RESOURCE LETTER

Roger H. Stuewer, *Editor*
School of Physics and Astronomy, 116 Church Street
University of Minnesota, Minneapolis, Minnesota 55455

This is one of a series of Resource Letters on different topics intended to guide college physicists, astronomers, and other scientists to some of the literature and other teaching aids that may help improve course contents in specified fields. No Resource Letter is meant to be exhaustive and complete; in time there may be more than one letter on some of the main subjects of interest. Comments on these materials as well as suggestions for future topics will be welcomed. Please send such communications to Professor Roger H. Stuewer, Editor, AAPT Resource Letters, School of Physics and Astronomy, 116 Church Street SE, University of Minnesota, Minneapolis, MN 55455.

Resource Letter CPP-1:Cosmology and particle physics

David Lindley
Theoretical Astrophysics Group, Fermi National Accelerator Laboratory, Batavia, Illinois 60510
Edward W. Kolb and David N. Schramm
Theoretical Astrophysics Group, Fermi National Accelerator Laboratory, Batavia, Illinois 60510 and University of Chicago, Chicago, Illinois 60637

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This Resource Letter provides a guide to the literature on cosmology and particle physics. The letter E after an item indicates elementary level or material of general interest to persons becoming informed in the field. The letter I, for intermediate level, indicates material of somewhat more specialized nature; and the letter A indicates rather specialized or advanced material. An asterisk (*) indicates those articles to be included in an accompanying Reprint Book.

I. INTRODUCTION

Cosmology is the study of the origin and evolution of the Universe, from its very beginning, through the primordial production of light nuclei, the decoupling of the present microwave background radiation, galaxy formation, up to the present structure of galaxies and clusters of galaxies.

The word cosmology is derived from the Greek κοσμοζ, meaning order. Our modern use of the word, to mean specifically the goal of describing and explaining the Universe using the order imposed by known physical law is rather recent: Historically, cosmological study includes philosophical and religious, as well as scientific, attempts to understand the Universe. Particle physics is the study of matter at the smallest scales. It is a search for the most fundamental forms of matter, and the rules by which they combine to form the world we observe. Like cosmology, it is the modern continuation of an old tradition: Democritus first proposed to explain the variety of the world by combining a few fundamental atoms. The modern particle physicist has dug down through more layers of structure, but is still looking for something finally indivisible.

After a millenium, these two avenues of inquiry have reached common ground. In the last half-century, it has become apparent that both the large and small scales of today had a common origin in the hot and dense beginning of the Universe. With this realization, particle physicists have begun to learn cosmology, and cosmologists particle physics.

This noble intellectual enterprise has its mundane aspects; enormous numbers of papers have been written. Figure 1, a revised version of a similar figure in the Resource Letter of Ryan and Shepley [Am. J. Phys. **44**, 223 (1976)], shows the increase in the number of papers under the heading "Cosmology" in Physics Abstracts. Figure 2 shows that even in the general inflation of the physical literature, cosmology has undergone a recent increase.

Our Resource Letter is intended as a guide to this new field of particle physics and cosmology. Both the selection of items and the comments on them represent our personal opinions: This is not meant to be an accurate atlas of cosmology and particle physics, but a sketch map for those who wish to begin their own exploration.

II. JOURNALS AND CONFERENCE PROCEEDINGS

A. Journals

Research on the early Universe is frequently published in physics rather than astronomy journals, but the latter are still the prime source for cosmological observations and data, and for work on the more astrophysical areas of cosmology, especially galaxy formation and clustering. Important physics journals are:

Annual Reviews of Nuclear and Particle Science
Nuclear Physics B
Physical Review D
Physical Review Letters
Physics Letters B
Reviews of Modern Phyiscs
Soviet Physics JETP

The major astronomy journals are:

Annual Reviews of Astronomy and Astrophysics
Astronomy and Astrophysics
Astrophysical Journal (including letters and Supplement sections)
Monthly Notices of the Royal Astronomical Society

Soviet Astronomy Letters
Soviet Journal of Astronomy

A miscellaneous selection of journals with occasional items of interest is:

Classical and Quantum Gravity
Comments on Astrophysics and Space Physics
Comments on Nuclear and Particle Physics
Communications in Mathematical Physics
General Relativity and Gravitation
Nature
Nuovo Cimento
Physics Reports
Proceedings of the Royal Society
Progress of Theoretical Physics
Reports on Progress in Physics

B. Conference proceedings

A number of schools and conferences convene at regular intervals in agreeable locations around the world. The Proceedings of these events are valuable because they provide not only a lot of information in one place, but also historical views of the state of their subject at one time.

1. **Texas Symposium on Relativistic Astrophysics,** Ann. N.Y. Acad. Sci. **XI** 422 (1984); **X** 375 (1982); **IX** 336 (1980); **VIII** 302 (1978).
2. **Workshops on Grand Unification: 5** (World Scientific, Singapore, 1984); **4** (Birkhauser, Boston, 1984); **3** (Birkhauser, Boston, 1983).
3. Proc. 4th Moriond Workshop: **Massive Neutrinos in Astrophysics and Particle Physics**, edited by J. Tran Thanh Van (Editions Frontiers, Paris, 1984).
4. IAU Symposium 63: **Confrontation of Cosmological Theories and Observational Data,** edited by M. S. Longair (Reidel, Dordrecht, 1974).
5. IAU Symposium 104: **Early Evolution of the Universe and Its Present Structure**, edited by G. O. Abell and G. Chincarini (Reidel, Dordrecht, 1983).
6. Les Houches 1979, Session XXXII: **Physical Cosmology**, edited by R. Balian, J. Audouze, and D. N. Schramm (North-Holland, Amsterdam, 1980).
7. **International Cosmic Ray Conferences: 19** (San Diego, 1985); **18** (Bangalore, 1983); **17** (Paris, 1981); **16** (Kyoto University, 1979); **15** (Bulgarian Academy of Sciences, 1977); **14** (Munich, 1975).

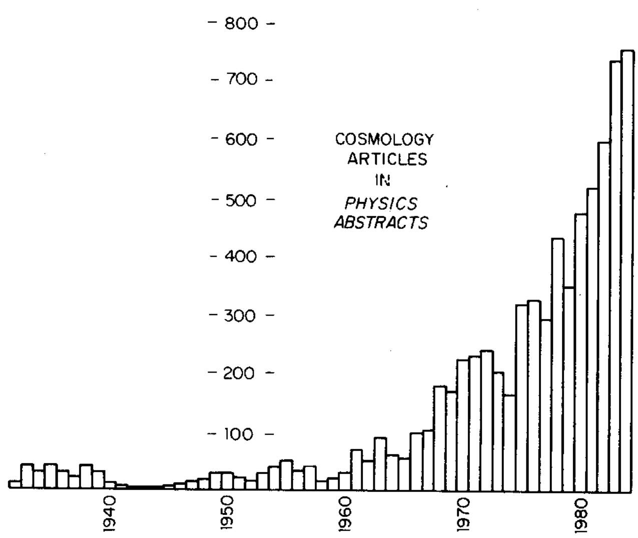

Fig. 1. This histogram, an updated version of the diagram shown by Ryan and Shepley [Am. J. Phys. **44**, 223 (1976)], illustrates the rapid increase, over the past two decades, of the publication rate of cosmological articles.

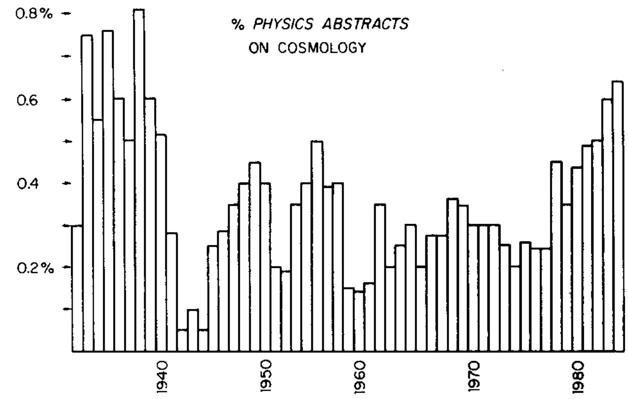

Fig. 2. Publication in cosmology, compared to all of physics, has had a more erratic history, but also shows a recent rise. It is left as an exercise for the reader to account for the peaks and troughs in the distribution.

