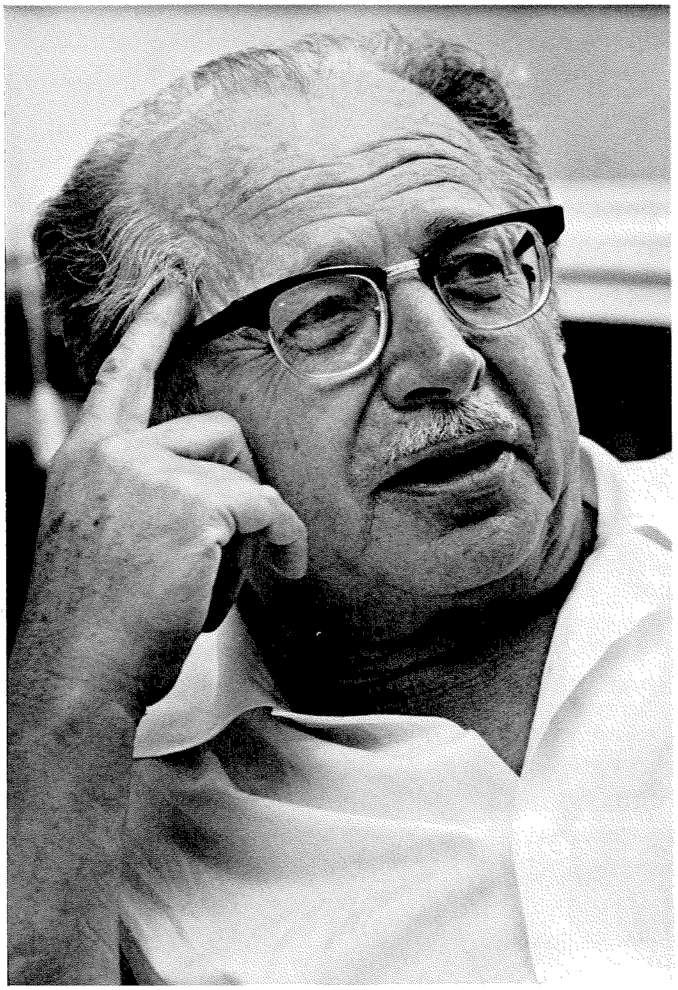


Jesse Greenstein, Lee A. DuBridge Professor of Astrophysics and staff member of the Hale Observatories and Owens Valley Radio Observatory, was chairman of the Astronomy Survey Committee which spent two years formulating a ten-year plan for the future of astronomy.

The Future of Astronomy

by Jesse Greenstein

After their startling discoveries of the last ten years, astronomers have come to realize that the actual universe is much stranger than science fiction.

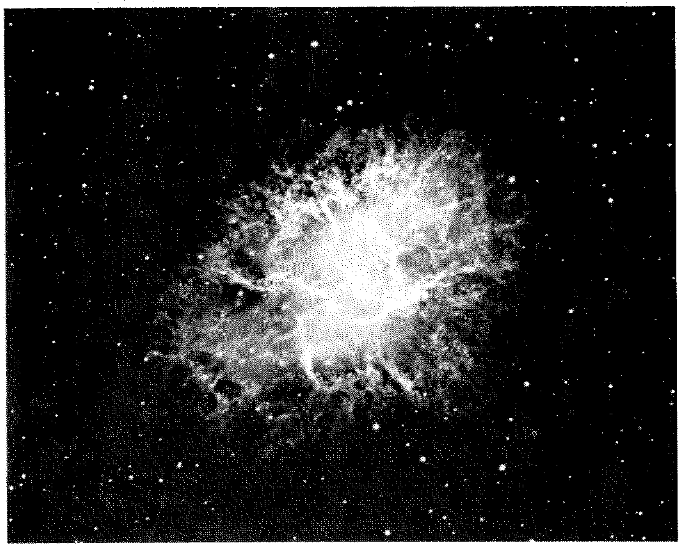
As in the age of Galileo, we are suddenly confronted with a new view of the universe. Instead of the sedate cosmos in which we thought we lived, we are in the midst of general cosmic violence—exploding galaxies and quasars, high-energy particles, magnetic fields—violence that suggests energy-releasing events like relativistic collapse, and other effects of the general theory of relativity.

