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


Organizers and convenors of the 1994 Snowmass Summer Study

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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 cosmologically 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 60 participants) signaled 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 enabled astronomers to scan millions of stars for the Macho searches. Conversely, remarkable astrophysical phenomena like super energetic air showers have served 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 drove the field. From COBE to Galactic and Quasar scale, to the new Sun telescopes and the instruments on CGRO and the Hubble observatary, data in profuse quantities has been flowing. These data are 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 aim 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 organizers of the Snowmass 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 weak 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 intense...
of our sun and supernovae, higher energy neutrinos could allow us to look into the centers of active galactic nuclei. These are also sources of cosmic rays, which could provide insights into the acceleration of cosmic rays. Supercomputer simulations have shown that cosmic rays could be accelerated to speeds approaching the speed of light, making them ideal probes of astrophysical processes.

As we enter the new millennium, neutrino physics stands at an important threshold, one driven by the remarkable technological revolution taking place in astrophysics. The past decade has brought significant advances in our understanding of neutrino oscillations and neutrino masses. Neutrino oscillations were first discovered in the early 1990s, and since then, studies have continued to shed light on the nature of these elusive particles. The discovery of neutrino oscillations has profound implications for our understanding of the universe, as it challenges our understanding of particle physics and the nature of space and time.

The challenge of detecting and understanding these incredibly weak neutrinos has led to the development of novel technologies and detection strategies. One of the most promising approaches is the use of giant detectors, such as the Super-Kamiokande and the IceCube experiment, which are designed to detect the tiny signals from neutrino interactions in vast volumes of water or ice.

Theorists and experimentalists are working together to develop new techniques for detecting and measuring neutrino oscillations, with the goal of unraveling the mysteries of neutrino physics and gaining a deeper understanding of the fundamental forces that govern the universe.

53 Cosmic Rays

The array of astrophysical objects gathered in the vicinity of our home galaxy, the Milky Way, offers a unique opportunity to study cosmic rays. These high-energy particles travel through the universe, coming from a variety of sources, including supernovae, pulsars, and active galactic nuclei. Their energy can span a wide range, from low-energy cosmic rays detected by satellites to ultra-high-energy cosmic rays observed at the Earth's surface.

Cosmic rays are a complex and fascinating subject, and their study continues to be a major focus of research in astrophysics and particle physics. The study of cosmic rays provides insights into the nature of matter, energy, and the interactions between different components of the universe. The quest for understanding cosmic rays is a testament to human curiosity and the power of science to explore the mysteries of the cosmos.
3.2 Ground-based gamma-ray astronomy

For gamma-ray energies above 20 GeV, the atmosphere shields them from being observed, but the Earth is an essential part of the detector. At these energies the gamma-rays produce air showers in the atmosphere that can be observed either through the Cherenkov radiation produced by the shower particles, or at high altitudes, the shower particles themselves. At present, the best results have been obtained with the Auger telescope. Images of the Cherenkov light on to a cluster of photomultipliers in the effective area of this detector can be determined from the measured energy of the gamma-rays. In recent years, two-particle experiments (the Crab and PSR 1706-441) have been convincingly observed at TeV energies. Even more remarkable has been the observation of AGN, Markarian 421. AGN are extragalactic objects that consist of accretion of material into massive black holes. These active nuclei are observed in the GeV range by the EGRET detector on the CGRO. Other AGN, such as the bright nearby galaxy Markarian 421, are not seen at TeV energies. The explanation of these remarkable observations may involve the concept of black holes. Other explanations for the observed gamma-rays are in the model of cosmic strings, which are thought to exist in the early universe.

3.3 Over the Knee

The cosmic-ray spectra that strike the earth atmospherically may be quite different from those that strike the ground. The cosmic-ray spectra are very steep, steepened by the solar system abundance, except that elements with high isotopic potential are differentially depressed. This is because the particles are detected near the knee energy. The knee is the particle energy at which the charged cosmic ray spectrum steepens at about 3 TeV. This energy is not well understood.

