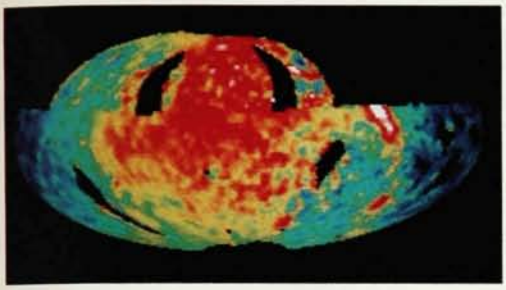
Microwave map of the sky made by a balloon-borne radiometer shows the dipole distribution of the microwave background radiation. The dynamic range is 10 mK and the angular resolution about 7°.



Gravitation, cosmology and cosmic-ray physics

In 1982 the Astronomy Survey Committee, under the direction of George Field, published *Astronomy and Astrophysics in the 1980s* (see PHYSICS TODAY, April 1982, page 96, and November 1982, page 25), a report similar in purpose to the current Brinkman report. Gravitation, cosmology and cosmic-ray physics were then, properly, considered as subfields of astrophysics. But these three fields, because they are concerned with the nature of the fundamental forces and constituents of matter, are also of direct interest to physicists. For this reason one volume of the Brinkman report is devoted to recounting the achievements in and identifying goals for the related fields of gravitation, cosmology and cosmic-ray physics.

Gravitation. In the last two decades gravitational physics has been transformed from a largely theoretical science to one in which meaningful experiments can be performed. Technological advances, particularly in radio- and radar astronomy, and the development of precision tracking capabilities for solar-system spacecraft have made experimental tests of the predictions of competing theories of gravity possible.

A cornerstone of Einstein's theory of gravitation is the principle of equivalence, which states that locally, gravitation and acceleration are equivalent. This implies that gravitational and inertial mass are equivalent. This equivalence has been repeatedly tested, with torsion balances for laboratory masses and by observations of the Earth–Moon–Sun system with the aid of accurate laser ranging of the Earth–Moon distance. With Earth-based experiments no violations of the equivalence principle have been observed to 1 part in 10^{11} for a variety of substances. When flown in Earth orbit such experiments should reach an accuracy of 1 part in 10^{15}.

Gravitational theory predicts that the propagation time of a radio signal between any two points is lengthened by the presence of mass near the signal path. By measuring the round-trip times of radio signals that graze the Sun as they travel from the Earth to the Viking Lander on the surface of Mars, experimenters have found agreement with the prediction to an accuracy of 0.1%.

All tests so far performed in the laboratory and the solar system confirm Einstein's original theory of gravity. These tests have all been of static aspects of Einstein's theory; predictions regarding moving masses, such as gravitational radiation and inertial-frame-dragging effects, have yet to be directly observed. But in both areas important strides have recently been made.

Gravitational radiation produced by astrophysical sources has to date proved too weak to be detected by existing experiments. Acoustic bar detectors, which measure the tiny deformation of a massive "Weber bar" when a gravity wave passes, are currently the most sensitive detectors in the world. However, laser interferometric detectors, which measure the time delay between two beams of light induced by a passing gravity wave, promise to exceed the sensitivity of bar detectors by several orders of magnitude. Plans for a pair of interferometers 5 km on a side are currently at an advanced stage.

Searches for still more subtle gravitational effects are planned. One such effect arises from an important but untested aspect of gravitation analogous to magnetism. Einstein's theory predicts that even in the absence of external torques a gyroscope orbiting the Earth will precess. The effect is extremely small, amounting to about 0.044 arcseconds/year, but should just be detectable. NASA's Relativity Gyroscope Experiment, which will search for this effect, will be by far the most technically advanced experiment to be performed in space. Plans are to fly an engineering test model of the experiment in the relatively low-g space shuttle. If this succeeds the instrument will be flown in a free-flying spacecraft to obtain ultra-low g.

Despite experimental advances, general relativity is still primarily a theoretical science. Some of the impressive theoretical results of the past decades include solutions to the Einstein equation for charged, rotating black holes; quantum "evaporation" of black holes; and proof that all solutions to the Einstein equation have positive energy. Numerical techniques have been used to study such things as the collision of black holes and gravitational collapse. Computers are also being used increasingly to help perform the intricate algebra of general relativity. The development of supercomputers and their availability to researchers will play an increasingly important role in research

Panel on Gravitation, Cosmology and Cosmic-Ray Physics

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Relativity Gyroscope Experiment, to be flown in polar orbit, will test the unexplored magnetismlike effects predicted by general relativity.

on certain important problems in gravitational theory.