8. **Inner Space/Outer Space**, edited by E. W. Kolb *et al.* (University of Chicago Press, Chicago, 1985).
9. **The Very Early Universe**, edited by G. W. Gibbons, S. W. Hawking, and S. T. Siklos (Cambridge U. P., Cambridge, 1983).
10. **General Relativity: An Einstein Centenary Survey,** edited by S. W. Hawking and W. Israel (Cambridge U. P., Cambridge, 1979).

III. BOOKS

Since this is a new field, most of the books in this compilation are fairly recent. We have also included some standard references on both particle physics and general relativity to provide the necessary background.

A. Popular books

11. **The First Three Minutes,** S. Weinberg (Basic, New York, 1977). A nice account of standard big-bang cosmology, starting about 1 s after the bang. (E)
12. **The Big Bang,** J. Silk (Freeman, San Francisco, 1980). Silk gives a broad discussion of the standard big bang and galaxy formation, concentrating on the more astrophysical aspects. The book is between elementary and textbook level. (E)
13. **The Left Hand of Creation,** J. Barrow and J. Silk (Basic, New York, 1983). A readable popular account bringing together the astrophysical world and the physical universe. (E)
14. **Atoms of Silence,** H. Reeves (MIT, Cambridge, MA, 1985). A description of the connection between the microscopic and the macroscopic worlds, by one of France's leading astrophysicists and popularizers of science. (E)
15. **The Cosmic Code,** H. Pagels (Simon and Schuster, New York, 1982). An award-winning book that makes the world of modern quantum theory understandable to the layman. (E)
16. **Cosmology plus One,** Scientific American reprint volume, edited by O. Ginerich (Freeman, San Francisco, 1977). A compilation of articles on classical cosmology, published before the influence of recent advances in particle physics. (E)
17. **From Atoms to Quarks,** J. Trefil (Scribner, New York, 1982). An attempt to explain at a popular level how we reached our current understanding of the microscopic world. (E)
18. **The Discovery of Subatomic Particles,** S. Weinberg (Freeman, San Francisco, 1983). (E)
19. **Superforce,** P. Davies (Simon and Schuster, New York, 1984). A very readable account of recent ideas in the unification of forces. (E)
20. **Constructing the Universe,** D. Layzer (Freeman, New York, 1985). A historical account of the development of our view of the Universe. (E)

B. Textbooks

21. **Gravitation and Cosmology,** S. Weinberg (Wiley, New York, 1972). This careful treatment of general relativity includes a standard account of physical cosmology. The book predates recent developments in particle physics and cosmology. (A)
22. **Gravitation,** C. W. Misner, K. S. Thorne, and J. A. Wheeler (Freeman, San Francisco, 1973). This standard general relativity text emphasizes the geometric aspects of gravity. Only closed cosmological models are treated in detail, and there is little discussion of physical processes in the big bang. (A)
23. **General Relativity,** R. M. Wald (University of Chicago Press, Chicago, 1984). A new and thorough relativity text, with a brief treatment of cosmology. (A)
24. **Physical Cosmology,** P. J. E. Peebles (Princeton U. P., Princeton, NJ, 1975). An intermediate-level text dealing with physical processes in the late (after 1 s) stages of the big bang. (E)
25. **Relativistic Astrophysics,** Vol. II, Ya. B. Zel'dovich and I. D. Novikov (University of Chicago Press, Chicago, 1983). A translation and revision of the classic 1975 textbook by two great Russian cosmologists. Although it anticipates developments in the particle physics–cosmology field, this book is basically an exposition of classical cosmology. (A)
26. **The Large-Scale Structure of the Universe,** P. J. E. Peebles (Princeton U. P., Princeton, NJ, 1980). A comprehensive textbook on the distribution of matter in the Universe, with special emphasis on the statistical analyses of galaxy clustering, and on the theory of the growth of perturbations in relativistic cosmologies. (I)
27. **Unity of Forces in the Universe,** A. Zee (World Scientific, Singapore, 1982), 2 vols., 464 pp. and 612 pp. A collection of reprints of major papers in both particle physics and cosmology, with useful introductory material. Volume I covers grand unification, Volume II cosmology. (A)
28. **Gauge Theories of the Strong, Weak and Electromagnetic Interactions,** C. Quigg (Benjamin/Cummings, Menlo Park, CA, 1983). A comprehensive account of the standard theory of the strong and electroweak forces. (A)
29. **Grand Unified Theories,** G. G. Ross (Benjamin/Cummings, Menlo Park, CA, 1985) 497 pp. A thorough treatment of grand unified theories. (A)

IV. STANDARD COSMOLOGY

Popular descriptions of the accepted big-bang model can be found in *The Big Bang* (Ref. 12) and *The First Three Minutes* (Ref. 11), while a more detailed and technical account is in *Gravitation and Cosmology* (Ref. 21).

A. Observational parameters

Although the Universe contains irregularities, in the form of galaxies, it is assumed to behave on the average as if it were completely homogeneous and isotropic. In this case, the large-scale evolution of the Universe is described by a Friedman–Robertson–Walker solution of Einstein's equation, and at any time its state is characterized by a few numbers: the Hubble constant, relating distance and recession velocity; the deceleration parameter, distinguishing positively and negatively curved models; the age; the ratio of the present density of the Universe to the critical density (which is the density of a Universe with zero curvature); and perhaps a cosmological constant. The effort to measure these interrelated numbers is the core of observational cosmology.

30. **"The Hubble Constant as Derived from 21 cm Linewidths,"** A. R. Sandage and G. Tammann, Nature **307**, 326–29 (1984). (I)
31. **"The Extragalactic Distance Scale. VII. The Velocity-Distance Relations in Different Directions and the Hubble Ratio Within and Without the Local Supercluster,"** G. de Vaucouleurs and G. Bollinger, Astrophys. J. **233**, 433–52 (1979). (I)
32. **"Evidence for Local Anisotropy of the Hubble Flow,"** M. Davis and P. J. E. Peebles, Annu. Rev. Astron. Astrophys. **21**, 109–30 (1983). (I)
33. **"An Unbound Universe,"** J. R. Gott, III, J. E. Gunn, B. M. Tinsley, and D. N. Schramm, Astrophys. J. **194**, 543–53 (1974). (I)
34. **"Single Star Evolution I. Massive Stars and Early Evolution of Low and Intermediate Mass Stars,"** I. Iben and A. Renzini, Phys. Rep. **105**, 329–406 (1984). (I)
35. **"Nucleocosmochronology,"** E. Symbalisty and D. N. Schramm, Rep. Prog. Phys. **44**, 293–328 (1981). (I)

B. The microwave background

The idea that the present Universe might have evolved from a hot, dense initial state was first proposed by Gamow in the late 1950s, but this notion languished until the observational discovery of a uniform microwave emission pervading all space. This was soon recognized as the cool remnant of the hot big bang, and modern cosmology began in earnest. Continued investigation of the microwave background is mostly directed toward accurate measurements of the spectrum and isotropy of the radiation; any departures from exactly thermal form have powerful implications for the detailed thermal history of the Universe.

36. **"A Measurement of Excess Antenna Temperature,"** A. Penzias and R. Wilson, Astrophys. J. **142**, 419–21 (1965). (I)
37. **"Cosmic Black-body Radiation,"** R. H. Dicke, P. J. E. Peebles, P. G. Roll, and D. T. Wilkinson, Astrophys. J. **142**, 414–419 (1965). (I)
38. **"New Measurements of the Spectrum of the Cosmic Microwave Background,"** J. B. Peterson, P. L. Richards, K. L. Bonomo, and T. Timusk, in *Inner Space/Outer Space* (Ref. 8), 119–25. (I)
39. **"The Microwave Background Temperature at 2.64 and 1.32 millimeters,"** D. Meyer and M. Jura, Astrophys. J. Lett. **276** L1–L3 (1984). (I)
40. **"Direction of Anisotropy in the Cosmic Blackbody Radiation,"** G. F. Smoot, M. V. Gorenstein, and R. A. Muller, Phys. Rev. Lett. **39**, 898–901 (1977). (I)
41. **"Anisotropies in the 2.7 K Cosmic Radiation,"** D. T. Wilkinson, in *Inner Space/Outer Space* (Ref. 8), 126–32. (I)

C. Galaxies and the distribution of matter

The nebula M31 in Messier's catalog was known to the ancients and was studied by many of the great European astronomers, but its identity as a galaxy beyond our own was not firmly established until the beginning of this century. Since then, galaxies numbering millions have been noted by modern astronomers. Hubble first began to classify galaxies by shape, but his morphological sequence is now known to have no evolutionary significance. Since then, astronomers have cataloged galaxies according to shape, position, brightness, and, most recently, redshift. The statistical properties of the distribution of galaxies on the sky have, following Peebles (Ref. 26), been used extensively as diagnostics of galaxy formation theories.

