanding of the early Universe. In the present volume they begin by treating those aspects of cosmology for which the fundamental physics is well established, that is events that occurred after the first 0.01 sec of the "big bang." In the second part of their book, they examine events that occurred before 0.01 sec for which the fundamental physics lies beyond the standard model of particle physics, and is therefore tied to speculation about the physics that lies beyond that model. In a joyously written finale, they give their personal views on the future of the particle physics–cosmology interface, while in a companion reprint volume, *Early Universe: Reprints*, they provide the reader with a collection of reprints, accompanied by lucid and lively commentaries. The present volume has been long awaited by the particle physics–astrophysics community, and I am confident that their hope—that together the two volumes will provide both the beginning graduate student and the interested outsider with a sound introduction to modern cosmology—will be realized.

David Pines
Urbana, Illinois
September, 1989

PREFACE TO THE PAPERBACK EDITION

In September 1989 we concluded *The Early Universe* with a very optimistic Finale, predicting that we would see not only the continued success of the basic framework of the hot big bang model, but also the confirmation of some of the speculations of early-Universe cosmology. Despite being four years older, we are no less optimistic; we are, in fact, even more optimistic!

There is very good reason for our continuing optimism: Important developments, both in observation and theory, have taken place in the last four years. In this update to the paperback edition we highlight some of these developments, and finish with another gaze into the crystal ball.

Before beginning our brief update we regret to report that, as we had feared, the flawless camera-ready manuscript we submitted was corrupted by the publishers, resulting in typos in the published version. We have not corrected these errors in this paperback edition (they weren't our fault anyway); early in 1994 we will make available a typo list. We thank alert readers for reporting problems.[1]

Observation

CMBR spectrum: After fifteen years in the planning, NASA's Cosmic Background Explorer (COBE) satellite was successfully launched in November 1989. A mere nine minutes of data from the Far InfraRed

[1]In the words of Umberto Eco, "I libri non sono fatti per crederci, ma per essere sottoposti a indagini."

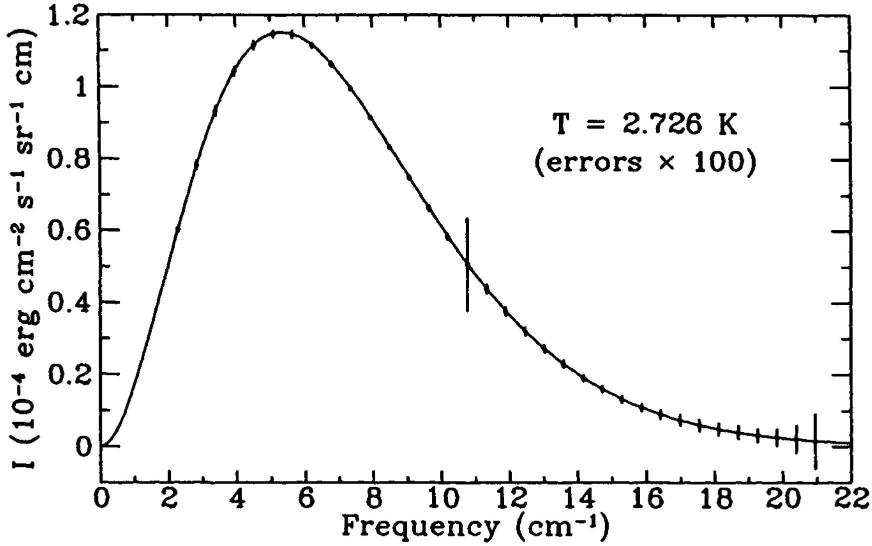

Fig. 1. The spectrum of the CMBR measured by FIRAS [2]; the solid curve is a $T = 2.726$ K blackbody.

Absolute Spectrophotometer (FIRAS) established that in the wavelength interval 0.05 cm to 0.5 cm the Cosmic Microwave Background Radiation (CMBR) has a black-body spectrum to an accuracy of 1% [1]. This put to rest claims of spectral distortions in the submillimeter range amounting to about 10% of the total CMBR energy density (see Fig. 1.8).

In Spring 1993 the FIRAS team published their final spectral data [2], illustrated in Fig. 1. Their results can be summarized as follows: (1) The best-fit black-body temperature is $T_0 = 2.726 \pm 0.01\,\mathrm{K}$;[2] (2) Deviations from a black-body spectrum over the wavelength interval 0.05 cm to 0.5 cm are less than 0.03% of the peak intensity; and (3) Limits to the distortion parameters y and μ are $y \leq 2.5 \times 10^{-5}$ and $|\mu/kT| \leq 3.3 \times 10^{-4}$ (95% CL).

These results severely constrain any process that distorts the CMBR, including radiative decays of relic particles (discussed in Section 5.5), energy release by a very early generation of stars, or the presence of hot gas between here and the last-scattering surface (e.g., as predicted in explosive scenarios of structure formation).

[2]In January 1990, a rocket-borne instrument probed a similar wavelength range and determined a black-body temperature of $T_0 = 2.736\,\mathrm{K} \pm 0.017\,\mathrm{K}$ [3].

CMBR anisotropy: Variation in the CMBR temperature in different directions is expected due to several effects: the motion of our local reference frame with respect to the cosmic rest frame (i.e., the FRW frame), rotation of the Universe, anisotropic expansion, and the presence of the density inhomogeneities presumed to have triggered the formation of structure. The Differential Microwave Radiometer (DMR) on COBE very accurately determined the amplitude of the dipole anisotropy, $\Delta T_{\rm dipole} = 3.365 \pm 0.027\,{\rm mK}$ (consistent with previous measurements), corresponding to a velocity of the local group of galaxies of $627 \pm 22\,{\rm km\,s^{-1}}$ in the general direction of Hydra-Centaurus (more precisely, $RA = 166^\circ \pm 3^\circ$ and $\delta = -27.1^\circ \pm 3^\circ$) [4].[3]

In April 1992 the DMR team announced the discovery of anisotropy in the CMBR temperature on angular scales from about 10° to 90° at the level of about 1 part in 10^5. Their strongest result is the measurement of the *rms* temperature variation on the sky averaged over a beam of FWHM 10°: $30 \pm 5\mu$K; additionally, they measured a quadrupole anisotropy of amplitude $11 \pm 3\mu$K [5]. The multipole amplitudes extracted from their data are shown in Fig. 2. (See Section 9.6.2 for a discussion of CMBR temperature anisotropies.)

This anisotropy is presumed to arise from the density inhomogeneities that triggered structure formation, providing the first evidence for their existence.[4] The DMR discovery is the culmination of the quest to find spatial anisotropy that began with Penzias and Wilson's anisotropy limit of around 10%. We hope that it represents the beginning of the mapping of anisotropy on angular scales from arcseconds upward, helping to reveal the primeval spectrum of density fluctuations as well as clarifying the post-recombination history of the Universe.

While measuring a temperature difference of order tens of microKelvins is in itself a technical challenge, even more daunting is shielding against sunshine, earthshine, and moonshine, and discriminating against foreground sources including synchrotron, bremsstrahlung and thermal dust emission from the Milky Way, as well as discrete sources between here and the last-scattering surface. With sampling at three frequencies (31.5 GHz, 53 GHz and 90 GHz), two sets of receivers at each frequency, and full-sky coverage, the DMR was able to discriminate against foreground

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[3]The DMR also measured a yearly modulation of the dipole anisotropy due to Earth's motion around the sun: $\Delta T = 0.27\,{\rm mK}$, corresponding to a mean orbital velocity of $30\,{\rm km\,s^{-1}}$ (Galileo is vindicated!).

[4]It is possible that some portion of the anisotropy is due to long-wavelength gravitational waves produced during inflation [6]; see Section 8.4.

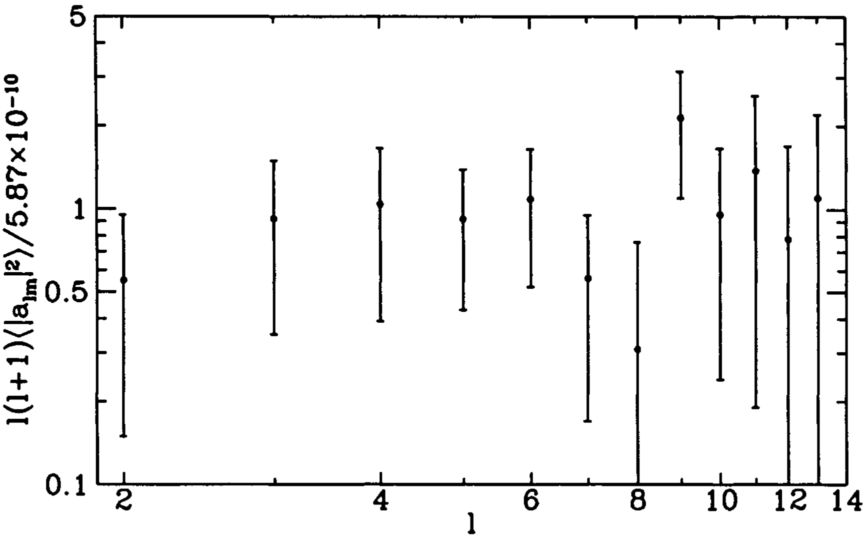

Fig. 2. The multipole amplitudes determined by the DMR [5]. See Section 9.6.2 for discussion and definitions.

sources and to present a very convincing case for CMBR anisotropy. Just recently, the DMR result received confirmation from a re-analysis of an earlier balloon-borne experiment on angular scales from about 4° to 100° [7]; moreover, this measurement was at a frequency of 170 GHz, providing further evidence that the anisotropy is thermal and associated with the CMBR.

Currently there are a dozen or so ongoing CMBR anisotropy experiments probing angular scales from about 10′ to 10° with sensitivities at the level of 10^{-5}. Five of these experiments have detected statistically significant anisotropy not associated with any *known* foreground source [8]. In the near future the anisotropy of the CMBR may well be measured on angular scales from 10′ to 90°, thereby probing the density field of the Universe on scales from about $10h^{-1}$ Mpc to 10^4h^{-1} Mpc (see Section 9.6.2).

Determination of Ω_0: A definitive measurement of the mean mass density of the Universe, one of the fundamental parameters of cosmology, still eludes us (see Section 1.7). While the bulk of the measurements are consistent with a value between 10% and 30% of critical density, recent work

[9] makes a very good case for $\Omega_0 = 1$. If this is true, it strongly suggests the existence of nonbaryonic dark matter since primordial nucleosynthesis constrains the baryonic fraction to be less than 10% of the critical density (see Section 4.6).