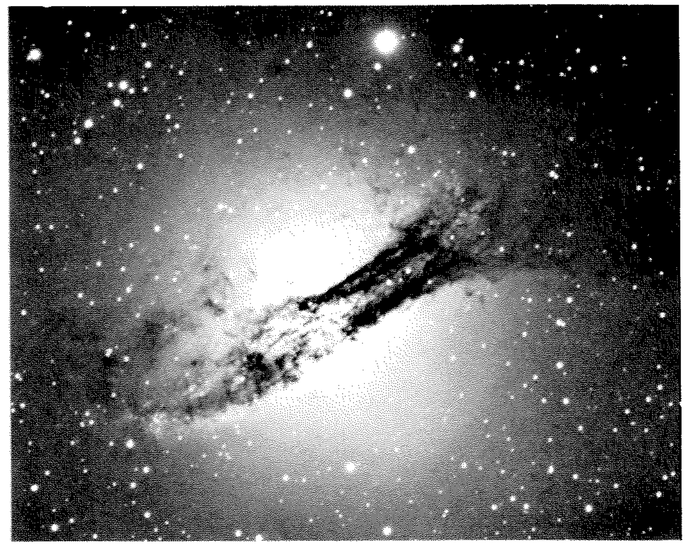
But the discoveries that have given us this new view of the universe have provided few answers—and raised many questions:

- ☐ Where do matter and energy come from?
- ☐ Are there forces and energies at work that we have not yet discovered?
- ☐ How long will the sun shine and the earth survive?
- ☐ How many other "earths" are there, and are any of them habitable or inhabited?
- ☐ What further strange new types of objects does the universe hold?
- ☐ What was it like at the beginning of time, 10 or 15 billion years ago?
- ☐ Does time stretch backward forever, or was there a beginning?

To define the possible ways to answer these questions, an Astronomy Survey Committee was set up in 1969 by the Committee on Science and Public Policy of the National Academy of Sciences. It was directed to formulate for the government, and for scientists, a ten-year plan for the future of astronomy.

After two years of work the 23 members of the committee—and more than 100 members of an advisory panel—completed a two-volume survey. The first volume, *Astronomy and Astrophysics for the Seventies*, published this spring, outlines the main areas in astronomy that should be pursued more actively:





Cosmology
Quasars and Exploding Galaxies
Studies of the Sun
Stellar Evolution
The Evolution of Molecules, Planets, and Life
Exobiology

Not everyone will want to read the detailed discussion of each of these subjects—or have access to the report. But the background information and recommendations it contains are of great importance to the future development of astronomy and astrophysics in the United States—and at Caltech. With this in mind, I offer these highlights.

COSMOLOGY

It is now generally believed that about 10 or 15 billion years ago a cosmic "big bang" flung all matter outward at tremendous speed. After the first few minutes, in which only radiation existed, the cosmic fireball cooled down enough to permit nuclear reactions to fuse part of the original hydrogen to helium—in about the same amount that is observed in all galaxies today.

After about 100,000 years the gas, which was largely hydrogen and helium, cooled to about 3,000 degrees above absolute zero. All that is left today of the residual energy from this primordial fireball is a pervasive cosmic background radiation, present even in the emptiest reaches of space. The intensity of this radiation, which is observed by radio telescopes in the long wavelengths, is roughly equal to a temperature of about 2.7 degrees above absolute zero.

As the gas continued to cool, it gathered together to form groups of galaxies—and in a small group our own Milky Way was formed. Some of these galaxies had violent internal explosions. By looking at the very edge of the observable universe with radio telescopes—in effect, looking back in time—we can now detect those events as quasars and radio galaxies.

