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RESOURCE LETTER:
COSMOLOGY AND PARTICLE PHYSICS

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INTRODUCTION

Cosmology is the study of the origin and evolution of the Universe; it includes everything from the very beginning of the Universe, through the primordial production of light nuclei, the decoupling of the present microwave background radiation, galaxy formation, the production of other photon backgrounds, up to the present structure of galaxies and clusters of galaxies.

The word cosmology is derived from the Greek κοσμος, 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. It is through this ancient connection that cosmology still excites the imagination of poets, writers, musicians and all those who ask 'What is our place in the Universe?' Answers to this question have always been greatly influenced by our perception of the answer to the cosmologist's question, 'What is the Universe?'

Particle physics is the study of matter at the smallest scales. It is a search for the simplest, most fundamental forms of matter, and the rules by which they interact and combine to produce all that we observe in the physical world. Like cosmology, it is the modern continuation of an old and basic tradition; it was Democritus who 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 enquiry have reached common ground. Only in the last half-century has it become apparent that both the large and small scales of today had a common origin. As the Universe, from a hot dense beginning, became rarefied, galaxies grew from tiny condensations, and as it cooled, a single force between particles split into the four different interactions we now observe. With this realisation, 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 (some of them different). 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.

In this resource letter we cover this new field of particle physics and cosmology. Although we have included where possible introductory books for the interested lay audience, the bulk of the material is somewhat technical and understandable at or above graduate student level. We hope that this letter will be particularly useful for specialists in related areas, such as particle physics, astrophysics and general relativity, who need a guide to the literature of this rapidly moving field.

Our guided tour is in two parts: first, we list books (some popular expositions, some textbooks) and journals which contain general reference material on a variety of subjects; second, we list under specific subject headings some of the major contributions to and reviews of cosmology and particle physics. In the first section especially, 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.

General references

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

1 **The First Three Minutes**, S. Weinberg (Basic Books, New York 1977) 188pp. A nice account of standard big bang cosmology, starting about one second after the bang.

2 **The Moment of Creation**, J. Trefil (Scribner, New York 1983) 240pp. Trefil discusses phase transitions and inflation in the very early Universe, as well as the cosmological production of massive magnetic monopoles.

3 **The Big Bang**, J. Silk (W. H. Freeman, San Francisco, 1980) 364pp. 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.

4 **The Left Hand of Creation**, J. Barrow and J. Silk (Basic Books, New York 1983) 256pp. A readable popular account bringing together the astrophysical world and the physical Universe.

5 **Atoms of Silence**, H. Reeves (MIT Press, Cambridge, 1985) 244pp. A description of the connection between the microscopic and the macroscopic worlds, by one of France's leading astrophysicists and popularisers of science.

6 **The Cosmic Code**, H. Pagels (Simon and Schuster, New York, 1982) 370pp. An award winning book that makes the world of modern quantum theory understandable to the layman.

7 **Cosmology plus One**, Scientific American reprint volume, edited by O. Gingerich (W. H. Freeman, San Francisco, 1977) 108pp. A compilation of articles on classical cosmology, published before the influence of recent advances in particle physics.

8 **From Atoms to Quarks**, J. Trefil (Scribner, New York 1982) 240pp. An attempt to explain at a popular level how we reached our current understanding of the microscopic world.

9 **Galaxies,** T. Ferris (Stewart, Tabori and Chang, New York 1982) 192pp. A beautiful coffee table picture book of objects in the Universe, with a discussion of the big bang.

10 **What is the World Made of?,** G. Feinberg (Anchor Press, New York 1977) 290pp.

11 **The Discovery of Subatomic Particles,** S. Weinberg (W. H. Freeman, San Francisco, 1983) 206pp.

12 **Superforce,** P. Davies (Simon and Schuster, New York 1984) 255pp. A very readable account of recent ideas in the unification of forces.

13 **Perfect Symmetry,** H. Pagels (Simon and Schuster, New York 1985).

14 **Constructing the Universe,** D. Layzer (W. H. Freeman, New York 1985) 313 pp. A historical account of the development of our view of the Universe.

B <u>Textbooks</u>

1 **Gravitation and Cosmology,** S. Weinberg (Wiley, New York 1972) 657pp. This careful treatment of general relativity includes a standard account of physical cosmology. The book predates recent developments in particle physics and cosmology.

2 **Gravitation,** C. W. Misner, K. S. Thorne, and J. A. Wheeler (W. H. Freeman, San Francisco, 1973) 1279pp. This standard general relativity text emphasises 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.

3 **The Classical Theory of Fields,** L. D. Landau and E. M. Lifshitz (Pergamon Press, Oxford, 1975) 402pp. In the latter part of their book, these authors give a brief but characteristically elegant treatment of cosmology, including a discussion of anisotropy and the Bianchi classification.

4 **General Relativity,** R. M. Wald (University of Chicago Press, Chicago, 1984) 491pp. A new and thorough relativity text, with a brief treatment of cosmology in the style of the preceding book.

5 **Physical Cosmology,** P. J. E. Peebles (Princeton University Press, Princeton, 1975) 320pp. An intermediate level text dealing with physical processes in the late (after one second) stages of the big bang.

6 **Relativistic Astrophysics,** Vol. II, Ya. B. Zel'dovich and I. D. Novikov (University of Chicago Press, Chicago, 1983) 718pp. 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.

7 **The Large-scale Structure of the Universe,** P. J. E. Peebles (Princeton University Press, Princeton, 1980) 422pp. A comprehensive textbook on the distribution of matter in the Universe, with special emphasis on the statistical analyses of galaxy clustering pioneered by Peebles and his colleagues, and on the theory of the growth of perturbations in relativistic cosmologies. There is no discussion of the role of exotic particles in galaxy formation, but the groundwork for such studies is here.

8 **Unity of Forces in the Universe,** A. Zee (World Scientific Press, Singapore, 1982) two vols, 464pp and 612pp. 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.

9 **Gauge Theories of the Strong, Weak and Electromagnetic Interactions,** C. Quigg (Benjamin/Cummings, Menlo Park 1983). A comprehensive account of the standard theory of the strong and electroweak forces.

10 **Grand Unified Theories,** G. G. Ross (Benjamin/Cummings, Menlo Park 1985) 497pp. A thorough treatment of grand unified theories.

C Journals and Conference Proceedings

(i) Journals

Research on the early Universe is frequently published in physics, rather then 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 Physics
Soviet Physics J.E.T.P

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 PParticle 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

(ii) 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. The foremost relativity and cosmology meeting is the biannual and peripatetic Texas conference, which in recent sessions has included contributions from particle physicists. The Workshops on Grand Unification have likewise had contributions from cosmologists. In addition, such conferences as the Moriond Astrophysics meetings, the Symposia of the International Astronomical Union, and the Les Houches Schools have occasionally been devoted to subjects in cosmology and particle physics. The Cosmic Ray Conferences are more specialised, but a mine of data.

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**, ed J. Tran Thanh Van, (Editions Frontieres, Paris, 1984)

4 IAU Symposium 63: **Confrontation of Cosmological Theories and Observational Data**, ed M. S. Longair, (D. Reidel, Dordrecht, 1974)

5 IAU Symposium 104: **Early Evolution of the Universe and its Present Structure**, eds G. O. Abell and G. Chincarini, (D. Reidel, Dordrecht, 1983)

6 Les Houches 1979, Session XXXII: **Physical Cosmology,** eds 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)

In addition to these regular meetings, there are many individual conferences on particular subjects. A large event devoted entirely to the connection between cosmology and particle physicists was Inner Space/Outer Space. The Cambridge meeting on the Very Early Universe was notable for the emergence at the conference of many of the features of the new inflationary Universe. The two Oxford Quantum Gravity conferences are less concerned with matters of practical interest to cosmology, but contain some useful contributions. The centenary of Einstein's birth, in 1979, was the occasion for a number of celebratory events: the Einstein Centenary Survey contains expert reviews of many fields in relativity and cosmology.

8 **Inner Space/Outer Space,** eds E. W. Kolb et al, (University of Chicago Press, Chicago, 1985) pp626

9 **The Very Early Universe,** eds G. W. Gibbons, S. W. Hawking and S. T. Siklos, (Cambridge University Press, Cambridge, 1983) pp440

10 **Quantum Gravity I and II,** eds C. J. Isham, R. Penrose and D. W. Sciama, (Oxford University Press, Oxford, 1975 and 1981)

11 **General Relativity: An Einstein Centenary Survey,** eds S. W. Hawking and W. Israel, (Cambridge University Press, Cambridge, 1979)

In the remainder of the resource letter, each section deals with some part of the very large domain of cosmology and particle physics, and gives brief descriptions of the most important observations and theories, with references. The reference list is certainly not exhaustive, but is designed to illuminate the major points.

D Standard Cosmology

Popular descriptions of the accepted big bang model can be found in 'The Big Bang' (A.3) and 'The First Three Minutes' (A.1), while a more detailed and technical account is in 'Gravitation and Cosmology' (B.1).

(i) Geometry

The first solutions of Einstein's equation for a homogeneous, isotropic, but time-varying Universe were given by Friedman. It was shown later by Robertson and Walker that the spacetime metric obtained by Friedman could in fact be derived solely from the assumptions of homogeneity and isotropy, independently of general relativity. To commemorate these discoveries, we refer to the Robertson-Walker metric, and to the Friedman equation which relates cosmological expansion to the density of matter.

1 A. Friedman, Z. Phys., 10, 377 (1922)
2 H. P. Robertson, Ap. J., 82, 284 (1935)
3 A. G. Walker, Proc. Lond. Math. Soc., 42, 90 (1936)

Detailed study of the dynamical evolution of cosmological models, with and without the cosmological constant, were begun by LeMaitre, who was also the first to explicitly relate these models to the galactic recession discovered by Hubble.

4 G. LeMaitre, Ann. Soc. Sci. Bruxelles, A47, 49 (1927)

The initial singularity in these models has always attracted study, mostly by people wishing to remove it. Hawking and Ellis give a very detailed and technical description of the mathematical identification and treatment of singularities, and discuss the theorems of Hawking and Penrose, proving that under very general conditions, certainly true of our present Universe, a singularity must have occurred in the cosmological past. The proof is classical, and implies nothing about what might have happened 'before' the Planck time, 10^{-43}s, when quantum gravitational effects were important.

5 S. W. Hawking and G. F. R. Ellis, **The Large Scale Structure of Space-Time**, (Cambridge University Press, Cambridge, 1973)
6 R. Penrose, Phys. Rev. Lett., 14, 57 (1965)
7 S. W. Hawking and R. Penrose, Proc. Roy. Soc. Lond A, 314, 529 (1970)

(ii) Observational Parameters

The present state of a Friedman-Robertson-Walker Universe can be characterised by a few numbers: H_o, the Hubble constant; q_o, the deceleration parameter; Λ_o, the cosmological constant; t_o, the age; and Ω_o, the ratio of the present density of the Universe to the critical density (which is the density of a Universe with zero curvature). These numbers are interrelated in a variety of ways: see any of the cosmology texts.