The physics underlying these recent measurements is simple: the peculiar velocities of galaxies are driven by the gravitational effect of the inhomogeneous distribution of matter, and thereby depend upon the level of inhomogeneity ($\delta\rho/\rho$) and the average density (Ω_0) [see Section 9.6.1, especially Eq. (9.135)]. Measurements of peculiar velocities (e.g., that of our own galaxy or those of thousands of nearby galaxies) and of the distribution of galaxies can thus be used to determine Ω_0. A crucial new ingredient are the red-shift surveys based upon the IRAS Catalogue of infrared selected galaxies. The IRAS Catalogue is especially useful since it is largely unaffected by galactic absorption, and thus provides a fair sample of galaxies in all directions which can be used to determine $\delta\rho/\rho$.[5]

Not only does this route to Ω_0 sample a very large volume, a cube of order $100h^{-1}$ Mpc on a side, but it also gives the "right" answer: $\Omega_0 = 1$ with an estimated standard error of about ± 0.2. While the Ω_0 issue is still far from being settled, this set of measurements provides a much needed shot in the arm for the FSU (Flat Universe Society).

Mapping the Universe: Red-shift surveys are the most widely used technique for mapping structure in the Universe (see Section 1.8). When the hardback edition went to press the total number of red shifts measured was around 30,000, and the largest survey, the CfA slices of the Universe, contained about 8,000 red shifts and probed the Universe out to $z \simeq 0.03$. The total number of red shifts measured is now about double that and growing rapidly. Several new red-shifts surveys exist [10]: the previously mentioned survey of IRAS galaxies; sparse surveys where the red shifts of only a small fraction of the galaxies in a catalogue are measured, e.g., that based upon the APM catalogue [11]; and pencil-beam surveys where a small patch of the sky (a square degree or so) is probed to great depth [12].

The most ambitious project in the works is the Sloan Digital Sky Survey [13]. A catalogue of over 100 million galaxies on the northern sky will be

[5]More precisely, the IRAS galaxies provide a means of determining $\delta n_{\rm GAL}/n_{\rm GAL}$. Assuming a simple relationship between the distribution of mass and light, $\delta n_{\rm GAL}/n_{\rm GAL} = b(\delta\rho/\rho)$ where b is the biasing factor (see Section 9.7), the peculiar-velocity field and the distribution of light can be used to infer $\Omega_0^{0.6}/b$.

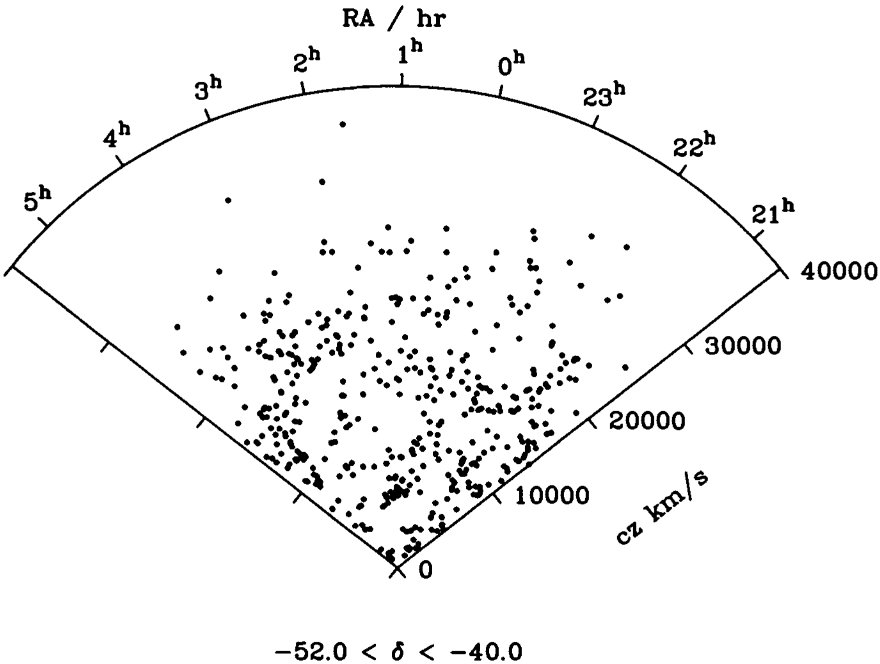

Fig. 3: A slice of a sparse sample of the APM catalogue [11]. The APM slices are about three times as deep as the CfA slices; cf. Fig. 1.12.

constructed using four-color CCD photometry, and red shifts of about a million galaxies and of about a hundred thousand QSOs will be measured. The red-shift survey will cover about π-sr on the sky and extend out to $z \sim 0.2$. This "π-in-the-sky" project is scheduled to be finished by the end of the millennium.

The picture of the Universe emerging from the deeper sparse surveys confirms the most prominent feature of the CfA slices—an abundance of voids of size $30h^{-1}$ Mpc—and reassures cosmologists that the Universe does indeed become smoother on large scales reflecting the smoothness implied by the isotropy of CMBR; see Fig. 3. This should end speculation that the Universe contains structures of ever increasing size or that the large-scale structure is a fractal. The pencil-beam surveys [12], which probe a small portion of the sky to great depth, have confirmed another feature in the CfA slices: the existence of sheet-like structures similar to the CfA "great wall."

Completing the standard model: Millions of Z^0 bosons have been produced and detected at CERN in the LEP collider, and trillions of protons and antiprotons have been collided at Fermilab in the Tevatron. These experiments have tested the electroweak model to very high precision, better than 1% in many instances. For example, precise measurements of the Z^0 resonance have determined the mass of the Z^0 to be $91.187\,\mathrm{GeV} \pm 7\,\mathrm{MeV}$ and the number of light neutrino species to be $N_\nu = 2.98 \pm 0.03$. The latter precludes the possibility of a fourth generation neutrino of mass less than about 45 GeV and all but eliminates a heavy neutrino as a dark matter candidate.

The search for the top quark goes on at this very moment at the Tevatron, with a current lower mass limit of 113 GeV. The search for the Higgs continues at LEP with a lower mass limit of about 64 GeV. Likewise, supersymmetry remains elusive, as all searches for the various supersymmetric partners continue only to set mass limits.

The good news is that the electroweak model is in great shape with only two key parameters to be determined: the top-quark mass and the Higgs mass. The good news is also the bad news: deviations from standard-model predictions are potential signals for physics beyond the standard model—and thus far there aren't any. While there continue to be hints of physics beyond the standard model in the neutrino sector, e.g., in solar neutrino experiments and atmospheric neutrino fluxes, there is no firm evidence yet.[6]

Theory

Inflation: Most of the discussion of inflation in Chapter 8 was devoted to "slow-rollover" inflation, the only viable model of inflation at that time. In slow-rollover inflation a very weakly coupled scalar field is initially displaced from the minimum of its potential, and the associated potential energy causes the Universe to inflate while the scalar field slowly evolves to the bottom of the potential (see Chapter 8). Though slow-rollover provides a viable implementation of inflation, the decoupled and disconnected nature of the scalar field responsible for inflation, and the very name given

[6] In the interim between the hardback and paperback editions, the specter of a 17 keV neutrino has come and gone. While experiment was the final arbitrator, consideration of the cosmological and astrophysical effects of a massive, unstable neutrino (as discussed in Chapter 5) proved important.

it, "inflaton," makes slow-rollover less than compelling.

In 1990 Steinhardt and La [14] proposed a new type of inflation, called extended inflation, where again inflation is associated with a first-order symmetry-breaking phase transition. The key difference between extended inflation and Guth's original model, which was also based on a first-order phase transition, is the underlying theory of gravity: Jordan–Brans–Dicke (JBD) rather than general relativity.

In JBD the gravitational "constant" is set by the value of a scalar field. During inflation this scalar field evolves and gravity becomes weaker; as a result the cosmic scale factor grows as a large power of time rather than exponentially. This means that in extended inflation the physical volume of space remaining in the false vacuum grows only as power of time and not exponentially, and unlike Guth's original model, bubble nucleation can convert all of space to the true vacuum.

On the face of it, extended inflation seems to combine the best features of old inflation (close connection with particle-physics models through a first-order phase transition) and new inflation (it works!).[7] Because reheating and the transition to the radiation-dominated era occur through bubble collisions some aspects of inflation are different, even leading to potentially observable signatures, e.g., gravitational waves from bubble collisions, creation of large voids, and the production of topological defects [15].

Extended inflation is not without problems, most notably "the big-bubble problem" [16]. Inflation ends through bubble nucleation and percolation; the faster the Universe expands, determined by the Brans–Dicke parameter ω, the broader the distribution of bubble sizes, and the higher the level of inhomogeneity. Achieving sufficient homogeneity requires ω to be less than about 20; unfortunately, solar-system tests of JBD theory constrain ω to be greater than about 500.

Clearly the La–Steinhardt model is not viable; it does provide a simple toy model that illustrates the general features of "first-order" inflation. Because attractive theoretical ideas such as superstrings, supergravity, and extra dimensions lead to a JBD-like description of gravity at high energies, there is both the motivation for pursuing extended inflation and the hope that a workable, realistic, and compelling model may be found. At the very least, extended inflation has shown that the inflationary paradigm is

[7] In fact, by means of a conformal transformation extended inflation can be recast as slow-rollover inflation with an exponential potential and general relativity as the gravity theory.

richer than imagined and that a simple, elegant, and viable model may still await discovery.

Structure formation: In Chapter 9 we focused on two theories of structure formation: hot dark matter (HDM) and cold dark matter (CDM), both with inflation-produced density perturbations. At that time CDM looked very promising and HDM looked very unpromising. After four years and a wealth of new data (especially the COBE DMR result), CDM still looks promising, HDM does not look any more promising, and there are two new contenders.

The first is Peebles' primeval isocurvature baryon (PIB) model [17]. In this model $\Omega_0 = \Omega_B \sim 0.2$ and $h \simeq 0.8$, with *isocurvature* fluctuations in the baryon-number density providing the seed perturbations. PIB is a minimalist model—start with what you see, not what you would like. It is not motivated by early-Universe microphysics (we're not offended), and in fact it is strongly disfavored by inflation and it violates the nucleosynthesis bound to $\Omega_B h^2$ by a factor of six. The model is currently consistent with the bulk of the data on large-scale structure (which motivated its spectrum of perturbations in the first place). However, it seems destined to have difficulty accounting for both the DMR detection and the observed level of CMBR isotropy on angular scales of degrees.