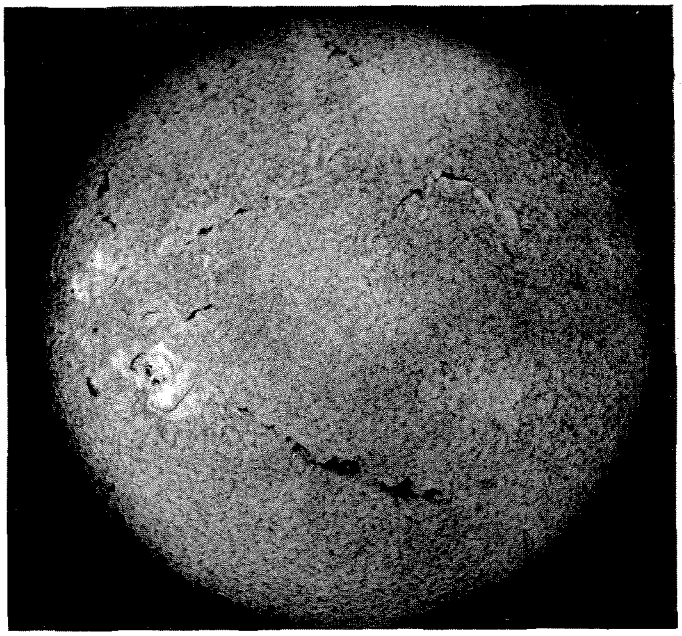
As each galaxy settled down, generations of stars were born—including the sun. Countless planets came into being. Life eventually emerged on earth—and perhaps also on other planets that had water and an atmosphere.

To some critics, the available data on the prevalence of violence suggest much more radical cosmologies than this one—which may indeed have many flaws. Even its main concepts might be erroneous, in fact, if some type of new physics is required to understand this entire universe. In any case, it will be a major task for astronomy in the next decade to test this broad picture of the evolution of the universe at every point.

QUASARS AND EXPLODING GALAXIES

The picture of an expanding, explosive universe, developed by astronomers in the 1960's and early 1970's, is largely the result of the advent of radio astronomy, the discovery of quasars, and the closer optical examination of many strange galaxies. Quasars, the brightest and probably most distant of all known objects in the universe, emit energy in amounts far out of proportion to their apparent size. They also appear to eject matter at very high velocities—bubbles traveling up to 62,000 miles a second (one-third the speed of light). Many galaxies have energetic explosions that are equally unbelievable. Something like 2 to 5 percent of all the galaxies in the observable universe show evidence of explosions, violent events, and excessive infrared radiation in their nuclei. Though such super explosions seem to be confined to quasars, the nuclei of quasar-like Seyfert galaxies, disturbed radio galaxies, and even "normal" galaxies like our own Milky Way, show evidence for the ejection of matter from their nuclei on a smaller scale and at lower speed.

When galaxies go through the stage in which violent events occur, lasting about 100 million years, they may eject enough matter to equal the mass of a small or possibly even a normal galaxy. Is new matter being created in the nuclei of exploding systems? That would be "new physics" indeed.



During a ten-day period starting last August 2, a series of gigantic eruptions took place on the sun. Photographs taken at the Big Bear Solar Observatory revealed a great flare cloud about 100,000 miles long, which spewed electrons and protons across the solar system and caused some of the worst magnetic storms on earth in recent years. The origin and nature of solar flares is one of the subjects slated for intensive study over the next decade.

What mechanism is responsible for the ejection of such a seemingly inexhaustible supply of matter? What role does the nucleus of a galaxy play in its evolution? Is it some strange massive object whose physics is only dimly understood? Could it be that all the matter of a galaxy is ejected from its nucleus, and that, as a galaxy ages, the explosive capability of the nucleus dies?