The Hubble constant H_o relates the recession velocity and distance of galaxies ($v = H_o r$) and can in principle be measured directly. Redshifts give velocities straightforwardly, but finding an independent and reliable measure of cosmological distances is extremely difficult; one has to construct a several runged ladder of distance indicators, from our near neighbourhood to the most distant galaxies. Hubble's first estimates of H_o were around 500 kms^{-1}Mpc^{-1}, but modern values run from 50 to 100 in the same units. Sandage and Tammann are the chief defenders of the low value, while de Vaucouleurs has always favoured the high end of the spectrum. Most investigators seem to fall into one camp or the other, and there are only a few advocates of intermediate values.

8 E. P. Hubble, Proc. Nat. Acad. Sci., 15, 168 (1927)
9 A. R. Sandage and G. Tammann, Nature, 307, 326 (1984)
10 M. Aaronson and J. Mould, Ap. J., 265, 1 (1983)
11 G. de Vaucouleurs and G. Bollinger, Ap. J., 233, 433 (1979)
12 G. de Vaucouleurs, in Texas Symposium X (1980)

Most of the factor of two difference in these estimates of H_o can be attributed to uncertainty in the distance of fairly nearby galaxies. Baade first suggested using supernovae to find these distances: if one can measure the apparent transverse expansion of a supernova gas shell by its angular enlargement on the sky, and also its actual radial expansion from the redshift of some emission line, then comparison of the two, with a little theoretical modelling, gives the distance. Wagoner reviews past applications and future prospects of the method. An alternative use of supernovae, advocated by Sandage and Tammann, is simply to fit the observed light curve to theoretical models, determining the absolute luminosity. The observations are simpler, but more theory is required.

13 W. Baade, Astr. Nachr., 228, 359 (1926)
14 R. Wagoner, in Les Houches XXXII, p. 179
15 A. R. Sandage and G. Tammann, in Inner Space/Outer Space

In the near future, the launch of Space Telescope at the end of this decade should allow some of the intermediate distance indicators to be jumped over, simplifying the tortuous route to the Hubble constant.

The deceleration parameter q_o is the dimensionless rate of change of H_o with time, and is also related to the curvature of the Universe. In the 1950s and 1960s, it was hoped that q_o could be directly measured; in principle, it can be found from the departure of the redshift-distance law from exact linearity, of from the effects of non-Euclidean geometry on the counts of radio sources as a function of luminosity (and therefore distance). In practice, neither of these attempts were very successful, because the sought effects are significant only at large redshift, and tend to be swamped by evolutionary trends in the objects observed.

16 A. R. Sandage, Physics Today, February 1970, p. 34
17 M. Ryle, Ann. Rev. Astr. Astrophys., 6, 249 (1968)
18 M. S. Longair and G. G. Pooley, Mon. Not. Roy. Astr. Soc., 45, 121 (1969)

Determination of the cosmological constant Λ_o has been the object of some local (solar system) tests of general relativity. Cosmologically, a non-zero Λ_o is entirely equivalent to a uniform vacuum energy density, and it is therefore bound up with determinations of the density Ω_o. Finding the density of the Universe by counting up everything we see and assigning masses is neither easy nor accurate. Rubin et al have, for many spiral galaxies, measured the rotation rates of gas clouds as a function of their distance from the center, and deduce that most galaxies have a mass which increases beyond the radius of their visible extent; Faber and Gallagher review galactic mass estimates. This dark matter may well be the major contributor to the density of the Universe. Gott and Turner obtain a similar conclusion from studying the dynamics of binary pairs of galaxies, and Davis and collaborators have worked extensively on the statistical analysis of large catalogues of galaxy redshifts, and similarly conclude that there is much more matter associated with galaxies, pairs, small groups, and clusters of galaxies than can be directly observed. Recently, Davis and Peebles have made detailed studies of the deviations from pure Hubble velocities in the local Virgo supercluster to estimate Ω_o. The upshot of all this is that dynamical measurements of the mass associated with galaxies, on the scale of large clusters, indicate values of Ω_o from 0.1 to 0.5. There is no observational evidence that $\Omega_o = 1$; however, most of the dynamical estimates are insensitive to a uniformly distributed component of the density, or to a cosmological constant.

19 V. C. Rubin, W. K. Ford, N. Thonnard and D. Burstein, Ap. J., 261, 439 (1982)
20 S. M. Faber and J. S. Gallagher, Ann. Rev. Astr. Astrophys., 17, 135 (1979)
21 J. R. Gott III and E. L. Turner, Ap. J. Lett., 232, 79 (1979)
22 M. Davis, M. J. Geller and J. Huchra, Ap. J., 221, 1 (1978)
23 M. Davis and P. J. E. Peebles, Ap. J., 267, 465 (1983)
24 M. Davis and P. J. E. Peebles, Ann. Rev. Astr. Astrophys., 21, 109 (1983)

An indirect estimate of the density of the Universe in baryonic matter can be obtained from big bang nucleosynthesis. By aiming for agreement with observed light element abundances, Yang et al deduce a best value for the ratio of baryon to photon number densities, a value which is constant in standard cosmology and leads to an estimate Ω_o=0.1 in baryons. Gott, Gunn, Schramm and Tinsley were the first to combine such arguments with observations, showing that an entirely consistent cosmology is possible with $\Omega_o = 0.1$, and implying that if the density is greater than this there must be non-baryonic and unclustered matter.

25 J. Yang, M. S. Turner, G. Steigman, D. N. Schramm and K. A. Olive, Ap. J., 281, 493 (1984)
26 J. R. Gott III, J. E. Gunn, B. M. Tinsley and D. N. Schramm, Ap. J., 194, 543 (1974)

In standard cosmology (that is, with $\Lambda = 0$), knowledge of Ω_o and H_o determines the age of the Universe. However, direct estimation of the age provides an important piece of corroborative evidence. Iben and Renzini review the ages of the oldest stars in globular clusters, which ought to be less than the age of the Universe itself. Nucleocosmochronology, proposed in detail by Fowler and Hoyle, is the analysis of the isotopic abundances of radioactive elements as a way of estimating their age. Symbalisty and Schramm review the cosmological significance of these age determinations, and Thieleman et al give some recent calculations. These arguments produce ages ranging from 10 to 20 billion years. The inverse of the Hubble constant is an upper limit to the age of the Universe, becoming exact for very low Ω_o. For $H_o = 50$ or 100 $kms^{-1}Mpc^{-1}$, this limit is 20 or 10 billion years, consistent with the age estimates. However, if $\Omega_o = 1$, the age is only 2/3 of the inverse Hubble constant, causing potential difficulties if H_o is near 100.

27 I. Iben and A. Renzini, Physics Reports, 105, 329 (1984)
28 W. A. Fowler and F. Hoyle, Ann. Phys., 10, 280 (1960)
29 E. Symbalisty and D. N. Schramm, Rep. Prog. Phys., 44, 293 (1981)
30 F. Thieleman, J. Metzinger and H. V. Klapdor, Astr. Astrophys., 123, 162 (1983)

(iii) Background Radiation

Although Gamow was undoubtedly the originator of the hot big bang model (section D.v below), his interest was mainly in element production, and it was his collaborators Alpher and Herman who drew attention to the significance of a temperature, of 5K, for the Universe in its present state. Even so, the significance of this temperature, as something real and measurable was apparently not grasped at the time. Modern big bang cosmology really begins with the discovery of the microwave background by Penzias and Wilson in 1965. Coincidentally, at the same time as this accidental discovery, Dicke and collaborators had rederived the theoretical prediction and were actively trying to detect the background radiation. Zel'dovich, on the other hand, had concluded that the absence of a measured cosmological temperature forced the abandonment of the hot big bang in favour of 'cold' initial conditions.

In recent times, effort has been concentrated in investigating the spectral form and spatial distribution of the microwave background, and although experimental claims for departures from both black-body spectrum and exact isotropy have from time to time been been made, none, with the exception of evidence for a dipole moment, have been substantiated. Richards reviews the present observations of the spectral shape; at a few particular wavelengths, the measurements by Meyer and Jura of the excitation temperature of interstellar CN molecules provide a very precise intensity determination. As a historical aside, it is interesting to speculate how much more rapidly cosmology might have progressed had Gamow and his collaborators realised that astronomers had known for some time of the excitation of interstellar CN at an implied temperature of about 3K (see the discussion by Herzberg, for example). The dipole moment, presumably due to the peculiar motion of the Earth, is discussed by Smoot, Gorenstein and Muller. Measurements of anisotropies, reviewed by Wilkinson, are becoming very precise. At angular scales of a few degrees, variation in the intensity of the radiation is no more than two parts in 10^5, and this kind of restriction is a severe test of theories of galaxy formation, where some initial density perturbation is essential.

31 R. A. Alpher and R. C. Herman, Phys. Rev., 75, 1089 (1949)
32 A. Penzias and R. Wilson, Ap. J., 142, 419 (1965)
33 R. H. Dicke, P. J. E. Peebles, P. G. Roll and D. T. Wilkinson, Ap. J., 142, 414 (1965)
34 Ya. B. Zel'dovich, Sov. J. E. T. P., 16, 1102 (1963)
35 P. Richards, in Inner Space/Outer Space
36 D. Meyer and M. Jura, Ap. J. Lett., 276, 1 (1984)
37 G. Herzberg, **Atomic Spectra and Atomic Structure**, (Dover, New York, 1944)
38 G. F. Smoot, M. V. Gorenstein and R. A. Muller, Phys. Rev. Lett., 39, 898 (1977)
39 D. T. Wilkinson, in Inner Space/Outer Space

The microwave background is easily the largest contributor to the present radiation energy density of the Universe, but there are significant and measurable backgrounds at other wavelengths. These are probably of non-cosmological origin, being the accumulated emission from various discrete sources, but provide a constraint on, for instance, cosmological models involving the decay of exotic particles.

40 Radio: T. A. Clark, L. W. Brown, J. K. Alexander, Nature 228, 847 (1970)
41 Infra-red: P. de Bernardis, S. Masi, B. Melchiorri, F. Melchiorri and G. Moreno, Ap. J., 278, 150 (1984)
42 Optical: B. A. Peterson, et al., Ap. J. 233, L109 (1979)
43 Optical: D. Koo and R. Kron, Publ. Astr. Soc. Pacific, 92, 537 (1980)
44 Ultra-violet: F. Paresce, C. F. McKee and S. Bowyer, Ap. J., 240, 387 (1980)
45 X-Rays: S. Bowyer and R. F. Malina, in Inner Space/Outer Space
46 Gamma-rays: G. F. Bignami, C. E. Fichtel, R. C. Hartman and D. J. Thompson, Ap. J., 232, 649 (1979)

There are also particle backgrounds constituting the cosmic radiation. Observations are detailed in the Proceedings of the International Cosmic Ray Conferences, held most recently in San Diego. Experiments (or theoretical interpretation of the experiments) which measure fluxes in various particles include:

47 Protons: R. Baltrusaitis et al, Phys. Rev. Lett., 31, 564 (1984)
48 Electrons: T. A. Prince, Ap. J., 227, 676 (1979)
49 Antiparticles: A. Buffington and S. Schindler, Ap. J. Lett., 247, 105 (1981)

(iv) Galaxies and the Distribution of Matter

The nebula M31 in Messier's catalogue 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. The names of several diligent astronomers are remembered in the titles of catalogues of galaxies and clusters of galaxies: Zwicky, Abell, Shane and Wirtanen, and Shapley and Ames have provided data still used today. A recent development has been the ability to obtain redshifts as well as luminosities for large numbers of galaxies. Two important surveys, by the Harvard-Smithsonian Center for Astrophysics and by the Durham/Anglo-Australian Telescope collaboration, have provided cosmologists with a genuinely three-dimensional view of the Universe, rather than a projection onto the sky.