The second encompasses a class of scenarios where the primeval perturbations are isocurvature perturbations arising from defects (cosmic strings, global monopoles, textures, and so on) produced in a very early phase transition (energy scale of about $10^{16}\,$GeV and $t \sim 10^{-38}\,$sec) (see Chapter 7 for discussion of topological defects). These scenarios have nonbaryonic dark matter, usually cold, though in the case of cosmic strings, the dark matter could be hot. Structure formation is more difficult to simulate numerically because the seed perturbations are constantly being formed as the network of defects evolves (unlike inflation where the perturbations were put in place in the distant past). To the extent to which numerical simulations have been carried out they are consistent with the observed large-scale structure. CMBR anisotropy measurements are crucial to testing these scenarios: to accommodate the DMR result a high level of biasing is required ($b \sim 4$) and their predictions for anisotropy on the $1°$ scale are very different than those of cold dark matter [18].

Cold dark matter continues to be the most scrutinized model. In fact, it is probably fair to say that it has helped to spur many of the important observations that are testing theories of structure formation. One of the

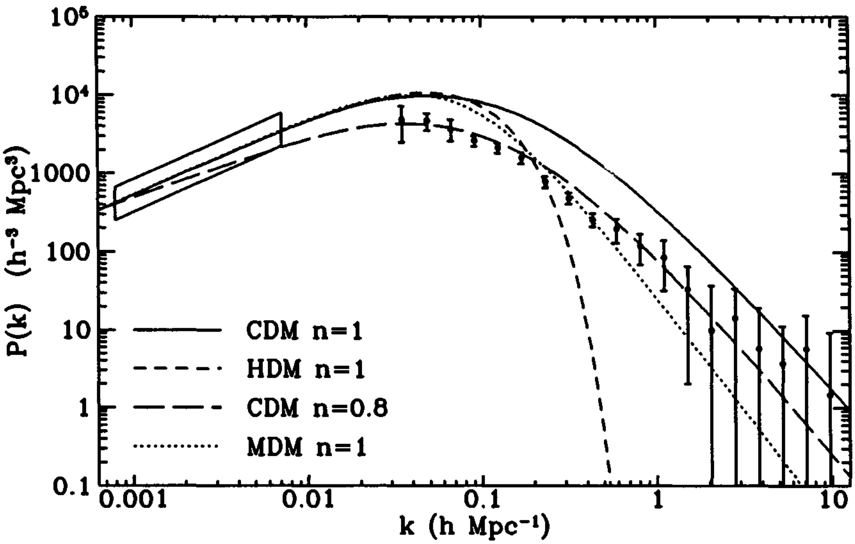

Fig. 4: The empirically determined power spectrum of density perturbations and the (linear-theory) predictions of several models. The power spectrum of density perturbations, cf. Sections 9.2 and 9.3, was inferred from the 1.2Jy IRAS red-shift survey [19] and the COBE DMR measurements. The models shown are cold dark matter; hot dark matter; tilted cold dark matter; and mixed dark matter.

virtues of cold dark matter is its specificity. Before the DMR result, biased cold dark matter with $b \sim 1.5$ was the favored model, though there were indications that fluctuations were too small on large scales to account for the observed structure. Since the shape of the spectrum is specified, only one measurement is needed to determine the entire spectrum (see Sections 9.2 and 9.4). Normalizing to the DMR result leads to a biasing factor of essentially unity, i.e., little or no bias. This is good news and bad news: $b = 1$ is the simplest model and seems to solve the problem of a deficiency of power on large scales; however, such a normalization appears to lead to fluctuations that are too large on small scales, which is illustrated in Fig. 4.

Although part of the attractiveness of cold dark matter has always been its specificity, as the quantity and quality of data have improved, slight variations on the basic theme have been put forth, largely to decrease the level of fluctuations on small scales. These variations involve the composition of the dark matter or the spectrum of perturbations. The oldest variant involves a cosmological constant: $\Omega_\Lambda = 0.8$, $\Omega_{\rm CDM} \simeq 0.15$ and $\Omega_B \simeq 0.05$ [20]. In addition to reducing power on small scales, the presence of a cosmological constant allows for a larger value of the Hubble constant, $h \sim 0.7 - 0.8$. (In a conventional matter-dominated Universe the Hubble constant has to be close to $h = 0.5$ to accommodate other age determinations; see Section 1.4.)

In the mixed dark matter variant a small amount of hot dark matter is added [21]: $\Omega_{\rm HDM} \sim 0.3$, $\Omega_{\rm CDM} \sim 0.65$, and $\Omega_B \sim 0.05$. The "pinch" of hot dark matter, e.g., in the form of neutrinos of mass 7 eV or so, leads to the suppression of fluctuations on small scales because of the free streaming of neutrinos (see Section 9.4).

The third variant involves a modification of the spectrum of perturbations. A generic prediction of inflationary perturbations is "almost scale-invariant" perturbations, the Harrison-Zel'dovich spectrum, characterized by $n = 1$ (or equivalently $\alpha = 0$, cf. Section 9.4). While it was realized from the beginning that there could be deviations from the scale-invariant form ($n = 1$), this fact did not seem important; now it may be [22]. When the spectrum of perturbations is normalized to the COBE DMR result, which fixes the spectrum on a very-large scale ($H_0^{-1} \sim 10^4$ Mpc), a modest amount of "tilt," say $n \simeq 0.8$, can reduce fluctuations on small scales (order $10h^{-1}$ Mpc or so) by the right amount (about a factor of two). If this is the resolution to the small-scale power problem, it provides important information about the inflationary potential, only some potentials predict this much tilt, and makes another prediction, such potentials generally lead to a higher level of gravitational waves [23].

In Fig. 4 the power spectra for the cold dark matter, hot dark matter, tilted cold dark matter, and mixed dark matter models are compared with the empirically determined power spectrum (Λ + cold dark matter is similar to mixed dark matter). All four models have been normalized to the COBE DMR result; by so doing, the resulting biasing factors on the $8h^{-1}$ Mpc scale are respectively: 0.85, 1.4, 1.5, and 1.35. The variants clearly provide better fits to the measured power spectrum; however, unbiased cold dark matter has the great virtue of being the simplest model.[8]

Key tests for CDM models as well as the other contenders are coming soon. For example, the various scenarios make different predictions for the level of anisotropy on the 1° scale, and a number of experiments are now

[8]One should keep the words of Francis Crick in mind: A theory that agrees with all the data at any given time is necessarily wrong, as at any given time not all the data are correct.

reporting results on these scales [8]. It is very likely that in the next few years one or more models of structure formation will be falsified. With the great effort focused on the problem of structure formation, this important aspect of the standard cosmology may soon be sorted out.

Electroweak phase transition: Now that almost all the parameters of the electroweak theory are known it is possible in principle to study the dynamics of the electroweak phase transition in some detail. A key word in the above sentence is *almost*. We must remind the reader that the top quark and Higgs masses are still unknown, and it may be that the mechanism for symmetry breaking is more complicated than that in the standard model. In any case, within the minimal electroweak model the problem is essentially well posed.

Throughout almost the entire parameter space (i.e., top quark and Higgs masses) the one-loop calculation predicts that the phase transition should be very weakly first order [24]. Were the transition second order or strongly first order, a number of well known and straightforward theoretical techniques would be applicable [25]. However because of the weakness of the transition the one-loop calculation is not reliable, and calculation of the details of the transition presents a theoretical challenge—one that is important enough to try hard to solve [24,25].

Toward the end of Chapter 6 we discussed baryon number violation within the standard electroweak model due to classical field configurations known as sphalerons. It is now generally believed that $B + L$ is violated rampantly through electroweak interactions at temperatures above the electroweak transition, as well as slightly below through sphalerons. The implications for baryogenesis are manifold: (i) the baryon number could be generated at high temperatures by a GUT process, but with a net $B - L$ so that it cannot be erased by electroweak $B + L$ violation; (ii) the baryon number could be generated at temperatures below the electroweak scale; or (iii) the baryon number could be generated during the electroweak transition itself.

In case (i), there are implications for Majorana neutrino masses and the structure of the neutrino sector. Majorana neutrino masses violate lepton number, and for large enough masses this L violation together with electroweak $B + L$ violation can completely erase any baryon asymmetry [26]. Moreover, it could be that a baryon asymmetry per se is never generated; rather, a lepton asymmetry is produced and is transmuted into a baryon asymmetry by electroweak $B+L$ violation. Possibility (ii) presents challenges, though models for baryogenesis at very low temperatures have been proposed (see Chapter 6). Possibility (iii) is the most intriguing: If the baryon asymmetry is produced at the electroweak scale, the underlying microphysics can probably be tested in laboratory experiments. In fact, a recent paper suggests that a baryon asymmetry of the correct magnitude can be produced within the framework of the standard model [27].

Another Gaze into the Crystal Ball

The Finale at the end of this book reflects upon past accomplishments in cosmology and looks toward the future. Since it was written 4 years ago, it is appropriate to update our view of the future here. (Unlike historians, our view of the past doesn't change!) A view of the future that is unchanged is our belief that we are poised for advances in several areas and that the golden age of cosmology is still ahead.

With the diversity of efforts focused on large-scale structure, it seems very likely that the basic outline of a "standard model" of structure formation will emerge within the next decade, or even sooner. This will occur as the result of a convergence of observation and theory. As mentioned above, there are several very specific and well motivated scenarios for structure formation, which have helped to spur observations and aid in their interpretation. The largest structures in the Universe have now been identified, the CfA voids and walls, and between red-shift surveys and measurements of CMBR anisotropy the spectrum of density perturbations is now being probed on all scales. Larger red-shift surveys and additional CMBR anisotropy measurements should further clarify matters and provide overlapping information that will shed important light on the issue of biasing. In addition, the development of new computational methods, e.g., combining smooth particle hydro and N-body codes, will strengthen the crucial phenomenological link between early-Universe theories and observations of the Universe today.

Not only will a standard model of structure formation fill in the final piece of the hot big-bang cosmology, but it may well open a new window on early-Universe microphysics. For example, if the standard model should turn out to be some variant of cold dark matter, observational data may well allow a "reconstruction" of the inflationary potential [28].

Of course the book on structure formation cannot be closed before the composition of dark matter is discovered. Since luminous matter contributes much less than 1% of the critical density, which is the lower bound to the baryonic contribution based on primordial nucleosynthesis, and there are strong indications that Ω_0 is greater than 0.1, which is the upper bound to the baryonic contribution based on primordial nucleosynthesis, there is evidence for two dark-matter problems, baryonic and nonbaryonic. While nature may prove more elusive than we expect, we are reasonably hopeful of breakthroughs because experimental efforts are underway to directly detect the most promising candidates: neutralinos, through their elastic scattering in cryogenic detectors (see Section 5.6); axions, by means of large-scale Sikivie-type detectors (see Section 10.5.1); and dark stars, through detection of microlensing of stars in the LMC. All three efforts are well underway and could solve the dark-matter riddle by the end of the decade.[9] In addition, a host of experiments will be carried out that bear on the issue of neutrino masses.

