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Particle and Nuclear Astrophysics and Cosmology in the Next Millennium - Snowmass 1994

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Organizers and conveners of the 1994 Snowmass Summer Study

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From June 29 to July 14, 1994, nearly 450 astronomers, astrophysicists, cosmologists, high-energy physicists, nuclear physicists, and gravitation physicists met in the mountains of Colorado to define and develop a vision for the future of an emerging interdisciplinary field. This book is the permanent record of their deliberations. The purpose of this introduction is to express some unifying themes, and provide an overview of the Snowmass summer study.

§1 Introduction

Snowmass 1994 brought together for the first time a very disparate, yet interconnected, group of astrophysicists, cosmologists, particle physicists, nuclear physicists, gravitation physicists, and astronomers for an intensive two-week Summer Study to discuss the gamut of problems that link them intellectually. The range of topics discussed was vast, but clear connections could be easily discerned. Thus, even though the Summer Study was organized in terms of five topical "supergroups" (Neutrinos, Cosmic Rays, Low-Background Experiments, Gravitational Phenomena, and Cosmology), there were clear overlaps. For instance, short-baseline neutrino oscillation experiments probe neutrino masses which are cosmological significant. Results in this area may well impact other searches for dark matter in low-background experiments. Similarly, searches for gravitational waves produced by violent events in the universe may illuminate other mysterious phenomena, like intense rapidly varying gamma-ray bursts.

The remarkable high attendance at Snowmass 1994 (nearly 450 participants) signalled a field coming of age. Although it is still difficult to draw a clear boundary around this emerging discipline of Particle and Nuclear Astrophysics and Cosmology, two facts are contributing to its vitality. First, there is a strong symbiotic synergy resulting from the joining of disparate disciplines. Thus, for example, the organizational and computational talents of particle physicists have emboldened astronomers to scan millions of stars for the Macho searches. Conversely, remarkable astrophysical phenomena like super energetic air showers have enticed physicists away from their laboratories to construct extensive open-air detector arrays to better understand these phenomena. Second, the development of new instruments, telescopes, and detectors has been most crucial. Indeed, it is this fact that drives the field. From COBE to Gallex and Kamiokande, to the new 8m telescopes and the instruments on CGRO and the Hubble observatory, data in profuse quantities has been flowing. These data is the lifeblood of this new field. What is particularly exciting is that this flow of new information is just beginning, with a number of second generation projects underway and many new initiatives already well advanced.

In this overview, we want to describe briefly some of the accomplishments of this field and the intellectual goals that guide it. At the same time we want to delineate some of the areas where one can expect progress in the future, outlining some of the proposed new initiatives. In keeping with the organization of the Summer Study this overview is structured in a similar fashion, except that we have incorporated the discussion of low-background experiments into that of the other areas.

§2 Neutrinos

Neutrinos are playing an increasingly crucial role in tests of the standard model of electroweak interactions, in cosmology, and in probing the nuclear and particle astrophysics of stars and supernovae. In particle physics neutrino properties may provide us with a window on new physics phenomena at energies scales well beyond the direct reach of accelerators. Measurements of neutrino masses and mixing could provide the experimental foundations for building a new and more general standard model. In cosmology, neutrinos are a leading candidate for the "missing mass" that appears to govern the clustering of galaxies on very large scales. Measurements by COBE and other groups of the angular variations of the temperature of cosmic microwave photons suggest that such "hot dark matter" is present. In nuclear and particle astrophysics, neutrinos provide a probe of the interiors of our sun and supernovae; higher energy neutrinos could allow us to look into the centers of active galactic nuclei.

There is also no small measure of serendipity in the relationship between these neutrino astrophysics subfields. In the past decade it was discovered that the effects of neutrino mass and flavor mixing are marvelously enhanced as solar neutrinos traverse the sun. It also appears that the tau neutrino masses favored by cosmologists could help explain how supernovae explode, and thus how our galaxy has become enriched in the heavy elements responsible for life. Such connections have greatly stimulated the field, allowing us to look at neutrino physics from new angles. It also has meant that we have added to our "toolbox" of laboratory neutrino experiments powerful new cosmological and astrophysical probes of neutrino properties.

As we enter the new millennium, neutrino physics stands at an important threshold, one driven by the remarkable technological revolution taking place in astrophysics. In the past decade detectors have been developed to see solar neutrinos event-by-event. Neutrinos from a supernova were detected for the first time, beginning an era where we can monitor our galaxy, and perhaps beyond, for stars in gravitational collapse. Detectors using the oceans, lakes, and antarctic ice have begun a new era of high-energy neutrino astronomy. Indirect probes, such as COBE and gravitational lensing measurements, have provided evidence of neutrino mass. In parallel with these astrophysical advances, laboratory experimenters have strived for and achieved unprecedented precision in measurements of the beta decay spectrum, double beta decay, and neutrino oscillations.

One of the driving forces behind this field is the expectation that new physics lies very close to our present experimental horizons. Almost all extensions of the standard model predict neutrino masses. In many of these the smallness of the neutrino mass - many orders of magnitude below the masses of other fermions - has a natural explanation in terms of the seesaw mechanism: $m_\nu = m_D^2/m_R$ where m_D is a typical quark or charged lepton mass and m_R is the scale of new physics. Values of $m_R \sim 10^{12}$ GeV produce neutrino masses relevant to the dark matter and solar neutrino problems, thus demonstrating the power of such experiments to probe beyond the scales of present colliders. The seesaw mechanism beautifully explains why neutrino masses are so different from the natural mass scale m_D of other standard model fermions: the small parameter m_D/m_R arises as a ratio of a familiar Dirac mass of the standard model and a new mass scale. Demonstration that neutrino masses follow a seesaw pattern might be the first step in understanding the puzzling pattern of masses throughout the standard model.

This possibility has motivated heroic efforts to detect neutrino masses. In the past decade direct searches for mass effects in the shape of the β decay spectrum of tritium have reduced the limits on the electron antineutrino mass to about 5 eV. Double beta decay experiments using isotopically enriched detectors have set limits on the Majorana mass of the electron neutrino of about 1eV. Majorana masses are associated with the identity of the neutrino and its antiparticle, a possibility that does not arise for other standard model fermions. This question is intimately connected with the seesaw mechanism and with the conservation of total lepton number.

While no evidence for neutrino masses has arisen from these experiments, others do suggest nonzero masses. The cosmological evidence for neutrino mass has often led to the conjecture that the third-generation neutrino, ν_τ, has a mass near 10 eV. Masses of this scale can be probed in short-baseline neutrino oscillation experiments. Indeed, one current experiment claims evidence for neutrino masses of a few eV.

But perhaps the most tantalizing suggestion for neutrino masses comes from efforts to detect solar neutrinos. The combined results of the ^{37}Cl, Kamiokande II/III, and SAGE/GALLEX experiments reveal a pattern of fluxes that is very difficult to reconcile with plausible variations in the standard solar model, but quite compatible with neutrino oscillations occurring in matter. The preferred solution corresponds to a mass difference between neutrino mass eigenstates of $\delta m^2 = m_2^2 - m_1^2 \sim 10^{-5}$ eV^2. If the seesaw mechanism is correct, this suggests that the heavier neutrino involved in the oscillation has a mass $\sim$ few $\times 10^{-3}$ eV. This would be a natural value for the mass of the ν_μ if the ν_τ is the source of hot dark matter. Flavor oscillations in matter (the MSW mechanism) produce distinctive experimental signals: there is a characteristic distortion of the ν_e spectrum and an appearance of ν_μ (or ν_τ) neutrinos. Thus there is great excitement in the community about new experiments, such as the Sudbury Neutrino Observatory (SNO) and Super Kamiokande, that can be mounted to detect such signals.

Several underground neutrino detectors indicate that there may be a deficit in the ratio of ν_μ to ν_e in neutrino interactions following cosmic ray interactions. If neutrino oscillations are responsible for the anomalies, the deficit is consistent with an m_2 of about 0.1 eV and requires large mixing angles. As these parameters can be explored in accelerator neutrino oscillation experiments employing long baselines, they have stimulated efforts to mount new experiments at Fermilab, CERN, BNL, and KEK.

It is likely that some of these hints for neutrino mass are false: all of the evidence is difficult to incorporate into a simple theory, given the Z width constraint of three light active neutrinos and the big-bang nucleosynthesis constraint on sterile neutrinos. But many believe that certain results, such as the solar neutrino problem, may hold up: four experiments are consistent and indicate a neutrino mass in a range favored by theory. Thus great

hope exists that neutrino physics may lead us beyond the standard electroweak model.

Because neutrinos are so weakly interacting, they play a special role in energy transport within dense stars. The central helium cores of red giants are cooled by neutrino emission. Because the onset of helium burning depends delicately on this cooling, red giant observations can be used to constrain neutrino properties such as magnetic moments. The astrophysical limits exceed the sensitivity of laboratory limits by about two orders of magnitude. Similarly, almost the entire binding energy of core-collapse supernovae (10^{53} ergs!) is carried off by neutrinos. One of the great challenges for the coming years is to measure the temperatures of the ν_e, $\bar{\nu}_e$, and heavy-flavor supernova neutrinos. Because of the MSW mechanism, a distinctive temperature inversion between ν_e and ν_τ should signal the existence of a cosmological interesting ν_τ mass. This phenomenon makes supernova neutrino physics enormously important to cosmology. If such an MSW crossing occurs, it would also lead to a more robust explosion by enhancing the energy neutrinos deposit in the star's mantle.