50 E. Hubble, **The Realm of the Nebulae**, (Yale University Press, New Haven, 1982) 226pp
51 F. Zwicky, E. Herzog, P. Wild, M. Karpowicz and C. T. Kowal, Catalogue of Galaxies and Clusters of Galaxies, 6 vols (California Institute of Technology, Pasadena, 1961-1968)
52 G. O. Abell, Ap. J. Suppl., 31, 211 (1958)
53 C. D. Shane and C. A. Wirtanen, Publ. Lick. Obs., 22, part 1 (1967)
54 H. Shapley and A. Ames, Harvard Ann., 88, no. 2 (1932)
55 J. Huchra, M. Davis, D. Latham and J. Tonry, Ap. J. Suppl., 52, 39 (1983)
56 A. J. Bean, et al., MNRAS, 205, 605 (1983)

The most important use of these data has been in the statistical analyses pioneered by Peebles and described in his book, 'The Large Scale Structure of the Universe' (B.7). By treating galaxies as point masses which trace the cosmological gravitational potential, one hopes to learn the relation of the present distribution of mass in the Universe to its origin in small primordial density perturbations. A potentially serious difficulty with this is that one measures, from galaxy catalogues, the correlation function of the distribution of luminosity, which may not be the same as the distribution of mass; indeed, the existence of dark matter implies differences. Bahcall and Soneira, and Khlypin and Kopylov, have measured the cluster-cluster correlation, and find that it is of different amplitude from the galaxy-galaxy correlation. According to Kaiser, this can be naturally explained if one assumes that, although galaxies and clusters come from the same parent population of density fluctuations, clusters come from a 'biased' set of higher magnitude peaks. Szalay and Schramm offer an alternative interpretation in which they find a dimensionless correlation function which joins the galaxy and cluster functions smoothly.

57 N. Bahcall and R. Soneira, Ap. J., 270, 20 (1983)
58 A. A. Khlypin and A. I. Kopylov, Sov. Astr. Lett., 9, 41 (1983)
59 N. Kaiser, Ap. J. Lett., 284, 9 (1984)
60 A. Szalay and D. Schramm, Nature, 314, 718 (1985)

From a map of galaxies on the sky, the eye tends to pick out structure - clusters, filaments, voids - and it is a disputatious matter whether these features are real, or purely in the eye of the beholder. The two-point correlation function of Peebles may be insensitive to large-scale features, because of the way it averages over the whole sky. Moody, Turner and Gott have tried to invent another statistic for the specific purpose of identifying voids and filaments, with mixed success. On the other hand, Kirshner et al present convincing observational evidence for the existence of large voids. As Zel'dovich, Einasto and Shandarin argue, there is undoubtedly more to the galaxy distribution than the two-point correlation reveals, but the identification and interpretation of this larger structure is difficult.

61 J. E. Moody, E. L. Turner and J. R. Gott III, Ap. J., 273, 16 (1983)
62 R. P. Kirshner, A. Oemler, P. L. Schechter and S. A. Schectman, Ap. J. Lett., 248, 57 (1981)
63 Ya. B. Zel'dovich, J. Einasto and S. F. Shandarin, Nature, 300, 407 (1982)

(v) 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 nuclear density. In the famous paper by Alpher, Bethe and Gamow, as well as in subsequent work by Alpher, Follin and Herman, the ideas both of a radiation background and of cosmological nucleosynthesis are put forward. (Hayashi refined the picture of the initial hot state). With hindsight, it is hard to see why this was not taken seriously at the time; the physics was straightforward, but the idea was daring. The realisation that cosmology could not in any case make all the observed elements in stars spurred the study of stellar evolution and nucleosynthesis. In turn, as noted by Hoyle and Tayler, stellar interiors could not make enough helium, which encouraged Peebles, and Wagoner, Fowler and Hoyle to begin the quantitative study of cosmological nucleosynthesis. The original emphasis was on the abundance of ^{4}He alone, because it was believed that the known trace amounts of D, ^{3}He and ^{7}Li were due to stellar nucleosynthesis; the quantities produced cosmologically were not thought significant. It was only in the early seventies, when a series of arguments showed that deuterium especially was almost impossible to create anywhere except in the big bang, that cosmological nucleosynthesis began to be taken seriously as a sensitive probe of the early Universe; its diagnostic power depends on the ability to fit the observed abundances of several elements, varying over several orders of magnitude. Schramm and Wagoner review the history and the current state of the art of these calculations, and the consistency with observations is reviewed by Yang et al (D.25).

62 G. Gamow, Phys. Rev., 70, 572 (1946)
63 R. Alpher, H. Bethe and G. Gamow, Phys. Rev., 73, 803 (1948)
64 R. Alpher, J. Follin and R. Herman, Phys. Rev., 92, 1347 (1953)
65 C. Hayashi, Prog. Theor. Phys., 5, 224 (1950)
66 F. Hoyle and R. Tayler, Nature, 203, 1108 (1964)
67 P. J. E. Peebles, Ap. J., 146, 542 (1966)
68 R. Wagoner, W. Fowler and F. Hoyle, Ap. J., 148, 3 (1967)
69 D. Schramm and R. Wagoner, Ann. Rev. Nucl. Part. Sci., 27, 37 (1977)

The use of nucleosynthesis as a means of testing non-standard cosmologies is described below, under appropriate headings.

(vi) Stellar evolution and nucleosynthesis

Burbidge, Burbidge, Fowler and Hoyle first discuss stellar processes as a solution to the cosmogonical problem of the origin of heavy elements, complementing big bang nucleosynthesis. Details of stellar evolution are somewhat peripheral to cosmological interests, but are of occasional importance; stellar ages are a pointer to the Hubble constant, and particle physics sometimes impinges on the physics of stellar interiors. A standard text on stars is by Clayton, and the proceedings of the Yerkes conference provide a sample of recent research.

70 E. Burbidge, G. Burbidge, W. Fowler and F. Hoyle, Rev. Mod. Phys., 29, 547 (1957)

71 D. Clayton, **Principles of Stellar Evolution and Nucleosynthesis**, (McGraw-Hill, New York, 1968) 612pp.

72 **Nucleosynthesis**, (Proc. of 1983 Yerkes conference), eds W. D. Arnett and 73 J. W. Truran, 320 pp. (University of Chicago Press, Chicago, 1985)

E Non-standard 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 acceptability 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 vagaries of the accelerator in order to interpret results, so the theorist should know the peculiarities of big bang cosmology before setting up cosmological experiments.

(i) Anisotropy and Inhomogeneity

The mathematical apparatus of anisotropic but homogeneous cosmology is explained by Ryan and Shepley. Inhomogeneity cannot be dealt with in any systematic way, so perturbation techniques offer the standard treatment (see Peebles' book, B.7). Nucleosynthesis gives strong constraints on both anisotropy (Barrow) and inhomogeneity (Barrow and Morgan). A more extreme anisotropic cosmology was the mixmaster Universe of Misner; it was hoped that viscous processes could damp the anisotropy, but this does not work (Matzner and Misner). Modern thinking on why the Universe is homogeneous and isotropic mostly appeals either to inflation or to mysterious quantum gravitational processes, for both of which see sections below.

1 M. P. Ryan and L. C. Shepley, **Homogeneous Relativistic Cosmologies**, (Princeton University Press, Princeton, 1975) 320pp.

2 J. D. Barrow, MNRAS, 175, 359 (1976)
3 J. D. Barrow and J. A. Morgan, MNRAS, 203, 393 (1983)
4 C. W. Misner, Ap. J., 158, 431 (1968); Phys. Rev. Lett., 22, 1071 (1969)
5 R. A. Matzner and C. W. Misner, Ap. J., 171, 415 (1972)

(ii) Cold and Tepid Universes

A tepid Universe has fewer photons per baryon at early times, and must therefore have a period of non-adiabatic evolution to bring the ratio of matter and radiation to its present state. A cold Universe is more extreme, and has no radiation to begin with. Zeldovich argued for such models because it was once thought that the primordial helium abundance must be less then 10%, which is impossible in the hot big bang. Nucleosynthesis in cold and tepid Universes is discussed by Wagoner, Fowler and Hoyle (D.68). Astrophysical aspects of these cosmologies, reviewed by Carr, include galaxy formation and the formation of an early generation of very massive stars.

6 Ya. B. Zeldovich, Sov. Phys. Usp., 6, 475 (1963)
7 B. Carr, in Inner Space/Outer Space

(iii) Lepton Degeneracy

The usual assumption, that the cosmological lepton distributions have a vanishing chemical potential, can be relaxed. Yahil and Beaudet, and more recently Scherrer, have made comprehensive calculations of the effect of neutrino degeneracy on nucleosynthesis, and the subject is reviewed by David and Reeves.

8 A. Yahil and G. Beaudet, Ap. J., 206, 26 (1976)
9 R. J. Scherrer, Mon. Not. Roy. Astr. Soc., 205, 683 (1983)
10 Y. David and H. Reeves, in Les Houches XXXII, p. 443

(iv) Baryon Symmetric Cosmologies

Before grand unification, the baryon to photon ratio of the Universe was an arbitrary, non-zero, initial condition. Omnes and Alfven argued that the only satisfactory initial condition was zero baryon number, but this leads to enormous difficulties in finding mechanisms to separate matter and antimatter on large scales at early times; as Steigman shows, there is no evidence for antimatter in our observable Universe, and plenty of evidence against it within our local neighbourhood. Grand unification allows baryon generation in the early Universe, and so makes much of the old argument redundant. However, Brown and Stecker proposed models which incorporate baryon number non-conservation, but which maintain global matter-antimatter symmetry, and Sato developed an inflationary model in which large regions of matter and antimatter could grow separate.

11 R. Omnes, Phys. Reports, 3, 1 (1970)
12 H. Alfven, Rev. Mod. Phys., 37, 652 (1965)
13 G. Steigman, Ann. Rev. Astr. Astrophys., 14, 339 (1976)
14 R. Brown and F. Stecker, Phys. Rev. Lett., 43, 315 (1979)
15 K. Sato, Phys. Lett. B, 99, 66 (1981)

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.

F 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 Particle' (A.11). The origins of the unified theory of electromagnetic and weak interactions are described in the Nobel prize speeches of the originators, Weinberg, Salam, and Glashow. Recent expositions of the theory are in 'Gauge Theories' (B.9) and in the review by Wilczek.

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 areas where the physics is speculative: the Universe provides a laboratory at high energies which 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. Langacker reviews the theory, and Ellis its implications for cosmology.

1 S. Weinberg; A. Salam; S. Glashow, Rev. Mod. Phys., 52, 515 (1980)
2 F. Wilczek, Ann. Rev. Nucl. Part. Sci., 32, 177 (1982)
3 P. Langacker, Physics Reports 72, 185 (1981)
4 J. Ellis, Phil. Trans. Roy. Soc. Lond. A, 307, 121 (1982)

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.

G Cosmic rays

Ironically, particle physicists were using the Universe as an accelerator before the first machines were built. Cosmic radiation in the upper atmosphere provided the first source of experimentally studied high energy particles, and even now the most energetic particles observed (up to 10^{20}eV) are cosmic rays. These are truly cosmological, because at energies of 10^{18}eV or more they cannot be confined by the magnetic fields of individual galaxies.

