Particle physics and cosmology

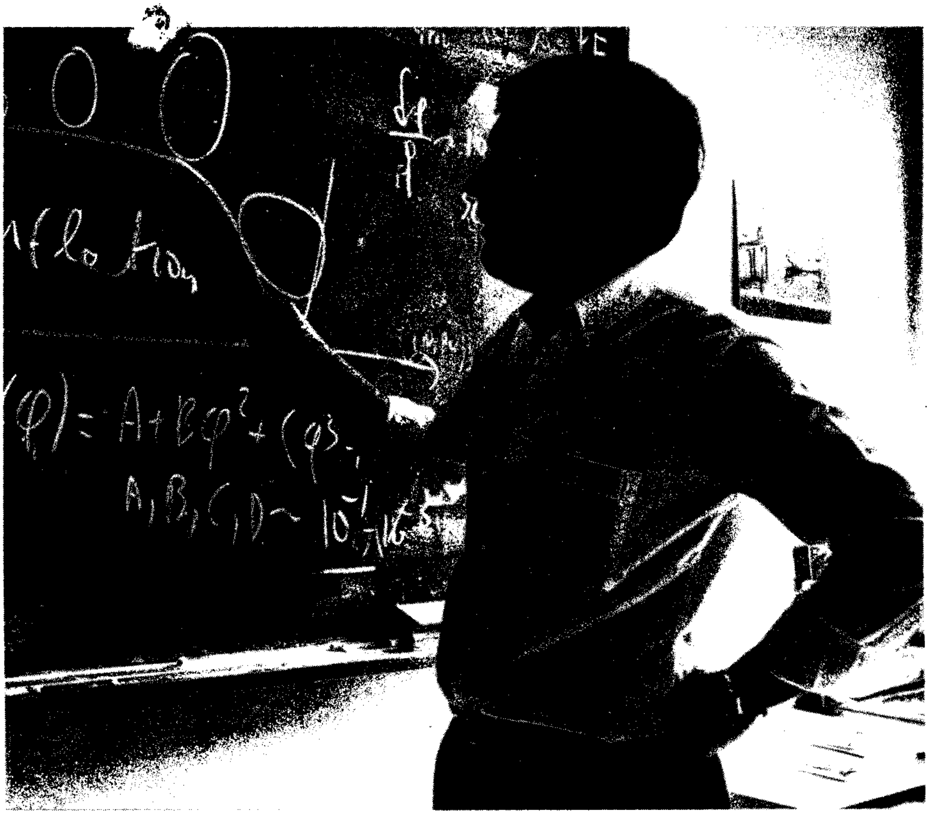
by John Ellis and Dimitri Nanopoulos

The reconciliation of particle physics — the study of the infinitesimally small — and cosmology — that of the infinitely large — is perhaps the ultimate problem that theoretical physicists can dare to attack. Some time ago (January/February 1981 issue, p. 3) we published distinguished cosmologist Stephen Hawking's view of particle physics. Here particle theorists John Ellis (presently at SLAC) and Dimitri Nanopoulos of CERN look through the other end of the telescope and describe how they see cosmology.

At first sight, one might think that these sciences of the very small and of the very large would have very little to say to each other. However, in the past few years the dialogue between particle physics and cosmology has been developing very rapidly. While some particle theorists are now very concerned about observations of light element abundances in distant gas clouds, cosmologists wait with bated breath to know the decay rate of the Z^0 boson. In this article we outline the reasons for this developing symbiosis between microphysics and macrophysics, and trace some of the development in this rapidly changing field.

This rapprochement has been speeded by recent progress within the disciplines of particle physics and cosmology. In the last few years both subjects have witnessed the establishment of a 'Standard Model'. In the case of particle physics this is the gauge theory of the strong, weak and electromagnetic interactions between quarks and leptons which combines Quantum Chromodynamics (QCD) and the Glashow-Salam-Weinberg model. While it describes successfully all data from

John Ellis



Dimitri Nanopoulos

elementary particle experiments, this Standard Model leaves many old questions unanswered and raises many new ones. How many quarks and leptons exist? Why do the masses of elementary particles take their observed values? Why are the strong interactions strong and the weak interactions weak? Theorists take many different directions in their speculative searches for answers to these and other questions. Common features of their speculations include the existence of light particles which are very weakly interacting and hence difficult to produce and detect in accelerator experiments, and the prediction of massive new particles whose production might require an accelerator costing more than the output of all the world's economy. It is natural that impatient theorists should turn for confirmation of their ideas to the only accelerator not subject to budgetary restrictions, namely the 'Big Bang.'