The nuclei synthesized in the big bang and during the evolution of our galaxy provide fossil evidence of past neutrino reactions. Big bang constraints on the production of helium suggested there were only 3-4 light neutrino species well before measurements of the Z width. Supernovae are the factories that produce, and then eject into the interstellar medium, most of the heavy nuclei found in second-generation stars like our sun. Many of these are made by rapid neutron capture in the hot plasma blown off the star by a neutrino wind. The MSW mechanism mentioned above frequently destroys the conditions necessary to this synthesis. Thus the issue of a massive ν_τ ties together cosmology, the supernova explosion mechanism, and the associated nucleosynthesis. An improvement in our understanding of one of these problems will limit the possibilities for the others.

This short introduction to the presentations at Snowmass is meant to provide a snapshot of a field in great flux. Driven by new experiments and by theories, such as supersymmetric grand unification, that predict new phenomenon within the reach of these experiments, interest in this field has exploded. The path for the next decade, not to mention the next millennium, is both exciting and unclear. It is possible, with SNO and Super Kamiokande nearing completion, that definitive proof of massive neutrinos and neutrino mixing could be in hand well before the 1990's end. If this occurs, neutrino physics will have provided the experimental foundations for the next standard model of particle physics, one having profound implications for cosmology and astrophysics. If no such "smoking gun" is found, we will continue to seek the pattern that accounts for dark matter, the absence of solar neutrinos, and the origin of the elements.

§3 Cosmic Rays

The array of astrophysical subjects gathered in the category of cosmic rays was deliberately chosen to be very broad, ranging from hard X-rays to protons and atomic nuclei with energies beyond 10^{20} eV. This grouping is related to the fact that there is no natural break in this vast energy range which covers sixteen orders of magnitude. There may be natural divisions marked by differences of instrumentation but in most cases these are bridged by natural scientific links. Examples abound. The space based gamma-ray astronomy as exemplified by the results of the Compton Gamma-Ray Observatory (CGRO) is linked with ground based observations which, when fully developed, can extend the energy range beyond the upper limit of the CGRO (20 GeV). The ground based techniques for gamma-ray astronomy merge into techniques of more traditional cosmic ray physics when the energies surpass 10 TeV. There are strong scientific links as well between phenomena at greatly different scales of energy. The synchrotron emission of low energy gamma-rays from the Crab nebula can be related to higher energy gamma-rays produced by inverse Compton scattering of the high energy electrons responsible for that synchrotron emission. Gamma-rays, unlike the charged cosmic ray particles, are unaffected by magnetic fields and can reveal sources of the charged cosmic ray particles. Thus, the study of all kinds of radiation incident on the earth provide insight into a broad range of astrophysical problems and mysteries.

3.1 Space-based gamma-ray astronomy

The existence of the earth's atmosphere dictates the choice of detection techniques to observe astrophysical objects in various ranges of the electromagnetic spectrum. From the ultra-violet to gamma-rays of energy $\sim$ 20 GeV the atmosphere is opaque. Thus, observations must be made from instruments on satellites or on high altitude balloons. It is a general rule that the intensity of electromagnetic radiation from an astrophysical source decreases with increasing photon energy. Fortunately the typical intensities are sufficient so that the acceptance of detectors placed above the atmosphere is reasonably matched to the aforementioned range. Interest at Snowmass was primarily devoted to the future of observations in three ranges: 0.01-1 MeV, 1-30 MeV, and 30 Mev to 10 GeV; with improvements suggested in both spatial and energy resolution. Most physicists and astronomers are aware of discoveries made by the CGRO, in particular of the gamma-ray bursts (GRB) made by the BATSE detector. These intense bursts of gamma-rays are isotropically distributed in the sky and do not correlate with bursts in other parts of the electromagnetic spectrum. The EGRET detector aboard the CGRO has discovered many active galactic nuclei (AGN's), which are very bright as seen in GeV gamma-rays. This is a discovery which was completely unexpected.

A number of new concepts for a space-based instrument to follow the CGRO are under consideration. These include new survey instruments to explore the entire sky with a wide field, good spatial and energy resolution, and increased sensitivity in the the hard X-ray region. These instruments require the large field of view because most of the activity in this area is strongly time varying. They will be dedicated to the exploration of a range of phenomena involving pulsars, AGN's, and black holes—all objects that are poorly understood.

3.2 Ground-based gamma-ray astronomy

For gamma-ray energies above 20 GeV, the atmosphere shifts from being an opaque shield to being an essential part of the detector. At these energies the gamma-rays produce air showers in the atmosphere that can be observed either by the Čerenkov radiation produced by the shower particles or, at high altitudes, the shower particles themselves. At present, positive results have been obtained only with the Čerenkov technique. Mirrors image the Čerenkov light on to a cluster of photomultipliers. The effective area of this detector is given by the size of the pool of Čerenkov light on the ground which is $\sim 10^4$ km^2. Nature cooperates by allowing the gamma-ray signal to be detected on the ground with an effective area much larger than what could have been possible for a space based detector.

In recent years two pulsars (the Crab and PSR 1706-44) have been convincingly observed at TeV energies. Even more remarkable has been the observation of an AGN, Markarian 421. AGN's are extra galactic objects thought to be powered by accretion of material onto massive black holes. These same objects are observed in the 10 GeV range by the EGRET detector on the CGRO. Other AGN's, seen by the CGRO much brighter than Markarian 421, are not seen at TeV energies. The explanation of these remarkable observations may involve the softening of the spectra at the higher energies or the absorption of the TeV gammas by infrared photons. Only the extension of gamma-ray astronomy between 20 GeV and 200 Gev will be able to answer these questions. To lower the threshold for ground-based gamma-ray astronomy is an imperative and is technically feasible. This was discussed at Snowmass, along with other projects, including a large water detector to extend the sensitivity to the higher energy components of the GRB spectra.

3.3 Over the Knee

The cosmic rays which strike the earth isotropically comprise nuclei with abundances which are very similar to solar system abundances, except that elements with high ionization potential are systematically suppressed. It is as if the particles are injected at low energy into an accelerator. It is believed that this scenario is correct with supernova shock waves serving as the accelerator. Shock acceleration naturally produces a power law spectrum as observed. Detailed examination of this acceleration mechanism suggests that the upper limit of this process occurs at about E/Z= 10^{15} eV. Curiously the cosmic ray spectrum steepens at about 3×10^{15} eV which may be related to the upper limit of acceleration.

The cosmic rays are contained in the galaxy by its magnetic field. As the cosmic rays pass through the dust and material in the galaxy, nuclear species, far in excess of the solar abundance, are produced by spallation reactions and give a measure of the average amount of galactic material traversed by the cosmic rays and hence their lifetime. The spallation products show that the mean life of the cosmic rays in the galaxy is about 10^7 years and that the particles with higher magnetic rigidity escape from the galaxy more easily. These facts imply that the mean atomic weight of the cosmic rays should increase with their total energy in the region of the knee. Since the flux of cosmic rays falls rapidly with energy, it has been difficult to directly measure the abundances above 10^{14} eV. New techniques and new instruments will permit the direct measurement of the relative abundances up to 10^{15} eV. Indirect measurements of the mean atomic number will be possible by means of the simultaneous measurement of a number of shower parameters. This technique will be effective above 10^{14} eV, so that an overlap of the two techniques is possible.

Beyond the knee little is known about the cosmic rays other than the energy spectrum. One knows neither the acceleration mechanism, nor the source (galactic or extra galactic), nor the mean atomic number. In the next decade technical means will be developed to answer these questions. Cosmic rays do not exist independently of other powerful astrophysical phenomena; the effort to understand the origin of cosmic rays bears on a much broader domain of astrophysics.

Among the charged cosmic rays there are also electrons, positrons, and antiprotons which are much less abundant. Their presence in the cosmic rays is expected at a predictable level due to interactions of the primary cosmic rays with galactic material. Excesses of the antiparticle components are signals of exotic phenomena such as annihilating dark matter. Improvements in technology will permit much more sensitive investigation of these components.

3.4 Highest Energy Cosmic Rays

Over thirty years ago a cosmic ray was observed that had an energy $\sim 10^{20}$ eV. Since that time some ten events have been observed with energies in excess of 10^{20} eV. With these extraordinary events, attention is brought to the upper end of the cosmic ray spectrum. Cosmic rays with energy above 10^{19} eV defy easy explanations for their acceleration. These cosmic rays have been observed by four independent detectors which agree on the shape and flux. There is structure at the end of the spectrum suggesting a complex set of sources. The fluxes are low, about one cosmic ray above 10^{19} eV per km^2 per year and about one above 10^{20} eV per century.

Recently two events with energies of 2.0 and 3.2×10^{20} eV have been observed. These events must have originated at distances cosmologically close to earth. Cosmic rays have a strong energy loss in their transport through the 2.7° cosmic background radiation and these two cosmic rays must have traveled ≤ 30 Mpc. Because of their high energy they travel in the galactic and extragalactic magnetic field with little deflection and hence should point close to their source. Neither of these cosmic rays points to any plausible source within the proscribed distance. Furthermore, there is no clear understanding how these energies can be reached using the properties of known astrophysical objects. This puzzle can only be answered with new massive detectors.