For high energy experiments, cosmic rays are neither controllable nor convenient, and research into them now is mostly done by astrophysicists wishing to discover their origin. However, exotic events discovered in cosmic ray experiments can still cause problems for particle physicists. A review of the use of cosmic ray data in determining high energy particle phenomenology is given by Gaisser and Yodh.

1 T. K. Gaisser and G. B. Yodh, Ann. Rev. Nucl. Part. Sci., 30, 475 (1980)

(i) High energy backgrounds

Hillas reviews the general features of the observed high energy (> 10^{15}eV) cosmic ray backgrounds. The spectrum is an approximate power-law, particle flux falling off roughly like $E^{-2.5}$, and measurements extend up to 10^{20}eV, though the statistics are poor and the shape of the spectrum is hard to determine.

Soon after the discovery of the microwave background, Greisen, and Zatsepin and Kuzmin, realised that the universe should be opaque to very high energy particles because of scattering off background photons. They concluded that there should be a cut-off in the cosmic ray spectrum at about 10^{19}eV. However, Berezinsky and Zatsepin showed a little later that the spectrum could be 'regenerated' at such energies; cosmic ray protons collide with microwave photons, producing pions, but the decay of the pions produces high energy neutrinos which, because of the increase of cross-section with neutrino energy, can cause detectable air showers in the Earth's atmosphere. Hill and Schramm have calculated in detail both the shape of the expected cosmic ray spectrum and the neutrino yield, as modified by interaction with microwave photons. A recent measurement of an upper limit on the ultra-high energy neutrino flux is by Baltrusaitis et al, at the Fly's Eye experiment in Utah, who look for upward moving air showers caused by neutrinos which have travelled through the Earth.

2 A. M. Hillas, Ann. Rev. Astron. Astrophys., 22, 425 (1984)
3 K. Greisen, Phys. Rev. Lett., 16, 748 (1966)
4 G. T. Zatsepin and V. A. Kuzmin, Sov. Phys. J.E.T.P. Lett., 4, 78 (1966)
5 V. S. Berezinsky and G. T. Zatsepin, Sov. J. Nucl. Phys., 11, 111 (1970)
6 C. T. Hill and D. N. Schramm, Phys. Rev. D, 31, 564 (1984)
7 R. Baltrusaitis et al, Ap. J. Lett., 281, 9 (1984)

(ii) Sources of high energy neutrinos

As well as their production by interaction of cosmic rays with microwave photons, high energy neutrinos can originate in astrophysical sources. A compact source of energetic protons, such as a quasar or a neutron star, will emit secondary neutrinos through the collision of the protons in surrounding material. Many people have studied such sources, and attempted to predict astrophysical fluxes of neutrinos.

8 S. Margolis, D. N. Schramm and R. Silberberg, Ap. J., 221, 990 (1978)
9 F. W. Stecker, Ap. J., 228, 919 (1979)
10 D. Eichler and D. N. Schramm, Proc. DUMAND Workshop (Honolulu), 2, 135 (1980)
11 R. Protheroe and D. Kazanas, Ap. J., 265, 620 (1983)
12 V. J. Stenger, Ap. J., 284, 810 (1984)

(iii) Exotic particles

The very high energies available in cosmic rays make it worthwhile to search them for exotic or hypothetical particles. Marini et al conducted an experiment to look for quarks, tachyons and particles of GeV mass, while Napolitano et al looked for fractionally charged particles; these experiments produced upper limits, but no positive detection. Gaisser and Stanev discussed the possibility of measuring neutrino oscillations in cosmic ray induced events, and Silk and Srednicki make theoretical estimates of the antiproton flux to be expected if the galactic halo contains annihilating photinos.

13 A. Marini et al, Phys. Rev. D, 26, 1777 (1982)
14 J. Napolitano et al, Phys. Rev. D, 25, 2857 (1982)
15 T. K. Gaisser and T. Stanev, Phys. Rev. D, 30, 985 (1984)
16 J. Silk and M. Srednicki, Phys. Rev. Lett., 53, 624 (1984)

H 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 which may limit its lifetime, mass, relative density, decay paths and so on. Some useful reviews of the arguments employed are given below.

1 A. D. Dolgov and Ya. B. Zeldovich, Rev. Mod. Phys., 53, 1 (1981)
2 G. Steigman, in Les Houches XXXII, p. 473

(i) Neutrinos

Neutrinos are not new particles, but their having mass is a recent idea. A standard cosmological argument, as given by Cowsik and McClelland, provides an upper limit to neutrino mass by requiring that the cosmological density of neutrinos should not exceed observational limits on the total density. Some time later, Lee and Weinberg showed that extremely massive neutrinos, of an MeV or greater, partially annihilate before decoupling; their density is thus lower as their mass increases, and a mass greater than a few GeV is tolerable. Gunn et al explore a variety of consequences of stable, massive, neutral leptons, and Freese and Schramm give an up-to-date review of the limits on mass.

A calculation of the effect of a massive neutrino species on nucleosynthesis is performed by Kolb and Scherrer.

3 R. Cowsik and J. McClelland, Phys. Rev. Lett., 29, 669 (1972)
4 B. W. Lee and S. Weinberg, Phys. Rev. Lett., 39, 165 (1977)
5 J. E. Gunn, B. W. Lee, I. Lerche, D. N. Schramm and G. Steigman, Ap. J., 223, 1015 (1978)
6 K. Freese and D. N. Schramm, Nucl. Phys. B, 233, 167 (1984)
7 E. W. Kolb and R. J. Scherrer, Phys. Rev. D, 25, 1481 (1982)

Neutrinos with mass in the forbidden range can be saved if they are unstable. Dicus, Kolb and Teplitz showed that, if the decay is purely to light neutrinos, then the lifetime has to be short enough for the energy density of the decay products to redshift away, but that if the decay produces photons, the lifetime must be shorter to avoid distortion of the microwave background by unthermalised photons. With Wagoner, they discussed how the decay photons would heat up the Universe and upset standard nucleosynthesis. (A more detailed calculation of the microwave background distortion is by Silk and Stebbins). For neutrinos of more than a few MeV in mass, Lindley obtained a stronger limit still by showing that energetic photons (produced directly, or indirectly through the thermalisation of other particles) can destroy, by photonuclear reactions, cosmologically produced deuterium. The question of whether these limits can be combined with experimental results to completely rule out a massive tau neutrino has been addressed by Kolb and Goldman, Sarkar and Cooper, and by Krauss.

8 D. A. Dicus, E. W. Kolb, and V. L. Teplitz, Phys. Rev. Lett., 39, 168 (1977); Ap. J., 221, 327 (1978)
9 D. A. Dicus, E. W. Kolb, V. L. Teplitz, and R. V. Wagoner, Phys. Rev. D, 17, 1529 (1978)
10 J. Silk and A. Stebbins, Ap. J., 269, 1 (1983)
11 D. Lindley, MNRAS, 188, 15p (1979); Ap. J., 294, 1 (1985)
12 E. W. Kolb and T. Goldman, Phys. Rev. Lett. 43, 897 (1979)
13 S. Sarkar and A. M. Cooper, Phys. Lett. B, 148, 347 (1984)
14 L. M. Krauss, Phys. Rev. Lett., 53, 1976 (1984)

Neutrinos which decay into photons might produce a detectable background radiation. Cowsik showed that lifetimes close to the age of the Universe are ruled out by the observed X-ray and optical background intensities. Later, Stecker, Melott and Sciama, and Kimble, Bowyer and Jakobsen suggested that the observed UV background might be due to the decay of a low mass (100eV) neutrino, with a lifetime of 10^{23}s or more. However, de Rujula and Glashow argued that theoretical models predict lifetimes even longer than this for such low masses.

15 R. Cowsik, Phys. Rev. Lett., 39, 784 (1977)
16 F. W. Stecker, Phys. Rev. Lett., 45, 1460 (1980)
17 R. Kimble, S. Bowyer and P. Jakobsen, Phys. Rev. Lett., 46, 80 (1981)
18 A. Melott and D. W. Sciama, Phys. Rev. D, 25, 2214 (1981)
19 A. de Rujula and S. Glashow, Phys. Rev. Lett., 45, 942 (1980)

Supernovae explosions release a large fraction of their energy in neutrinos. Cowsik (H.14) estimated the background of photons resulting from the decay of such neutrinos, and showed that they must be very long-lived. Falk and Schramm, on the other hand, observed that neutrinos decaying in the immediate vicinity of a supernova would contribute excessively to the photon luminosity. This allows only very short lifetimes, milliseconds or less, for masses up to about 10MeV. A limit in the same vein was derived by Toussaint and Wilczek, who looked at decays into electrons and positrons, rather than photons.

20 S. Falk and D. N. Schramm, Phys. Lett. B, 79, 511 (1978)
21 D. Toussaint and F. Wilczek, Nature, 289, 777 (1981)

Another variation on neutrino physics is the addition of more species, beyond the usual three. Schvartsman showed how any increase in cosmological density would alter nucleosynthesis, and specific application of this idea to neutrino species was made by Steigman, Schramm and Gunn. Yang et al (D.25) give a recent rehearsal of this argument and show that a best fit of cosmological nucleosynthesis to observations follows from assuming just three massless neutrino species, as in the standard model. Four species are marginally consistent, and more are inconsistent. If the neutrinos have mass, the calculation is a little different; see Kolb and Scherrer (H.7). 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 (Schramm and Steigman); this will be the first time that high energy physics experiment will be a check of standard cosmology. Some general considerations of the effects of more neutrinos (or other weakly coupled particles) on stellar cooling rates and evolution are given by Ellis and Olive.

22 V. F. Schvartsman, Sov. Phys. J.E.T.P. Lett., 9, 184 (1969)
23 G. Steigman, D. N. Schramm, and J. E. Gunn, Phys. Lett. B, 66, 202 (1977)
24 D. N. Schramm and G. Steigman, Phys. Lett. B, 141, 337 (1984)
25 J. Ellis and K. Olive, Nucl. Phys. B, 223, 252 (1983)

(ii) 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 is 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.

Because the lightest superino cannot decay, the simple cosmological density argument is more restrictive than it is for neutrinos, which may be unstable. Pagels and Primack, Weinberg, and Krauss translate these restrictions into limits on supersymmetric models. (More recently, these limits have been sidestepped by the supposition of an inflationary phase in the early Universe; instead, there are now limits on the post-inflation reheating temperature. See the inflation section below for more details). The implications for nucleosynthesis of additional, superweakly coupled particles, such as superinos, is estimated by Olive, Schramm and Steigman.

26 J. Ellis, J. S. Hagelin, D. V. Nanopoulos, K. Olive, and M. Srednicki, Nucl. Phys. B, 238, 453 (1984)
27 H. Pagels and J. R. Primack, Phys. Rev. Lett., 48, 223 (1982)
28 S. Weinberg, Phys. Rev. Lett., 48, 1303 (1982)
29 L. M. Krauss, Nucl. Phys. B, 227, 556 (1983)
30 K. Olive, D. N. Schramm and G. Steigman, Nucl. Phys. B, 180, 497 (1981)

The second lightest superino decays into the lightest, plus photons, gravitons, gluons, or whatever theory dictates. Ellis et al have explored the destruction of light elements by high energy photons; see also Lindley (H.11). If gluons are produced in the decay, and then give rise to hadrons, the destructive effects of energetic nucleons, especially anti-protons, are important. This is discussed by Khlopov and Linde.