Our optimism for the future must be tempered by the realization that some problems in cosmology never seem to reach closure. In a classic paper written in 1961 [30], Sandage discussed how the 200 inch Hale telescope at Palomar could be used to determine our "world model," that is, the basic kinematical parameters which describe the expansion, H_0 and q_0 (see Section 2.3). In one sense, our knowledge of both parameters is about the same today as it was then—poor. However, there is reason to be optimistic. There is a new generation of astronomers attacking the problem of the distance scale (and thereby H_0), armed with new techniques. The Hubble Space Telescope has calibrated the distance to M101 with Cepheid variables, and when the second-generation instruments are installed, Cepheid variables in the Virgo Cluster will be within reach. Most astronomers believe that a reliable distance to Virgo is necessary, if not sufficient, to settle the issue.

Early-Universe cosmologists have a lot at stake in the determination of H_0. If the Hubble constant lies close to $80\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, then it is hard to see how to avoid an "age crisis" (see Section 3.2). While estimates of the age of the Universe based upon the cooling of white dwarfs, isotopic ratios of radioactive elements, and determination of the age of the oldest stars, all have large inherent uncertainties, it is difficult to imagine that the Universe could be as young as 10 Gyr. And, it is impossible to reconcile $H_0 = 80\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ with a Universe older than 10 Gyr without either

[9] In fact, as this paperback edition goes to press, three collaborations have reported candidate microlensing events [29]. If these events are due to microlensing by astrophysical objects in the halo of our galaxy, then one of the dark matter problems, the form of the dark baryons, will have been solved.

abandoning $\Omega_0 = 1$ or invoking a cosmological constant, both, equally unpalatable to us. Therefore, we remain steadfast in our prediction that the Hubble constant is $50 \pm 5\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$.[10]

The other parameter that describes our "world model" is q_0, where $2q_0 = \Omega_0(1 + 3p/\rho)$. While the evidence for $\Omega_0 = 1$ is far from conclusive, there is reason to believe that the case will strengthen in the near future. We mentioned earlier the techniques involving peculiar velocities. As larger samples of red shifts become available (e.g., the SDSS will produce four-color CCD measurements of 200 million galaxies) the classic techniques of galaxy number counts and angular size (see Section 2.3) may help determine q_0. In addition, other, new approaches are being pursued, e.g., automated searches for high red-shift supernovae.

The effort focused on looking for physics beyond the standard particle physics model exceeds that focused on structure formation. While everyone is sure that there is new physics beyond the standard model, when and where it will be revealed remains a mystery. The neutrino has a 60-year history of shedding light on new physics; with the diversity of experiments involving neutrinos—four solar-neutrino experiments in operation and several new experiments under construction, a new generation of long-baseline neutrino-oscillation experiments in the planning, and a variety of other experiments sensitive to new physics in the neutrino sector—perhaps history will repeat itself.

Let us now turn to theory. With our present understanding of the standard model of particle physics, there is every reason to believe that both the quark/hadron transition and the electroweak phase transition will soon be understood well enough to extend the "known history" of the Universe back to a time of about $10^{-12}\,\mathrm{sec}$ or so ($T \sim 1000\,\mathrm{GeV}$).

Some argue that the birth of particle cosmology traces to the development of baryogenesis. While present limits on proton decay seem to push the original GUT scenario of baryogenesis (see Chapter 6) beyond the reach of laboratory verification, new scenarios may be amenable to laboratory tests. For instance, baryogenesis may simply involve electroweak physics, or perhaps neutrino physics, that can be tested in terrestrial laboratories. This issue seems likely to be resolved sooner, rather than later.

Even with unlimited energy, accelerators are the wrong tool to probe the non-perturbative sector of field theories. Early-Universe phase transitions continue to provide the best arena for the study of aspects of particle-

[10] We acknowledge a generous contribution to the Chicago Cosmologists' Retirement Fund from Allan Sandage.

physics theories related to coherent, soliton-like objects. The only plausible site for the production of objects such as monopoles, strings, walls, sphalerons, and the like is an early-Universe phase transition. All of these can have very significant implications for the evolution of the Universe. Sphalerons, as well as other solitons produced in the electroweak transition, have some promise of a cosmological payoff. Of course there is an enormous difference between finding a soliton-like solution to the field equations and finding solitons in the Universe. However, even if they are not are found, the techniques developed for their study will be useful additions to the theorist's toolbox.

Of course, disappointments over lack of progress in specific areas are inevitable. We would be remiss if we did not mention them (while reminding the reader that the fact that we do not work in the fields of slow progress is purely coincidental). Any payoff of superstring theory for cosmology seems as remote today as ever. Whatever physics lies beyond the standard-model of particle physics is certain to have cosmological implications, and the standard model has yet to crack under incredible experimental scrutiny. On another front, it is difficult to see identifiable progress in quantum cosmology. As with superstrings, perhaps the mist of early enthusiasm obscured the enormity of the task.

Finally, let us not underestimate the power of a single new idea or discovery to change cosmology. We would be most surprised if the future did not include a revolutionary idea or unexpected discovery. In fact, our biggest disappointment would be if, ten years from now, we did not have to write another book.

Rocky and Mike
Warrenville & Hinsdale, Illinois
September, 1993

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PREFACE

The past decade has witnessed an explosion of activity and progress in both theoretical and observational cosmology. The catalyst has been the infusion of ideas from modern particle physics. These ideas include the "Standard Model" of the strong and electroweak interactions, which provides an understanding of physics up to the weak scale (about 250 GeV), and attractive, albeit speculative, ideas about grand unification—the unification of the strong and electroweak forces—and about super unification—the unification of all the forces (including gravity). Using these theoretical constructs theorists are able to discuss in a sensible way physics at energies up to the Planck scale (10^{19} GeV) and beyond. Moreover, particle physicists and cosmologists have applied these theoretical ideas to the study of the earliest moments of the Universe. Their speculations have led to very interesting and even compelling scenarios about the events that may have taken place at these early times: baryogenesis, inflation, the production of exotic relics—monopoles, strings, axions, photinos, and so on—and even the possibility of extra spatial dimensions. While these early-Universe scenarios are still untested, it has become clear that the answers to some of the most pressing and fundamental questions facing cosmology today *must* involve events that took place during the first 0.01 sec of the history of the Universe. These fundamental questions include: the origin of the matter–antimatter asymmetry, the nature of the dark matter, the origin of the smoothness and flatness of the Universe, the origin of the density inhomogeneities that initiated structure formation, the origin of the expansion, and even the ultimate fate of the Universe.

A second, equally important, development has been the use of astrophysical and cosmological observations to test and constrain particle physics theories. At present, the most exciting and fundamental ideas in particle theory involve energy scales well beyond the reach of conventional terrestrial accelerators: The highest energies achieved in accelerator laboratories are only 1000 GeV, while the energy scale of grand unification is believed to be in excess of 10^{14} GeV, and that of super unification, in excess of 10^{19} GeV. For this reason, some of the important tests of the most promising theories involve the early Universe or unique contemporary astrophysical environments.

Developments have been taking place in observational cosmology as well: Red shift surveys have begun to reveal the nature of the large-scale structure of the Universe; measurements of the velocity field of the Universe are beginning to shed light upon the distribution of matter (as opposed to just the light); more precise measurements of the spectrum and anisotropies of the microwave background should soon reveal important information about the nature of the primeval inhomogeneities as well as the early history of the Universe; and a number of experiments are being built to search directly for the relic elementary particles that may comprise the dark matter. In brief, observations are beginning to test the very interesting and exciting speculations about the first 0.01 sec that have been put forward in the past decade.

Our purpose in putting together this monograph was to fill the void that now exists between the current standard treatments of cosmology (S. Weinberg, *Gravitation and Cosmology*; C. W. Misner, K. Thorne, and J. A. Wheeler, *Gravitation*; Ya. B. Zel'dovich and I. D. Novikov, *Relativistic Astrophysics Vol. II*; P. J. E. Peebles, *Physical Cosmology*) and the present frontiers of research in early Universe cosmology. While these and other texts discuss the standard hot big-bang cosmology, beginning at the epoch of primordial nucleosynthesis ($t \simeq 0.01$ to 200 sec), they mention only briefly the earliest epoch (the first 0.01 sec)—then referred to as the "hadron era." When these texts were written it was believed that the fundamental particles were leptons and hadrons, and that at a time of about 10^{-5}sec and a temperature of a few hundred MeV the strongly interacting particles should have been so dense that average particle separations would have been less than typical particle sizes, making an extrapolation to earlier times nonsensical. Moreover, the exponential rise with mass in the number of hadronic resonances suggested a maximum temperature for the Universe of only a few hundred MeV. The recognition in the 1970's that the fundamental particles of the strong interaction are point-like quarks and gluons and the discovery of the asymptotic freedom of the strong interaction made it clear that the early Universe should have been a dilute gas of weakly-interacting quarks, leptons, and gauge bosons, and opened the door for the study of the very early Universe.

Our presentation here covers many of the topics of current research in early Universe cosmology. The first three Chapters serve as an introduction to the standard cosmology. In the Fourth Chapter we review primordial nucleosynthesis, discuss recent observations of the light element abundances, and explain how these observations can be used to limit the properties of weakly-interacting particles. The final seven Chapters concern subjects in particle cosmology that were developed after the standard texts were written. In the Fifth Chapter we address the topic of thermodynamics in the expanding Universe, describe the decoupling of massive particles, and discuss neutrino cosmology. Chapter 6 is devoted to baryogenesis—the very attractive theory for the origin of the baryon asymmetry which is based upon grand unification. In Chapter 7 we review cosmological phase transitions and the production of topological defects—domain walls, cosmic string, and massive magnetic monopoles—and discuss in detail the cosmological and astrophysical effects of monopoles. Inflation has revolutionized the way cosmologists view the earliest moments of the Universe and it is the theme of Chapter 8. Chapter 9 addresses the topic of structure formation. Although the basic picture that cosmologists have of structure formation—amplification of small primeval inhomogeneities through the Jeans instability—has not changed significantly, the advent of particle cosmology has led to a renaissance in the subject with the development of the hot and cold dark matter scenarios. The astrophysical and cosmological consequences of axions are the subject of the penultimate Chapter. We devote the final Chapter to recent speculations about the Planck era, including the wave function of the Universe, cosmology with extra dimensions, and superstring cosmology.