At present, a detector with acceptance of 200 km^2-ster is operating in Japan and a detector with 500 km^2-ster is under construction in Utah. While these detectors will begin to work on this puzzle, the final resolution will require massive new detectors of $\sim 5,000$ km^2 area placed in the northern and southern hemispheres.

§4 Gravitational Phenomena

Gravitation physicists seek to understand the nature of gravity, both classical and quantum. Is general relativity really the correct classical theory, not only in the solar system where gravity is weak, but also in compact objects and on cosmological scales where it is nonlinearly strong? What are the (as yet ill-understood) laws of quantum gravity that govern the birth of the universe and the cores of black holes and black-hole evaporation? What kinds of new phenomena are predicted to exist by general relativity (black holes, singularities, soliton stars, cosmic strings, ...) and by quantum gravity (black-hole evaporation, the birth of the Universe, the creation and destruction of classical spacetime in "singularites", ...).

Many of these issues are beyond the reach of 20th century human technology and remain the sole province of theorists—both gravitation theorists and particle theorists. However, other gravitational issues have become experimentally accessible or will be so in the near future, most notably black holes, and gravitational waves as a tool for probing black holes, neutron stars, soliton stars, cosmic strings, and the early universe. These experimentally accessible phenomena have much intellectual contact with Particle and Nuclear Astrophysics and Cosmology, and thus were included in the Snowmass Study. Also included were two quantum-gravity phenomena (quantum cosmology and black-hole evaporation) which, though not directly experimentally accessible today, nevertheless may have long-term import for Particle and Nuclear Astrophysics and Cosmology.

4.1 Quantum Aspects of Gravity

General relativity theory insists that the Universe began in a big-bang singularity where the density of matter and the curvature of spacetime were both infinite. Relativity also insists that singularities of infinite density and curvature reside inside black holes. Simple quantum mechanical considerations predict, however, that when the density and curvature exceed "Planckian" values constructed from Planck's constant $\hbar$, Newton's gravitation constant G and the speed of light c (density $c^5/\hbar G^2 \sim 10^{94}$g/cm^3, radius of curvature $\sqrt{\hbar G/c^3} \sim 10^{-33}$cm), general relativity must break down, space and time as we know them must cease to exist, and a new set of physical laws and phenomena called "quantum gravity" must take over. Thus, the cores of black holes and the origin of the universe should be the domain of quantum gravity.

There is hope, from cosmological observations of what came out of the big bang, to get a handle on the quantum-gravity origin of our Universe, i.e., on its "Planck era". One can come at this from two different directions. The first is that of quantum cosmologists who use candidate, partial formulations of the laws of quantum gravity to try to deduce what emerged from the big bang and how the Universe made its transition from an initially quantum mechanical object to the largely classical object in which we now live. This is the direction taken by participants in the Snowmass G1 working group. The second direction is that of astrophysicists and physical cosmologists who begin with observations of the universe today and try to extrapolate back toward the Planck era. This direction, which was taken by Snowmass supergroup C and is explored in Sec. 5, is now awash with wonderful, new observational data and new ideas that might lead it into firm contact with the quantum-gravity direction. Such contact might seriously constrain candidate theories of quantum gravity, or it might simply reveal that (by virtue of inflation of the early universe; cf. Sec. 5) the Universe today is not very sensitive to the details of quantum gravity and the Planck era.

A successful partial step toward quantizing gravity was achieved in the 1970s, when several theorists, coming from different directions, converged on an apparently unique way to treat quantum fields that reside in the classical, curved spacetime of general relativity. Much to everyone's amazement, the resulting *quantum field theory in curved spacetime* predicted that a black hole must emit radiation ("Hawking radiation") and thereby must evaporate, if one waits long enough (far far longer than the Universe's age for stellar mass black holes, but much less for holes less massive than $\sim 10^{-19} M_{\odot}$).

The prediction of black-hole evaporation has led to a theoretical conundrum, the resolution of which may teach us much about the full laws of quantum gravity: One can imagine forming a black hole by the implosion of matter that is in a quantum mechanically pure state. Since the Hawking radiation, by which the hole ultimately evaporates, is (or appears to be) in a thermally randomized, mixed state, the hole's formation and subsequent evaporation seems to transform a pure state into a mixed state. In other words, information about quantum mechanical correlations is lost not just in practice, but even in principle. Such an information loss and pure-to-mixed transition is forbidden by the standard Hamiltonian formulation of quantum mechanics, but is permitted by certain generalizations of quantum theory based on Feynman's path integral methods.

Since the endpoint of the evaporation is governed by the (ill-understood) full laws of quantum gravity, it may be this information loss is trying to tell us that quantum gravity cannot be formulated in a Hamiltonian way. However, this is just one of several possible implications of the apparent information loss—and the one that most theorists find least palatable. While there is great disagreement about the real message, there is general agreement that theorists are likely to learn much about the interface between general relativity, quantum theory, and particle theory by struggling to decipher the endpoint of black-hole evaporation and other quantum aspects of small black holes. That struggle was the principle focus of Snowmass Group G1.

4.2 Black Hole Astrophysics

Black holes are predicted to exist by general relativity, and there is compelling *circumstantial* evidence that they do exist in relative profusion in the Universe in two varieties: stellar-mass black holes ($M \sim 3$ to $50 M_{\odot}$) that are remnants of the evolution of massive but normal stars, and supermassive black holes ($M \sim 10^5$ to $10^9 M_{\odot}$) that reside in the nuclei of galaxies and quasars. A third variety, primordial black holes formed in the very early universe with masses as small as $\sim 10^{-19} M_{\odot}$ and quantum mechanical evaporation times as short as the Universe's age, might well exist but there is no compelling observational evidence for them.

The general relativistic, classical theory of black holes (which is relevant to all stellar-mass and supermassive holes) is in fairly complete shape: Thanks to the "no-hair" theorem, we know that all the properties of such a hole should be fully determined by its mass and spin; and thanks to many years of analysis by many gravitation theorists, we now fully understand those predicted properties, with one major exception. We do not yet understand in any detail the behaviors of highly dynamical black holes (e.g., colliding and coalescing black holes). That dynamical understanding may come within the next decade, as a result of combined numerical solutions of Einstein's equations on supercomputers and gravitational-wave observations of black-hole collisions (Sec. 4.3).

With classical black-hole theory mostly in hand, black-hole research has become largely observational. Current and future observational studies have four main goals: (i) to test, observationally, the predicted properties of black holes (for example, to measure the details of the curvature of spacetime around a black hole and see whether they are in accord with the no-hair theorem), (ii) to prove unequivocally that one or more of the observed black-hole candidates is indeed a black hole, so we no longer have to make do with circumstantial evidence, (iii) to determine the distributions of black holes in the universe (their numbers, spatial distributions, and distributions of mass and spin), and (iv) to explore the roles of black holes in astrophysical phenomena (their births, and their interaction with stellar companions and with accretion disks and the interstellar medium).

The latter goals (black-hole distributions and astrophysical roles) are part of main-stream astronomy and astrophysics, and are being pursued with moderate success (assuming the objects studied really are black holes), using a variety of astronomical instruments and analyses. The former goals (uniquivocal proof that an observed candidate is truly a black hole, and quantitative tests of black-hole theory) have been more problematic, and were a primary focus of the Snowmass black-hole group G2.

The keys to these elusive goals are observational studies of a black hole's immediate vicinity, from its horizon (its "surface", inside which one can never see) out to roughly ten horizon radii. There are two promising vehicles for such studies: X and gamma rays emitted by hot gas in an accretion disk swirling inward toward the horizon of a stellar-mass black hole, and gravitational waves produced when two black holes coalesce or when a neutron star or white dwarf spirals into a more massive black hole (Sec. 4.3).

The X and gamma rays, emitted by gas spiraling into black-hole candidates, are observed to fluctuate on a wide variety of timescales, from years down to milliseconds. The shortest timescales are thought to be associated with gas near the hole's horizon: It seems reasonable to expect the radiation from a blob of near-horizon gas to fluctuate, due to moderate beaming and gravitational lensing effects, at the blob's orbital period (which is a few milliseconds); and as the blob spirals inward, that period should decrease. The result should be an X-ray or gamma-ray "chirp" that cuts off at the period of the last stable orbit or a bit shorter. A number of such chirps may occur at once, but by statistical studies of the millisecond fluctuations one may hope to determine whether such chirping is indeed occuring, and if it is, one may hope to learn details of the near-horizon environment and confirm firmly that the central body is a black hole.

In the 1970s there was much hope that such studies would be performed by HEAO-A, the first of the high-energy astronomical observatories, which carried a large-area, fast-timing X-ray detector. Unfortunately, a malfunction prevented HEAO-A from taking extensive data of the required sort. It has been nearly 20 years, but at last two new X-ray missions with the required timing capabilities are being readied: the X-Ray Timing Explorer (XTE), and the Unconventional Stellar Aspect (USA) X-Ray Telescope. The XTE and USA data, when analyzed with new techniques such as wavelets, give promise of much improved understanding of the inner regions of accretion disks, and perhaps they will bring the long-sought unequivocal proof of black holes and the first evidence of their detailed properties.