42. **The Realm of the Nebulae,** E. Hubble (Yale U. P., New Haven, 1982). (E)
43. **"A Survey of Galaxy Redshifts, IV. The Data,"** J. Huchra, M. Davis, D. Latham, and J. Tonry, Astrophys. J. Suppl. **52**, 89–119 (1983). (I)
44. **"A Complete Galaxy Redshift Sample—I. The Peculiar Velocities Between Galaxy Pairs and the Mean Mass Density of the Universe,"** A. J. Bean *et al.*, MNRAS **205**, 605–24 (1983). (I)

45. **"A Million Cubic Megaparsec Void in Boötes?"** R. P. Kirshner, A. Oemler, P. L. Schechter, and S. A. Schectman, Astrophys. J. Lett. **248**, L57–L60 (1981). (I)
46. **"Giant Voids in the Universe,"** Ya. B. Zel'dovich, J. Einasto, and S. F. Shandarin, Nature **300**, 407–13 (1982). (I)

D. The hot big bang

Gamow is credited with the notion of taking seriously the increasing density, at early times, of a Friedman Universe, and proposing that all the matter we see was once hot, and of nulcear density. Later, with collaborators, the ideas both of a radiation background and of cosmological nucleosynthesis are put forward. The calculation, using huge computer codes, of element production in the first minute of the big bang has been cosmology's most quantitative achievement, and has become in turn the most stringent test of new ideas.

47. **"Expanding Universe and the Origin of Elements,"** G. Gamow, Phys. Rev. **70**, 572–573 (1946). (E)
48. **"On the Synthesis of Elements at Very High Temperatures,"** R. Wagoner, W. Fowler, and F. Hoyle, Astrophys. J. **148**, 3–36 (1967). (I)
49. **"Element Production in the Early Universe,"** D. Schramm and R. Wagoner, Annu. Rev. Nucl. Part. Sci. **27**, 37–74 (1977). (I)
50. **"Primordial Nucleosynthesis: A Critical Comparison of Theory and Observation,"** J. Yang, M. S. Turner, G. Steigman, D. N. Schramm, and K. A. Olive, Astrophys. J. **281**, 495–511 (1984). (I)

V. NONSTANDARD COSMOLOGY

The usual application of particle physics to cosmology is to take some new theory of high-energy interactions, to add it to the conventional hot big bang, and then to make a judgment on the acceptibility of the resulting unconventional cosmology. It must not be forgotten in this exercise that the hot big bang can itself be altered without appeal to exotic particle physics, leaving open the possibility that a combination of unconventional physics and cosmology could devilishly produce conventional results. Just as the experimental particle physicist must know the vargaries of the accelerator in order to interpret results, so the theorist should know the peculiarities of big-bang cosmology before setting up cosmological experiments. There are many ways in which the standard big bang can be altered, both subtly and grossly, but most of them have undesirable consequences.

51. **Homogeneous Relativistic Cosmologies,** M. P. Ryan and L. C. Shepley (Princeton U. P., Princeton, NJ, 1975) 320 pp. (A)
52. **"Dissipative Effects in the Expansion of the Universe. I,"** R. A. Matzner and C. W. Misner, Astrophys. J. **171**, 415–32 (1972). (A)
53. **"The ABC of Population III,"** B. Carr, in *Inner Space/Outer Space* (Ref. 8), pp. 83–102. (I)
54. **"Big-Bang Nucleosynthesis With Nonzero Lepton Numbers,"** A. Yahil and G. Beaudet, Astrophys. J. **206**, 26–29 (1976). (A)
55. **"The Possibility of Neutrino Degeneracy: What Nucleosynthesis Does Say,"** Y. David and H. Reeves, in *Les Houches XXXII* (Ref. 6), pp. 443–63. (A)
56. **"Observational Tests of Antimatter Cosmologies,"** G. Steigman, Annu. Rev. Astrophys. **14**, 339–72 (1976). (E)

Another source of variation lies in theories of gravity other than general relativity. On the principle of dealing with only one crazy theory at a time, we will not discuss exotic particle physics *and* non-Einsteinian gravity.

VI. STANDARD PARTICLE PHYSICS

Modern particle physics is about the same age as modern cosmology, if we count Rutherford's experiments and Hubble's observations as the starting points. In the first tanglings of particle physics and cosmology, the physics was assumed known by other means, and cosmologists were left to deal with the consequences; the winding path by which present theories of particle physics have been reached has no cosmological connection, and we will not discuss it in this Resource Letter. A good historical review is *The Discovery of Subatomic Particles* (Ref. 18).

Recently, though, the partnership has become more equitable, and physicists are likely to test their theories in part by judging the health of the ensuing cosmology. Cosmology has been most useful to particle physicists in those area where the physics is speculative: The Universe provides a laboratory at high energies that Earthbound experiments cannot reach. The recent embrace of particle physics and cosmology became intimate over grand unification, which sought to unify the strong and the electroweak interactions, and as a bonus explained the predominance of matter over antimatter in the universe.

57. **"Conceptual Foundations of the Unified Theory of Weak and Electromagnetic Inteactions,"** S. Weinberg, A. Salam, and S. Glashow, Rev. Mod. Phys. **52**, 515–23 (1980). (I)
58. **"Quantum Chromodynamics: The Modern Theory of The String Interaction,"** F. Wilczek, Annu. Rev. Nucl. Part. Sci. **32**, 177–209 (1982) (I)
59. **"Grand Unified Theories and Proton Decay,"** P. Langacker, Phys. Rep. **72**, 185–385 (1981). (I)
60. **"Grand Unified Theories in Cosmology,"** J. Ellis, Phil. Trans. R. Soc. London Ser. A **307**, 121–40 (1982). (I)

Ultimately, physicists would like to include gravity in a unified scheme of forces, but at present there are only a few hopeful signs in this direction. These include (in order of increasing speculation) supersymmetry and its extension, supergravity, Kaluza–Klein, and other theories with extra dimensions and superstrings. These are all new subjects, and their application to cosmology is so far fragmentary and uncertain; references are given below under suitable headings.

VII. NEW PARTICLES

In the seventies, a resurgence of interest in the possibility of neutrino masses spawned a number of papers on the cosmological consequences. From simple arguments on the contribution of massive neutrinos to the density of the Universe, more complex considerations emerged of unstable neutrinos, and the effects of energetic decay products. The lessons learned apply not just to neutrinos, and now any newly proposed particle is routinely subjected to a battery of tests that may limit its lifetime, mass, relative density, decay paths, and so on. Some useful reviews of the arguments employed are given below.

61. **"Cosmology and Elementary Particle Physics,"** A. D. Dolgov and Ya. B. Zeldovich, Rev. Mod. Phys. **53**, 1–41 (1981). (I)
62. **"Particle Physics in the Early Universe,"** G. Steigman, in *Les Houches XXXII* (Ref. 6), pp. 473–92. (I)

A. Neutrinos

Neutrinos are not new particles, but their having mass is a recent idea. Massive neutrinos contribute to the present density of the Universe, and this leads to restrictions on the allowed mass. Neutrinos with mass in the forbidden range can be saved if they are unstable, but then one has to worry about the effects of the decay products. There are many ingenious arguments constraining the mass and lifetime for various decay modes.