The trend of the monograph is clear: The first five Chapters treat traditional big bang cosmology from a modern perspective, while the last six Chapters are devoted to more speculative ideas. The first part of the book reviews areas of cosmology for which we have the most complete observational data base, deals mostly with events that occurred after the first 10^{-2} sec, and is based upon "well-known" low-energy physics. The second part of the book covers the most modern subjects in cosmology for which the observational data base is only now emerging, concerns events that occurred before 10^{-2} sec, and is based upon speculations beyond the standard model of particle physics.

Including all the relevant background material for the wide range of topics covered in the book is impractical, and so we have also prepared a reprint volume, *Early Universe: Reprints* (Addison-Wesley, Redwood City, Calif., 1988), as a companion to this monograph. In the reprint volume we provide a collection of key papers for the important topics that are not thoroughly covered in the monograph—observational cosmology, finite-temperature field theory, light-element abundances, etc. We hope that together these two volumes will provide the graduate student or the interested outsider with a sound introduction to modern cosmology, and even prepare the reader to carry out research in particle cosmology.

This monograph grew out of lectures given by the authors over the years at a number of Summer and Winter Schools and in graduate courses at The University of Chicago. The emphasis of the material covered reflects the judgment (or lack thereof) of the authors. The references are by no means complete. A more thorough review of the literature can be found in the reprint volume.

We are grateful to colleagues, friends, and students who have offered suggestions for improving the book. In particular we would like to thank Marc Davis, Sasha Dolgov, Alan Dressler, George Efstathiou, Margaret Geller, James Hartle, John Huchra, Marc Kamionkowski, Robert Kirshner, Andre Linde, John Preskill, Pierre Sikivie, Sharon Vadas, and Helmut Zaglauer for their careful reading of the manuscript and valuable suggestions. We especially wish to thank Ted Ressell for his preparation of the Index and Richard Holman for his detailed critical comments on several of the Chapters.

As the camera-ready book goes to press, it is completly free of any typographical errors, errors of physics, or errors of judgment. Any errors present in the final product must have crept in during the production process, and are wholly the fault of the publisher.

Edward W. Kolb
Michael S. Turner
Warrenville, Illinois
August, 1989

1

THE UNIVERSE OBSERVED

1.1 Introduction

Our current understanding of the evolution of the Universe is based upon the Friedmann-Robertson-Walker (FRW) cosmological model, or the hot big bang model as it is usually called. The model is so successful that it has become known as the standard cosmology. In this first Chapter we will review the observational basis for the standard cosmology. Direct evidence supporting its validity extends back to the beginning of the epoch of primordial nucleosynthesis, about 10^{-2} sec after the bang. Current speculations about the earliest history of the Universe, the subject of this monograph, derive from an extrapolation of the standard cosmology to very early times. The FRW cosmology is so robust that it is possible to make sensible speculations about the Universe at times as early as 10^{-43} sec after the bang! Of course, such speculations are necessarily based upon some theory of the fundamental interactions at very high energies, energies approaching the Planck scale (10^{19} GeV). At present there exists a standard model of particle physics, the $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ gauge theory of the strong and electroweak interactions. It provides a fundamental theory of quarks and leptons and has been tested up to energies approaching 1000 GeV. In addition, the past decade has produced very interesting and important speculations about particle physics at very short distances, e.g., grand unification, supersymmetry, superstring theory, etc. It is these theories of fundamental physics at ultra-high energies which allow us to speculate about the earliest history of the Universe.

Astronomy is a data-starved science. Cosmology is even more so. Observers (and their funding agencies) must pay dearly for each particle detected from distant objects in the Universe. In spite of this handicap, there is indeed a firm observational basis for the standard cosmology, with fossils dating back to about 10^{-2} sec after the bang. Moreover, there is the reasonable expectation that the cosmological data base will grow in the next decades, both in the quantity and in the quality of the observations. At present the cosmological observables include: the expansion of the Universe; the Hubble constant H_0; the deceleration parameter q_0; the age of the Universe t_0; the present mass density ρ_0 and composition of the Universe (ρ_i, i = baryons, radiation, etc.); the cosmic microwave background radiation (CMBR), including its spectrum and spatial structure; other cosmological background radiations (IR, UV, x ray, γ ray, etc.); the abundance of the light elements (particularly D, ^{3}He, ^{4}He, and ^{7}Li); the baryon number of the Universe, quantified as the baryon-to-photon ratio; and the distribution of galaxies and larger structures (clusters of galaxies, superclusters, and voids).

In the companion volume to this monograph, *Early Universe: Reprints* [1], we have reprinted or referred to many of the key papers describing the observed Universe. Here we will briefly summarize the observational evidence that supports the standard cosmology, and in the process describe the present state of the Universe.

Unless explicitly displayed, we will set the fundamental constants $\hbar$, c, and k_B equal to unity. Some handy conversion factors and a list of useful physical parameters for astrophysics and cosmology are given in Appendix A. We will assume that the reader is at least familiar with the basic ideas of the standard model of particle physics and unified gauge theories; we provide a brief primer on modern particle theory in Appendix B. We refer those interested in the standard model and current speculations beyond the standard model to the excellent monographs that exist on these subjects [2].

1.2 The Expansion

A most fundamental feature of the standard cosmology is the expansion of the Universe. The expansion, discovered in the 1920's, plays a most basic role in observational cosmology. Of the almost 28,000 galaxy spectra measured by observers all over the world, all but a handful (those of nearby galaxies) are red shifted, illustrating the universality of the expansion. Many quasi-stellar objects (QSO's) with red shifts in excess of 3 have been observed, and the current record holder has a red shift slightly greater than 4.7 [3]. Many radio galaxies with red shifts in excess of 2 have been

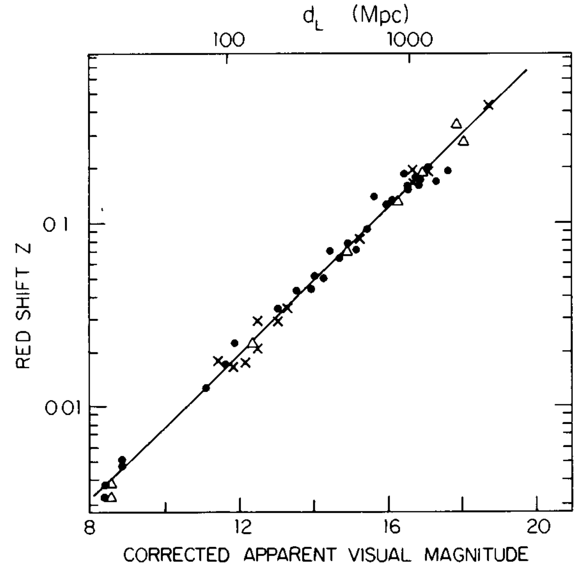

Fig. 1.1: The Hubble diagram. The corrected apparent magnitude is proportional to the logarithm of the luminosity distance. The straight line indicates the theoretical relationship for $q_0 = 1$ (from [7]).

observed, with the current record holder having a red shift of 3.8 [4].[1] The most distant cluster of galaxies observed has a red shift of 0.94 [6]. The light we see today from the most distant objects was emitted when the Universe was only a few billion years old. Thus, galaxies and QSO's provide a probe of the Universe back to times as early as a few billion years after the bang.

The relationship between the luminosity distance, $d_L \equiv (\mathcal{L}/4\pi\mathcal{F})^{1/2}$ ($\mathcal{L}$ = object's luminosity, $\mathcal{F}$ = measured flux),[2] and the red shift of a galaxy z can be written in a power series:

$$H_0 d_L = z + \frac{1}{2}(1 - q_0)z^2 + \cdots \tag{1.1}$$

[1]Few ordinary galaxies with red shifts greater than one have been seen—perhaps because they are more difficult to detect. Very recently a candidate field galaxy has been detected with a purported red shift of 3.38 [5].

[2]The precise definition of d_L and details of the $d_L - z$ relationship will be discussed further in Chapter 2.

or

$$z = H_0 d_L + \frac{1}{2}(q_0 - 1)(H_0 d_L)^2 + \cdots \tag{1.2}$$

where the Hubble constant is the present expansion rate of the Universe, $H_0 \equiv \dot{R}(t_0)/R(t_0)$, and the deceleration parameter measures the rate of slowing of the expansion, $q_0 \equiv -\ddot{R}(t_0)/R(t_0)H_0^2$ [$R(t)$ is the FRW cosmological scale factor, defined in the next Chapter, and subscript 0 denotes the present value of a quantity]. Red shifts are relatively simple (albeit time consuming) to measure, while determining galaxy distances requires well-established standard candles (i.e., objects with "known" $\mathcal{L}$). Due to the difficulty of calibrating the cosmic distance ladder, the distance scale still has a factor of 2 uncertainty even at modest cosmological distances. Moreover, for the most distant objects in the Universe (red shifts of order unity or greater) one must worry about evolutionary effects: Do the luminosities of the standard candles evolve with time?—after all, some evolution must occur because 20 Gyr ago $\mathcal{L} = 0$.

At modest red shifts, say $z \lesssim 1$, the linear relationship between d_L and z is quite clear and convincing (see Fig. 1.1). Using galaxies at relatively modest red shifts ($z \ll 1$) one may determine H_0: On a $\log z$ vs. $\log d_L$ plot, $\log H_0$ is the intercept on the $\log z$ axis. At present, reported values for H_0 span the range 40 to 100 km sec^{-1} Mpc^{-1}, with many authors quoting standard errors of 10 km sec^{-1} Mpc^{-1} or less! Clearly, systematic uncertainties still dominate in the determination of H_0. [For a historical perspective, compare these values with Hubble's initial determination: $H_0 = 550$ km sec^{-1} Mpc^{-1}.] Without trying to address the complicated issues in determining this most significant number (and risk making even more enemies than we already have!), we summarize the current state of affairs by writing

$$H_0 = 100h \text{ km sec}^{-1} \text{ Mpc}^{-1}, \tag{1.3}$$

and, like all cosmologists, bury our lack of precise knowledge of H_0 in "little h:"

$$0.4 \lesssim h \lesssim 1.0. \tag{1.4}$$

It then follows that the Hubble time or Hubble distance H_0^{-1} is

$$\begin{aligned} H_0^{-1} &= 9.78h^{-1} \times 10^9 \text{ yr} \\ &= 3000h^{-1} \text{ Mpc} \\ &= 9.25 \times 10^{27} h^{-1} \text{ cm}. \end{aligned} \tag{1.5}$$

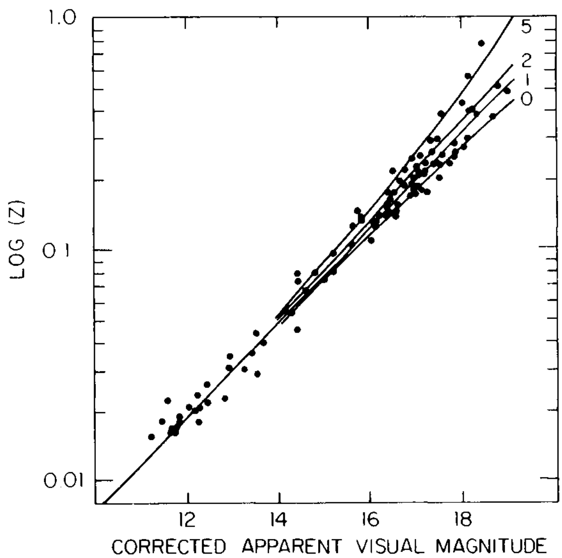

Fig. 1.2: An optical Hubble diagram. The corrected visual magnitude is proportional to the logarithm of the optical luminosity distance. The curves refer to models with $q_0 = 0, 1, 2, 5$. No correction for galactic evolution has been included (from [9]).