3.4 High-energy Cosmic Rays

Over thirty years ago a cosmic ray was observed that had energies of 30 PeV. The cosmic ray detectors have been observed with energies in excess of 10^18 eV. With these extraordinary events, attention is directed to the upper end of the cosmic ray spectrum. Cosmic ray spectra with energies above 10^19 eV are very difficult to explain. These cosmic rays have been observed by four independent detector groups, which agree on the shape and flux. There is structure at the end of the spectrum indicating a complex set of sources. The cosmic rays that are very energetic are very difficult to explain by our understanding of the solar system.

4 Quantum Aspects of Gravity

4.1 Quantum effects on the structure of quantum gravity

Quantum gravity is thought to be a fundamental theory that describes the behavior of the universe at the Planck scale. The Planck scale is characterized by the Planck length, which is approximately 10^-33 meters. At this scale, the laws of quantum mechanics and general relativity are expected to be unified. The Planck length is defined as the distance at which the wavelength of a gravitational wave becomes equal to the Planck length. This is an imaginary situation that cannot be observed directly, but it provides a fundamental limit to the size and structure of the universe.

4.2 Quantum cosmology

Quantum cosmology is a branch of theoretical physics that studies the structure and evolution of the universe at the Planck scale. It is based on the principles of quantum mechanics and general relativity. In quantum cosmology, the universe is treated as a quantum system, and its evolution is described by a wave function. This wave function is influenced by the initial conditions of the universe, such as the distribution of matter and energy. The evolution of the universe is determined by the principles of quantum mechanics, and it is possible to calculate the probabilities of different outcomes. However, the exact state of the universe at the Planck scale is not known, and it is a subject of ongoing research.
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 exist (also known as Hawking radiation) and thereby 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 \(10^{-6} M_{\odot}\)).

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 in general a thermodynamically 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 part, 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 that this information loss is tying up to tell us about 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 issue, 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 deepen the endpoint of black hole evaporation and other quantum aspects of small black holes. That struggle was the principal focus of Stephen Hawking’s work.

4.3 Black Hole Quantum Mechanics

Black holes are predicted to exist by general relativity, and there is compelling circumstantial evidence that they do exist in relative prominence in the Universe in two varieties: stellar mass black holes and supermassive black holes (\(M \sim 10^6 - 10^{10} M_{\odot}\)) that reside at the centers of most galaxies, known as quasars. A third variety, primordial black holes formed in the very early universe with masses as small as \(10^{-22} - 10^{-18} M_{\odot}\), 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 black 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 described by its mass and spin, and thanks to many years of analysis by many gravitational theorists, we now fully understand those predicted properties, with one major exception. We do not yet understand in detail the behavior of highly dynamical black holes (e.g., colliding and colliding black holes). That dynamical understanding may come with the next decade, as a result of combined numerical solutions of Einstein’s equations on supercomputers and gravitational wave observations of black hole collisions (Section 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:

1. 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);
2. to prove unambiguously 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,
3. to determine the distributions of black holes in the universe (their numbers, spatial distributions, and distributions of mass and spin), and
4. 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 (black hole distributions and astrophysical roles) are part of main-stream astronomy and astrophysics, and are being pursued with moderate success (assuming that indeed black holes are widespread in our galaxy), using a variety of astronomical instruments and analyses.

The former goals (unambiguous proof that an observed stellar-mass black hole is 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 (G 4).

The keys to these observational 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 horizon radius. There are two promising venues for such studies. X and gamma rays emitted by hot gas in an accretion disk should be scattered toward the horizon of the black hole, and X-ray telescopes in space might observe the resulting X rays emitted by the hot gas. Gamma rays from black hole mergers can also be detected by X-ray telescopes in space.