*63. **"An Upper Limit on the Neutrino Mass,"** R. Cowsik and J. McClelland, Phys. Rev. Lett. **29**, 669–70 (1972). (E)

*64. **"Cosmological Lower Bound on Heavy-Neutrino Masses,"** B. W. Lee and S. Weinberg, Phys. Rev. Lett. **39**, 165–71 (1977). (E)

*65. **"Cosmological Upper Bounds on Heavy Neutrino Lifetimes,"** D. A. Dicus, E. W. Kolb, and V. L. Teplitz, Phys. Rev. Lett. **39**, 168 (1978). (E)

*66. **"Radiative Decay of Massive Neutrinos and Cosmic Element Abundances,"** D. Lindley, MNRAS **188**, 15–19 (1979). (E)

*67. **"Cosmological Constraints on the Lifetime of Massive Particles,"** D. Lindley, Astrophys. J. **294**, 1–8 (1985). (E)

68. **"Mass and Mixing Angles of the τ Neutrino,"** E. W. Kolb and T. Goldman, Phys. Rev. Lett. **43**, 897–900 (1979). (I)

69. **"Cosmological and Experimental Constraints on the Tau Neutrino,"** S. Sarkar and A. M. Cooper, Phys. Lett. B **148**, 347–54 (1984). (I)

70. **"Limits on the Radiative Decay of Neutrinos,"** R. Cowsik, Phys. Rev. Lett. **39**, 784–87 (1977). (I)

71. **"Have Massive Cosmological Neutrinos Already Been Detected?,"** F. W. Stecker, Phys. Rev. Lett. **45**, 1460–1462 (1980). (I)

72. **"Galactic Neutrinos and UV Astronomy,"** A. de Rujula and S. Glashow, Phys. Rev. Lett. **45**, 942–44 (1980) (I).

Supernovae explosions release a large fraction of their energy in neutrinos, which, if they decay into photons in or near the supernova, increase the luminosity. Only very short lifetimes are then allowed for neutrinos with mass up to about 10 MeV.

73. **"Limits From Supernovae on Neutrino Radiative Lifetimes,"** S. Falk and D. N. Schramm, Phys. Lett. B **79**, 511–13 (1978). (J)

74. **"Constraints on Heavy Neutrinos,"** D. Toussaint and F. Wilczek, Nature **289**, 777–78 (1981). (I)

Another variation on neutrino physics is the addition of more species, beyond the usual three. This significantly alters the cosmological density at nucleosynthesis, and changes the predicted element abundances. Four species are marginally consistent, and more are inconsistent. The neutrino story can be counted the first example of cosmologists helping out particle physicists, and being taken seriously. In turn, it may soon happen that experimental measurements of the properties of the Z particle may directly count the number of neutrino species; this will be the first time that a high-energy physics experiment will be a check of standard cosmology.

*75. **"Cosomological Limits to the Number of Massive Leptons,"** G. Steigman, D. N. Schramm, and J. E. Gunn, Phys. Lett. B **66**, 202–04 (1977). (E)

76. **"On the Relation of the Cosmological Constraints on Neutrino Flavors to the Width of the Z°,"** D. N. Schramm and G. Steigman, Phys. Lett. B **141**, 337–41 (1984). (I)

B. Superinos

Supersymmetric particle theories introduce fermionic partners for all bosons, and vice versa. The photon has its photino, the graviton its gravitino, and so on. Of these new particles, one is lightest and is absolutely stable. The most popular candidates for the lightest superino are the gravitino and the photino; Ellis *et al.* discuss and weigh the possibilities.

Many of the restrictions applied to massive neutrinos apply with equal force to superinos. An important difference is that superinos, being more weakly interacting, decouple earlier than neutrinos, and their relative abundance is diluted by entropy creation from the annihilation of lower mass particles. In addition, where neutrino mass if often treated in an *ad hoc* way, phenomenological supersymmetry models usually predict, within limits, the properties of new particles, and therefore cosmological reasoning can significantly influence model building.

*77. **"Supersymmetric Relics From the Big Bang,"** J. Ellis, J. S. Hagelin, D. V. Nanopoulos, K. Olive, and M. Srednicki, Nucl. Phys. B **238**, 453–76 (1984). (I)

78. **"Supersymmetry, Cosmology, and New Physics at Teraelectronvolt Energies,"** H. Pagels and J. R. Primack, Phys. Rev. Lett. **48**, 223–26 (1982). (I)

79. **"Limits on New Superweakly Interacting Particles From Primordial Nucleosynthesis,"** K. Olive, D. N. Schramm, and G. Steigman, Nucl. Phys. B **180**, 497–515 (1981). (I)

80. **"The Cosmology of Decaying Gravitinos,"** J. Ellis, D. V. Nanopoulos, and S. Sarkar, Nucl. Phys. B **259**, 175–88 (1985). (I)

81. **"Is it Easy to Save the Gravitino?,"** M. Yu Klopov and A. D. Linde, Phys. Lett. B **138**, 265–68 (1984). (I)

C. Axions

The axion is a hypothetical particle that appears in a class of theories invented to explain why the strong interaction conserves P and CP. In these theories, P and CP conservation is a consequence of the relaxation of a new field toward the minimum of a potential; the axion is an oscillation of this field about the minimum. Sikivie gives a comprehensive review of particle physics, cosmology, and astrophysics with the axion.

82. **"Axions in Astrophysics and Cosmology,"** P. Sikivie, in *Inner Space/Outer Space* (Ref. 8), 518–32. (I)

Since stars are large nuclear reactors, they can also emit axions. If the axion is not to carry away so much energy from red giants that models of stellar evolution would be upset, then it must be lighter than about 0.01 eV. Although the axion must be light, it is produced in much greater numbers than simple thermal equilibrium arguments would suggest, and therefore still has important cosmological implications.

83. **"Astrophysical Bounds on the Masses of Axions and Higgs Particles,"** D. A. Dicus, E. W. Kolb, V. L. Teplitz, and R. V. Wagoner, Phys. Rev. D **18**, 1829–1834 (1978). (I)

84. **"Cosmology of the Invisible Axion,"** J. Preskill, M. B. Wise, and F. Wilczek, Phys. Lett. B **120**, 127–32 (1983). (I)

85. **"A Cosmological Bound on the Invisible Axion,"** L. F. Abbott and P. Sikivie, Phys. Lett. B **120**, 133–36 (1983). (I)

87. **"Experimental Tests of the 'Invisible' Axion,"** P. Sikivie, Phys. Rev. Lett. **51**, 1415–1417 (1983); **52**, "Errata," 695 (1984). (I)

D. Magnetic monopoles

Speculation on the existence of free magnetic monopoles goes back to Dirac, who proved that the charge of any such object must be quantized. Dirac had no solid reason to expect monopoles to occur, but in grand unified theories they are predicted to exist.

88. **"Quantified Singularities in the Electromagnetic Fields,"** P. A. M. Dirac, Proc. R. Soc. London Ser. A **133**, 60–72 (1931). (E)

89. **"Magnetic Monopoles in Unified Gauge Theories,"** G. 't Hooft, Nucl. Phys. B **79**, 276–84 (1974). (A)

90. **"Isomeric States of Quantum Fields,"** A. M. Polyakov, Sov. Phys. JETP **41**, 988–95 (1975). (A)

Monopoles are produced in the early Universe when grand unified symmetry breaks, at a temperature of about 10^{15} GeV; the mass of the monopole is somewhat higher than this, perhaps 10^{16} GeV. Conventional models predict a huge density of monopoles, which would dominate the Universe today by as much as 12 orders of magnitude. Many ways of reducing their density have been suggested, but most are unworkable or unappealing. Guth and Tye proposed what is currently the most popular solution, using inflation to dilute the density of monopoles; in fact, solving the monopole was the first motive for inflation, and its other benefits were noticed later.

*91. **"On the Concentration of Relic Magnetic Monopoles in the Universe,"** Ya. B. Zel'dovich and M. Yu. Khlopov, Phys. Lett. B **79**, 239–41 (1978). (I)

92. **"Cosmological Production of Superheavy Magnetic Monopoles,"** J. P. Preskill, Phys. Rev. Lett. **43**, 1365–1368 (1979). (I)

93. **"Massive Magnetic Monopoles in Cosmology and Astrophysics,"** E. W. Kolb, in Texas Symposium XI (Ref. 1), 33–44. (I)

94. **"Phase Transitions and Magnetic Monopole Production in the Very Early Universe,"** A. H. Guth and S-H. H. Tye, Phys. Rev. Lett. **44**, 631–35 (1980). (I)

An obvious and much studied effect of monopoles in astrophysics is their ability to discharge magnetic fields. Parker estimated a limit on the local flux of monopoles from the simple observation that our galaxy has a finite magnetic field. This "Parker limit" is straightforward, but there may be a loophole in the argument if monopoles around the galaxy have collective modes of oscillation that maintain a magnetic field.