According to the standard Big Bang model of cosmology, one can extrapolate the present expanding Hubble flow of distant objects in the Universe backwards in time, to epochs when the matter in the Universe was much denser and hotter than it is today. Unless some new physics intervenes, this extrapolation may be valid all the way back to a 'Planck' epoch when the energies of the particles in the Universe were of order 10^{19} GeV, at which energies gravitational effects would be important. These energies are likely to have been attained for the first 10^{-43} seconds of the Big Bang, and the Universe would subsequently have cooled as it expanded. In addition to the present Hubble expansion, there are two important pieces of circumstantial evidence for the Big Bang model. One is the observation of the $3K$ microwave background radiation, which is generally believed to be the relic of an epoch when the Universe was over a thousand times smaller and hotter than it is today, and all matter was ionized. The photons in the microwave background are interpreted as relics that escaped when the Universe cooled out of this epoch and the ionized nuclei and electrons combined to form the neutral atoms which populate our familiar world. There is another piece of evidence that the Universe was once a

billion (10^9) times smaller and hotter than it is today. This is the observation that about ¼ of the matter in the Universe is in the form of helium 4, while only a few percent could have been manufactured in stars. It is generally accepted that this helium 4 was cooked up from neutron and proton ingredients by thermonuclear reactions in the first three minutes of the Big Bang, along with smaller amounts of other light nuclei. Although there is no direct experimental evidence for the validity of such a leap, these successes of the Big Bang model have encouraged physicists to extrapolate a billion billion (10^{18}) times further back into the Big Bang when typical particle energies were about 10^{15} GeV, almost as a matter of routine.

While the Big Bang theory is very successful, it leaves unanswered many questions and raises new ones. Why is the Universe so old and so large? The original density of the Universe must have been tuned very finely for it to have survived 10^{60} times longer than the Planck epoch and to have expanded to the size it has. Indeed, the Universe is still very 'flat' with a density close to the critical value which would cause it to collapse again in a 'Big Crunch'. Why is the Universe almost homogeneous and isotropic? Domains of the Universe which were causally separated in the past appear to have behaved identically, as inferred for example from the uniformity of the microwave background. On the other hand, where did the small perturbations originate which have led to galaxies and other structures in the Universe today? What was the origin of all the matter in the Universe? The visible matter in the Universe consists of about one proton or neutron for every 10^9 or 10^{10} photons, while there are apparently no large concentrations of antimatter. Is there concealed matter in the Universe in the form of light weakly interacting particle such as neutrinos? The Big Bang theory predicts that there should be about as many neutrinos as there are photons, in which case most of the mass of the Universe could be in the form of neutrinos if they weigh more than a few eV. Have neutrinos played an important role in the formation of structure in the Universe? Massive neutrinos or other light weakly interacting particles might have aided the growth of perturbations in the Universe, including galaxies themselves. How many species of light particle exist? The answer is relevant not only to theorists of galaxy formation but also to calculations of the cosmological nucleosynthesis of helium 4.

This recital of cosmological problems already reveals many important interfaces with particle physics, some of which do not require audacious extrapolations in time or energy. Calculations of cosmological nucleosynthesis are sensitive to the number of particle species weighing less than about 1 MeV, because their thermal energy density could have increased the expansion rate of the Universe during nucleosynthesis, and thereby increased the efficiency of helium 4 production. For this to be below the observational fraction of ¼ by mass, there should not have been more than three or at most four light neutrino-like species. We know already about the electron, muon and tau neutrinos, so there is not much room left. Particle physicists would dearly like this conclusion to be confirmed, as it would answer one of their fundamental questions about the number of quark and lepton species. Cosmology does much better than particle physics experiments in this regard, since the best present experimental limit on the number of neutrinos, coming from J/psi decay, is several hundred thousand! Forthcoming experiments in electron-positron annihilation and in the decay of heavy quark-antiquark bound states (upsilon particles) in particular could improve this limit, as could charged kaon decay experiments albeit with greater uncertainties. However, it may only be observations of the Z^0 decay rate into unobserved neutrals that can confirm the cosmological limit on the number of neutrinos.