This X and gamma rays, emitted by gas spiraling into black hole candidate(s) and scattered toward the horizon, are a 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 that the radiation from a disk of near-horizon gas to fluctuate due to moderate heating and gravitational lensing effects, at the hole’s orbital period (which is a few millihertz), and as the hole spirals inward, that period should decrease. The result should be an X 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 nullclines flexure one may hope to determine whether such chirping is indeed occurring, 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 chirps would be performed by the black hole, the first of the high-energy astronomical observations, which can be observed. Unfortunately, a method function predicted, Head-A (from taking extensive data of the required sort). It has been nearly 20 years, but at last two X-ray missions with the required sensitivity have been launched: the X-Ray Timing Explorer (XTE), and the Unconventional Stellar Array (USA) X-Ray Telescope. The XTE and USA data, when combined with new techniques such as wavelets, give promise of much more detailed understanding of the inner regions of accretion disks, and perhaps one will bring the high-sounding unipolar proof of black holes and the first evidence of their detailed properties.
operate at the upper end of this band, where the interferometers lose sensitivity. This network of interferometers will be able to map the spatial distribution of stars in the Milky Way, as well as the angular momentum of the universe. The interferometers will also be sensitive to the gravitational waves emitted by black holes and neutron stars in binary systems, allowing us to study the dynamics of these objects.

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

The development of this enhanced interferometer technology—wherein monitoring distances between kilometer-separated test masses to a precision ~1/1000 the diameter of the nucleus of an atom—in a major effort involving a number of research groups world-wide, as is the development of the remnant dust detectors. These technologies, which were a central topic of discussion by Snowmass Group G2, are likely to find many applications outside the gravitational-waves field.

The low-frequency band (~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 > 10^9 M☉), their births and collisions, and the imprint of smaller objects into them—and also of known binary star systems such as 44 T Boo, and our galaxy's closest periodic compact object binary (a neutron star-neutron star, and black hole).

The premier instrument for this low-frequency band will be the space-based, several-million-kilometer-long variant of the LIGO/VIRGO earth-based interferometers. This Laser Interferometer Space Antenna (LISA) will be launched by the European Space Agency's (ESA) Cornerstone 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 by 5%, and a final decision remains to be made. Members of the American gravitational community and the European Space Agency's (ESA) Cornerstone Committee should be祺ing together with ESA in this endeavor, and working jointly, ESA and NASA will be able to fly this mission at considerably lower cost than in 2014.

The scientific payoffs of LISA and the LIGO/VIRGO network arise from their broad-based nature: they can contribute to a new generation of gravitational wave detectors, and may change the directions of the waves' sources with accuracies of ~1 degree or better.

Waveform studies, most especially via the choice of LISA, are likely to bring us to map the spacetime warp going around black holes and jets of the black hole co-hair theorm, and with those maps and tests, unquenched 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 gravitational waves generated by various sources are detectable, and whether the gravitational waves generated by various sources are detectable.

The gravitational waves from these events would be the first direct observation of general relativity, and an important test of Einstein's theory of gravity. The gravitational waves would allow us to study the properties of black holes and neutron stars, and to gain a better understanding of the fundamental laws of nature.

The recent development of the LIGO/VIRGO interferometers and the LISA mission has brought us closer to observing these gravitational waves. The LIGO/VIRGO network is currently in a phase of commissioning and calibration, and the LISA mission is scheduled for launch in 2014.

Cosmology

As the new millennium approaches, cosmology is entering an exciting epoch in which some of the fundamental questions concerning the origin and evolution of the Universe may be answered. Many of the questions we ask today are probably not far from being answered. Many of the remaining questions will be answered by the next generation of cosmologists and astrophysicists.

The future of cosmology depends on the continued expansion of the Universe. As we look back into the past, we see evidence that the Universe was expanding at a faster rate than it is today. This suggests that the expansion of the Universe may have been driven by a new form of matter, such as dark energy, that is not visible to us today.

The first results from the LIGO/VIRGO collaboration have confirmed the existence of gravitational waves, providing direct evidence for the inflationary Big Bang model. These results have encouraged further research into the nature of dark energy and the early universe.