With the continued refinement of statistically-based distance indicators,[3] and the advent of the Hubble Space Telescope, there is hope that this frustrating uncertainty in H_0 soon will be be eliminated. For further discussion of the cosmic distance scale see [8] and *Early Universe: Reprints.*

In principle, the deceleration parameter q_0 can be measured without recourse to knowledge of H_0, as it merely measures the deviation of the red shift–distance relationship from the linear "Hubble law," $z = H_0 d_L$. In practice, however, the distance scale is again a problem as one requires reliable distances to objects at moderate to large red shifts. At such red shifts the "look back" times are a significant fraction of the age of the object, and one must worry about evolution. Uncertainties about the effects of galactic evolution on the intrinsic luminosity of galaxies have

[3]Essentially all of the traditional techniques for determining distances to distant galaxies involve the use of only a single object as a standard candle, e.g., the first-ranked galaxy in a cluster or a supernova. Statistical methods like the IR Tully-Fisher, Faber-Jackson, or similar relationships allow one to determine the distance to a cluster by using the properties of a large number of galaxies, e.g., by constructing an IR luminosity vs. rotation speed (or galaxy diameter) diagram.

prevented a definitive (or even near definitive) determination of q_0. In fact, there is not even agreement as to whether the "young" galaxies (i.e., galaxies at large red shift) should be intrinsically brighter or dimmer than the "old" galaxies (i.e., galaxies at small red shift).

An optical Hubble diagram compiled in 1978 [9], and IR and optical Hubble diagrams compiled in a recent review [10] are shown in Figs. 1.2 and 1.3.[4] At present, the Hubble diagram probably only constrains q_0 to be between 0 and a few. As we will discuss in Chapter 3, q_0 is related to Ω_0[5]

$$q_0 = \Omega_0(1 + 3w)/2, \tag{1.6}$$

where w is the present ratio of the pressure to energy density (for non-relativistic matter, $w \simeq 0$). Thus, current observations only restrict Ω_0 to the interval [0, *few*].

As we will discuss in Chapter 2, the functional dependence of the angular size of a standard ruler (e.g., the angular size of a galaxy or a cluster) depends upon Ω_0, and can be used to determine Ω_0. The results of such an attempt are shown in Fig. 1.4. Once again, this technique only restricts q_0 to the range 0 to a few.

Finally, we mention a very promising kinematic test of the standard cosmology which can be used to determine q_0 (or Ω_0): the galaxy number count vs. red shift test. The number of galaxies in a volume element comoving with the expansion, defined by the solid area $d\Omega$ and red shift interval dz, depends upon the number density of galaxies (per comoving volume), and the cosmological model. By counting galaxies as a function of red shift it is in principle possible to deduce q_0 (or Ω_0). Loh and Spillar [12] have made a preliminary (and somewhat controversial) attempt to measure Ω_0 based upon this technique and they infer a value of $\Omega_0 = 0.9^{+0.7}_{-0.5}$ (see Fig. 1.5). While this test is also subject to the effects of evolution, it is more sensitive to the evolution of the number density of galaxies than to the evolution of galactic luminosity. We will discuss the galaxy number count test at greater length in Chapter 2.

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[4]As emphasized in [10], evolutionary effects may be minimized by using the "IR" luminosity distance. Because of the red shift effect, optical light from distant galaxies comes predominately from hot, young, high-mass stars whose evolutionary time scale is short, while IR light comes from older, low-mass stars whose evolutionary time scale is longer.

[5]The quantity $\Omega_0 \equiv \rho_0/\rho_C$, where ρ_0 is the present mass density of the Universe, and ρ_C is the critical density, $\rho_C \equiv 3H_0^2/8\pi G = 1.88 \times 10^{-29}h^2\text{g cm}^{-3}$.

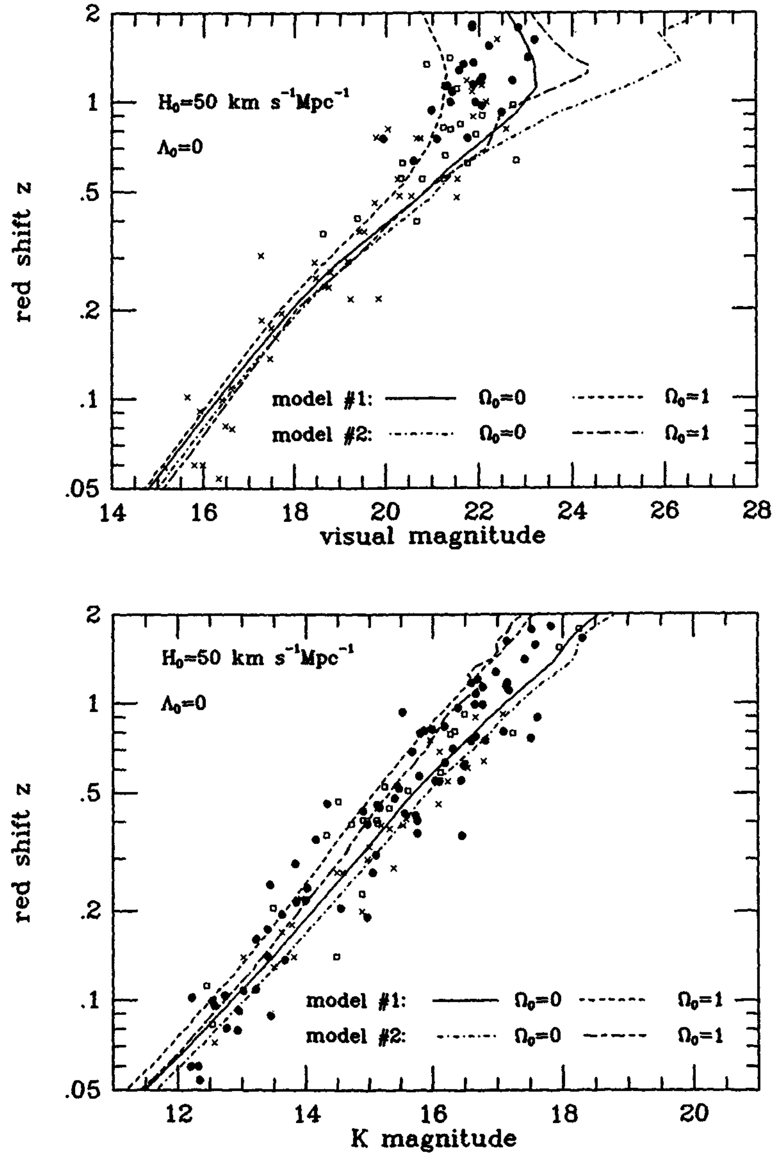

Fig. 1.3: Optical (top) and infrared (bottom) Hubble diagrams. For the infrared diagram, the K magnitude is proportional to the logarithm of the 2 μm luminosity distance. The solid and broken curves in the diagrams indicate effects of galactic evolution for a simple model. Note that evolutionary effects are more severe for the optical case (from [10]).

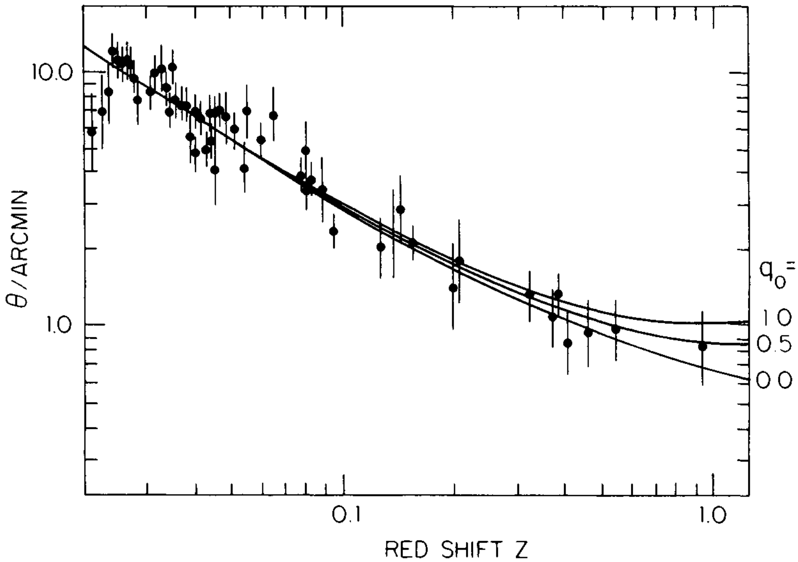

Fig. 1.4: The angle-red shift test. Shown are the angular diameters of galaxy clusters at different red shifts, and the theoretical curves for $q_0 = 0$, 0.5, and 1.0 (from [11]).

1.3 Large-Scale Isotropy and Homogeneity

A cornerstone of the FRW model is the high degree of symmetry of the FRW metric. As a practical matter the simplicity of the metric, which depends upon only one dynamical variable, the cosmic scale factor $R(t)$, makes the theoretical analysis tractable (even for unsophisticated physicists like ourselves!).

The assumption of isotropy and homogeneity dates back to the earliest work of Einstein, who made the assumption not based upon observations, but as theorists often do, to simplify the mathematical analysis. Today there is ample evidence for the isotropy and homogeneity for the part of the Universe we can observe, our present Hubble volume, whose size is characterized by $H_0^{-1} \simeq 3000h^{-1}$ Mpc $\simeq 10^{28}h^{-1}$ cm.