Astrophysics at Fermilab

Several years ago, Fermilab, with the aid of David Schramm of the University of Chicago, began to forge closer links with astrophysicists and thereby celebrate the intellectual unity of particle physics and the cosmological origins of creation. For the past year, there has been an active astrophysics seminar, with many astrophysicists visiting the Laboratory for extended stays. All these efforts have now culminated in the establishment of an astrophysics group at the Laboratory.

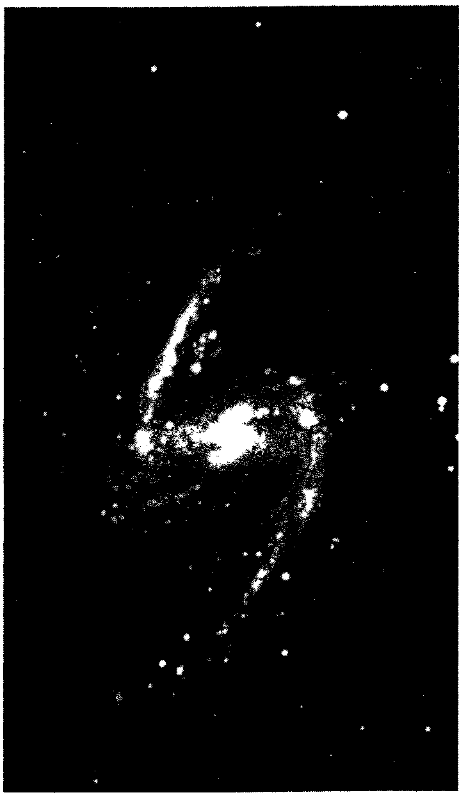
This was the result of a successful application to NASA for a grant to fund such a group. (The particle physics research at Fermilab is supported by the US Department of Energy.) In September, four astro-particle physicists will be in residence at the Laboratory — Edward (Rocky) Kolb, Michael Turner, Keith Olive, and David Seckel, with Schramm continuing to be present several days a week. Alex Szalay will be joining the group in June 1984. The group is preparing a workshop — 'Inner Space — Outer Space', to be run next Spring. Office space for the new group is being prepared adjacent to the existing Fermilab theory area.

Neutrinos lighter than 1 MeV would have had difficulty decaying or annihilating after nucleosynthesis without messing up astrophysical or cosmological observations such as that of the microwave background radiation. If they are indeed stable, their masses must be less than about 100 eV, or else their mass density would exceed observational limits on the density of the Universe. Since the best experimental limits on the muon neutrino and tau neutrino masses are about 300 keV and 200 MeV respectively, this cosmological limit is quite an advance! Recently there have been indications that the electron neutrino may weigh about 30 eV. If so, it would have profound cosmological implications. Neutrinos would be the dominant form of matter in the Universe, and their gravitational perturbations could have been the precursors of galaxy formation. They might enable some theories of galaxy formation to be reconciled with the smoothness of the microwave background radiation. These 'adiabatic' perturbation theories in which matter and radiation vary together are those favoured by the grand unified theories of baryosynthesis which we will meet later. In the absence of massive neutrinos they would be disfavoured by comparison with 'isothermal' perturbations according to which the microwave background is naturally smoother. Some recent astrophysical observations can be interpreted as favouring the model of adiabatic perturbations with massive neutrinos, according to which galaxies should be arranged in 'pancakes' and 'strings'. Particle physicists are not the only ones anxious to hear news about neutrino masses from new experiments, such as those using the low energy neutrino beam at CERN.

There may be other light neutral weakly interacting particles cluttering up the Universe. Many theories based on supersymmetry predict the existence of light neutral gravitinos, photinos and 'shiggses', the supersymmetric partners of gravitons, photons and Higgs bosons respectively. These might have been less copious than neutrinos during nucleosynthesis and at the present day, and could weigh up to 1 keV. In this case they would have aided the formation of individual galaxies and might be responsible for missing mass on galactic scales. Stable neutral particles weighing more than a few GeV are also compatible with cosmology, since most of them would have annihilated before cosmological nucleosynthesis. Evidence for such heavier neutral particles can be searched for at the CERN proton-antiproton collider and in electron-positron annihilation.

So far we have mainly discussed interfaces between particle physics and cosmology involving epochs of the Big Bang for which there is observational evidence. Now we will start extrapolating back before cosmological nucleosynthesis. When the Universe was about 10^{12} times smaller and hotter than it is today, it is believed to have made the transition from a plasma of quarks and gluons to the familiar hadrons. It is possible that perturbations and shock waves generated during this transition may have triggered the formation of galaxies. Experiments on the quark-hadron phase transition would therefore be very interesting for cosmologists as well as to astrophysicists speculating about the existence of 'quark stars'. Such experiments may be feasible with future heavy-ion accelerators.