4.3 Gravitational Wave Astrophysics

Gravitational waves are ripples of warpage in the fabric of spacetime. General relativity predicts their existence and predicts that they should be produced strongly by highly compact, massive bodies (e.g., black holes and neutron stars) that orbit, collide, or vibrate in a highly nonspherical manner. Although gravitational waves have not yet been detected experimentally, a massive international effort is likely to capture them within the coming decade, and harness them for research in fundamental physics, astrophysics, and cosmology.

There are enormous differences between these gravitational waves, and the electromagnetic waves on which our present knowledge of the Universe is based: (i) Astronomical electromagnetic waves have frequencies that begin at $f \sim 10^7$ Hz and extend on *upward* by roughly 20 orders of magnitude; by contrast, astronomical gravitational waves should begin at $\sim 10^4$ Hz (1000-fold lower than the lowest-frequency astronomical electromagnetic waves), and should extend on *downward* from there by roughly 20 orders of magnitude. (ii) Astronomical electromagnetic waves are almost always incoherent superpositions of emission from individual electrons, atoms, or molecules; by contrast, cosmic gravitational waves are produced by coherent, bulk motions of huge amounts of mass-energy—either material mass, or the electromagnetically-dark energy of oscillating, nonlinear spacetime curvature as in the collision of two black holes. (iii) Electromagnetic waves are easily absorbed, scattered, and dispersed by matter and thus can only be seen coming from optically thin regions such as diffuse gas clouds and stellar atmospheres; by contrast, gravitational waves travel nearly unscathed through all forms and amounts of intervening matter and thus, for example, can emerge from the core of a supernova or the Planck era of our Universe unscathed by material absorption or scattering.

These enormous differences make it likely that gravitational waves not only will bring us valuable new information about phenomena such as black holes, for which we already have electromagnetic evidence; they may also bring us great surprises. In the past, when a radically new window has been opened onto the Universe, the resulting surprises have had a profound, indeed revolutionary, impact. For example, the radio universe, as discovered in the 1940s, 50s and 60s, turned out to be far more violent than the optical universe; radio waves brought us quasars, pulsars, and the cosmic microwave radiation, and with them our first observational evidence for black holes, neutron stars, and the heat of the big bang It is reasonable to hope that gravitational waves will bring a similar "revolution".

The technology for gravitational wave detection has been under development for 35 years, and is now nearing fruition in several different frequency bands:

In the ***extremely low frequency band***, $\sim 10^{-18}$ to 10^{-15} Hz (wavelengths of order the size of the observable universe), observations of the cosmic microwave anisotropy are constraining a predicted stochastic background of primordial gravitational waves. It may even be that a portion of the quadrupolar microwave anisotropy is due to such primordial gravitational waves with strengths (energy density in units of the energy to close the universe) $\Omega_g \sim 10^{-10}$.

In the *very low frequency band*, $\sim 10^{-9}$ to 10^{-7} Hz (periods of a few years), the observed steadiness of millisecond-pulsar periods is placing limits $\Omega_g \sim 10^{-7}$ on any stochastic gravitational wave background due to early-universe processes (primordial waves, waves from phase transitions, waves from cosmic strings).

Black holes, neutron stars, and other compact, strongly gravitating bodies that exist in the Universe today are expected to radiate in the ***low-frequency band***, $\sim 10^{-4}$ to 1 Hz, and the ***high-frequency band***, ~ 1 to 10^4 Hz.

In the high-frequency band, the "LIGO-VIRGO" international network of laser interferometer gravitational wave detectors is now under construction, and spherical, resonant-mass detectors ("bars") are being designed to operate at the upper end of this band, where the interferometers lose sensitivity. This network of interferometers and bars is likely to see and study the waves from the inspiral and final coalescence of stellar-mass black-hole black-hole binaries, black-hole neutron-star binaries, and neutron-star neutron-star binaries out to near-cosmological distances; and from spinning, slightly asymmetric neutron stars in our own galaxy, and perhaps non-axisymmetric supernovae well beyond the VIRGO cluster of galaxies.

When the first LIGO/VIRGO interferometers turn on, most and perhaps all these sources will be beyond their reach; but the interferometers will then be improved step by step by more than an order of magnitude, with a resulting event rate enhancement of more than 1000, thereby probably bringing these sources into view.

The development of this enhanced interferometer technology — which involves monitoring distances between kilometer-separated test masses to a precision ~ 1/1000 the diameter of the nucleus of an atom — is a major effort involving a number of research groups world wide, as is the development of the resonant-mass detectors. These technologies, which were a central topic of discussion by Snowmass Group G3, are likely to find many applications outside the gravitational-wave field.

The low-frequency band, $\sim 10^{-4}$ to 1 Hz, is to the high-frequency band what radio astronomy is to optical astronomy. Each band will bring us different kinds of information about different kinds of phenomena.

Low frequencies are the domain of massive and supermassive black holes ($M \sim 100$ to $10^{8} M_{\odot}$) — their births and collisions, and the inspiral of smaller objects into them —, and also of known binary star systems such as 44 i Boo, and our galaxy's shortest-period compact-body binaries (white-dwarf, neutron-star, and black-hole).

The premier instrument for this low-frequency band will be a space-based, several-million-kilometer-long variant of the LIGO/VIRGO earth-based interferometers. This *Laser Interferometer Space Anteanna* (LISA) has been recommended by the European Space Agency's Survey Committee as the third of three Cornerstone Missions in ESA's Horizon 2000 Plus Program, with a flight in ~ 2014. However, its implementation may require an augmentation of the Program's budget level by 5%, and a final decision remains to be made. Members of the American gravitation community and of the LISA team hope that NASA will join together with ESA in this endeavor, and that working jointly, ESA and NASA will be able to fly this exciting mission considerably sooner than 2014.

The scientific payoffs of LISA and the LIGO/VIRGO network arise from their broad-band nature: they can monitor the two waveforms of a gravitational wave in the time domain, over frequency bands of several orders of magnitude, and they can determine the directions to the waves' sources with accuracies of ~ 1 degree or better.

Waveform studies, most especially with LISA, are likely to bring us maps of the spacetime warpage around black holes and tests of the black-hole no-hair theorem, and with these maps and tests, unequivocal proof that black holes do exist in our Universe. If the LIGO/VIRGO network were now in a mature stage of operation, it would tell us whether the enigmatic, observed gamma-ray bursts are coming from the coalescence of binary neutron stars at near cosmological distances, since those coalescences should produce observable gravitational waves. Moreover, the gravitational observations would identify, to within about one millisecond, the time at which the final neutron-star collision occurs, thereby (depending on one's viewpoint) determining how long after the collision the gamma ray burst begins, or determining to within a fraction of a second (out of roughly a billion years) the relative propagation times and thus speeds of gravitational and electromagnetic waves. If LIGO/VIRGO had been in operation at the time of supernova 1987A, it should have seen gravitational waves produced by the boiling supernova core whose bubbling neutrino-sphere (analog of photosphere) is thought to have produced the observed neutrinos; and by cross correlating the observed gravitational and neutrino signals, we could have gained valuable additional information about the supernova mechanism.

These are just a few examples of the payoffs that may come from the gravitational window onto the universe. But as with radio astronomy, the biggest payoffs of all are likely to be wholly unexpected discoveries.

§5 Cosmology

As the new millennium approaches, cosmology is entering an historic epoch in which some of the fundamental questions concerning the origin and evolution of the Universe may be answered. Many of the questions date back before recorded history: how big is the Universe? how old is the Universe? How did it begin and how did it evolve? Many solutions have been proposed over time by scientists, philosophers, and religious leaders. What makes this period in history distinctive is the advent of new technologies which give us the capability of peering far into space and gathering data which can test our answers to these questions. The technology has developed over the course of this century, beginning with the advent of the giant optical telescopes, and is now progressing at an incredible pace. Numerous new technologies are coming together at the same time and breaking new ground in cosmology, including: the use of novel bolometer and solid state detectors to measure the anisotropy in cosmic microwave background radiation at the microkelvin level; the application of CCDs to measure red shifts of distant galaxies and to construct three-dimensional maps of the universe; the development of satellites to detect potential cosmological sources of gamma-ray bursts, x-ray glow, and infrared radiation; computer-coordinated surveys of gravitational lensing by intragalactic and extragalactic sources; and experiments for direct detection of axions and supersymmetric weakly interacting massive particles (WIMPs) utilizing novel detectors. It is fair to say that, for the first time in human history, cosmology is undergoing a period in which the subject is as much observation-driven as theory-driven, just what is desired for a true, healthy science. Historical precedents suggest that, when a discipline reaches this balance for the first time, a heroic age of major breakthroughs ensues. There is every reason to suspect that cosmology will follow this precedent.

The grand ambition of cosmology is to explain the evolution of the universe in terms of a simple, predictive model. At this point in time, there is no single complete picture. The hot big bang model explains the expansion and thermal history of the universe, and is extremely well tested. But the big bang picture is incomplete: it does not explain why the universe is so homogeneous, or why the universe is made almost entirely of matter with little antimatter or how large-scale structure formed. A number of concepts, including inflation, cosmic defects, dark matter, and baryogenesis, have been put forward as additions to the big bang model that may provide explanations. Entering the new millennium, the primary focus will be in precision tests of the big bang predictions, measurement of cosmic parameters, and resolution of the various competing ideas that enhance the big bang picture.