31 J. Ellis, J. E. Kim and D. V. Nanopoulos, Phys. Lett. B, 145, 181 (1984)
32 J. Ellis, D. V. Nanopoulos and S. Sarkar, Nucl. Phys. B, 259, 175 (1985)
33 M. Yu. Khlopov and A. D. Linde, Phys. Lett. B, 138, 265 (1984)

(iii) Axions

The axion is a hypothetical particle which 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 towards 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; here we select a few important points. As originally conceived, the axion was incorporated into the Weinberg-Salam electroweak theory. However, Weinberg and Wilczek showed that because the axion is coupled to quarks, and therefore to matter, it would be copiously produced in, for instance, nuclear reactors, and should have been observed. Later, Kim, and Shifman, Vainshtein and Zakharov came up with axion models in which the characteristic energy scale was much higher, and perhaps associated with grand unification. Dine, Fischler and Srednicki invented a more economical model in the same vein. This 'invisible' axion (because it cannot be seen terrestrially) nevertheless has astrophysical and cosmological consequences.

34 P. Sikivie in Inner Space/Outer Space
35 S. Weinberg, Phys. Rev. Lett., 40, 223 (1978)
36 F. Wilczek, Phys. Rev. Lett., 40, 279 (1978)
37 J. E. Kim, Phys. Rev. Lett., 43, 103 (1979)
38 M. A. Shifman, A. I. Vainshtein, and V. I. Zakharov, Nucl. Phys. B, 166, 493 (1980)
39 M. Dine, W. Fischler, and M. Srednicki, Phys. Lett. B, 104, 199 (1981)

Since stars are large nuclear reactors, they can also emit axions. Dicus et al, and Fukugita, Watamura and Yoshimura, both showed that if the invisible 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 0.1 eV. Recent calculations by Dearborn, Schramm and Steigman push this limit to 0.01 eV. In contrast to the case of neutrinos or superinos, such very light axions can still contribute significantly to the energy density of the Universe. Axions emerge from the early Universe not as the result of particle collisions, but as the residual oscillations of a scalar field. Their primordial energy density is characteristic of the early epoch when they are produced, but they are non-relativistic, and so their density does not redshift away. Preskill, Wise and Wilczek, Abbott and Sikivie, and Dine and Fischler all found that the axion mass must be greater than about 10^{-5} eV if the Universe now is not to be dominated excessively by axions. (The lighter the axion, the weaker its coupling, and the harder it is to reduce its density). Finally, another difficulty was raised by Sikivie. Many axion theories have 'multiple vacua': these are different minima into which the axion field can relax. As the Universe cools, one expects different regions to fall at random into different vacua, separated by domain walls which carry a large energy density. This is problematic, and Sikivie discusses possible resolutions.

40 D. A. Dicus, E. W. Kolb, V. L. Teplitz, and R. V. Wagoner, Phys. Rev. D, 18, 1829 (1978); 22, 839 (1980)
41 M. Fukugita, S. Watamura, and M. Yoshimura, Phys. Rev. Lett., 48, 1522 (1982)
42 D. Dearborn, D. N. Schramm and G. Steigman, Phys. Rev. Lett., 56, 26 (1986)
43 J. Preskill, M. B. Wise, and F. Wilczek, Phys. Lett. B, 41 120, 127 (1983)
44 L. F. Abbott and P. Sikivie, Phys. Lett. B, 120, 133 (1983)
45 M. Dine and W. Fischler, Phys. Lett. B, 120, 137 (1983)
46 P. Sikivie, Phys. Rev. Lett., 51, 1415 (1983) ; 52, 695 (1984)

(iv) 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 quantised. Dirac had no solid reason to expect monopoles to occur, and so their absence could be attributed to a peculiarity of nature. However, 't Hooft and Polyakov showed that grand unified theories allowed, but did not force, monopoles to exist. This unusual circumstance comes about because, although monopoles are not part of the fundamental particle spectrum of grand unified theories, they can occur as a stable ground state of the theory once the strong-electroweak symmetry has been broken. This cryptic statement is clarified below, in the section on phase transitions. For most astrophysical and cosmological purposes, the monopole is a stable particle with mass and magnetic charge, and with all the classical properties connoted by Maxwell's equations.

47 P. A. M. Dirac, Proc. Roy. Soc. Lond. A, 133, 60 (1931)
48 G. 't Hooft, Nucl. Phys. B, 79, 276 (1974)
49 A. M. Polyakov, Sov. Phys. J. E. T. P., 41, 988 (1975)

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. As first shown by Zel'dovich and Khlopov, and by Preskill, conventional models predict a huge density of monopoles, which would dominate the Universe today by as much as twelve orders of magnitude. A review of some ways of avoiding this disaster is given by Kolb. A simple idea which does not work is enhancement of the monopole-antimonopole annihilation rate by gravitational clumping (Fry and Schramm; Fry; Goldman, Kolb and Toussaint), although Fry and Fuller suggest that monopole stars may form and 'burn' in an extreme monopole dominated Universe. Some ideas which do work, but which necessitate contrived physical models include altering the thermal history of the early Universe (Linde; Harvey, Kolb and Wolfram), binding monopoles and antimonopoles with magnetic flux tubes (Lazarides and Shafi), and having a low temperature phase transition (Langacker and Pi). 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.

50 Ya. B. Zel'dovich and M. Yu. Khlopov, Phys. Lett. B, 79, 239 (1978)
51 J. P. Preskill, Phys. Rev. Lett., 43, 1365 (1979)
52 E. W. Kolb, in Texas Symposium XI, p. 33
53 J. N. Fry and D. N. Schramm, Phys. Rev. Lett., 44, 1361 (1980)
54 J. N. Fry, Ap. J. Lett., 246, 93 (1981)
55 T. E. Goldman, E. W. Kolb and D. Toussaint, Phys. Rev. D, 23, 867 (1981)
56 J. N. Fry and G. M. Fuller, Ap. J., 286, 397 (1984)
57 A. D. Linde, Phys. Rev. D, 14, 3345 (1976)
58 J. A. Harvey, E. W. Kolb and S. Wolfram, Phys. Rev. D, 27, 315 (1983)
59 G. Lazarides and Q. Shafi, Phys. Lett. B, 94, 149 (1980)
60 P. Langacker and S.-Y. Pi, Phys. Rev. Lett., 44, 1563 (1980)

61 A. H. Guth and S-H. H. Tye, Phys. Rev. Lett., 44, 631 (1980)

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' has been calculated in more detail by Turner, Parker and Bogdan. Rephaeli and Turner find a somewhat stronger bound from the persistence of intergalactic fields in clusters. There is a possible loophole here; if the galaxy is embedded in a halo of monopoles, magnetic fields can be generated by their distribution and motion. Salpeter, Shapiro and Wasserman, and Arons and Blandford noticed this possibility, and Farouki, Shapiro and Wasserman have constructed detailed models in which they claim a population of monopoles exceeding the Parker limit actually maintains a galactic magnetic field.

62 E. N. Parker, Ap. J., 160, 383 (1970)
63 M. S. Turner, E. N. Parker and T. J. Bogdan, Phys. Rev. D, 26, 1296 (1981)
64 Y. Rephaeli and M. S. Turner, Phys. Lett. B, 121, 115 (1983)
65 E. E. Salpeter, S. L. Shapiro and I. Wasserman, Phys. Rev. Lett., 49, 1114 (1982)
66 J. Arons and R. D. Blandford, Phys. Rev. Lett., 50, 544 (1983)
67 R. Farouki, S. L. Shapiro and I. Wasserman, Ap. J., 284, 282 (1984)

A new and important discovery was the realisation 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. A number of groups (Kolb, Colgate and Harvey; Dimopoulos, Preskill and Wilczek; Bais et al) showed that dense stars, especially neutron stars, would gravitationally capture monopoles, which would then catalyse 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. More recent calculations of this limit, which is much stronger then the Parker limit are by Kolb and Turner (for neutron stars), by Freese, Turner and Schramm (individual old pulsars), and by Freese (white dwarfs). Kuzmin and Rubakov suggest that these limits would be weakened if monopoles were sufficiently numerous within the stars that their annihilation rate would rise. Harvey has looked at this and other aspects of the interaction of monopoles with neutron star interiors. and magnetic fields.

68 V. A. Rubakov, Nucl. Phys. B, 203, 311 (1982)
69 C. G. Callan, Phys. Rev. D, 26, 2058 (1982)
70 E. W. Kolb, S. Colgate and J. A. Harvey, Phys. Rev. Lett., 49, 1373 (1982)
71 S. Dimopoulos, J. P. Preskill and F. Wilczek, Phys. Lett. B, 119,, 320 (1982)
72 F. A. Bais, J. Ellis, D. V. Nanopoulos and K. Olive, Nucl. Phys. B, 219, 189 (1983)
73 E. W. Kolb and M. S. Turner, Ap. J., 286, 702 (1984)

74 K. Freese, M. S. Turner and D. N. Schramm, Phys. Rev. Lett., 51, 1625 (1983)
75 K. Freese, Ap. J., 286, 216 (1984)
76 V. A. Kuzmin and V. A. Rubakov, Phys. Lett. B, 125, 372 (1983)
77 J. A. Harvey, Nucl. Phys. B, 236, 255 (1984)

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 have failed to reveal new detections. Errede et al also report a negative result from a detector designed for proton decay experiments, which is thereby sensitive to nucleon decay caused by the passage of a monopole. At present, we have to conclude that the monopole is a purely hypothetical particle.

78 B. Cabrera, Phys. Rev. Lett., 48, 1378 (1982)
79 B. Cabrera, M. Taber, R. Gardner and J. Bourg, Phys. Rev. Lett., 51, 1933 (1983)
80 S. Errede et al, Phys. Rev. Lett., 51, 245 (1983)

I 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.

1 J. Silk, A. S. Szalay and Ya. B. Zel'dovich, Scientific American, October 1983, 72.

(i) Observational evidence for dark matter

Dark matter is a general term for anything which can be detected by its dynamical influence, but cannot be seen. It exists on all astronomical scales, and perhaps in several different forms. The motion of stars near the Sun reveals unseen matter of perhaps equal density to what is visible (Bahcall). Studies of dwarf galaxies (Faber and Lin) and of galaxies in general (Peebles; Faber and Gallagher, D.20) show that their dynamics may be dominated by dark matter, and detailed analysis of the motion of individual galaxies in superclusters (Davis et al; Ford et al) also implies that there is more matter in the Universe invisible than visible.

2 J. N. Bahcall, Ap. J., 276, 169 (1984)
3 S. M. Faber and D. N. C. Lin, Ap. J. Lett., 266, 17 and 20 (1983)
4 P. J. E. Peebles, in Les Houches XXXII, p. 213.