Extrapolating two or three orders of magnitude further back, we come to the epoch when the Glashow-Salam-Weinberg unified gauge theory of the weak interactions made the transition to the low energy and temperature broken phase that we know today. Before this epoch, the Standard Model of elementary particles would have been an exact symmetry, and further extrapolation necessarily involves speculation about further stages in the unification of the fundamental particle interactions. We have already mentioned the possibility of supersymmetry. Many of the most interesting ideas about the fundamental cosmological problems introduced earlier involve speculations about the grand unification of the strong, weak and electromagnetic interactions.



The Standard Model is unsatisfactory because of its untidy structure with three independent gauge group factors: $SU(3) \times SU(2) \times U(1)$, each with its own gauge coupling. Ultimately one would like a theory with a universal gauge coupling. There are many other aspects of particle physics which are not explained within the Standard Model. For example, why the electric charges of the electron and proton are equal and opposite to one part in 10^{20}, as is evidenced by the undetectability of electrostatic attractions or repulsion between different galaxies. Also, the Standard Model gives no hint of a connection between quarks and leptons, which is suggested by their appearance in three or more generations of particles with similar masses. At first sight, the unification of strong and weak interactions looks very difficult because the magnitudes of their couplings are so different. However, the renormalization group has enabled particle theorists to calculate how these couplings vary with the energy of the experiment in which they are measured. Since they change logarithmically with the energy scale, the energy at which the strong and weak couplings would come together if no new physics intervenes is astronomically high, namely about 10^{15} GeV. Fortunately, this energy scale is significantly less than the Planck scale of 10^{19} GeV at which quantum gravity effects become important, so it might be possible to neglect gravity in a first attempt at unifying the strong, weak and electromagnetic interactions. The simplest such grand unified theories (GUTs) are based on the symmetry group SU(5).

In all such theories, the embedding of the electric charge in a non-Abelian group implies that charges are quantized, and hence that the charges of the electron and proton are exactly equal and opposite. This step also implies the existence of magnetic monopoles, of which more anon. The weak neutral current mixing parameter (the Weinberg angle) is calculable in GUTs, and the prediction of simple models agrees with the experimental data. Quarks and leptons are arranged in common multiplets of the GUT group, which implies relations between the quark and lepton masses. For example, if there are only six quarks, the tau lepton mass of about 1.8 GeV implies a beauty quark mass of about 5 GeV in minimal GUTs, in agreement with experiment. Thus GUTters have a stake in the cosmologists' suggestion that there may only be three neutrinos and hence three generations containing only six quarks. Since GUTs put quarks and leptons into the same multiplet, they expect new interactions to cause quark-lepton transitions which can lead to baryon decay. In the simplest models, the dominant nucleon decay modes are expected to give a positron and a pion, with a lifetime of order 10^{30} years. A recent experiment has not yet found this decay mode, but GUTters are not disheartened since in supersymmetric GUTs the most natural prediction is antineutrino and a kaon, a mode which has not yet been examined exhaustively.

When we apply GUTs to cosmology we must extrapolate back to an epoch 10^{18} times hotter than that of nucleosynthesis. What do we find there? When a poetess hears that all matter should decay, she wonders how it was born. GUTs enable quarks and hence baryonic matter to be synthesized in preference to antimatter in a natural realization of an idea due to Sakharov. Interactions which violate baryon number conservation, as well as charge conjugation and charge-parity conservation, can take an initially symmetric Universe into a state with more matter than antimatter as soon as they drop out of thermal equilibrium. A natural GUT scenario is the out-of-equilibrium decays of superheavy GUT bosons or fermions. The synthesis of a quark asymmetry does not work if the GUT scale is much less than about 10^{14} GeV. Around the time of the quark-hadron phase transition, all the antiquarks will be annihilated by quarks to form mesons, photons and leptons, and the small surplus of matter survives to become the matter visible in the Universe today. It is natural to speculate whether the required charge-parity violation may be related to that observed in the neutral kaons, but this seems unlikely. However, many GUTs which predict a large enough matter-antimatter asymmetry also predict that the neutron electric dipole moment may be large enough to be observed soon.