5.1 *The Big Bang Model: Present Status and Future Tests*

We enter the new millennium with a highly successful paradigm in hand: the hot big bang model. According to this model, the universe began as an infinitesimal patch of space filled with hot, dense gas which suddenly began to expand and cool. The universe we see today is the result of fifteen billion years of expansion and cooling. This simple picture successfully explains: 1) the Hubble red shift of distant galaxies, a result of the continued expansion of the universe; 2) the abundance of light nuclei, a consequence of fusion processes that took place in the hot universe during the first seconds after the big bang; and, 3) the existence of the cosmic microwave background, a remnant of radiation that filled the universe and decoupled from matter when the first atoms began to form.

The successful predictions of the big bang model verify it as a valid description of the universe from the present back to the first hundredths of a second after the big bang. The Hubble-distance relation, which relates the red shift of distant galaxies to the expansion of the universe, is verified out to several hundred megaparsecs (Mpc=3×10^{14} cm), using galactic markers that date back to the first billion years or so after the big bang. In the past few years, the COBE Far Infrared Absolute Spectrophotometer (FIRAS) experiment and the the rocket experiments of the University of British Columbia group have verified the Planckian spectrum of the cosmic microwave background in exquisite detail. This result is an extraordinarily compelling verification that the universe was once hot and has been expanding and cooling dating back to the period when the cosmic microwave background photons decoupled from matter, some 100,000 years or so after the big bang. The successful predictions of nucleosynthesis of the light elements verify the big bang picture back in time to when the universe was hot enough to fuse protons and neutrons into nuclei, 0.01 sec or so after the big bang.

Important new tests of the big bang model are anticipated in the next millennium. Although the linearity of the Hubble-distance relation is well-verified, the magnitude of the proportionality factor, the Hubble constant, H_0, remains uncertain to within a factor of two. Since this constant determines the age of the universe, and thereby substantially constrains competing models for large-scale structure formation, eliminating the uncertainty in the value of H_0 is one of the primary goals of cosmology. Although the issue has been the subject of considerable controversy for decades, there is real hope for resolution in the new millennium thanks to several new technologies and observational approaches. The Hubble Space Telescope (HST) will provide a major improvement in the traditional astrometric methods of measuring H_0, using Cepheid variable stars in other galaxies as standard candles. The first results from this work based on 13 Cepheids in one galaxy in the Virgo cluster have produced the result $H_0 = 80 \pm 17$ km/s/Mpc. It seems likely that further observations will significantly reduce the uncertainty. Various alternative approaches for measuring H_0 are also being pursued, including studies of supernova photospheres, supernova luminosities, gravitational lenses, and the Sunyaev-Zel'dovich effect (the rescattering of microwave background radiation by the hot gas within galaxy clusters). Progress can best be made in this field by developing all of these techniques and seeking convergence among them.

The age of the universe has been traditionally estimated using nuclear cosmochronology, cooling rates of white dwarfs, and globular clusters. Globular clusters provide the most stringent age constraint, $t_0 > 11.5$ Gyrs. The age is determined by plotting the distribution of stars in globular clusters on a color-magnitude diagram. One can identify stars that are turning off from the main sequence and measure their apparent luminosity. Knowing the distance to the cluster then determines the absolute luminosity. Then from stellar evolution, it is well-known how long it takes for stars to turn off the main sequence branch as a function of their luminosity. The limitation in this approach is in capturing stars close to the main sequence turn-off. Recent reviews based on taking limits of stars on the main sequence suggest an age of $t_0 > 13.7$ Gyrs, whereas the limit cited above is based on studies along the giant sequence. Hubble Space Telescope studies may improve resolution of stars near the turnoff and significantly improve the limits.

The product of the Hubble constant and the age, $H_0 t_0$, are directly linked to Ω, the ratio of the energy density to the critical density of the universe, and to the energy content. For the simplest model, a universe with $\Omega = 1$ comprised of non-relativistic matter, $H_0 t_0 = 2/3$. Yet, the current best-estimates correspond to $H_0 t_0$ near one. This conflict comprises the "age crisis," which either indicates a problem with the measurements or a different energy density or energy content. For example, if there is a significant vacuum density (or, equivalently, cosmological constant) contribution to the total energy density, a value of $H_0 t_0$ can be obtained which is consistent with present measurements. At present, the error bars on the measurements are too large to definitively determine if there is an age crisis, but the anticipated progress in the new millennium will settle the issue.

The Planckian form of the cosmic microwave background spectrum has been precisely verified near the peak of the spectrum (tens to hundreds of GHz). The spectrum obeys a thermal distribution with a temperature of $T = 2.326 \pm .010$ degrees, corresponding to a photon density of 420 cm^{-3}. However, verification of the Planckian shape at long-wavelengths (< 1 GHz) is much less precise. Improvements in these measurements would confirm simple big bang evolution and further rule out exotic models, such as late-decaying particles.

Primordial nucleosynthesis has been established as a primary test of the big bang picture and as one of the best means of measuring the abundance of baryons in the universe. Current best-estimates on Ω_B, the ratio of baryon density to the critical density needed to close the universe, lie between 0.01 and 0.1. To improve upon these limits, more quantitative measurements of primordial abundances are needed along with improved understanding of chemical evolution, stellar processing, stellar atmospheres, and recombination/collisional excitation rates. The development of multi-dimensional hydrodynamic codes to model stellar atmospheres and supernova will be important developments. Also, recent attempts to measure the abundances of light nuclear elements using pre-galactic hydrogen clouds (Lyman-α clouds) appears to be a very promising, independent approach perhaps less subject to evolutionary assumptions. Continued improvement in lithium abundances is especially critical both as corroborating evidence and as the most precise method for narrowing the uncertainty in Ω_B.

The big bang models is left incompletely specified unless one also determines Ω, the ratio of the energy density to the critical density separating an open from closed universe, and Λ, the cosmological constant or vacuum density. The best approaches, in principle, are global approaches which measure the universe over very large distances and/or very long times. The cosmic microwave background anisotropy entails radiation from the furthest observational reaches of the universe. In many cosmological models, including inflation, the temperature autocorrelation spectrum includes sharp features which can be used to determine Ω (see below) using instruments with current sensitivities. Resolving other cosmological parameters, including Λ, through the cosmic wave background anisotropy alone will require substantial improvements in detector sensitivities and new satellite and/or long-duration balloon projects which can scan nearly the full sky. Measurements of cosmic deceleration, q_0, have been notoriously difficult. The method relies on comparing the geometrical sizes of similar objects near and far, but one must beware that the far objects are also much older and that evolutionary effects may alter their perceived size or luminosity. With improved modeling of evolution and a major effort to obtain spectra from a large sample of faint galaxies (see below), progress may be made in the coming decades. Surveys of gravitational lenses is another global approach. Compared to $\Omega = 1$ and $\Lambda = 0$ models, flat universes with non-zero Λ predict significantly more lensing of quasars by galaxies. Detection of "standard events" over a range of cosmological distances is another evolving approach. An example is the effort to detect Type Ia supernovae in high redshift galaxies.

5.2 Beyond the Big Bang

The most exciting developments in cosmology for the next millennium entail ideas that stretch beyond the standard hot big bang model. It is clear that, in spite of its phenomenal successes, the big bang picture is an incomplete model of the evolution of the universe. The big bang model does not provide any answer to a number of key questions: Why is the universe so homogeneous or anisotropic? Why is the energy density of the universe today so close to the critical density (Ω near one)? How did the inhomogeneities in the universe arise that are observed in the cosmic microwave background anisotropy and/or are responsible for the formation of large-scale structure? How did galaxies form? Why is the universe composed predominantly of matter with insignificant fractions of antimatter? What is the dark matter that comprises the halos of galaxies and perhaps the missing matter of the universe?

Most likely, the answers to these questions entail events that took place in the first instants after the big bang. Whereas the concepts and tests of the big bang model entail nuclear physics, atomic physics, and astrophysics, new ideas that go beyond the big bang picture entail early times in the universe when the temperature throughout the cosmos was sufficient to excite interactions among elementary particles ($\gg 1$ GeV). Hence, the answers to the problems of cosmology may be directly linked to our understanding of the fundamental forces and constituents of nature. Theory and observation in cosmology in the next millennium will be focused on exploring the cosmic connection between the very large and the very small.

A New Generation of Cosmological Models

To address the questions left unanswered by the big bang model, new cosmological models are needed. The inflationary model of the universe is the leading candidate for an explanatory and predictive theory that extends beyond the standard big bang picture. The inflationary model proposes that the universe underwent a brief period of extraordinary, superluminal expansion, "inflation," during the first instants after the big bang. The remarkable stretching smooths the distribution of matter and energy, explaining why the universe is so homogeneous and isotropic. The stretching flattens any spatial curvature, explaining why space appears to be Euclidean. According to Einstein's theory of general relativity, a spatially flat universe must have energy density equal to the critical value that divides an open from a closed universe. Hence, the flattening induced by inflation also explains why the observed energy density, ρ, is close the critical density today. A key, testable prediction is that the ratio of the energy density to the critical value, $\Omega \equiv \rho/\rho_{crit}$, is indistinguishable from unity today. The inflationary stretching dilutes the density of magnetic monopoles and other particle monsters created near the Planck temperature, thus explaining their absence in the universe today. Finally, inflation predicts a spectrum of inhomogeneities were produced during inflation that might leave an imprint on the cosmic microwave background and act as seeds for large scale structure formation. The spectrum of fluctuations is predicted to be nearly scale-invariant, which is consistent with the observations of the COBE Differential Microwave Radiometer (DMR) experiment. Inflation is the only viable cosmological model which explains so many, diverse aspects of the universe.