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 with a hot, dense state that expanded and cooled. This simple picture successfully explains: 1) the Big Bang redshift 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 few seconds after the Big Bang; and 3) the existence of cosmic microwave background radiation, a remnant of radiation that filled the universe and decoupled from matter when the first atoms began to form. The success of the Big Bang model verifies it as a valid description of the universe from the present back to the first hundredths of a second after the Big Bang. The Big Bang model is now the best explanation for the nature of the universe, and it has revolutionized our understanding of the cosmos.
tances 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 or a function of their luminosity. The luminosity 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 $\tau = 13.7$ Gyr, whereas the limit cited above is based on studies along the giant sequence. Bubble Space Telescope studies may improve resolution of stars near the turnoff and significantly improve the limits.

The product of Hubble constant and the age, $H_0 t_0$, are directly linked to $\Omega$, the ratio of the energy density to the critical density of the universe, and to the energy density. For a flat universe in general, a universe with $\Omega$ is comprised of non-relativistic matter, $H_0 t_0 = 2/3$. Yet, the current best-estimate is $H_0 t_0$ 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 energy (or, equivalently, cosmological constant) contribution to the total energy density, a value of $H_0 t_0$ cannot 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 future will settle the issue.

The Planckian form of the cosmic microwave background spectrum has been precisely verified near the peak of the spectrum (less than a hundred GHz). The spectrum obeys a thermal distribution with a temperature of $T = 2.725 \pm 0.002$ degrees, corresponding to a photon density of $k_B T = 2.725 \times 10^{-23}$ J. Yet, verification of the Planckian shape at long wavelengths (<1 GHz) is much less precise. Improvements in these measurements would confirm cold dark matter evolution and further rule out exotic models, such as late-decaying particles.

Primordial nucleosynthesis has been established as a primary test of the cold dark matter picture and as one of the best means of measuring the abundance of baryons in the universe. Current best-estimates on $\Omega$, the ratio of its energy 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 the key parameters of the nucleosynthesis. The development of multi-dimensional hydrodynamic nucleosynthesis codes to model stellar atmospheres and supernovae will be important for this purpose. This will allow us to measure the abundances of light nuclear elements using pre-galactic hydrodynamic clouds (Lyman-alpha clouds) and subject to evolutionary assumptions. Continued improvements in lithium abundances is especially critical both as corroborating evidence and as the most precise method for narrowing the uncertainty in $\Omega$.

The big bang models needed to be completely specified unless one also determines $\Omega$, the ratio of the energy density to the critical density, specified by an open universe model, the flat cosmological constant or vacuum energy 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 radiation from the farthest observable universe is a significant contribution to the total energy density, a value of $H_0 t_0$ cannot 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 future will settle the issue.

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 has been 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 smoothes 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 universe from a closed universe. Hence, the flattening by inflation also explains why the observed energy density, $\rho$, is close to the critical density today. A key, testable prediction is that the ratio of the energy density to the critical value, $\Omega \equiv \rho/\rho_{\text{crit}}$, is distinguishable from unity today. The inflationary stretching also determines the scale of structure formation and other parameters for particle physics scatterers created near the Planck temperature, explaining their absence in the universe today.

Our important theoretical challenge is to understand the inflationary cosmology and is to understand that process which may have caused the large period of rapid inflation. If the microwave background anisotropy ($\Omega \approx 10^{-5}$) 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 $m^2T^2$, where $m$ is the Planck mass, $m \approx 10^{16}$ GeV, and $T \approx 10^{-5}$ GeV is the characteristic energy of whatever physics drove inflation. Hence, inflation is linked by the microwave background to high scale factor scales. Relating inflation to unification models of particle interactions, such as supersymmetry, is an important element needed to complete the inflationary picture.

Another important theoretical challenge which is incoherent to inflation and more general theoretical models, is to understand the source and value of the cosmological constant. Inflation relies on the notion that particle physics interactions produce a positive contribution to the vacuum energy 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 superstring theory.

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 and to find properties of the universe which are consistent with the initial conditions of the universe. However, there are numerous computing 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 away when the universe occurred a subinterval of the Planck time. As the universe inflated, the fluctuations, ripples in the fabric of space, stretched also, ultimately spanning a cosmological range over the density scales. As the critical density for particle physics scatterers created near the Planck temperature, explaining their absence in the universe today. Finally, inflationary models predict that large, supercritical density fluctuations could have occurred during inflation that might leave an imprint on the cosmic microwave background and act as seeds for large scale structure formation. The spectra of fluctuations is predicted to be nearly scale-invariant, which is consistent with the observations of the CMBR. Differential Microwave Radiometer (DMR) experiment. Inflation is the only viable cosmological model which explains so many diverse aspects of the universe.