Cosmology. Advances in the ability to observe the universe as it now is and as it was in the remote past have, over the past two decades, created a revolution in cosmology. Observational evidence such as the Hubble expansion and the existence of a cosmic background of 3-K blackbody radiation strongly supports Big Bang cosmology. Light nuclei, relics of the Big Bang, give another important handle on the quantitative aspects of the cosmological model.

A few minutes after the origin of the universe conditions were appropriate for the fusion of protons and neutrons to form light elements. The present abundance of these elements reflects the baryon density and the expansion rate at that early epoch. The abundance of He^4 can be calculated from the standard cosmological model, and this number is in good agreement with the abundance of He^4 in the Sun. Moreover, the agreement depends strongly on there being only a small number of species of neutrinos. This has important implications for particle physics.

In fact the connection between cosmology and elementary-particle physics has gotten closer in recent years. One of the most intriguing cosmological models, the inflationary universe, is based on notions from elementary-particle physics. Attempts have been made to explain the dominance of matter over antimatter in the universe in terms of grand unified theories. Elementary-particle theorists believe that at the extreme energy density of the early universe the fundamental symmetry of the universe is restored; cosmology provides a possible means of testing this idea.

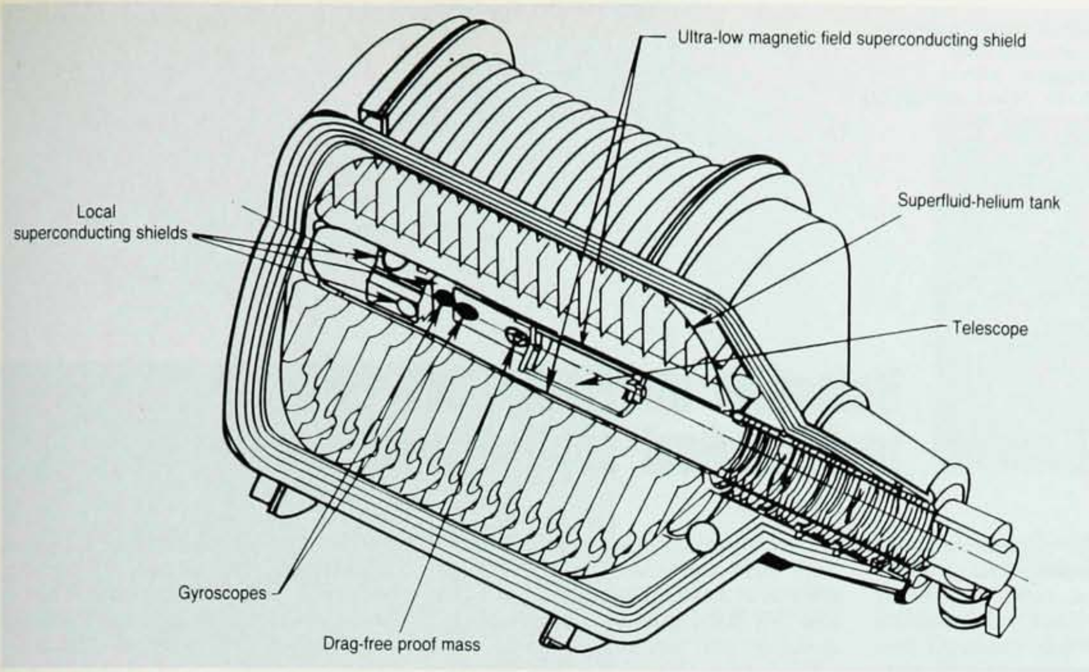
Cosmologists have long been puzzled by indications that most of the matter in the universe is invisible. Evidence for this comes from the observation that the gravitational field of visible matter cannot account for the virial motion of galaxies in clusters or the rotation of outer parts of galaxies. Currently fashionable theories of particle physics provide candidates for these particles, such as heavy neutrinos and axions. Cosmological considerations place constraints on these theories: Relic particles must be sufficiently abundant today to bind the galaxies and must have become nonrelativistic for gravitational clumping to have taken place.

Cosmology is a science starved for data. Observations from astronomical satellites have brilliantly demonstrated that the deeper exploration of space in many spectral regions holds great potential for making discoveries, solving old problems and raising important new questions. Cosmologists are eagerly awaiting observations from a variety of Earth-orbiting satellites in the coming decade. A broad slice of the electromagnetic spectrum will be covered by the proposed missions: the Gamma Ray Observatory, the Advanced X-Ray Astrophysics Facility, the Hubble Space Telescope, the Shuttle Infrared Telescope Facility, the Cosmic Background Explorer and the Large Deployable Reflector as well as an antenna in space to extend the Very Long Baseline Array.