One important theoretical challenge in inflationary cosmology is to understand that process that may have caused the brief period of superluminal expansion. If the microwave background anisotropy ($\Delta T/T \approx 10^{-5}$) is a consequence of inflation, then most inflationary models would predict that the magnitude of the observed fluctuations in $\Delta T/T \approx 10^{-5}$ is equal to M^2/M_P^2, where M_P is the Planck mass, 1.2×10^{19} GeV, and $M \approx 10^{16}$ GeV is the characteristic energy of whatever physics drove inflation. Hence, inflation is linked by the microwave background to unification scales. Relating inflation to unification models of particle interactions, such as superstrings, is an important element needed to complete the inflationary picture.

Another important theoretical challenge, which applies both to inflation and more general theoretical models, is to understand the source and the value of the cosmological constant. Inflation relies on the notion that particle physics interactions produce a positive contribution to the vacuum density of the universe, adding a non-negligible contribution to the cosmological constant. It is normally presumed, based on observations, that the cosmological constant is zero or near-zero today. But, the inflation picture (or any other cosmological model) is not complete until it is understood why the cosmological constant is small today. Particle theorists believe that the answer lies in the unification of gravity and particle interactions into a unified quantum theory, such as superstrings.

At present, there are no models competing with inflation to explain the homogeneity, isotropy, flatness, and mass density of the universe. The only alternative has been to assume these unusual and unstable properties as part of the initial conditions of the universe. However, there are numerous competing models for explaining the source of inhomogeneities that are observed in the cosmic microwave background and that may be the seeds for large-scale structure formation.

According to inflation, the inhomogeneities are the result of quantum fluctuations in the energy density and space-time metric that ran rampant when the universe occupied a subnuclear volume prior to inflation. As space inflated, the fluctuations, ripples in the fabric of space, stretched also, ultimately spanning a cosmological range of wavelengths. The predicted fluctuations are gaussian, adiabatic (equal fluctuations in all species of energy), and nearly scale-invariant.

Cosmic defect models presume that the universe underwent a phase transition which resulted in the formation of topological defects, which act as the seeds for large-scale structure formation. A topological defect results if, following a phase transition, there are many possible vacuum states corresponding to different values of quantum fields. Different, causally-disconnected regions of space fall randomly into one or another vacuum state. After time passes, the formerly disconnected regions make contact and, where there are mismatches in vacuum states, stable knots in the quantum fields form. Depending on the nature of the vacuum degeneracy, these knots may take the form of points ("monopoles"), curves ("cosmic strings"), surfaces ("domain walls"), or textures. The notion of defect models is that these concentrated knots of energy might be the origin of inhomogeneity in the universe. One key difference from inflation is that these inhomogeneities are strongly non-gaussian. General arguments suggest that the distribution of defects is scale-invariant. A consequence is that there are always defects within our Hubble horizon. For each type of defect, there is a characteristic signal to be found if one should pass through the field of view. For example, a cosmic string would leave a line-like discontinuity in a high-resolution map of the cosmic microwave background.

A theoretical challenge for cosmic defect models continues to be finding reliable methods for computing their predictions. Whereas inflation predicts a simple spectrum of fluctuations which can be understood analytically, defect models require very large-scale numerical simulations. The defects enter the horizon with cosmological size, but decay and interact on microscopic scales. The implications for cosmology are sensitive to the entire range of dimensions. New theoretical methods are needed to reliably circumvent this problem and obtain trustworthy predictions of cosmic microwave background anisotropy and large-scale structure formation.

Both inflation and cosmic defect models invoke dynamical processes based on particle physics to explain the origin of inhomogeneity in the universe. Some cosmologists prefer a more phenomenological approach in which one uses present observations to infer an initial spectrum of inhomogeneities without explaining their origin. One such model is the primeval isocurvature baryon (PIB) model. The model is intended to be conservative with the virtue that it does not require dark matter and any other unverified physical processes. So, it presumes only baryons comprise the matter of the universe and, given nucleosynthesis constraints, this means that the universe is open. Also, one presumes an ad hoc initial spectrum of perturbations in the baryons relative to the photons. The obvious disadvantage of such models is that they are not truly predictive. By presuming different initial spectra, one can get arbitrarily different answers. However, the development of such phenomenological fitting models is an important tool for guiding the development of alternatives to our present, rather restrictive set of predictive models.

Why is There an Excess of Matter over Antimatter in the Universe?

A striking feature of the observable universe is that it is composed primarily of matter, with a negligible proportion of antimatter. The observed baryon excess is ten orders of magnitude higher than would be obtained if the universe began with equal numbers of baryons and antibaryons and simply had them annihilate as the universe cooled and expanded. One explanation may be that the universe began with precisely the observed baryon excess, and that the excess has simply maintained itself over time. Not only is this unsatisfying, but, if inflation is correct, then any initial excess would have been wiped out during the inflationary stretching of the universe. Hence, current research has focused on the notion that the matter excess was generated by dynamical processes as the universe cooled from Planckian temperatures, e.g., after inflation.

In the late 1960's, Sakharov realized that dynamical baryogenesis would require three conditions: (1) deviation from thermal equilibrium; (2) violation of baryon conservation; and, (3) violation of CP conservation. The advent of grand unified theories in the 1970's provided a theoretical framework for achieving all three conditions at grand unification energy scales, 10^{14} GeV or so, using decays of long-lived relics to achieve the deviation from equilibrium. In the past decade, the focus has switched to lower energy-scale (100 GeV) baryogenesis associated with the electroweak phase transition. It has been noted that the required baryon-violation could arise from non-perturbative effects in the standard model.

The biggest uncertainty is the origin of CP violation. It now seems likely that the CP violation associated with the standard model is insufficient, so that new CP violation sources are needed. There are numerous workable suggestions, but none that is compelling. Future experiments to improve constraints on the electron and neutron electric dipole moments could strongly influence developments in the field since most proposals suggest a substantial non-zero value.

On the theoretical side, there remain open issues about the detailed mechanism by which baryogenesis takes place in the case of the electroweak phase transition. One issue is whether the phase transition is a sufficiently strong first-order phase transition to provide the needed deviation from thermal equilibrium. Investigations thus far suggest that the experimentally allowed mass range for the Higgs in the minimal standard model precludes a first order transition, although the issue remains controversial. The minimal model also appears inadequate for providing sufficient CP violation. Consequently, the focus of the field is likely to be on other models of weak symmetry breaking. If a sufficiently strong first-order transition is achieved, it will proceed through the nucleation of bubbles of true vacuum which grow and coalesce to complete the transition. The interaction of quarks and gluons with the bubbles is believed to be a critical contributor to baryogenesis, but the progress is needed in developing a quantitative and predictive understanding of the process. More generally, progress on electroweak baryogenesis will benefit from measurements at the LHC and future accelerators which will explore electroweak symmetry breaking

and quark and lepton Yukawa couplings.

5.3 Dark Matter

Another area of overlap and complementarity between cosmology and particle physics may be provided by dark matter. There are increasingly compelling pieces of evidence that at least 90 percent of the mass in the universe is dark, by which we mean that it does not emit or absorb any form of electromagnetic radiation. Once a subject of controversy among astronomers, its existence is now acknowledged by a large majority as its presence is inferred on a variety of scales. Not only does the non- Keplerian character of rotation curves around spiral galaxies indicate that they are at least ten times more massive than the sum of the stars that we can see, but velocity dispersion of stars and x-ray emission in elliptical galaxies show that these objects are also dominated by a dark component. These galactic measurements show that dark matter represents at least a few percent of the critical density. At the scale of clusters of galaxies, three independent sets of measurements point at an even greater amount of the dark matter. The large velocity dispersion of galaxies inside the cluster, the temperature of the x-rays emitted by gas falling into the center of the clusters, the arclets resulting from gravitational lensing of galaxies located behind the clusters, all lead to very similar estimate of the depth of the potential well. This pushes estimates of the mean density in the universe to at least 20 percent of the critical density. Velocity correlation and flows on large scale indicate even greater values.

The combination of all these observations makes it rather convincing that dark matter does indeed exist. The only other (even more earthshaking) possibility is that the laws of gravity are violated on the large scale. Uncovering the nature of this "dark matter" has become one of the more central problems in astronomy and cosmology: it is certainly embarrassing not to understand the dominant component of the universe.