The best evidence for the isotropy of the observed Universe is the uniformity of the temperature of the CMBR: Aside from the observed dipole anisotropy, the temperature difference between two antennas separated by angles ranging from about 10 arc seconds to 180° is smaller than about one part in 10^4 (see Fig. 1.6). The simplest interpretation of the dipole anisotropy is that it is the result of our motion relative to the cosmic rest

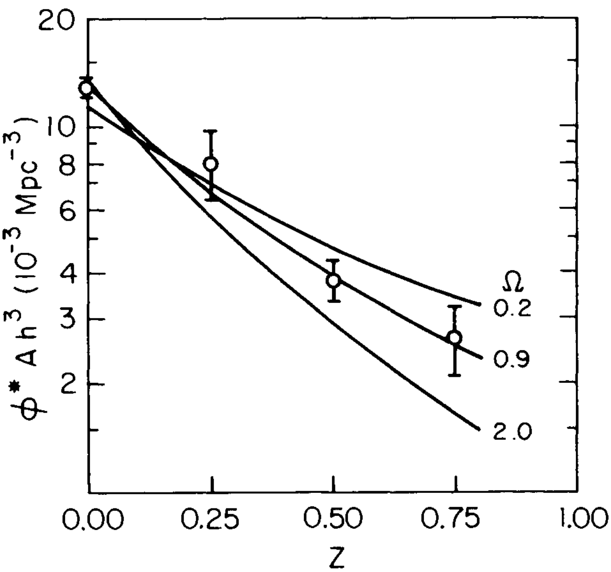

Fig. 1.5: Determination of Ω_0 from the galaxy number count test. The number of galaxies counted in the counting volume (dz, $d\Omega$) is proportional to $z^2 dz d\Omega H_0^{-3} A(z)\phi^*$, where ϕ^* is proportional to the galaxy number density per comoving volume and $A(z)$ depends upon the cosmological model (from [12]).

frame. If the expansion of the Universe were not isotropic, the expansion anisotropy would lead to a temperature anisotropy in the CMBR of similar magnitude. Likewise, inhomogeneities in the density of the Universe on the last scattering surface would lead to temperature anisotropies. In this regard, the CMBR is a very powerful probe: It is even sensitive to density inhomogeneities on scales larger than our present Hubble volume.[6] The remarkable uniformity of the CMBR indicates that at the epoch of last scattering for the CMBR (about 200,000 yr after the bang) the Universe was to a high degree of precision (order of 10^{-4} or so) isotropic and homogeneous.

There is additional supporting evidence for the isotropy of the Universe: the isotropy of the x-ray background radiation (to about 5%),[7] of

[6]Its sensitivity decreases as $(H_0^{-1}/\lambda)^2$; λ = length scale of the inhomogeneity [14].

[7]In addition, there is weak evidence for a dipole anisotropy of the cosmic x-ray background, with magnitude and direction consistent with that of the CMBR dipole anisotropy [15]. If the x-ray background arises from high-red shift sources, and the x-ray anisotropy indeed coincides with the CMBR anisotropy, this would indicate that

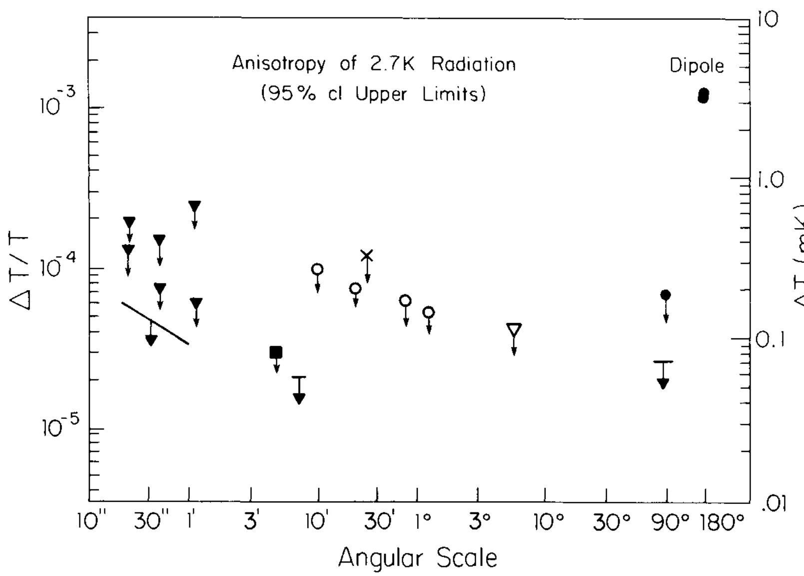

Fig. 1.6: RMS variation of the CMBR temperature as a function of the angular separation of the two antennas (from [13]).

the distribution of faint radio sources, and of galaxies themselves. Some substantial fraction of the x-ray background is believed to be from unresolved sources (e.g., QSO's) at high red shift. Likewise, a substantial fraction of the faint radio sources are radio-bright galaxies at high red shift. Both the Shane-Wirtanen (Lick) catalogue of about a million galaxies with effective depth of about 200 h^{-1} Mpc (see Fig. 1.7) and the IRAS catalogue of infrared selected galaxies with an effective depth of about 60 h^{-1} Mpc provide evidence for the isotropy of the galaxy distribution.

Direct evidence for the homogeneity of the distribution of galaxies is more tenuous. Galaxy counts in deep surveys provide supporting evidence, but their interpretation is not so straightforward. Moreover, since light does not necessarily trace mass, such surveys only determine the distribution of light (i.e., bright galaxies) and not a priori that of mass. In particular, if the mass-to-light ratio varies depending on the local environment (e.g., the local density), the light distribution will not reflect the true distribution of the mass. Moreover, it is somewhat disturbing—although perhaps not totally unexpected—that in the largest red shift surveys com-

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the frame defined by these distant sources is at rest with respect to the CMBR.

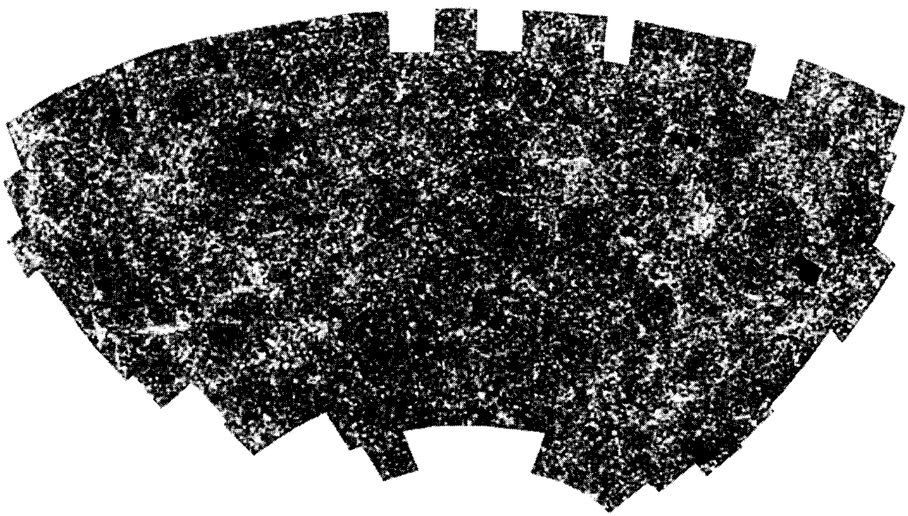

Fig. 1.7: Equal-area projection of a southern sky portion (4080 deg^2) of the APM catalogue. The density of galaxies per pixel (1 pixel = 14 (arc min)^2) is indicated by a grey scale. About 2 million galaxies are represented in this image (from [16]).

pleted, the biggest structures are as large as the limits set by the size of the surveys themselves. As larger red shift surveys are completed (the largest survey completed contains only about 9,000 galaxies), the distribution of light, if not mass, should be better understood.

Finally, we mention the evidence for homogeneity from determination of the "peculiar velocity field of the Universe." Peculiar velocity refers to the motion of an object (e.g., a galaxy) with respect to the cosmic rest frame (defined by the rest frame of the CMBR). In practical terms, it corresponds to a galaxy's velocity after its "expansion velocity" has been subtracted. The inhomogeneous distribution of matter leads to gravitationally-induced peculiar velocities of the order of

$$\delta v/c \simeq \Omega_0^{0.6}(\lambda/H_0^{-1})(\delta\rho/\rho)_\lambda \tag{1.7}$$

on the scale λ, where $(\delta\rho/\rho)_\lambda$ characterizes the amplitude of the mass inhomogeneity on the scale λ. Measured peculiar velocities extend to scales as large as $60h^{-1}$ Mpc or so, where peculiar velocities of order 600 km sec^{-1} have been measured, indicating very roughly that $(\delta\rho/\rho)_\lambda \sim 10^{-1}$ on these scales [17]. Note too, that in principle, peculiar velocity measurements have the attractive feature that galaxies serve only as test particles tracing out the gravitational potential and thus provide direct information about the mass distribution rather than just that of the light. We will discuss the peculiar velocity field in more detail in Chapter 9.

1.4 Age of the Universe

The age of the Universe can be measured in a variety of different ways: by using the expansion rate of the Universe to compute the time back to the bang; by dating the oldest stars in globular clusters; by dating the radioactive elements; by considering the cooling of white dwarf stars; by calculating the cooling time for hot gas in clusters, etc. At present, all techniques yield results consistent with the range 10 to 20 Gyr.

However, the uncertainties, especially the unknown systematics, preclude a definitive determination by any of the above techniques. In principle the present age of the Universe provides a very important test of cosmological models. We remind the reader of the discrepancy that existed until the 1950's between the expansion age, 2 Gyr for the then Hubble constant of $500\,\mathrm{km\,sec^{-1}Mpc^{-1}}$, and the age of the solar system, about 4.5 Gyr. That discrepancy led to the birth of the "ageless" steady state cosmology.

As we will discuss in Chapter 3, the expansion age is set by the Hubble time H_0^{-1} and Ω_0: for $\Omega_0 = 0$, $t_0 = H_0^{-1}$, with the age decreasing with increasing Ω_0 (e.g., for a matter-dominated model, $t_0 = (2/3)H_0^{-1}$ for $\Omega_0 = 1$). For the range of plausible values of H_0 ($h \simeq 0.4$ to 1.0), the Hubble age $H_0^{-1} \simeq 9.8$ to 24.5 Gyr.