Further studies of quasars, the nuclei of expanding and normal galaxies, and of supernovae, will not only tax the ingenuity of the theoreticians dealing with new and unexpected states of matter; they will also require significantly greater observational effort with the largest telescopes, using the most sophisticated electro-optical technology.

THE SUN

Because the sun is the closest star to us, we can study it in greater detail than any other star. In the last decade, the opening up of the extreme ultraviolet and X-ray regions of the solar spectrum by rocket and satellite observations has provided important new advances in solar research.

The solar corona is where mechanical energy—generated just below the surface of the outer layer of the sun—is deposited, in the form of steady heating and in violent events such as solar flares. The dominant emissions of the solar corona appear in the invisible regions of the spectrum, and abundance determinations of the elements in the solar spectrum—verified by analysis of the solar radiation—have given us a tool for a similar analysis of elements in stellar spectra. Such information about a star allows us (provided we know the stellar mass and radius) to determine the energy production in the star's nuclear furnace and to predict the star's future.

Observations of the solar chromosphere, solar flares, and magnetic fields have stimulated the search for these phenomena in the stars. Analogs have been found, since in some stars the same effects are present on a much greater scale. A light and radio stellar flare detected on a nearby star was a million times more intense than any on the sun.

Measurements from satellites, particularly the Orbiting Solar Observatory (OSO) series, permit study of rapid events and slow variations of radiation over periods up to a year, adding immeasurably to our knowledge of solar and stellar structure. Improvements in the angular resolution of the OSO spacecraft, four of which have been orbited in space around the earth since 1967, would make possible further progress in understanding solar flares and similar activity on other stars.

Improved observations from space go hand in hand with improvement and extension of observations from the ground. To get information of comparable scope and resolution to that obtained in space, we must continuously update existing ground-based and aircraft facilities and construct small specialized telescopes for the visible and infrared spectral regions.

More attention should also be given to detecting the elusive solar neutrino radiation. Using what must be the most remarkable telescope in existence (a 30,000-gallon tank of cleaning fluid placed deep in a mine in the hills of South Dakota), physicists have been counting neutrinos, the subatomic particles produced in nuclear reactions in the sun's core. They find that the sun produces only one-sixth as many neutrinos as are predicted by present theories of solar structure. The results of this experiment show either that the central temperature of the sun is lower than we have thought, or that we must question the weak-interaction (Feynman—Gell-Mann) theory of particle physics.

STELLAR EVOLUTION

The basic physical laws and processes that govern the structure and evolution of stars are now quite well known. Stars condense from the gas and dust of the interstellar medium, spend a few million years deriving their initial energy from gravitational collapse, and thereafter show little change during life-spans that range from about 1 million to 100 billion years. However, once the central supplies of hydrogen are eventually exhausted in their cores (where temperatures are highest and the reactions most rapid), a new phase of evolution begins. Hydrogen fusion is now restricted to a shell around the core; the core itself—now helium—contracts, the outer surface of the star expands and cools, and the star becomes a red giant or a supergiant. The greater the mass of the star, the greater the tendency for further heavy-element fusion processes to take place in its core. Thus, helium "burns" to carbon; then to oxygen, neon, magnesium, and so on, up the periodic table toward iron—the process of nucleosynthesis. Eventually, when all supplies of accessible fuel are exhausted, the star contracts to a very dense state, becoming either a white dwarf or—after a catastrophe—a neutron star. A massive star falls into a relativistic "black hole."

Although astronomers are increasingly confident of the basic validity of this picture of stellar evolution, present understanding of these fundamental topics is incomplete at best. It will take decades to reach a secure understanding of the formation of the elements and stellar evolution—with all their implications for the rest of astronomy and cosmology.

MOLECULES, PLANETS, AND LIFE

The formation of the earth and the solar system was once believed to be an extraordinary event. Now most astronomers think solar systems are commonplace, arising in a natural way during the formation of the stars themselves. How life begins on the planets is still obscure and is a subject best left to the biologist. How life becomes intelligent is perhaps the ultimate question. One of the more fascinating recent discoveries is that some molecules necessary for the development of life may have been present in the original dust cloud from which the solar system formed.