5 M. Davis, J. Tonry, J. Huchra and D. W. Latham, Ap. J. Lett., 238, 113 (1980)
6 H. C. Ford, R. J. Harms, R. Ciardullo and F. Bartko, Ap. J. Lett., 245, 53 (1981)

(ii) Galaxy Formation

Galaxy formation is a subject which 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 (B.7) and by Zel'dovich and Novikov (B.6) 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. The reviews by Gott and by Fall are also useful. Although there is a standard picture of galaxy development from initial small fluctuations, there are also schemes in which large structures are produced by purely astrophysical processes. Carr and Rees propose that galaxies could result from the formation of an initial population of massive stars, and Ostriker and Cowie have shown how large structures may be built up from local events such as the explosion of such early stars.

7 J. R. Gott III, Ann. Rev. Astr. Astrophys., 15, 235 (1977)
8 S. M. Fall, Rev. Mod. Phys., 51, 21 (1979)
9 B. J. Carr and M. J. Rees, M. N. R. A. S., 206, 315 (1984)
10 J. P. Ostriker and L. L. Cowie, Ap. J. Lett., 243, 127 (1983)

An important technique has been the use of N-body computer codes. These are programs which integrate the gravitational equations of motion for large numbers of point-like 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.

11 S. J. Aarseth, J. R. Gott III and E. L. Turner, Ap. J., 234, 13 (1979)
12 A. G. Doroshkevich, E. B. Kotok, I. D. Novikov, A. N. Polyudov, S. F. Shandarin, and Yu. S. Sigov, Mon. Not. Roy. Astr. Soc., 192, 321 (1980)
13 G. Efstathiou and J. W. Eastwood, Mon. Not. Roy. Astr. Soc., 194, 503 (1981)
14 R. H. Miller, Ap. J., 270, 390 (1983)
15 C. S. Frenk, S. D. M. White and M. Davis, Ap. J., 271, 417 (1983)
16 A. Melott, J. Einasto, E. Saar, I. Suisalu, A. A. Klypin and S. F. Shandarin, Phys. Rev. Lett., 51, 935 (1983)

The fluctuations which 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. Sachs and Wolfe first described the effect of density fluctuations on the microwave background, and some recent calculations are by Kaiser and Wilson. Hogan, Kaiser and Rees review the theoretical significance of the measurements, and Uson and Wilkinson have made the most sensitive experiment to date.

17 R. K. Sachs and A. M. Wolfe, Ap. J., 147, 73 (1967)
18 N. Kaiser, Mon. Not. Roy. Astr. Soc., 198, 1033 (1982)
19 M. Wilson, Ap. J., 273, 2 (1983)
20 C. J. Hogan, N. Kaiser and M. J. Rees, Phil. Trans. Roy. Soc. Lond. A, 307, 97 (1982)
21 J. M. Uson and D. T. Wilkinson, Ap. J., 283, 471 (1984)

(iii) Dark matter candidates

Because it can't be seen, it is hard make observations of dark matter. However, that fact also imposes restrictions on its nature. The idea that the dark matter might be dead stars, black holes, or other 'conventional' stuff has been critically examined by Hegyi and Olive. Bond, Carr and Arnett discuss generally the constraints on black holes as dark matter candidates, while Freese, Price and Schramm give a specific model using planetary sized black holes. The dynamics of galactic halos impose restrictions on the properties of any elementary particle candidate, as explained by Tremaine and Gunn. Schramm and Steigman. elaborate this into a scheme which requires baryonic material on small scales and non-baryonic matter on large scales.

22 D. Hegyi and K. Olive, Phys. Lett. B, 126, 28 (1983)
23 J. R. Bond, B. J. Carr and W. D. Arnett, Ap. J., 247, 445 (1984)
24 K. Freese, R. Price and D. N. Schramm, Ap. J., 275, 405 (1983)
25 S. Tremaine and J. Gunn, Phys. Rev. Lett., 42, 467 (1979)
26 D. N. Schramm and G. Steigman, Gen. Rel. Grav., 13, 2 (1981)

Theoretical studies focus on the question of whether a particular candidate for dark matter is consistent with what we know about galaxy structure and the large-scale distribution of galaxies and clusters; different candidates have different gross kinematical properties, and impose different characteristic mass, length and velocity scales on the final distribution of matter. White and Rees first discussed the general features of galaxy formation in a background of dark matter. The particular example of massive neutrinos was put forward by, among others, Bond, Efstathiou and Silk, but more recently Kaiser, and White, Frenk and Davis have shown that the details of the observed galaxy distribution do not fit with calculations of neutrino-dominated galaxy formation in a standard model of Gaussian, adiabatic fluctuations.

27 S. D. M. White and M. J. Rees, Mon. Not. Roy. Astr. Soc., 183, 341 (1978)
28 J. R. Bond, G. Efstathiou and J. Silk, Phys. Rev. Lett., 45, 1980 (1980)
29 N. Kaiser, Ap. J. Lett , 273, 17 (1983)

30 S. D. M. White, C. S. Frenk and M. Davis, Ap. J. Lett., 274, 1 (1983)

The problems with neutrinos have brought other particles into the picture. Bond and Szalay discuss the differences between 'hot' dark matter which, like a neutrino component, is relativistic when the Universe first becomes matter dominated and 'cold' dark matter, which is correspondingly non-relativistic. Blumenthal, Pagels and Primack show how a heavier particle can resolve some problems, and Bond, Szalay and Turner specifically propose gravitinos. Turner, Wilczek and Zee describe the case of axions, and Peebles gives an account of galaxy formation in a Universe dominated by cold dark matter of a generic kind. This seems to do the best job at present of reproducing the observed Universe, but Vittorio and Silk, and Bond and Efstathiou raise difficulties with excessive microwave background fluctuations. On a more exotic note, Zel'dovich, Vilenkin and Shafi, and Turok have suggested that cosmic strings, produced in certain grand unified theories, might explain both the density fluctuations responsible for galaxies and also the dark matter; in addition, strings can produce non-Gaussian fluctuations which may, in a composite model, save neutrinos.

31 J. R. Bond and A. S. Szalay, in Texas Symposium XI, p. 82.
32 G. R. Blumenthal, H. Pagels and J. R. Primack, Nature, 299, 37 (1982)
33 J. R. Bond, A. S. Szalay and M. S. Turner, Phys. Rev. Lett., 48, 1636 (1982)
34 M. S. Turner, F. Wilczek and A. Zee, Phys. Lett. B, 125, 35 and 519 (1983)
35 P. J. E. Peebles, Ap. J., 277, 470 (1983)
36 N. Vittorio and J. Silk, Ap. J. Lett., 285, 39 (1984)
37 J. R. Bond and G. Efstathiou, Ap. J. Lett., 285, 45 (1984)
38 Ya. B. Zel'dovich, Mon. Not. Roy. Astr. Soc., 192, 663 (1980)
39 A. Vilenkin and Q. Shafi, Phys. Rev. Lett., 51, 1716 (1983)
40 N. Turok, Phys. Lett. B, 126, 437 (1983)

J Baryosynthesis

Grand unification has provided a solution to one of the most perplexing of cosmological problems, why the Universe contains matter but no antimatter. The review by Kolb and Turner discusses how the loss of baryon symmetry in microphysics opens a path for the generation of baryon number in cosmology. However, the essential ingredients were noted by Sakharov when unification was still a distant vision. As well as violation of baryon number, the particle physics model has to supply C and CP breaking processes. Cosmological expansion and cooling provides another necessary ingredient, a means of forcing particle distributions out of thermal equilibrium. (Since baryons and antibaryons have the same mass, thermal equilibrium forces a vanishing overall baryon number). Sakharov and later Kuzmin invented illustrative models, but the advent of grand unification gave Ignatiev et al, Yoshimura, and many others a realistic means of estimating the cosmological generation of baryon number. Kolb and Wolfram, Harvey et al, and Fry, Olive and Turner, have calculated numerically the evolution of the abundances of particles whose decays lead to a non-zero baryon number. The final baryon to photon ratio depends on, among other things, a parameter controlling the magnitude of CP violation. This parameter is theoretically undetermined, and so none of these calculations can be said to predict the baryon number of the Universe.

1 E. W. Kolb and M. S. Turner, Ann. Rev. Nucl. Part. Sci., 33, 645 (1983)
2 A. D. Sakharov, Sov. Phys. J.E.T.P. Lett, 5, 24 (1967)
3 V. A. Kuzmin, Sov. Phys. J.E.T.P. Lett, 12, 228 (1970)
4 A. Yu. Ignatiev, N. V. Krasnikov, V. A. Kuzmin and A. N. Tavkhelidze, Phys. Lett. B, 76, 436 (1978)
5 M. Yoshimura, Phys. Rev. Lett., 41, 281 (1978)
6 S. Dimopoulos and L. Susskind, Phys. Rev. D, 18, 4500 (1978)
7 D. Toussaint, S. B. Treiman, F. Wilczek and A. Zee, Phys. Rev. D, 19, 1036 (1979)
8 S. Weinberg, Phys. Rev. Lett., 42, 850 (1979)
9 J. Ellis, M. K. Gaillard and D. V. Nanopoulos, Phys. Lett. B, 80, 360 and 82 , 464 (1979)
10 E. W. Kolb and S. Wolfram, Phys. Lett. B, 91, 217 (1980), and Nucl. Phys. B, 172, 224 (1980)
11 J. A. Harvey, E. W. Kolb, D. B. Reiss and S. Wolfram, Nucl. Phys. B, 201, 16 (1982)
12 J. N. Fry, K. Olive and M. S. Turner, Phys. Rev. D, 22, 2953 and 2977 (1980); Phys. Rev. Lett., 45, 2074 (1980)

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. Some general features have been discussed. Density fluctuations in the early Universe will develop into purely adiabatic fluctuations through baryosynthesis (Turner and Schramm, Lindley) although one can artificially arrange for isothermal perturbations to appear if density fluctuations are suppressed in favour of shear (anisotropic) inhomogeneities (Barrow and Turner; Bond, Kolb and Silk). Rothman and Matzner analyse in general terms the evolution of anisotropy through the baryosynthesis epoch, and conclude that no useful limit on departures from isotropy can be obtained.

13 M. S. Turner and D. N. Schramm, Nature, 279, 303 (1979)
14 D. Lindley, Nature, 291, 133 (1981)
15 J. D. Barrow and M. S. Turner, Nature, 291, 469 (1981)
16 J. R. Bond, E. W. Kolb and J. Silk, Ap. J., 255, 341 (1982)
17 A. Rothman and R. Matzner, Ap. J., 263, 501 (1982)

A number of variations on the standard picture of baryosynthesis have been proposed: most can give the right results, with suitable choice of parameters, and none are particularly compelling. Harvey et al incorporate superheavy fermions, as well as bosons, into grand unification, while Claudson et al abandon grand unification altogether in favour of low temperature baryon number violating effects. The remaining papers describe cosmologies in which very low mass primordial black holes evaporate, providing a source of superheavy particles to generate baryon number.

18 J. A. Harvey, E. W. Kolb, D. B. Reiss and S. Wolfram, Nucl. Phys. B, 177, 456 (1982)
19 M. Claudson, L. J. Hall and I. Hinchliffe, Nucl. Phys. B, 241, 309 (1984)
20 M. S. Turner, Phys. Lett. B, 89, 155 (1980)
21 J. D. Barrow, Mon. Not. Roy. Astr. Soc., 192, 427 (1980)
22 D. Lindley, Mon. Not. Roy. Astr. Soc., 196, 317 (1981)
23 A. D. Dolgov, Sov. Phys. J.E.T.P., 52, 169 (1980)

K 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 non-uniformities 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.