Much work has been carried out to determine the ages of the oldest globular clusters, those which contain very metal-poor, pop II stars.[8] By detailed stellar modeling a theoretical Hertzsprung-Russell diagram can be constructed, and then compared to that observed for the cluster. Roughly speaking, the age of the globular cluster is determined by the position of the turn-off point on the main sequence for the red giant phase. The point where this occurs determines the mass of the stars that are just now entering the red giant phase. With recourse to stellar models for such stars one can calculate their ages. Most estimates of the ages of the oldest stars

[8]The oldest generation of stars, those which have low metal abundances (elements with $A > 4$), are referred to as pop II, while younger stars, like our sun, with metal abundances of order 2% (by mass) are referred to as pop I. The hypothetical generation of even older stars (possibly pre-galactic in origin) are referred to as pop III.

in the galaxy determined this way are in the range 10 to 20 Gyr. Systematics inherent to this ingenious and powerful technique (stellar mass loss, convection, metallicity effects, uncertainties in the distance scale, interstellar reddening, etc.) prevent determination of a more precise age or even a definitive estimate of the uncertainty. Since the oldest globular clusters likely formed much less than 1 Gyr after the Galaxy formed, and the Galaxy itself formed less than a few Gyr after the bang, these age determinations also serve to date the Universe.

Since Rutherford, cosmologists have used radioactive clocks to date the Universe (and many other objects within it). For cosmological purposes the most suitable radio isotopes are: ^{232}Th (mean lifetime $\tau = 20.27$ Gyr); ^{235}U ($\tau = 1.015$ Gyr); ^{238}U ($\tau = 6.446$ Gyr); ^{87}Rb ($\tau = 69.2$ Gyr); and ^{187}Re ($\tau = 62.8$ Gyr). In order to use these clocks one must know the relative abundances of these isotopes (or pairs of isotopes) today and at the epoch of their production. All of these isotopes are so-called r-process elements, elements thought to be produced by rapid neutron capture in an early generation of stars. To illustrate this technique, consider the pair ^{235}U and ^{238}U. The production ratio is calculated to be $[^{235}\mathrm{U}/^{238}\mathrm{U}]_P \simeq 1.71$, while the present abundance ratio is $[^{235}\mathrm{U}/^{238}\mathrm{U}]_0 \simeq 0.00723$. The time elapsed since production is then

$$\Delta t = \frac{\ln[^{235}\mathrm{U}/^{238}\mathrm{U}]_P - \ln[^{235}\mathrm{U}/^{238}\mathrm{U}]_0}{\tau_{235}^{-1} - \tau_{238}^{-1}} \simeq 6.6 \text{ Gyr}. \tag{1.8}$$

What does this time interval indicate? If we knew that all the r-process elements were produced shortly after the Galaxy formed, Δt would provide an accurate age for the Galaxy—but we don't! If r-process elements have been formed continuously since the formation of the Galaxy then the age of the Galaxy must be considerably greater. Our simple example illustrates some of the inherent difficulties involved with this technique. Many, much more sophisticated, analyses have been carried out, with derived ages for the Galaxy spanning the range 10 to 20 Gyr.

Recently, Winget, et al. [18] have used the cooling of white dwarf stars to determine the age of the Galaxy. The oldest white dwarf stars are of course the coolest and least luminous. The observed number of white dwarfs drops precipitously below a luminosity of $3 \times 10^{-5} L_\odot$—presumably due to the finite age of the Galaxy. Based upon this observation and models of white dwarf cooling, these authors conclude that the age of the Universe is 10.3 ± 2.2 Gyr.[9]

[9]Since white dwarf stars are only observed in the disk, the authors have actually

To summarize our brief and very pedestrian review of age determinations for the Universe, we can say that all techniques yield an age consistent with the range 10 to 20 Gyr. This in itself is very reassuring, cf. the "age crisis" in cosmology which lasted until the 1950's. Moreover, even this somewhat inprecise dating of the Universe provides an important test of cosmological models. In Chapter 3 we will show that for a matter-dominated model a lower bound to the age of the Universe of 10 Gyr provides an upper bound to Ω_0 of 6.8 (for $h \geq 0.4$) or 3.2 (for $h \geq 0.5$). Further, if we consider a flat ($\Omega_0 = 1$), matter-dominated model, then $t_0 \geq 10$ Gyr, necessarily implies that $h \leq 0.65$. That is, a value of $H_0 \geq 65$ km sec^{-1} Mpc^{-1} would rule out such a cosmological model. A determination of H_0 to a precision of 10% is believed possible with the Hubble Space Telescope; if and when this is done, there could be important cosmological implications.

1.5 Cosmic Microwave Background Radiation

The CMBR provides the fundamental evidence that the Universe began from a hot big bang. As we will discuss in Chapter 3, the surface of last scattering for the CMBR was the Universe at a red shift $z \sim 1100$ and age of $180,000(\Omega_0 h^2)^{-1/2}$ yr. Flux measurements of the CMBR ranging from wavelengths of about 70 cm down to wavelengths of less than 0.1 cm are consistent with that of a black body at temperature 2.75 ± 0.015 K (see Fig. 1.8). Such a temperature corresponds to a present photon number density of 422 cm^{-3}.[10]

As mentioned earlier, the temperature of the CMBR across the sky is remarkably uniform: $\Delta T/T \lesssim 10^{-4}$ on angular scales ranging from 10 arc seconds to 180° (after the dipole anisotropy has been removed); see Fig. 1.6. The observed high degree of isotropy not only provides strong evidence for the present level of large-scale isotropy and homogeneity of our Hubble volume, but also provides an important probe of conditions in the Universe at red shifts of order 1100.

As we will discuss in Chapter 9, the primeval density inhomogeneities necessary to initiate structure formation result in predictable temperature

estimated the age of the disk. If, as some suspect, the disk formed several Gyr after the galaxy, then several Gyr should be added to these estimates for the age of the galaxy.

[10]We mention that recently Lange and his collaborators [19] have reported evidence for a distortion in the CMBR spectrum in the submillimeter region (Wien part of the spectrum). This submillimeter excess corresponds to about 10% of the total energy in the CMBR. If their result stands it will have profound implications for cosmology.

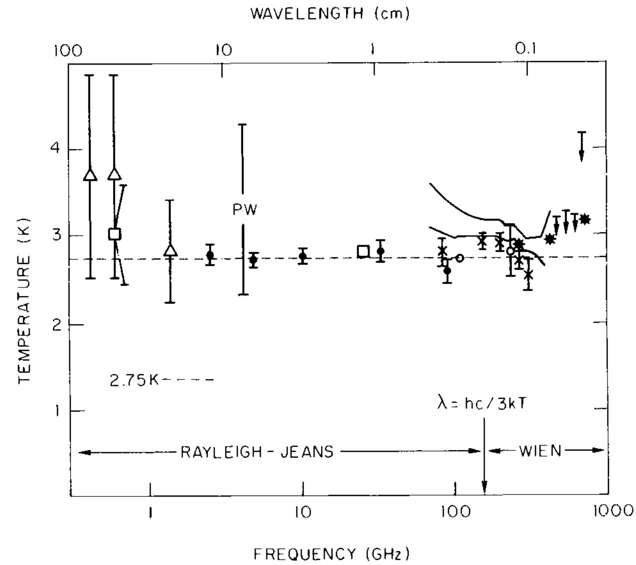

Fig. 1.8: Temperature measurements of the CMBR (from [20]). PW indicates the discovery measurement of Penzias and Wilson, and ⋆ indicates the recent measurements of Lange et al. [19].

fluctuations in the CMBR, and so anisotropies of the CMBR provide a powerful test of theories of structure formation. In fact, the current limits to the anisotropy come within factors of 3 to 10 of the predictions of the most attractive scenarios of structure formation: inflation-produced adiabatic density perturbations with hot or cold dark matter, and cosmic string-induced density perturbations with hot or cold dark matter. Spectral distortions in the CMBR, if they exist, may provide fossil evidence for the early history of galaxy, and possibly even star, formation.

1.6 Light-Element Abundances

Primordial nucleosynthesis is the earliest test of the standard model. Nuclear reactions that took place from $t \simeq 0.01$ to 100 sec ($T \simeq 10$ MeV to 0.1 MeV) resulted in the production of substantial amounts of D (D/H $\simeq$ *few* $\times 10^{-5}$), ^{3}He (^{3}He/H $\simeq$ *few* $\times 10^{-5}$), ^{4}He (mass fraction $Y \simeq 0.25$), and ^{7}Li (^{7}Li/H $\simeq$ 1 to 2 $\times 10^{-10}$). Deuterium and Helium-4 are of particular importance as there are apparently no contemporary astrophysical processes that can account for their observed abundances. While ordinary stars produce ^{4}He, even in regions where there has been significant stellar processing, the stellar contribution is only about $\Delta Y_{\rm stellar} \simeq 0.05$. While the observed Deuterium abundance is very small, even this small amount is difficult, if not impossible, to account for, as almost all astrophysical processes destroy the weakly-bound deuteron which burns at the relatively low temperature of about 0.5×10^6 K.

The comparison of the predicted abundances with "inferred" primordial abundances provides a very powerful test of the standard cosmology. At present there is concordance between the predicted and observed abundances for these four isotopes, provided that the baryon-to-photon ratio η is in the interval $\eta = (4 \text{ to } 7)\times 10^{-10}$, corresponding to $0.015 \leq \Omega_B h^2 \leq 0.026$, or taking $0.4 \leq h \leq 1.0$, $0.014 \leq \Omega_B \leq 0.16$. The standard cosmology passes this very stringent test with flying colors, and further provides important information about the density of baryons in the Universe. In fact, primordial nucleosynthesis provides the most precise determination of the baryon density. Most significantly, primordial nucleosynthesis implies the fraction of critical density in baryons, Ω_B, must be less than one: For $\Omega_B \sim 1$, Deuterium would be severely underproduced, and both ^{4}He and ^{7}Li would be overproduced. If Ω_0 is equal to 1, then primordial nucleosynthesis provides the strong indication that most of the mass density of the Universe is in a form other than baryons.[11]

Finally, we add that primordial nucleosynthesis has also been used as a probe of the early Universe and particle physics. We have already mentioned that it provides an important constraint to the baryon density. It has also been used to constrain the existence of additional hypothetical, light ($\lesssim$ MeV) particle species predicted by some particle theories (e.g., additional light neutrino species). Such species would contribute to the energy density of the Universe, and thereby affect the predicted abundances. Chapter 4 is devoted to a detailed discussion of primordial nucleosynthesis.

1.7 The Matter Density: Dark Matter in the Universe

Previously, we discussed kinematical methods of determining Ω_0; here we discuss dynamical means of measuring Ω_0. Measuring the mass density of the Universe is a challenging task! Figuratively speaking, the average

[11] In Chapter 4 we will discuss two unconventional scenarios of primordial nucleosynthesis which, if correct, would allow $\Omega_B \sim 1$.