What could it be? The average density may be an important clue. If $\Omega < 0.1$, dark matter may'be made of ordinary baryonic matter, as this density is quite consistent with the measurement of primordial abundances of light elements and the standard nucleosynthesis scenario in a homogeneous universe. However, this baryonic component must neither radiate nor absorb light. This basically excludes gas (unless it is in a very exotic state) and dust, and leads to the conclusion that this form of dark matter is viable only in the form of condensed objects: stars too small to start thermonuclear reactions or black holes. Both types can be combined under the name Massive Compact Halo Objects (MACHOs).If, as may be indicated by cluster observations and large scale velocity flows, Ω is significantly higher than 0.1, it would be incompatible with Ω_B determined from the primordial nucleosynthesis. We may then be forced into the hypothesis that at least some dark matter is nonbaryonic. So far attempts to modify the standard nucleosynthesis scenario (e.g., through inhomogeneities generated by the quark-hadron phase transition) have been unsuccessful in extending significantly the upper bound on Ω_B. If indeed we could show that dark matter is not made of ordinary matter, we would have to deeply modify our vision of the universe and of our place in it: a few clumped baryons floating in a sea of foreign particles. Paradoxically, as it dominates gravity, this most inert component of the universe may be responsible for the formation of structure by gravitational collapse and therefore of galaxies, stars, planets and ultimately life. Elucidating the nature of dark matter is therefore a high priority endeavor which can be approached in two complementary ways. Cosmology gives us information on this nature through the value of the cosmological parameters, the detailed shape of the temperature fluctuations of the cosmic microwave background, and the evolution of the large scale structure. And we could make progress through attempts to detect this dark matter directly. A number of such direct searches are already in progress.

Microlensing provides us with a method of detecting the only natural form of baryonic dark matter still compatible with observations, Massive Compact Halo Objects. If one of these MACHOs happens to cross the line of sight to a star, say in the Large Magellanic Cloud, a temporary increase of the star's intensity will be observed. This increase would be symmetric in time, achromatic and non-repetitive, contrary to sporadic phenomena in stars. At least five collaborations are now actively searching for such events, an effort which requires the regular observation of some ten million stars. At this writing, microlensing has clearly been established but the results are puzzling: We observe too many events towards the galactic bulge, and apparently too few (within meager statistics) towards the Large Magellanic Cloud, indicating that our previous ideas of the structure of the galaxies were too naive. Before we can conclude, we need both to increase the statistics and to better pin down the halo structure.

As explained above, if Ω is significantly greater than 0.1, some dark matter has to be nonbaryonic. If we discard exotica such as a shadow universe or primordial black holes, the most attractive hypothesis then is that dark matter is made of particles that were created in the hot early universe and managed to stay around.

One of the well-motivated candidates is the axion. Such a particle has been proposed in order to suppress the strong CP violation implied by the otherwise very successful Quantum Chromodynamics. It has not been observed, but it is interesting to note that the combination of laboratory and astrophysics experiments has constrained its mass in such a way that if it does exist, it must be cosmologically significant, accounting for a large fraction of the critical density. These "invisible" axions from the halo of our galaxy could in fact be detected through their conversion into monochromatic microwave photons inside a tunable microwave cavity in a large magnetic field. In the past ten years, two pilot efforts explored the technology, but lacked about three orders of magnitude in sensitivity to reach a cosmologically interesting limit. A second generation experiment is currently in preparation at Livermore, which should have the needed sensitivity range over one decade in mass. If no signal is unraveled, a significant experimental challenge will be to cover the other two decades which will still be allowed.

Without further information from a specific model, it is quite natural to assume that these dark matter particles were once in thermodynamic equilibrium with the quarks and leptons. In this case, their current density depends on whether they were relativistic or not at the time they decoupled from the rest of the universe. If they are light enough to be relativistic at that time, their density is just related to the decoupling temperature and is basically equal to that of the photons in the universe. This is, for instance, what is expected to have happened for light neutrinos, and a neutrino of 25 eV would give a value of Ω of the order of unity. Unfortunately such a neutrino is extremely difficult to detect in the astrophysical environment. It should, however, be possible to test this hypothesis in the laboratory through neutrino oscillation experiments which are described in this volume. Note that these efforts are complementary to attempts to solve the solar neutrino puzzle, and to confirm atmospheric neutrino oscillations. Although the neutrino mass range covered by these experiments is much lower than necessary to account for the dark matter, confirmation that neutrinos have indeed finite masses will be invaluable in reconstructing the general framework.

For particles which happen to have decoupled when they were non- relativistic, their density today is inversely proportional to their annihilation cross section. A density close to the critical density leads to a cross-section of the order of the Weak Interaction, indicating that the physics at the W^1/Z^0 intermediate vector boson scale (e.g., supersymmetry) may be responsible for the dark matter in the universe. This generic class of particles is usually called Weakly Interacting Massive Particles (WIMPs). A first generation of experiments looking for elastic scattering of such WIMPs in the laboratory with solid state detectors proved that heavy Dirac neutrinos cannot be a major component of our galactic halo, and almost eliminated a class of WIMPs designed both to be dark matter and to account for the paucity of solar neutrinos. A second generation of laboratory experiments is being brought into operation; depending on the groups, they use larger masses of germanium detectors, large scintillating crystals of NaI, or novel "cryogenic detectors" working at millikelvin temperatures. While the first methods promise sensitivity gains of a factor of a few, the cryogenic detectors allow an active rejection of the radioactive background (e.g., through the simultaneous measurement of the phonons and ionization produced in particle interactions) and may give gains of one hundred or more. These experiments will begin to probe the rate region expected for the theoretically favored neutralinos, the lightest particles in supersymmetry. It will also be possible to use the large high energy neutrino detectors to indirectly search for these particles.

To conclude, the dark matter problem occupies a central place in the current cosmological debate, and elucidating its nature is closely linked to a number of other questions and observations in particle astrophysics. We are poised to make significant experimental progress in the coming years. The beginning of the next millennium may well see the solution of this fascinating puzzle!

5.4 The Large-scale Structure of the Universe

One of the greatest challenges of cosmology is to explain the large-scale structure of the universe. The present notion is that tiny inhomogeneities in the distribution of energy were generated in the early universe, and then these were amplified through the action of gravity over time into the structure we observe today. To transform this notion into a predictive theory, three key questions need to be answered. What are the values of cosmological parameters: the mass density, the cosmological constant, and the Hubble constant? What is the quantity and composition of matter/energy in the universe? And, what is the origin of the initial inhomogeneities? Current and future progress on these issues have been discussed under the prior sections on Big Bang cosmology, on Dark Matter and on Cosmological Models, respectively.

In addition, for a truly detailed understanding of the formation of large-scale structure, substantial advances in both theory and observation are needed. On the theoretical front, the detailed tests of theory require numerical simulation of the formation of large-scale structure, including hydrodynamics, star formation, supernova, chemical evolution, etc. At present, numerical simulations only span a dynamical range of three or four orders of magnitude. One key challenge is to improve numerical techniques to expand the simulation range. Another is to improve physical understanding of the process of galaxy and star formation, which is crucial input into the simulations. Better statistical or analytical methods of comparing observational data with models are needed which take account of the real selection biases in experiment.

The advent of large-area red shift surveys is radically transforming observational studies of large-scale structure. Current surveys probe only a relatively small volume of the local cosmic neighborhood spanning of order 10,000 galaxies. The next generation of surveys, such as the Sloan Digital Sky Survey and the Anglo-Australian 2dF, will measure the red shifts of over one million galaxies and extend the cosmic range by more than an order of magnitude. In addition, the surveys will capture images of tens of millions of galaxies. The surveys will measure the galactic power spectrum over a range of wavelengths that will overlap measurements of the cosmic microwave background, providing critically important, redundant tests of the power-spectrum at long-wavelengths, measurements of Ω, and determinations of the bias parameter as a function of wavelength. The surveys will also provide information about the distribution of peculiar velocities at large scales, which is an additional test of cosmological models of large-scale structure formation. While the red shift surveys are direct probes of luminous matter, another much-anticipated development are studies of weak lensing, which probes the distribution of foreground dark matter. The diverse array of new measurements being initiated as we enter the new millennium will provide our first detailed look of the universe at large scales and profoundly affect our ideas about the origin of the universe.

5.5 The Cosmic Microwave Background

The cosmic microwave background is, in many ways, our best cosmological probe. Assuming the standard interpretation of its origin, the cosmic microwave background provides direct information about the largest distances and the earliest times accessible (until some means is found for probing the cosmological graviton or neutrino backgrounds). In addition, cosmic microwave background measurements are much less sensitive to subjective or model-dependent assumptions compared to most cosmological measurements.

Measurements of the energy spectrum of the cosmic microwave background, beginning with the initial discovery of the 3 K background by Penzias and Wilson through the recent COBE FIRAS and UBC rocket precision measurements, have provided exquisite tests of the standard hot big bang explanation of how the universe evolved from the 100,000 year mark to the present. Although current measurements are quite impressive, extending the spectral measurements to longer wavelengths will provide further support for the simple, adiabatic expansion picture or could provide evidence of some exotic thermal processes (e.g., late decays of elementary particles). Significant improvements probably require a space-borne mission using a small-sized satellite.

The revolution that is occurring as we enter the new millennium is the first detections of anisotropy, spatial variations in the temperature of the microwave background. These variations provide a detailed, quantitative fingerprint which can be used to decisively discriminate competing models for the evolution of the universe. Precise measurements of anisotropy also provide novel ways of determining the values of cosmological parameters, such as Ω, the Hubble constant and the cosmological constant.

The revolution began in 1992 with the announcement by the COBE Differential Microwave Radiometer (DMR) experimental that they had detected anisotropies of $\Delta T/T \sim 10^{-5}$. Since COBE DMR, more than a dozen new detections have been reported on angular scales ranging down to one-half degree, and significant upper bounds have been reported on yet smaller scales. The field is still in its infancy, though: Improvements in instrumentation and sky coverage could dramatically improve the precision of the measurements within the next decade.