95. **"The Origin of Magnetic Fields,"** E. N. Parker, Astrophys. J. **160**, 383–404 (1970). (I)

*96. **"Magnetic Monopoles and the Survival of Galactic Magnetic Fields,"** M. S. Turner, E. N. Parker, and T. J. Bogdan, Phys. Rev. D **26**, 1296–1305 (1981). (I)

97. **"The Magnetic Monopole Flux and the Survival of Intracluster Magnetic Fields,"** Y. Rephaeli and M. S. Turner, Phys. Lett. B **121**, 115–18 (1983). (I)

98. **"Number Simulation of the Plasma and Gravitational Dynamics of a Galactic Magnetic Monopole Halo,"** R. Farouki, S. L. Shapiro, and I. Wasserman, Astrophys. J. **284**, 282–98 (1984). (I)

A new and important discovery was the realization by Rubakov and Callan that monopoles, because of their finite internal structure, could undergo baryon number violating processes with a rate typical of strong interactions. Dense stars, especially neutron stars, could gravitationally capture monopoles, which would then catalyze nucleon decay and heat the stars. Observations of the x-ray background provide a limit on the number and luminosity of neutron stars, and thus on the density of monopoles.

99. **"Adler–Bell–Jackiw Anomaly and Fermion-Number Breaking in the Presence of a Magnetic Monopole,"** V. A. Rubakov, Nucl. Phys. B **203**, 311–48 (1982). (A)

100. **"Dyon-Fermion Dynamics,"** C. G. Callan, Phys. Rev. D **26**, 2058–2068 (1982). (A)

101. **"Monopole Catalysis of Nucleon Decay in Neutron Stars,"** E. W. Kolb, S. Colgate, and J. A. Harvey, Phys. Rev. Lett. **49**, 1373–1375 (1982). (I)

102. **"Limits From the Soft x-Ray Background on the Temperature of Old Neutron Stars and on the Flux of Superheavy Magnetic Monopoles,"** E. W. Kolb and M. S. Turner, Astrophys. J. **286**, 702–10 (1984). (I)

103. **"Monopole Catalysis of Nucleon Decay in Old Pulsar,"** K. Freese, M. S. Turner, and D. N. Schramm, Phys. Rev. Lett. **51**, 1625–1628 (1983). (I)

104. **"Do Monopoles Keep White Dwarfs Hot?,"** K. Freese, Astrophys. J.

Cabrera has reported direct detection of a monopole by its passage through a superconducting ring. However, the short experimental running time implies either a flux well in excess of the Parker limit, or an extraordinary piece of luck. Later experiments by Cabrera and collaborators, and others, have failed to reveal new detections.

105. **"First Results From a Superconductive Detector for Moving Magnetic Monopoles,"** B. Cabrera, Phys. Rev. Lett. **48**, 1378–1381 (1982). (I)

106. **"Upper Limit on Flux of Cosmic-Ray Monopoles Obtained With a Three-Loop Superconductive Detector,"** B. Cabrera, M. Taber, R. Gardner, and J. Bourg, Phys. Rev. Lett. **51**, 1933–1936 (1983). (I)

107. **"Experimental Limits on Magnetic Monopole Catalysis of Nucleon Decay,"** S. Errede *et al.*, Phys. Rev. Lett. **51**, 245–48 (1983). (I)

VIII. DARK MATTER AND GALAXY FORMATION

Galaxies are presumed to form because small irregularities in the distribution of matter amplify as the Universe expands. The study of galaxy formation therefore involves everything from the origin of those density fluctuations in the very early Universe to the complex dynamics of collapsing and cooling matter. This section is devoted to the impact of new particle physics on the evolution of fluctuations and the formation and structure of galaxies. A good introductory review of the large-scale structure of the Universe is by Silk, Szalay, and Zel'dovich, and Peebles' book provides a technical exposition.

108. **"The Large-Scale Structure of the Universe,"** J. Silk, A. S. Szalay, and Ya. B. Zel'dovich, Sci. Am. **249** (10), 72–80 (1983). (E)

A. Observational evidence for dark matter

Dark matter is a general term for anything that can be detected by its dynamical influence, but cannot be seen. Direct analysis of the motion of stars, galaxies, and clusters of galaxies reveals the existence of dark matter on all astronomical scales.

109. **"Self-Consistent Determinations of the Total Amount of Matter Near the Sun,"** J. N. Bahcall, Astrophys. J. **276**, 169–181 (1984). (I)

110. **"Is There Non-Luminous Matter in Dwarf Spheroidal Galaxies?,"** S. M. Faber and D. N. C. Lin, Astrophys. J. Lett. **266**, L17–L20 (pt. 2) (1983). (I)

111. **"Masses of Galaxies and Clusters of Galaxies,"** P. J. E. Peebles, in *Les Houches XXXII* (Ref. 6), 213–70. (I)

112. **"On the Virgo Supercluster and the Mean Mass Density of the Universe,"** M. Davis, J. Tonry, J. Huchra, and D. W. Latham, Astrophys. J. Lett. **238**, L113–L116 (1980). (I)

B. Galaxy Formation

Galaxy formation is a subject that merits a Resource Letter of its own. Current understanding of this area is largely independent of the role of particle physics in cosmology; new particles may alter the final appearance of the large-scale structure of the Universe, but the physics is the same. Accordingly, we give here only a few general references, from which the interested reader may learn something of the history of galaxy formation theories, as well as the fundamental principles. The books by Peebles (Ref. 26) and by Zel'dovich and Novikov (Ref. 25) contain detailed accounts of the classification and evolution of density fluctuations, the description of galaxy distributions, and the physics of the later stages of galaxy development.

113. **"Recent Theories of Galaxy Formation,"** J. R. Gott III, Annu. Rev. Astron. Astrophys. **15**, 235–66 (1977). (I)

114. **"Galaxy Correlations and Cosmology,"** S. M. Fall, Rev. Mod. Phys. **51**, 21–42 (1979). (I)

115. **"How Large Were the First Pregalactic Objects?"** B. J. Carr and M. J. Rees, MNRAS **206**, 315–25 (1984). (I)

116. "Galaxy Formation in an Intergalactic Medium Dominated by Explosions," J. P. Ostriker and L. L. Cowie, J. Lett. **243**, L127–L131 (1983). (I)
117. "Formation of Galaxies and Large-Scale Structure with Cold Dark Matter," G. R. Blumenthal, S. M. Faber, J. R. Primack, and M. J. Rees, Nature **311**, 517–521 (1984). (I)
*118. "The Evolution of Large-Scale Structure in a Universe Dominated by Cold Dark Matter," M. Davis, G. Efstathiou, C. Frenk, and S. D. M. White, Astrophys. J. **292**, 371–394 (1985). (I)

An important technique has been the use of N-body computer codes. These are programs that integrate the gravitational equations of motion for large numbers of pointlike masses in a cosmological background. The following references describe recent applications, and also give some idea of the potential pitfalls in applying the results to the real Universe.

119. "N-Body Simulations of Galaxy Clustering. II. The Covariance Function," J. R. Gott, III, E. L. Turner, and S. J. Aarseth, Astrophys. J. **234**, 13–26 (1979). (A)
120. "On the clustering of Particles in an Expanding Universe," G. Efstathiou and J. W. Eastwood, Mon. Not. R. Astron. Soc. **194**, 503–25 (1981). (I)
121. "Non-Linear Evolution of Large-Scale Structure in the Universe," C. S. Frenk, S. D. M. White, and M. Davis, Astrophys. J. **271**, 417–430 (1983). (I)
122. "Cluster Analysis of the Non-Linear Evolution of Large-Scale Structure in an Axion/Gravitino/Photino-Dominated Universe," A. Melott, J. Einasto, E. Saar, I. Suisalu, A. A. Klypin, and S. F. Shandarin, Phys. Rev. Lett. **51**, 935–39 (1983). (I)

The fluctuations that gave rise to the present existence of galaxies ought also to leave an imprint of irregularities in the microwave background. The complete lack of measured fluctuations in the spatial distribution of the radiation imposes severe constraints on galaxy formation theories.