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strings), surfaces ("domain walls"), or textures. The notion of defect models is that these considerably kinked strings may be the origin of inhomogeneity in the universe. One key difference from inflation is that these textures are strongly non-gaussian. General agreement of experiments 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 physical principles to explain the origin of inhomogeneity in the universe. Some cosmologists propose 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 primordial curvature-baryon (PIR) model. The model is intended to be conservative with the virtue that it does not require dark matter and any other unexplained physical process. 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 photon. 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 step for guiding the development of alternative 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 negligible proportions 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 infeasible, but, if it were 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^{16} GeV or so, using decays of long-lived states 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 nonperturbative 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 are compelling. Future experiments to improve constraints on the electron and neutron electric dipole moments could strongly influence developments in the field and may even require a substantial source to be discovered.

On the theoretical side, there remain open issues about the detailed mechanisms by which baryogenesis takes place in the case of 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 range for the Higgs boson mass in the minimal standard model precludes a first-order transition, although the issue remains controversial. The minimal model also does not mitigate for providing sufficient CP violations. 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 number of bubbles and the density of the process will be quite consistent with the measurement of primordial abundances of light elements and the standard nucleosynthesis picture to an increasing degree. However, this baryonic component must neither radiate nor absorb light. This basically excludes gas (unless it is in a very exotic state) and dark matter. In the conclusion that this form of dark matter is viable only in the form of condensed objects: stars too small to be single-proton nuclei and black holes. Both types can be combined under the name Massive Compact Halo Objects (MAHCs). If, as may be indicated by observations of X-ray counts and large-scale velocity flows, at an significantly higher than 0.1, it would be incompatible with the detect above from the primordial baryogenesys. We may then be forced into the hypothesis that at least some dark matter is nonbaryonic nonradiative, unless some scenario (e.g., through inhomogeneities generated by the weak hadron phase transition) was rending significantly the upper bound on 0. 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 demarcated bubbles 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. Eliciting the nature of dark matter is therefore a high priority endeavor which can be approached in two complementary ways. Cosmology gives us an information to 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.

Moreover, providing us with a method of detecting the only natural form of bary matter dark matter still compat with observations, Massive Compact Halo Objects (MACOs) if one of these MACOs happens to cross the line of sight to a star, say in the large Megallanic Cloud, a tremendous increase of the star density will be observed. This increase would be symmetric in time, anachronistic the non-explosive, 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, no evidence has clearly been established but the results are puzzling. We observe too many events towards the galactic bulge, and apparently too few (within our previous statistical evidence). We could conclude, we need both to increase the statistics and to better pin down the halo structure.

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

One of the well suited candidates is the axion. Such a particle has been predicted to have a strong CP violation and to be extremely weakly coupled to other particles. The natural axion models have been extensively studied, and it is interesting to note that the combination of lab astrophysics and experiments has constrained its
mase 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 own Galaxy can be detected through their conversion into monochromatic microwave photons inside a tunable microwave cavity at high magnetic field. In the past ten years, two pilot efforts have 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 observed, 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 a thermal equilibrium 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 \( \Omega \) 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 astro-physical 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 particles at the W/Z* intermediate vector boson scale (e.g., super-symmetry) 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 WIMPs is being brought into operation. Depending on the groups, they use large masses of germanium detectors, large scintillating crystals of NaI or novel "cylindrical detectors" working at millikelvin temperatures. While for the first generation of experiments using the weak nuclear sensitivity gains of a factor of two, the cyclopean detectors (i.e., a subtraction of the radioactive background, e.g., through the simultaneous measurement of the sum and the difference of the produced in particle interactions) and may give gains of one hundred or more. These experiments will begin to probe the dark sector expected for the theoretically favored neutralino, the lightest particle 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 clarifying 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 situation is that tiny inhomogeneities in the distribution of energy were generated to some extent, while the rest 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 mean 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 hydrodynamical, star formation, supernova, chemical evolution, etc. At present type of analyses can span a dynamical range of three to four orders of magnitude. One key challenge is to improve numerical techniques to the point where the simulations of the behavior of galaxies and stars, now in quotes, can be used as a novel means of testing the models of large-scale structure formation (e.g., in relation to cosmic defects, etc.).