Of prime importance to cosmologists is the Hubble Space Telescope, whose high spatial resolution (better than 0.1 arcseconds) and broad spectral coverage make it an ideal instrument for determining the extragalactic distance scale and thus the Hubble constant. Detailed observations of nearby and distant galaxies will lead to better understanding of the physical properties of galaxies, including their evolution. The Hubble Space Telescope's spectrometers, by operating at ultraviolet wavelengths (inaccessible from the ground), will be able to probe the thermal history of the intergalactic medium, which has been strongly influenced by the formation of structure in the universe.

The study of cosmology is currently carried out by a diverse group of scientists, including astrophysicists, astronomers, relativists, particle physicists, nuclear physicists and plasma physicists. This diversity, the panel points out, is good for cosmology, which must draw on a wide range of physics. However, as interest in the field intensifies and more cosmology-oriented research groups form, the need for coordinated funding is becoming apparent. The panel encourages NSF to consider how it might help solve this growing problem.

Cosmic-ray physics. The emphasis of cosmic-ray studies has shifted in recent years from investigations of cosmic rays produced by collisions in the upper atmosphere to the compositions and energy spectra of the primary parti-



cles—the atomic nuclei and electrons that cause the atmospheric showers and are our only direct sample of matter from beyond the solar system.

The material that makes up the solar system represents the local interstellar medium as it was approximately 4.6 billion years ago. Cosmic rays are much younger, having been accelerated only about 10 million years ago. Recent observations suggest that cosmic rays may actually represent a more typical sample of the average interstellar medium than does the solar-system material, which may have been contaminated by a nearby supernova explosion. Understanding the differences between the compositions of cosmic rays and of solar-system material is a difficult problem that will require better experimental data, a more complete understanding of the processes by which cosmic rays are accelerated and possibly new scenarios of nucleosynthesis. At energies above 10^{14}–10^{15} eV galactic acceleration and containment mechanisms begin to fail. Nevertheless the measured spectrum of cosmic rays extends to 10^{20} eV. Cosmic rays of such high energies might come from the local supercluster of galaxies, or they might come from our galaxy, bent back to the galactic plane by the still unknown magnetic fields of the galactic halo. Whatever their origin, these ultra-high-energy cosmic rays are significant probes of cosmology and astrophysics as well as an important bridge to high-energy particle physics. Because the flux of cosmic rays at these energies is very low, they cannot be studied with the relatively small detectors available in spacecraft and balloons. Large, ground-based instruments are currently used to study these cosmic rays, but the method has severe drawbacks. Only the shower of secondary cosmic rays produced when the primaries interact in the upper atmosphere can be studied at the Earth's surface. Working backward from the secondaries to the primaries involves inferring the identity of the primary cosmic ray and extrapolating the interacting processes studied in the laboratory to the much higher energies being studied.

The most ambitious experiment in the US to detect cosmic-ray air showers is the Fly's Eye experiment being carried out in Utah. Extensive air showers of cosmic rays produce scintillation of light in the upper atmosphere. Two arrays of detectors, 5 kilometers apart, detect this light and provide enough data for complete reconstruction of the air shower.

The panel gives highest priority in ground-based cosmic-ray physics to programs in gamma-ray astronomy. They particularly stress continued support for the Fly's Eye and its improvements as well as for studies of complementary surface detectors such as muon counters and scintillation-counting air-shower detectors. They also recommend that funding be sought for detectors for neutrino astronomy if their feasibility and cost effectiveness can be clearly established. Searches for monopoles, the panel says, should be pursued with detectors at least 1000 m^2 in area. Existing underground experiments designed to search for proton decay should be explored as muon and neutrino detectors.

Space-based experiments, however, are the heart of observational cosmic-ray physics. The panel recommends two major new programs. The first, to which it gives highest priority, is the development of the Superconducting Magnet Spectrometer Facility for the space station, which will be capable of conducting a wide variety of measurements on the energetic galactic particles above 1 GeV. The second program is the Cosmic-Ray Composition Explorer, essentially the Explorer described in the astronomy survey committee's recommendations. The panel hopes that in these future plans, as in past programs, there will be a significant degree of international cooperation.

With the establishment of a space station, the assembly of very large instruments in space will be possible. The panel believes that this opens up important new opportunities for cosmic-ray physics. It identifies three experiments that could be constructed using the space station: a large detector array to detect high-energy cosmic rays, a large electronic detector to study hundreds of the rarest actinide nuclei and determine their energy spectra, and a down-looking detector that will observe the atmospheric scintillation from air showers of the highest-energy cosmic rays. It also recommends that a study be made of the possibility of sending an advanced set of instruments out beyond the influence of the Sun, to at least 100 astronomical units.

—Bruce Schechter □