123. "Perturbations of a Cosmological Model and Angular Variations of the Microwave Background," R. K. Sachs and A. M. Wolfe, Astrophys. J. **147**, 73–90 (1967). (I)
124. "On the Anisotropy of the Cosmological Background Matter and Radiation Distribution II. The Radiation Anisotropy in Models with Negative Spatial Curvature," M. Wilson, Astrophys. J. **273**, 2–15 (1983). (I)
125. "Interpretation of Anisotropy in the Cosmic Background Radiation," C. J. Hogan, N. Kaiser, and M. J. Rees, Philos. Trans. R. Soc. London Ser. A **307**, 97–110 (1982). (I)
126. "Small-Scale Isotropy of the Cosmic Microwave Background at 19.5 GHz," J. M. Uson and D. T. Wilkinson, Astrophys. J. **283**, 471–78 (1984). (I)

C. Dark matter candidates

Because it cannot be seen it is hard to make observations of dark matter. However, that fact also imposes restrictions on its nature: Any dark matter candidate, conventional or hypothetical, must both be invisible in the quantitites required, and also conform to the observed dynamical structure of the Universe. Massive neutrinos were originally a popular choice, but problems with getting the observed small-scale structure right have turned attention to more exotic possibilities: axions, gravitinos, and strings.

127. "Can Galactic Halos Be Made of Baryons?" D. Hegyi and K. Olive, Phys. Lett. B **126**, 28–32 (1983). (I)
128. "Cosmological Consequences of Population III Stars," B. J. Carr, J. R. Bond, and W. D. Arnett, Astrophys. J. **277**, 445–69 (1984). (I)
129. "Dynamical Role of Light Neutral Leptons in Cosmology," S. Tremaine and J. Gunn, Phys. Rev. Lett. **42**, 407–10 (1979). (I)
130. "Core Condensation in Heavy Halos: A Two-State Theory For Galaxy Formation and Clustering," S. D. M. White and M. J. Rees, Mon. Not. R Astron. Soc. **183**, 341–58 (1978). (I)
*131. "Massive Neutrinos and the Large-Scale Structure of the Universe," J. R. Bond, G. Efstathiou, and J. Silk, Phys. Rev. Lett. **45**, 1980–1984 (1980). (I)
132. "Constraints on Neutrino-Dominated Cosmologies From Large-Scale Streaming Motion," N. Kaiser, Astrophys. J. Lett. **273**, L17–L20 (1983). (I)
133. "Clustering in a Neutrino-Dominated Universe," S. D. M. White, C. S. Frenk, and M. Davis, Astrophys. J. Lett. **274**, L1–L5 (1983). (I)
134. "Adiabatic Theories of Galaxy Formation and Pancakes," J. R. Bond and A. S. Szalay, in Texas Symposium XI (Ref. 1), 82–89. (I)
135. "Formation of Galaxies in a Gravitino-Dominated Universe," J. R. Bond, A. S. Szalay, and M. S. Turner, Phys. Rev. Lett. **48**, 1636–1639 (1982). (I)
*136. "Dark Matter and the Origin of Galaxies and Globular Star Clusters," P. J. E. Peebles, Astrophys. J. **277**, 470–77 (1983). (I)
137. "Fine-Scale Anisotropy of the Cosmic Microwave Background in a Universe Dominated by Cold, Dark Matter," N. Vittorio and J. Silk, Astrophys. J. Lett. **285**, L39–L43 (1984). (I)
138. "Cosmological Fluctuations Produced Near a Singularity," Ya. B. Zel'dovich, Mon. Not. R. Astron. Soc. **192**, 663–67 (1980). (I)
139. "The Evolution of Cosmic Density Perturbations Around Grand Unified Strings," N. Turok, Phys. Lett. B **126**, 437–70 (1983). (I)

IX. BARYOGENESIS

Grand unification has provided a solution to one of the most perplexing of cosmological problems, why the Universe contains matter but no antimatter. The essential ingredients were noted by Sakharov when unification was still a distant vision, but more or less quantitative estimates of the baryon-to-photon ratio are now possible. The expected ratio depends on, among other things, a parameter controlling the magnitude of CP violation in the grand unified theory, but this parameter is theoretically undetermined, so none of these calculations can be said to predict the baryon number of the Universe.

140. "Grand Unified Theories and the Origin of the Baryon Asymmetry," E. W. Kolb and M. S. Turner, Annu. Rev. Nucl. Part. Sci. **33**, 645–96 (1983). (I)
*141. "Violation of CP Invariance, C. Asymmetry, and Baryon Asymmetry of the Universe," A. D. Sakharov, Sov. Phys. JETP Lett. **5**, 24–27 (1967). (E)
142. "Cosmological Production of Baryons," S. Weinberg, Phys. Rev. Lett. **42**, 850–53 (1979). (I)
143. "Baryon Number Generation in Grand Unified Theories," J. Ellis, M. K. Gaillard, and D. V. Nanopoulos, Phys. Lett. B **80**, 360–64, Errata 464 (1979). (I)
144. "Baryon Number Generation in the Early Universe," Nucl. Phys. B **172**, 224–84 (1980). (I)
145. "Calculation of Cosmological Baryon Asymmetry in Grand Unified Gauge Models," J. A. Harvey, E. W. Kolb, D. B. Reiss, and S. Wolfram, Nucl. Phys. B **201**, 16–100 (1982). (I)
146. "Evolution of Cosmological Baryon Asymmetries. I. The Role of Gauge Bosons," J. N. Fry, K. Olive, and M. S. Turner, Phys. Rev. D **22**, 2953–2976 (1980). (I)

For lack of a completely determined grand unified theory, baryosynthesis is by no means so precise a subject as nucleosynthesis, and its utility for constraining cosmological or particle properties is limited. Nevertheless, the general effect of inhomogeneity and anisotropy has been discussed.

148. "The Origin of Baryons in the Universe," M. S. Turner and D. N. Schramm, Nature **279**, 303–04 (1979). (I)

149. "**Baryosynthesis and the Origin of Galaxies,**" J. D. Barrow and M. S. Turner, Nature **291**, 469–72 (1981). (I)
150. "**The Generation of Isothermal Perturbations in the Very Early Universe,**" J. R. Bond, E. W. Kolb, and J. Silk, Astrophys. J. **255**, 341–60 (1982). (I)
151. "**Grand Unified Reactions and Dissipation in Anisotropic Cosmologies,**" A. Rothman and R. Matzner, Astrophys. J. **263**, 501–07 (1982). (I)

X. PHASE TRANSITIONS

In standard cosmology, the temperature falls in strict inverse proportion to the scale factor, maintaining, for example, a constant baryon-to-photon ratio. However, there are certain moments in the evolution of the Universe when the state of matter may change abruptly, and such phase transitions may have significant effects, such as causing a temporary departure from adiabatic evolution, or producing nonuniformities in the density. These phase transitions may be associated with physics that we know about (or think we know about), including the transition from free to confined quarks, of the symmetry breaking in the Weinberg–Salam or grand unified theories, or they may be more speculative in origin, the results of quantum gravitational effects, for example.

152. "**Macroscopic Consequence of the Weinberg Model,**" D. A. Kirzhnits and A. D. Linde, Phys. Lett. B **42**, 471–74 (1972). (I)
153. "**Symmetry Behavior at Finite-Temperature,**" L. Dolan and R. Jackiw, Phys. Rev. D **9**, 3320–3341 (1974). (A)
154. "**Gauge and Global Symmetries at High Temperature,**" S. Weinberg, Phys. Rev. D **9**, 3357–3378 (1974). (A)
155. "**Phase Transitions in Gauge Theories and Cosmology,**" A. D. Linde, Rep. Prog. Phys. **42**, 389–437 (1979). (I)

A. Topological defects

When, as in grand unification or the Weinberg–Salam theory, a symmetry is broken, the new vacuum has, in general, some symmetry of its own: There is a group of field transformations that leave the vacuum unchanged. A consequence of this is that there can be stable vacuum states in which these fields vary from place to place. A topological defect occurs when such a field, although it occupies the vacuum at infinity, cannot be connected over the whole space without the introduction of singularities. Such defects are of three generic kinds: walls, monopoles, and strings. Monopoles have been discussed, and walls are disastrous for cosmology, but strings are potentially more interesting.