The general principle of symmetry breaking in gauge theories as a result of temperature change was noted heuristically by Kirzhnits and Linde, and worked out in detail by Dolan and Jackiw, and Weinberg. A recent review of the theory as it applies to cosmology is by Linde.

1 D. A. Kirzhnits and A. D. Linde, Phys. Lett. B, 42, 471 (1972)
2 L. Dolan and R. Jackiw, Phys. Rev. D, 9, 3320 (1974)
3 S. Weinberg, Phys. Rev. D, 9, 3357 (1974)
4 A. D. Linde, Rep. Prog. Phys., 42, 389 (1979)

(i) 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 which 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. As shown by Kibble, the symmetry of the vacuum dictates whether defects can occur, and if so, whether they have the form of points (monopoles), lines (strings) or planes (domain walls). Monopoles have been discussed already, and domain walls are disastrous for cosmology (Zel'dovich, Kobzarev and Okun). Strings are potentially more interesting; Vilenkin, Shafi and Turok discuss their cosmological evolution and possible importance for galaxy formation. The detectability of strings in the present Universe is discussed by Kaiser and Stebbins and by Hogan and Rees.

5 T. W. B. Kibble, J. Phys. A, 9, 1387 (1976); Phys. Rep., 67, 183 (1980)
6 Ya. B. Zel'dovich, I. Ya. Kobzarev and L. B. Okun, Sov. Phys. J.E.T.P., 40, 1 (1974)
7 A. Vilenkin, Phys. Rev. D, 24, 2082 (1981); in 'The Very Early Universe', p. 163
8 Q. Shafi, in 'The Very Early Universe', p. 147
9 A. Vilenkin, Phys. Rep., 121, 263 (1985)
10 N. Turok and P. Bhattacharjee, Phys. Rev. D, 29, 1557 (1984)
11 N. Kaiser and A. Stebbins, Nature, 310, 391 (1984)
12 C. J. Hogan and M. J. Rees, Nature, 311, 109 (1984)

(ii) Symmetry breaking

Even if symmetry breaking creates no ugly 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.

12 D. A. Kirzhnits and A. D. Linde, Ann. Phys., 101, 195 (1976)
13 M. A. Sher, Phys. Rev. D, 22, 2989 (1980)
14 A. H. Guth and E. Weinberg, Phys. Rev. Lett., 45, 1131 (1980)
15 E. Witten, Nucl. Phys. B, 177, 477 (1981)

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; a few papers address some of the consequences of the the breaking of supersymmetry regardless of the inflationary connotations.

16 S-Y. Pi, Phys. Lett. B, 112, 441 (1982)
17 H. E. Haber, Phys. Rev. D, 26, 1317 (1982)

(iii) 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, because the transition is the result of non-perturbative strong interactions. Olive gives a thermodynamic analysis of the transition, while Crawford and Schramm argue that quark confinement could generate a cosmologically interesting spectrum of density perturbations, leading to the formation of planetary mass black holes which might constitute the dark matter. Witten proposes a transition of a somewhat different nature, in which some fraction of the Universe ends up in 'nuggets' of strange nuclear matter, a stable state composed of equal numbers of up, down and strange quarks, but Applegate and Hogan have cast doubt on the cosmological formation of these nuggets. Hogan investigates the 'shattering' of nuclear matter in an initially cold Universe. As a different (and by now unpopular) model of dense matter, Hagedorn suggests an exponential increase in the number of hadronic states as temperature and density rise; in the early Universe there is then not a gas of free quarks, but rather a cold pressureless ensemble of massive hadrons.

18 K. Olive, Nucl. Phys. B, 190, 483 (1980)
19 M. Crawford and D. N. Schramm, Nature, 298, 538 (1982)
20 E. Witten, Phys. Rev. D, 30, 272 (1984)
21 J. H. Applegate and C. J. Hogan, Phys. Rev. D, 31, 3037 (1985)
22 C. J. Hogan, Ap. J., 252, 418 (1982)
23 R. Hagedorn, Cargese Lectures in Physics, 6, 643 (Gordon and Breach, New York, 1973)

L 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 which produce the same cosmological end; as well as grand unification, phase transitions due to supersymmetry or quantum gravity are included. Guth and Steinhardt give a non-technical review of the development and present standing of inflationary theories.

1 A. H. Guth and P. J. Steinhardt, Scientific American, May 1984, 116

(i) Some near misses

Although Guth's paper was undoubtedly the first complete exposition of what we now call inflation, some of the ideas in it had been scattered in the literature before, unconnected. Exponential expansion through the dominance of vacuum energy was noted in 1966 by Gliner, and later Gliner and Dymnikova proposed a cosmological model with a period of such expansion; they noticed the rapid increase in size of this universe, but did not grasp its significance. The closest of the near misses was probably by Kazanas, who pointed out that entropy generation could solve the homogeneity problem by increasing the horizon size far beyond the present Hubble radius. An interesting parallel development was the work by Englert and Gott on the creation of separate universes by some kind of quantum transition from a Minkowski or de Sitter initial state.

2 E. B. Gliner, Sov. Phys. J.E.T.P., 22, 378 (1966)

3 E. B. Gliner and I. G. Dymnikova, Sov. Astr. Lett., 1, 93 (1975)
4 D. Kazanas, Ap. J. Lett., 241, 59 (1980)
5 F. Englert, in Les Houches XXXII, p. 515
6 J. R. Gott III, in Inner Space/Outer Space

(ii) Inflation

Guth put together these ideas in his proposal of the inflationary Universe. He recognised that a strongly first order transition could solve a number of cosmological problems; although Kazanas had noticed that exponential expansion could vastly increase the causal scale of the Universe, Guth noted also that it would push the Universe towards flatness, or zero curvature. The model failed because, as Guth and Weinberg demonstrated, 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; here, the Higgs potential was chosen to be of such a form that a single bubble could inflate enough to encompass the whole of the present Universe.

7 A. H. Guth, Phys. Rev. D, 23, 347 (1981)
8 A. H. Guth and E. J. Weinberg, Phys. Rev. D, 23, 876 (1981) and Nucl. Phys. B, 212, 321 (1983)
9 A. D. Linde, Phys. Lett. B, 108, 389 (1982)
10 A. Albrecht and P. J. Steinhardt, Phys. Rev. Lett, 48, 1220 (1982)

(iii) Reheating

In the new inflationary universe, the Higgs field rolls down the potential slope towards the minimum, suffering frictional loss through particle creation as it does so. When the Higgs begins to oscillate in the potential well, there is a calculable 'reheating' temperature, related to the amplitude of these oscillations, and this temperature must be high enough that baryosynthesis can proceed, to create the matter content of the universe. A number of authors have analysed this problem, and found constraints on the Higgs potential and particle masses so that new inflation produces an acceptable baryon to photon ratio.

11 A. Albrecht, P. J. Steinhardt, M. S. Turner and F. Wilczek, Phys. Rev. Lett., 48, 1437 (1982)
12 A. D. Dolgov and A. D. Linde, Phys. Lett. B, 116, 327 (1982)
13 L. F. Abbott, E. Farhi and M. B. Wise, Phys. Lett. B, 117, 29 (1982)
14 A. Hosoya and M. Sakagama, Phys. Rev. D, 29, 2228 (1984)

(iv) 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 which lead to fluctuations in the density. Although the spectrum of these inhomogeneities is of the scale-free Zel'dovich form, popular for galaxy formation, their magnitude is much too large and would lead to a grossly non-uniform universe. Many people pointed this out, though Hawking and Bardeen, Steinhardt and Turner also suggested a possible remedy in using not a Coleman-Weinberg potential, but one of a different form predicted in some supersymmetric theories. Brandenberger gives a review of this technically complex subject.

15 S. W. Hawking, Phys. Lett. B, 115, 295 (1982)
16 A. H. Guth and S-Y. Pi, Phys. Rev. Lett., 49, 1110 (1982)
17 A. A. Starobinsky, Phys. Lett. B, 117, 175 (1982)
18 J. M. Bardeen, P. J. Steinhardt and M. S. Turner, Phys. Rev. D, 28, 679 (1983)
19 R. H. Brandenberger, Rev. Mod. Phys., 57, 1 (1985)

(v) New variations

Inventing a successful inflationary theory necessitates finding a physics model which can accommodate a Higgs potential with all the right properties; it must inflate, reheat, and not produce excessive fluctuations. Shafi and Vilenkin, and Pi, have added a special scalar, the inflaton, to grand unification, with the sole purpose of performing inflation. Ellis, Nanopoulous, Olive and collaborators have turned to supersymmetry and supergravity to provide the inflaton. Recent progress in inflationary universe models, especially in supergravity theories, is reviewed by Ovrut and Steinhardt, Srednicki and Holman in their contributions to Inner Space/Outer Space.

20 Q. Shafi and A. Vilenkin, Phys. Rev. Lett., 52, 691 (1984)
21 S-Y. Pi, Phys. Rev. Lett., 52, 1725 (1984)
22 J. Ellis, D. V. Nanopoulos, K. Olive and K. Tamvakis, Nucl. Phys. B, 221, 524 (1983)
23 D. V. Nanopoulos, K. Olive, M. Srednicki and K. Tamvakis, Phys. Lett. B, 123, 41 (1983)
24 D. V. Nanopoulos, K. Olive and M. Srednicki, Phys. Lett. B, 127, 30 (1983)
25 B. A. Ovrut and P. J. Steinhardt, in Inner Space/Outer Space
26 M. Srednicki, in Inner Space/Outer Space
27 R. Holman, in Inner Space/Outer Space

M 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. A review of some of the avenues of enquiry is by deWitt.

1 B. deWitt, Scientific American, December 1983, 112

(i) Particle creation

The attempt to use conventional quantum theory in curved spacetimes constitutes the semiclassical approach to quantum gravity, in which the aim is to retain the classical description of spacetime 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 (similarly to the way magnetic fields can create electron pairs). Parker was the first to analyse quantitatively how this happens, and Zel'dovich discussed whether particle creation can act as an effective viscosity to damp anisotropy. (In isotropic spacetimes, particle creation is largely absent, occurring only through the time dependence of the curvature, but in anisotropic spacetimes, with spatially varying curvature, particle creation can damp out the spatial variations). More elaborate recent calculations of the damping of anisotropy are by Fischetti, Hartle and Hu; it is not possible for semiclassical effects to remove completely arbitrary anisotropies, quashing the idea that Robertson-Walker universes could emerge from any initial conditions.

2 L. Parker, Phys. Rev. Lett., 21, 562 (1968) ; Phys. Rev., 183, 1057 (1969) ; Phys. Rev. D, 3, 346 (1971)
3 Ya. B. Zeldovich, Sov. Phys. J.E.T.P. Lett., 12, 307 (1970)
4 Ya. B. Zeldovich and A. A. Starobinski, Sov. Phys. J. E. T. P, 34, 1159 (1981); 26, 252 (1977)
5 M. Fischetti, J. B. Hartle and B-L. Hu, Phys. Rev. D, 20, 1757 (1979)
6 J. B. Hartle and B-L. Hu, Phys. Rev. D, 20, 1772 (1979); Phys. Rev. D, 21, 2756 (1979)
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(ii) 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 solar mass, the temperature is only 10^{-7}K, so for black holes of astrophysical origin, evaporation is quite negligible. However, it was suggested by Zel'dovich and Novikov, and again later by Hawking, that large density fluctuations in the early universe could collapse to form primordial black holes of very low mass. Any such black hole 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, as discussed by Novikov et al and by Lindley. Turner and Schramm (J.13), Turner, Barrow, and Lindley all consider cosmological models in which the evaporation of extremely small (near Planck mass) black holes is a source of particles of about 10^{15}GeV, whose decay creates a universal baryon number.