What were the initial conditions in the interstellar medium out of which the solar system formed? We know that both gas and dust were present. Photographic studies of the sky long ago revealed luminous clouds, which spectroscopic analysis has shown to be mainly hot hydrogen gas. Radio observations have mapped cool hydrogen clouds in spiral arms stretching around our galaxy, and they have detected such gas in other galaxies. Other molecules, such as combinations of carbon and hydrogen, and carbon and nitrogen, were discovered with the large spectrographs on conventional telescopes, and some have been found in other galaxies.

The most dramatic molecular discoveries, however, were made in the radio spectrum—the existence in interstellar space of the hydroxyl radical, carbon monoxide and its isotopes, carbon sulfide, silicon oxide, water, and ammonia, among others. Are there also more complex structures? Only a few years ago we would have said no. But by now we have found an undreamed-of array of such complex forms in space—molecules like formaldehyde, methyl alcohol, cyanoacetylene, formic acid, and formamide.

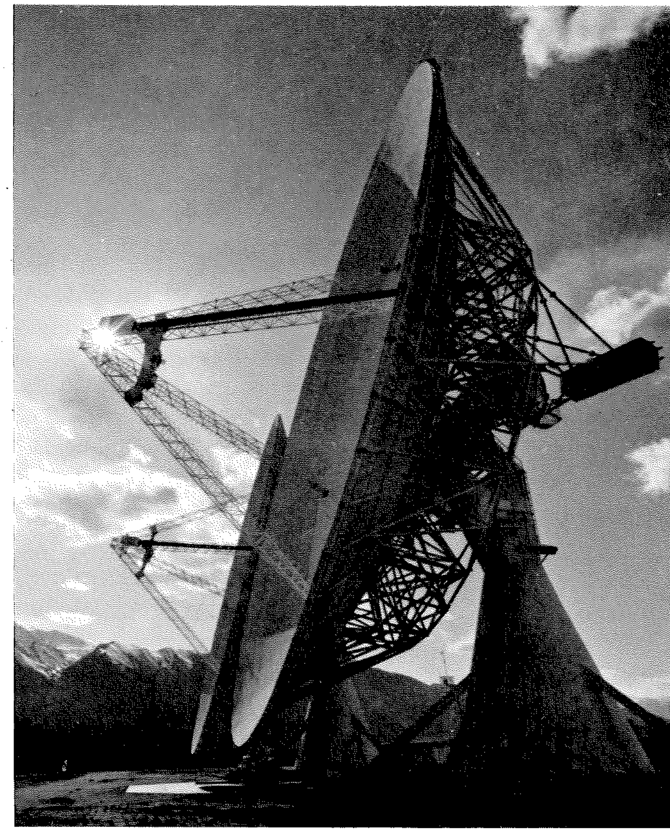
An important factor in constructing any theories of molecular formation will be the determination of the numbers of atoms—the building blocks of molecules—within the dust clouds. Since only a few of the important elements have their strongest absorption lines in the visible part of the spectrum, we must look to ultraviolet spectroscopy from space vehicles to provide this information.

EXOBIOLOGY

Our civilization may soon take one of the greatest steps in its evolution: It may discover the existence, nature, and activities of independent civilizations in space. As we point out in *Astronomy and Astrophysics for the Seventies*: "At this very instant, through this very page, radio waves are passing. Some may bear conversations that we could record if we pointed a radio telescope in the right direction and tuned to the right frequency."