*156. "**Topology of Cosmic Domains and Strings,**" T. W. B. Kibble, J. Phys. A **9**, 1387–1398 (1976). (I)
157. "**Cosmological Consequences of a Spontaneous Breakdown of a Discrete Symmetry,**" Ya. B. Zel'dovich, K. Ya. Kobzarev, and L. G. Okun, Sov. Phys. JETP **40**, 1–5 (1974). (I)
158. "**Cosmic Strings,**" A. Vilenkin, Phys. Rev. D **24**, 2082–2089 (1981); in "The Very Early Universe," 163–169. (I)
159. "**Strings in the Very Early Universe,**" Q. Shafi, in *The Very Early Universe* (Ref. 9), 147–161. (I)
160. "**Cosmic Strings and Domain Walls,**" A. Vilenkin, Phys. Rep. **121**, 263–315 (1985). (I)
*161. "**Stretching Cosmic Strings,**" N. Turok and P. Bhattacharjee, Phys. Rev. D **29**, 1557–1562 (1984). (I)
162. "**Microwave Anisotropy Due to Cosmic Strings,**" N. Kaiser and A. Stebbins, Nature **310**, 391–93 (1984). (I)
*163. "**Gravitational Interactions of Cosmic Strings,**" C. J. Hogan and M. J. Rees, Nature **311**, 109–14 (1984). (I)

B. Symmetry breaking

Even if symmetry breaking creates no topological defects, the associated phase transition can be of first order, leading perhaps to excessive creation of entropy (as measured by the photon-to-baryon ratio) through the release of latent heat. The cosmology of the Weinberg–Salam phase transition can be used to constrain some of the parameters of the theory, especially the mass of the Higgs boson.

164. "**Symmetry Behavior in Gauge Theories,**" D. A. Kirzhnits and A. D. Linde, Ann. Phys. **101**, 195–238 (1976). (E)
165. "**Effects of Phase Transitions on the Evolution of the Early Universe,**" M. A. Sher, Phys. Rev. D **22**, 2989–2994 (1980). (I)
166. "**Cosmological Lower Bound on the Higgs-Boson Mass,**" A. H. Guth and E. Weinberg, Phys. Rev. Lett. **45**, 1131–1134 (1980). (I)
167. "**Cosmological Consequence of a Light Higgs Boson,**" E. Witten, Nucl. Phys. B **177**, 477–488 (1981). (I)

A first-order phase transition from the breaking of grand unified symmetry, or perhaps supersymmetry, gives rise to what is now called the inflationary Universe. This is dealt with separately in the next section.

C. Quark confinement

At high temperatures and densities, quarks behave as free particles, and constitute a radiation gas, but as the Universe evolves they must eventually be confined in pairs, to form mesons, or in threes, to form hadrons. Exactly how this happens, and at what temperature, is not known, beause the transition is the result of non perturbative strong interactions.

168. "**The Thermodynamics of the Quark-Hadron Phase Transition in the Early Universe,**" K. Olive, Nucl. Phys. B **190**, 483–503 (1980). (I)
169. "**Spontaneous Generation of Density Perturbations in the Early Universe,**" M. Crawford and D. N. Schramm, Nature **298**, 538–540 (1982). (I)
170. "**Cosmic Separation of Phases,**" E. Witten, Phys. Rev. D **30**, 272–85 (1984). (I)
171. "**Relics of Cosmic Quark Condensation,**" J. H. Appelgate and C. J. Hogan, Phys. Rev. D **31**, 3037–3045 (1985). (I)

XI. INFLATION

As originally conceived, the inflationary Universe was a model in which the breaking of grand unified symmetry was strongly first order, causing a period of exponential expansion. Its great achievement was that it promised to explain how the present Universe could be homogeneous over a region not causally connected, and so close to the critical density at late times. The models have now become more varied and more sophisticated, and the term inflation is used to describe a range of theories that produces the same cosmological end; as well as grand unification, phase transitions due to supersymmetry or quantum gravity are included. Guth and Steinhardt give a nontechnical review of the development and present standing of inflationary theories.

172. "**The Inflationary Universe,**" A. H. Guth and P. J. Steinhardt, Sci. Am. **250**(5), 116–28 (1984). (E)

A. Inflation

Guth first recognized that a strongly first-order transition could solve a number of cosmological problems; he noticed that exponential expansion could vastly increase the casual scale of the Universe, and also that it would push the Universe toward flatness, or zero curvature. The model failed because the phase transition could not be ended with a smooth return to a conventional cosmology: Many small bubbles of the new phase would form, constituting a very inhomogeneous final state. However, the potential successes of inflation encouraged more thought and Linde, and Albrecht and Steinhardt, came up with the new inflationary universe, in which a careful choice of theory allowed a single bubble to inflate enough to encompass the whole of the present Universe.

*173. **"Inflationary Universe: A Possible Solution to the Horizon and Flatness Problems,"** A. H. Guth, Phys. Rev. D **23**, 347–56 (1981). (I)

*174. **"A New Inflationary Scenario: A Possible Solution of the Horizon, Flatness, Homogeneity, Isotropy and Primordial Monopole Problems,"** A. D. Linde, Phys. Lett. B **108**, 389–93 (1982). (I)

*175. **"Cosmology for Grand Unified Theories With Radiatively Induced Symmetry Breaking,"** A. Albrecht and P. J. Steinhardt, Phys. Rev. Lett. **48**, 1220–1223 (1982). (I)

B. Reheating

In all inflationary models, the temperature falls exponentially throughout a prolonged period of supercooling. When the delayed phase transition eventually occurs, the universe must reheat to a large enough temperature for baryosynthesis to proceed. Meeting this requirement puts a number of constraints on the underlying theory.

176. **"Reheating an Inflationary Universe,"** A. Albrecht, P. J. Steinhardt, M. S. Turner, and F. Wilczek, Phys. Rev. Lett. **48**, 1437–1440 (1982). (I)

177. **"Reheating an Inflationary Universe,"** A. D. Dolgov and A. D. Linde, Phys. Lett. B **116**, 329–34 (1982). (I)

178. **"Particle Production in the New Inflationary Cosmology,"** L. F. Abbott, E. Farhi, and M. B. Wise, Phys. Lett. B **117**, 29–33 (1982). (I)

179. **"Time Development of Higgs Field at Finite Temperature,"** A. Hosoya and M. Sakagama, Phys. Rev. D **29**, 2228–2239 (1984). (I)

D. Fluctuations

It soon became apparent that the new inflationary Universe suffered from a serious problem. Within the single bubble, there are fluctuations in the field that lead to fluctuations in the density. Although the spectrum of these inhomogeneities is of a good form for galaxy formation, their magnitude is much too large. Remedying this problem necessitates even more careful construction of the theory than does the inflation.

180. **"The Development of Irregularities in a Single Bubble Inflationary Universe,"** S. W. Hawking, Phys. Lett. B **115**, 295–97 (1982). (I)

181. **"Fluctuations in the New Inflationary Universe,"** A. H. Guth and S.-Y. Pi, Phys. Rev. Lett. **49**, 1110–1113 (1982). (I)

182. **"Dynamics of Phase Transition in the New Inflationary Universe Scenario and Generation of Perturbations,"** Phys. Lett. B **117**, 175–78 (1982). (I)

183. **"Spontaneous Creation of Almost Scale-Free Density Perturbations in an Inflationary Universe,"** J. M. Bardeen, P. J. Steinhardt, and M. S. Turner, Phys. Rev. D **28**, 679–93 (1983). (I)

184. **"Quantum Field Theory Methods and Inflationary Universe Models,"** R. H. Brandenberger, Rev. Mod. Phys. **57**, 1–60 (1985). (I)

E. New Variations

Inventing a successful inflationary theory means finding a physics model with all the right properties; it must inflate, reheat, and not produce excessive fluctuations. Supersymmetry and supergravity provide some of the contending models.

185. **"Inflation With SU(5),"** Q. Shafi and A. Vilenkin, Phys. Rev. Lett. **52**, 691–94 (1984). (I)

186. **"Inflation Without Tears: A Realistic Cosmological Model,"** S-Y. Pi, Phys. Rev. Lett. **52**, 1725–1728 (1984). (I)

187. **"After Primordial Inflation,"** D. V. Nanopoulos, K. Olive, and M. Srednicki, Phys. Lett. B **127**, 30–34 (1983). (I)

188. **"Supersymmetric Inflation: Recent Progress,"** B. A. Ovrut and P. J. Steinhardt, in *Inner Space/Outer Space* (Ref. 8), 302–24. (I)

189. **"Primordial Inflation in $N=1$ Supergravity: A Brief Review,"** M. Srednicki, in *Inner Space/Outer Space* (Ref. 8), 325–29. (I)

190. **"Supersymmetric Inflationary Cosmology,"** R. Holman, in *Inner Space/Outer Space* (Ref. 8), 330–34. (I)

XII. QUANTUM GRAVITY

Physicists have always wondered what happened near the beginning of the Universe, at the Planck time, when gravity can no longer be treated by a purely classical theory. Ignorance of quantum gravity means ignorance of how the Universe began, and of how it emerged from the near-singular state into the era of classically understood evolution. Attempts to reach beyond the Planck era have necessarily been rather limited, but some interesting ideas, with potential importance for understanding the present state of the Universe, have been turned up in these investigations.