Experiments measuring inhomogeneities spanning in intermediate scales (half degree to several degrees) probe the smooth nature of the microwave background, and discriminate qualitatively different models of large scale structure formation (e.g., inflation vs. cosmic defects, etc.). The next generation of experiments, which range in smoothing scale from a few degrees to 1000 square degrees, 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 extensive, they have been hindered by the large-scale variations in the temperature of the microwave background. These variations probe a detailed, quantitative fingerprint which can be used to decisively discriminate competing models for the evolution of the universe. In particular, measurements of anisotropy also provide novel ways of determining the values of cosmological parameters, such as the Hubble constant and the density of baryonic matter.

The resolution method is that COBE. Diffuse Microwave Radiometer (DMR) experiment that they had detected anisotropies of \( \Delta T/\sqrt{ T} \approx 10^{-6} \). Since COBE, DMR, more than a dozen new detections have been reported on angular scales ranging from one-half degree, and angular scales 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 initial periods of development 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 feature to the determination of the anisotropy and the spectral index of the power spectrum, the microwave anisotropy measurements allow us to search for the large-scale structure formation. COBE has provided a rough measure, but greater precision is needed to discriminate and rule out many models.
long-duration balloons which circumnavigated 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 promising 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 pattern. Such a mission would be a monumental and historic contribution to our understanding of cosmicology.

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 value 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 associated 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 spatial measurements, e.g., by a small satellite mission, is a secondary priority.

A balanced program of land, air and space missions is needed to extract the extraordinary wealth of information that 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.

59 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 boundaries be established so that new researchers 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 upon which new proposals can be evaluated?

Particle and nuclear astrophysics and cosmology is a case in point. Most agree that a far-reaching 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, 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, or galvanization by three separate divisions of the American Physical Society and attended by over 450 physicists, typifies to the breadth 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 $265M/yr.; the NSF at a level of $13M, and the NASA at a level of $150M. A study is currently being conducted to cosmic rays above 1 GeV. The "gravitational lens" represents another $13M (of which perhaps half is in space/astrophysics/mollecular-relevant), 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 aspects. New generations of experiments incorporate methodology and people across many disciplines. Nevertheless, as a result of somewhat infrequent cooperation growth, growth field finds itself in an agency management structure not quite reflective of natural intellectual relations.

It is obvious that we do not fit readily within the traditional framework of NSF and NASA astrophysics, and 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 and that reviewers do not have access to the overall picture and ad hoc subcommittees (e.g., of HEAPF) have been sparse and has lacked the community to support development.

There is widespread consensus that there should be more intra-agency and inter-agency communication. Finally, there is the worry that in any terms 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 engaged 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 $135M and $100M; proposals for second-generation space-mirror microwave background satellite, dedicated cosmology telescopes, a new generation of solar neutrino detectors, an astrophysical survey to extend the measurement of the gamma-ray aspect of AGN and black hole candidates, giant air shower arrays to explore the highest energy cosmic rays, x-ray kilometer neutrino detectors to look for high-energy neutrinos and sources, a space-based gravitational wave interferometer, and so on.

While NASA may have in place the necessary machinery to support 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 (HEAPF, NSAIC, 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 such a central processing 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 panel 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 for 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 emerging 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 combination of theoretical ideas, experimental realities, and technological capabilities which allow us for the first time to address many of the most fundamental questions about our Universe. The most hopeful phrase during the many forward-looking talks of the Summer Study was "now for the first time we have the ability to..."

It is in this context 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 invest the cultural legacy and 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, 400 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.