First ESO-CERN Symposium

Another example of the growing collaboration between particle physicists and cosmologists is the organization this year of the first European Southern Observatory (ESO) — CERN symposium on the large scale structure of the universe, cosmology and fundamental physics. It will be held at CERN from 21-25 November. Among the highlights and scheduled list of speakers are (some details are still provisional) — electroweak unification by P. Darriulat of CERN, unified field theories by P. Fayet of Paris, experimental tests of unified field theories by E. Fiorini of Milan and G. Giacomelli of Bologna, dynamical parameters of the universe by S. Faber of Santa Cruz, clusters by J. Oort of Leiden, galaxy formation by Ya. Zeldovich of Moscow, neutrinos by R. Mössbauer, nucleosynthesis by J. Audouze of Paris, observational evidence for the evolution of the universe by L. Woltjer of ESO, unified field theories and the early universe by A. Linde of Moscow, and quantum gravity by S. Hawking of Cambridge, together with an introduction by D. Sciama of Oxford and Trieste, and concluding talks by J. Ellis of SLAC and M. Rees of Cambridge.

The aim of the symposium is to establish the status of knowledge and to provide a forum for interdisciplinary discussion. Equal time will be given to formal lectures and to general discussion on each topic. A distinguished list of Chairmen and discussion leaders is being drawn up.

The audience will be composed of about equal numbers of astrophysicists and particle physicists, and will be limited to about 150. Participation is by invitation only, and those definitely interested in participating should write to one of the chairmen of the organizing committee before 31 July — Prof. G. Setti, ESO, Karl-Schwarzschildstrasse 2, D-8046 Garching b. München, West Germany; Prof. L. van Hove, CERN, Theory Division, 1211 Geneva 23, Switzerland.

This was some cosmological good news from GUTs, and now comes some bad news. The grand unified monopoles are a great embarrassment, since conventional Big Bang cosmology makes it difficult to understand how less than one monopole could have been created in every causally connected volume during the GUT era. Since monopoles do not annihilate very efficiently, this suggests there should be many more monopoles around today than are allowed by limits on the mass density in the Universe and by the persistence of galactic magnetic fields. Furthermore, it has recently been discovered that grand unified monopoles may catalyze baryon decay at a fierce rate which is incompatible with observations of neutron stars unless the monopole flux is very low. This monopole problem helped set theorists thinking about cosmological inflation.

The breaking of GUT symmetry at a temperature of about 10^{15} GeV occurs through a phase transition. It is possible that the cooling Universe might have stuck in a false vacuum with large energy and supercooled. The vacuum energy would have caused the Universe to expand exponentially in a De Sitter phase until the phase transition was completed. This exponential expansion could have explained the present large size of the Universe, as well as why it is almost flat, with a mass density very close to that required to terminate the expansion with an eventual Big Crunch. Unfortunately, in the original version of this inflationary Universe it was difficult to understand how the phase transition could be completed in an orderly way with few inhomogeneities and monopoles.

However, it was subsequently realized that if the GUT Higgs potential were quite flat, each bubble of the true vacuum would expand exponentially after it was formed. Sufficient expansion would mean that our entire Universe could have originated from a single bubble, and that the closest monopole would probably be more than 10^{10} light years away. At first it seemed likely that such a bubble Universe would be very flat, homogeneous and isotropic, much like the surface of a balloon that has been inflated. When theorists studied the spectrum of perturbations in such a new inflationary Universe, they discovered that they were almost independent of distance scale, as is favoured by astrophysical observations. Unfortunately, the magnitude of the perturbations was much too large. Furthermore, making the GUT Higgs potential flat enough for inflation required a fine tuning of parameters which is unnatural in conventional GUTs.

Both of these problems can be avoided in supersymmetric theories which allow the magnitude of the perturbations and the flatness of the potential to be adjusted at will. Although these adjustments are technically feasible, they become progressively more precise as the temperature of the phase transition falls further below 10^{19} GeV. For this reason, it is interesting to consider the possibility of primordial inflation occurring before the GUT phase transition, in which case monopoles may not be much rarer than the present astrophysical limits. Further development of the primordial inflation scenario requires tackling gravity, which is another long adventure.

This is the time to end our study of particle physics and cosmology. We see that it is a vigorous field which is rapidly developing. Many particle theories can only be tested by the Great Accelerator in the Sky, and many cosmologists anxiously await data from particle physics experiments. The dialogue between the very large and the very small will continue to enthral us in the future.