191. **"Quantum Gravity,"** B. deWitt, Sci. Am. **249**(12), 112–29 (1983). (E)

A. Particle creation

The attempt to use conventional quantum theory in curved space-times constitutes the semiclassical approach to quantum gravity, in which the aim is to retain the classical description of space-time by a smooth manifold, but to introduce correction to Einstein's equations, usually in the form of additional terms in the stress-energy tensor, arising from a quantum description of particle interactions. For cosmologists, an interesting idea is that gravitational fields can create particles (similar to the way magnetic fields can create electron pairs), but recent calculations show that these semiclassical effects cannot remove completely arbitrary anisotropies, quashing the idea that Robertson–Walker universes could emerge from any initial conditions.

192. **"Quantized Fields and Particle Creation in Expanding Universes II,"** L. Parker, Phys. Rev. D **3**, 346–62 (1971). (A)

193. **"Particle Production and Vacuum Polarization in an Anisotropic Gravitational Field,"** Ya. B. Zeldovich and A. A. Starobinski, Sov. Phys. JETP **34**, 1159–1166 (1972); 252 (1977). (A)

194. **"Quantum Effects in the Early Universe. I. Influence of Trace Anomalies on Homogeneous, Isotropic, Classical Geometries,"** M. Fischetti, J. B. Hartle, and B-L. Hu, Phys. Rev. D **20**, 1757–1771 (1979). (A)

195. **"Quantum Effects in the Early Universe. II. Effective Action for Scalar Fields in Homogeneous Cosmologies with Small Anisotropy,"** J. B. Hartle and B-L. Hu, Phys. Rev. D **20**, 1772–1782 (1979). (A)

196. **"Quantum Effects in the Early Universe. IV. Nonlocal Effects in Particle Production in Anisotropic Models,"** J. B. Hartle, Phys. Rev. D **22**, 2091–2095 (1980). (A)

B. Primordial black holes

Another established phenomenon in semiclassical quantum gravity is the evaporation of black holes by the emission of a thermal spectrum of particles, an effect discovered by Hawking. The temperature of a black hole is inversely proportional to its mass; for a black hole of astrophysical origin, evaporation is quite negligible. However, large density fluctuations in the early universe could collapse to form primordial black holes of very low mass, and any such object with an initial mass less than about 10^{15} g will have evaporated during the lifetime of the universe. The emission of energetic particles leads to constraints on the allowable density and mass spectrum of primordial black holes, but there are also models in which the evaporation of extremely small black holes is a source of particles whose decay creates a universal baryon number.

197. **"Particle Creation by Black Holes,"** S. W. Hawking, Comm. Math. Phys. **43**, 199–220 (1974). (I)
198. **"The Hypothesis of Cores, Retarded During Expansion and the Hot Cosmological Model,"** Y. B. Zel'dovich and I. D. Novikov, Sov. Astron. **10**, 602 (1967). (I)
199. **"Gravitationally Collapsed Objects of Very Low Mass,"** S. W. Hawking, Mon. Not. R. Astron. Soc. **152**, 75–78 (1971). (I)
200. **"Primordial Black Holes,"** I. D. Novikov, A. G. Polnarev, A. A. Starobinski, and Ya. B. Zel'dovich, Astron. Astrophys. **80**, 104–09 (1979). (I)
201. **"Primordial Black Holes and the Deuterium Abundance,"** D. Lindley, Mon. Not. R. Astron. Soc. **193**, 593–601 (1980). (I)
202. **"Baryon Production by Primordial Black Holes,"** M. S. Turner, Phys. Lett. B **89**, 155–59 (1979). (I)
203. **"Primordial Baryon Generation by Black Holes,"** J. D. Barrow, Mon. Not. R. Astron. Soc. **192**, 427–38 (1980). (I)

C. Semiclassical cosmology

A more ambitious aim has been to apply the ideas of semiclassical gravity to cosmology as a whole. Quantum corrections to Einstein's equations may make possible a de Sitter phase near the Planck time, leading to a model of "primordial inflation." In a somewhat different vein, Vilenkin has applied the semiclassical analysis of phase transitions and bubble formation in an attempt to show how the universe might have been created as a quantum tunnelling event from literally nothing.

204. **"A New Type of Isotropic Cosmological Models Without Singularity,"** A. A. Starobinski, Phys. Lett. B **91**, 99–102 (1980). (A)
*205. **"Wave Function of the Universe,"** J. B. Hartle and S. W. Hawking, Phys. Rev. D **28**, 2960–2975 (1983). (A)
*206. **"Creation of the Universe From Nothing,"** A. Vilenkin, Phys. Lett. B **117**, 25–28 (1982). (I)

D. Extra dimensions

An old idea for the unification of gravity and electromagnetism was the proposal of Kaluza and Klein that there might be an extra dimension of space, which is invisible to us because its characteristic size is extremely small. The observable low-energy manifestation of this extra dimension is electromagnetism, which is interpreted as gravity in the fifth dimension. Such theories, generalized to more than one extra dimension, have recently enjoyed a revival, because supergravity and superstring theories seem to have a predilection for more than four dimensions.

207. **"Zum Unitätsproblem der Physik."** T Von Kaluza, Sitzungsber. Preuss. Akad. Wiss. Berlin Kl. 966–72 (1921). (E)
208. **"Quantum Theorie und Funfdimensionale Relativitatstheorie,"** O. Klein, Z. Phys. **37**, 895–906 (1926). (E)
209. **"Where Has the Fifth Dimension Gone?"** A. Chodos and S. Detweiler, Phys. Rev. D **21**, 2167–2170 (1980). (I)
210. **"Kaluza-Klein Cosmologies,"** P. G. O. Freund, Nucl. Phys. B **209**, 146–156 (1982). (I)
211. **"Towards a Realistic Kaluza-Klein Cosmology,"** D. Sahdev, Phys. Lett. B **137**, 155–59 (1984). (I)
212. **"More Dimensions—Less Entropy,"** E. W. Kolb, D. Lindley, and D. Seckel, Phys. Rev. D **30**, 1205–1213 (1984). (I)
213. **"Kaluza-Klein Cosmologies and Inflation,"** R. B. Abbott, S. M. Barr, and S. D. Ellis, Phys. Rev. D **30**, 720–27 (1984). (I)

Another putative theory of quantum gravity, also living in extra dimensions, is the theory of superstrings. Superstrings are supposed to constitute the fundamental theory of all interactions, including gravity, and their theoretical appeal lies in their complete lack of infinities; all interactions should be calculable without renormalization. However, these mathematical niceties are apparent only at the Planck scale, and the way that such theories break down to give us our familiar low-energy world is almost completely unknown.

214. **Superstrings: The First Fifteen Years**, edited by J. H. Schwarz, 2 vols. (World Scientific, Singapore, 1985). (A)
215. **"Unification of Forces and Particles in Superstring Theories,"** M. B. Green, Nature **314**, 409–14 (1985). (A)
216. **"The Shadow World of Superstring Theories,"** E. W. Kolb, D. Seckel, and M. S. Turner, Nature **314**, 415–19 (1985). (I)

PROBLEM: ON KEPLER MOTION

It is a simple matter to show that the speed, acceleration, and angular speed of a planet are all maxima at perihelion ($\theta = 0°$) and minima at aphelion ($\theta = 180°$). The first and the third follow from Kepler's law of areas, whereas the second result is a direct consequence of Newton's law of gravitation. In this problem, the reader is asked to show that the angular acceleration and the angular deceleration of the planet are maxima at

$$\theta = 2\pi - \cos^{-1}[(\sqrt{1+48e^2} - 1)/8e]$$

and

$$\theta = \cos^{-1}[(\sqrt{1+48e^2} - 1)/8e],$$

respectively. Here, e is the eccentricity of the orbit. (Solution is on p. 558.)