8 S. W. Hawking, Comm. Math. Phys., 43, 199 (1974); Nature, 248, 30 (1975)

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10 S. W. Hawking, Mon. Not. Roy. Astr. Soc., 152, 75 (1971)
11 I. D. Novikov, A. G. Polnarev, A. A. Starobinski and Ya. B. Zel'dovich, Astron. Astrophys, 80, 104 (1979)
12 D. Lindley, Mon. Not. Roy. Astr. Soc., 193, 593 (1980)
13 M. S. Turner, Phys. Lett. B, 89, 155 (1979)
14 J. D. Barrow, Mon. Not. Roy. Astr. Soc., 192, 427 (1980)
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(iii) Semi-classical cosmology

A more ambitious aim has been to apply the ideas of semiclassical gravity to cosmology as a whole. Starobinski has shown how quantum corrections to Einstein's equations make possible a de Sitter phase at and before the Planck time, while Hartle and Hawking have tried to derive a universal wave function from a cosmological Schroedinger equation; they also find that a de Sitter initial state seems to be favoured. 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.

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17 J. B. Hartle and S. W. Hawking, Phys. Rev. D, 28, 2960 (1983)
18 A. Vilenkin, Phys. Lett. B, 117, 25 (1982); Phys. Rev. D, 27, 2848 (1983); Phys. Rev. D, 30, 509 (1984)

(iv) 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, generalised 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.

Cosmological models in Kaluza-Klein theories, obtained simply from application of Einstein's equations on higher dimensions, have been studied by Chodos and Detweiler and by Freund. The contraction of the extra dimensions has been discussed by Sahdev, Kolb et al, and Abbott et al as a source of cosmological entropy to 'inflate' the universe in an unusual way.

19 T. Kaluza, Sitz. Preuss. Akad. Wiss. Berlin K, 966 (1921)
20 O. Klein, Z. Phys., 37, 895 (1926)
21 A. Chodos and S. Detweiler, Phys. Rev. D, 21, 2167 (1980)
22 P. G. O. Freund, Nucl. Phys. B, 209, 146 (1982)
23 D. Sahdev, Phys. Lett. B, 137, 155 (1984)
24 E. W. Kolb, D. Lindley and D. Seckel, Phys. Rev. D, 30, 1205 (1984)

25 R. B. Abbott, S. M. Barr and S. D. Ellis. Phys. Rev. D, 30, 720 (1984)

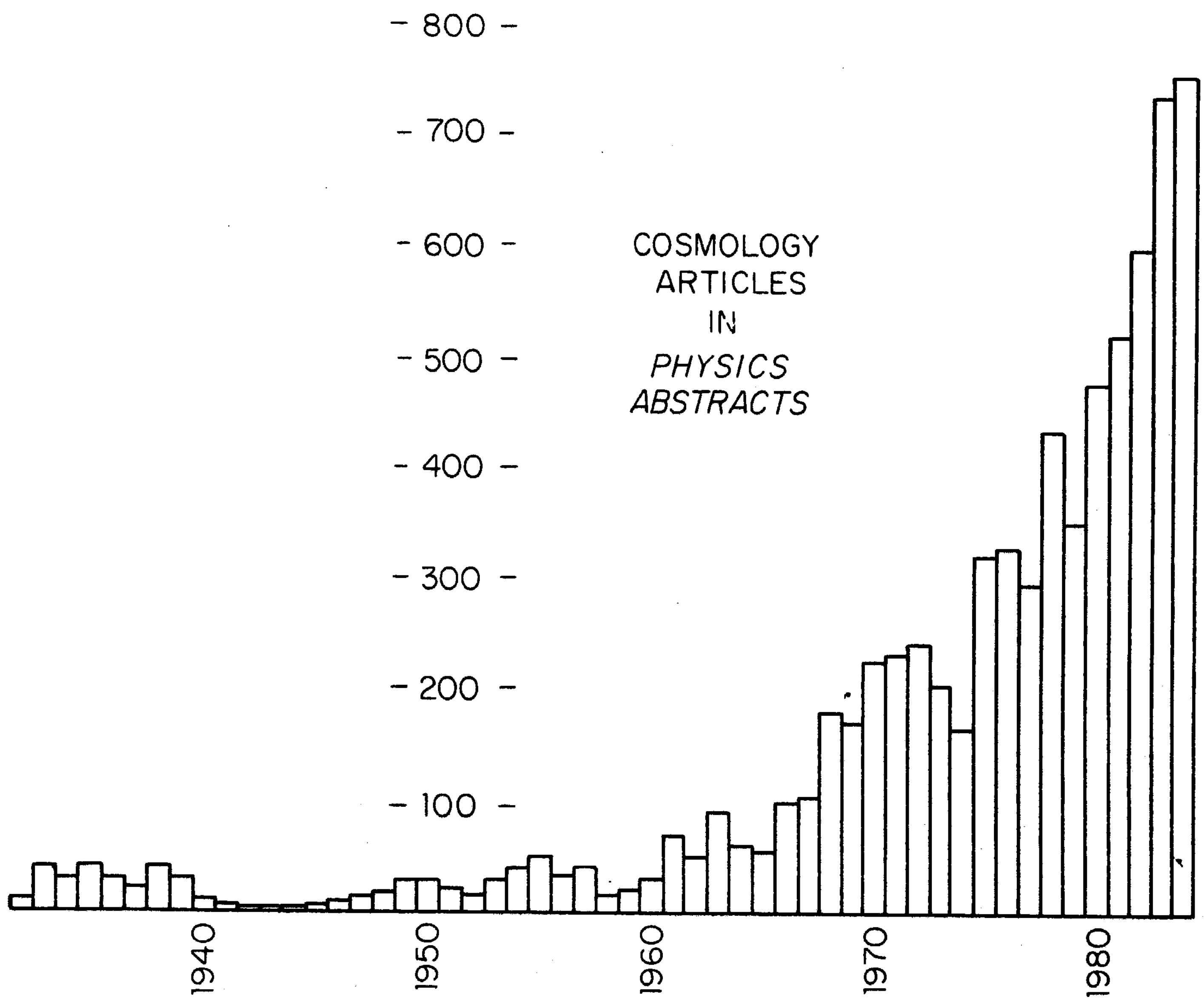
Another putative theory of quantum gravity, also living in extra dimensions, is the theory of superstrings. Superstrings are supposed to constitute the fundamental theory of all interactions, including gravity, and their theoretical appeal lies in their complete lack of infinities; all interactions should be calculable without renormalisation. 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. Their cosmological implications are tentative so far. The book by Schwarz gives basic ideas and mathematical formulations of such theories, while Green reviews the current position and future prospects. of the theory, and Kolb, Seckel and Turner discuss some possible remnants of the high energy theory which might inhabit our universe.

26 J. H. Schwarz, ed, **Superstrings: The First Fifteen Years**, two vols, (World Scientific Press, Singapore, 1985)
27 M. B. Green, Nature, 314, 409 (1985)
28 E. W. Kolb, D. Seckel and M. S. Turner, Nature, 314, 415 (1985)

Figure Captions

Figure 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 papers.

Figure 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.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1980

Figure 1

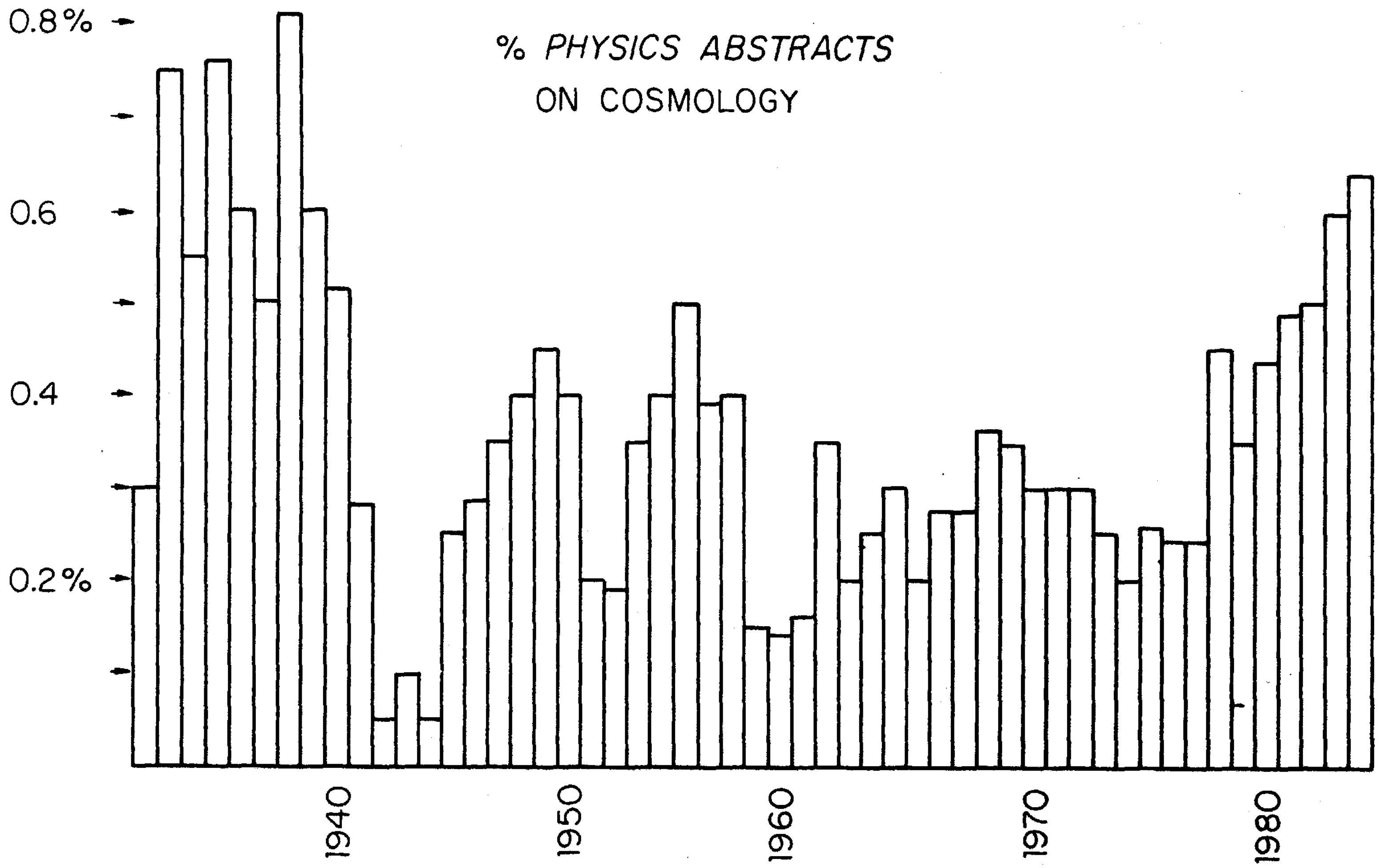
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Figure 2