Future cosmic microwave background anisotropy experiments can be categorized into three regimes, large-, intermediate-, and small-angular scale measurements, each of which reveals a different, key aspect of our cosmology. Experiments measuring inhomogeneities stretching over large angles in the sky (> 2 degrees) probe the largest structures in the universe. When the microwave background radiation last scattered from matter and began its trek across the universe, there had not yet been time for these large structures to evolve since whatever events created them, e.g., inflation. Hence, large-angle experiments reveal the directly primal universe dating back to the first instants after creation. In terms of our efforts to understand large-scale structure formation, large-angle experiments measure the magnitude of the initial inhomogeneities before gravity had a chance to amplify them. The most important features to be determined are the amplitude and the spectral index of the power spectrum, the key input parameters for any theory of large-scale structure formation. COBE has provided a rough measure, but greater precision is needed to discriminate and refine models.

Experiments measuring inhomogeneities spanning intermediate scales (half-degree to several degrees) probe features in the sharp features in the spectrum which discriminate qualitatively different models of large-scale structure formation (e.g., inflation vs. cosmic defects). For any given type of model, these features can also be used as a novel means of determining Ω, and for determining the ionization history of the universe.

What we learn from large- and intermediate-scale measurements will play a leading and profound role in determining our vision of the evolution of our universe. The challenge for both regimes is that a very large fraction of the sky must be measured in order to obtain good statistical measures. This dictates an experiment that flies at high altitude for the very long periods of time need to scan the sky with fine resolution. One set of proposal entails long-duration balloons which circumnavigate Antarctica, for example, for weeks or months. The balloon projects will evolve quickly, obtain good results soon, and be critical in developing advanced technologies. The most precise results, however, are likely to come from a future satellite mission which avoids atmospheric and side-lobe problems of earth- and balloon-borne missions and is able to measure the full-sky in a controlled, redundant patterns. Such a mission would be a monumental and historic contribution to our understanding of cosmology.

Experiments at small-angle scales (less than half-degree) are important because features observed in the spectrum at these scales can be used to determine the values of cosmological parameters, such as the cosmological constant, the Hubble constant, and the baryon density. They can also be used to distinguish the nature of dark matter, e.g., the proportion of hot or cold dark matter. Measurements at these angular scales are also optimal for detecting the polarization of the microwave background, non-gaussian contributions to primordial fluctuations, the Sunyaev-Zel'dovich effect, and secondary anisotropies association with reionization of the microwave background. Land-based and balloon-borne experiments will be the dominant contributors to our understanding of this regime, since larger instruments are needed to obtain the fine resolution and there is less demand for full-sky coverage.

In sum, a program of high-resolution measurements of the cosmic microwave background anisotropy is the highest priority for microwave background studies and probably for cosmology in general. Each of the three angular-scale regimes reveals different, fundamental facets of the universe. Improving long-wavelength spectral measurements, e.g., by a small satellite mission, is a second priority.

A balanced program of land, air and space missions is needed to extract the extraordinary wealth of information which the cosmic microwave background has to offer. Combined with measurements of large-scale structure and peculiar velocities, the cosmic microwave background will provide a new understanding of the origin and evolution of the universe, a truly profound breakthrough that will be one of the historic achievements of the new millennium.

§6 Structure of the Field

By its very nature science is a continually evolving endeavor, with exciting new fields arising at the interface between well established disciplines. In fostering and nurturing new fields, three important issues of science policy arise:

1. In a severely constrained budget climate, how can one support a developing field without an established "budget line?"
2. How can cross-disciplinary priorities be established so that new endeavors may be judged relative to well established activities?
3. As new fields develop and their financial needs grow, how can the community organize to set long-term strategies that can serve as a basis by which new proposals can be evaluated?

Particle and nuclear astrophysics and cosmology is a case in point. Most agree that a fascinating field is now emerging at the border between particle and nuclear physics, cosmology, stellar astrophysics, high-energy astrophysics, and gravitation. This area of research is undergoing a dramatic expansion that occurs only rarely in the history of science, akin perhaps to the intellectual and technological impetus that gave rise to particle and nuclear physics in the 30's, 40's, and 50's. This meeting, organized by three separate divisions of the American Physical Society and attended by over 450 physicists, testifies to the breath and depth of a field that barely existed 15 years ago.

The number of scientists and the total funding of the field are already quite substantial. Even restricting the definition of the field to astrophysical activities explicitly linked to particle and nuclear physics, we estimate that more than 300 experimentalists are involved at a substantial level in these activities. With an equal number of theorists, the total number of people in the field is quite impressive. The Department of Energy supports such activities in universities and national labs at a total level of roughly $26M/yr, the NSF at a level of $13M, and the NASA at a level of $2M (restricting the field to cosmic rays above 1 GeV). The "gravitational field" represents another $11M (of which perhaps half is astrophysics/cosmology related), plus current construction money for LIGO.

Irrespective of funding, there is a strong feeling in the community that this emerging field is under-represented, and tends to "fall between the cracks." This is perhaps unavoidable in a field that has so many distinct roots and where new generation of experiments incorporate methodology and people across many disciplines. Nevertheless, as a result of its somewhat helter-skelter growth, this burgeoning field finds itself in an agency management structure not quite reflective of natural intellectual relationships. It is obvious that it does not fit readily within the traditional framework of NSF and NASA astronomy funding. DOE officials historically have worried that such activities may conflict with their interpretation of the agency mission. There is a general perception within the community that the review process could be improved: mail reviewers do not have access to the overall picture and *ad hoc* subcommittees (*e.g.*, of HEPAP) have been sparse and have lacked the continuity required to develop a long-term vision for the field. There is widespread consensus that there should be more intra-agency and inter-agency communication. Finally, there is the worry that in any triage generated by a financial crisis, entrenched fields of science will receive attention while emerging fields will be declared dead on arrival.

To be sure, over the last few years significant progress has been made. For instance, the NSF has put into effect an explicit mechanism of collaboration in particle astrophysics encompassing the Physics, Astrophysics, and Polar Programs Divisions. Solar neutrinos have been adopted by the DOE Nuclear Physics Division, and DOE high-energy physics laboratories have become deeply involved in the field. More importantly, there is a widening recognition at DOE that particle and nuclear astrophysics is an integral part of its basic science mission of fundamental physics.

However, it is clear that we do not yet have in place the machinery necessary to address in a coherent fashion large international projects on the drawing boards. There is no shortage of proposed projects with price tags between $15M and $100M: proposals for second-generation cosmic microwave background satellites, dedicated cosmology telescopes, a new generation of solar neutrino detectors, an air-Cerenkov farm to extend the measurement of the gamma-ray spectra of AGN and black hole candidates, giant air shower arrays to explore the highest energy cosmic rays, cubic-kilometer neutrino detectors to look for high energy neutrino sources, a space-based gravitational wave interferometer, and so on.

While NASA may have in place the necessary mechanisms to compare satellite proposals, the other funding agencies (DOE and NSF) lack the reviewing and prioritization tools normally employed for sizable projects (e.g., program advisory committees at accelerators). None of the existing advisory committees to the three agencies (HEPAP, NSAC, SAC) are fully suitable for the advocacy role, and setting up a specific standing committee may be difficult in the current political climate. Regular summer studies sponsored by relevant divisions of the American Physical Society are important, but they are only a part of the process of developing a long-term vision. The APS may be ill equipped for a difficult prioritization. One might envision one or more of the national laboratories stepping in as the main support structure for this new science and setting up a program advisory committee which may *de facto* develop into a national advisory role. But a committee so constituted may lack the proper balance. Finally, one could think of extending the role that the National Research Council, through the various reports and strategic analysis from the Board on Physics and Astronomy, the Space Studies Board, and their joint Committee on Astronomy and Astrophysics, plays in the process.

There is much we could do to decrease the potential barrier encountered by excellent proposals, to welcome young investigators into a more nurturing environment, to optimize the scientific output in the framework of a very limited budget, and to pursue and develop the necessary international partnerships in large projects. An innovative mix of some of the above suggestions may go a long way towards building the framework required to realize the potential of the exciting scientific issues.

If there was any spirit that characterized the two weeks of the Snowmass Summer Study, it was a shared feeling across all disciplines that we are in the midst of a unique conjunction of theoretical ideas, experimental realities, and technological possibilities, which allow us for the first time to address many of the most fundamental questions about our Universe. The most repeated phrase during the many forward-looking talks of the Summer Study was "... now for the first time we have the ability to..."

It is a sad testament to the times that the potential for new discoveries does not seem to be limited by the lack of ideas, technology, or proposals, but by fiscal realities and the artificially constructed barriers of the existing science policy framework.

At the end of this millennium, both as scientists and members of society, we inherit the cultural legacy and reap the benefits of a proud scientific tradition. The 1994 Snowmass Summer Study was witness to the fact that we do not lack the intellectual boldness or technological imagination to address questions once thought to be beyond the realm of human comprehension. For two weeks in the summer of 1994, 450 physicists in the mountains of Colorado united in the conviction that we must enter the next millennium with the same intellectual fervor and hope for the future that led to the great scientific achievements of the 20th century. From the top of the mountains of Colorado we saw unlimited horizons in the field, and we are dedicated to the establishment of a framework to realize the vision of Snowmass.