In a hunt for extraterrestrial civilizations, however, it is clearly restrictive to construct a search aimed at detecting only signals generated to attract our attention. It would be preferable to detect signals that a civilization uses for its own purposes. Such signals would be more numerous—but unfortunately they would also be weaker, they would be at unpredictable frequencies, and they would require unscrambling. Even though no single signal indicative of civilized communication rises above the noise of natural radiation on a radio telescope, it is possible to analyze the spectrum for peculiar groupings of artificially produced "civilized" noise. Such methods call for observations of large numbers of frequencies and extensive analyses of the recordings with high-speed computers. We have the mathematical theory and technology to do both.

In today's rush of exciting "hard" astrophysical research, no major search for extraterrestrial civilizations has taken place. But more and more scientists feel that confirming the existence of such civilizations—and making



Number 1 on the list of programs recommended by the Astronomy Survey Committee is development of a radio telescope array far larger than any now operating, including that at Caltech's Owens Valley Radio Observatory.

contact with them—is now within our capabilities. It may happen in the lifetime of many of us. In the long run, this may be astronomy's most important and most profound contribution to mankind.

RECOMMENDATIONS

If astronomy is to continue to progress, new facilities must be constructed, and new directions in research must be pursued. Federal expenditures in ground-based astronomy have averaged about $50 million, and in space astronomy about $200 million, annually. The entire program proposed by the Astronomy Survey Committee involves an additional $84.4 million a year over the next decade—about $51 million a year for new space projects and about $33.4 million a year for new ground-based programs. The committee has defined four programs of highest priority for federal support. In order of importance, they are:

1. A very large radio array, designed to attain resolution equivalent to that of a single radio telescope 26 miles in diameter. This should be accompanied by increased support for existing smaller radio programs and advanced, new, small facilities at universities and research laboratories.

2. An optical program that will vastly increase the efficiency of existing telescopes, by use of modern electronic auxiliaries, and at the same time create the new large telescopes necessary for research at the limits of the known universe.

3. A significant increase in support and development of the new field of infrared astronomy, including construction of a large ground-based infrared telescope, high-altitude balloon surveys, and design studies for a very large stratospheric telescope.

4. A program for X-ray and gamma-ray astronomy from a series of orbiting High Energy Astronomical Observatories, supported by construction of ground-based optical and infrared telescopes.

The committee has also identified several items of high scientific importance, which, although urgently needed, should not delay the funding of the other programs. These include:

- ☐ A very large millimeter-wavelength antenna for the study of new complex molecules in space, and of quasars in their early, explosive stages.
- ☐ Updating existing solar observatories on the ground.
- ☐ Continued support of the Orbiting Solar Observatories.
- ☐ An expanded program of optical space astronomy.
- ☐ A large orbiting space telescope.
- ☐ Doubled support for infrared and gamma-ray observations from high altitudes.
- ☐ Increased support for theoretical investigations.
- ☐ A large steerable telescope for observing wavelengths of one centimeter and above with more resolution.
- ☐ Increased support for astrometry to provide additional needed information on the positions and apparent motions of stars.

CALTECH'S ROLE

This outline of the major facilities required by the nation for the next ten years neglects, of course, the contributions of individual institutions. The universities of this country spend nearly $35 million annually on instruction and research in astronomy. Much of what the Astronomy Survey views as central to the future of astronomy (radio observations, X-ray astronomy, infrared astronomy, astronomical observations from orbit, the construction of new auxiliary electronic instruments to increase the light-gathering of modern optical telescopes—to name a few) is, in fact, going on at Caltech.

The effort in astronomy at Caltech is one of the broadest and most active in the world; it includes work over the entire range of wavelengths. Studies dealing with relativistic cosmology, observations of galaxies and quasars, radio astronomy, the origin of the chemical elements in stars, nuclear reaction rates that keep the stars shining, solar astronomy on the ground and in space—are all being actively pursued. The infrared program here is one of the most exciting in the world and has shown the enormous energies released both by explosions in in galaxies and by cool (nearly cold) stars, young and old.

It is depressing to see how unlikely is the growth in federal support we recommend. It is also not encouraging to see how little of the proposed increased support of new facilities and programs by federal funds would come to Caltech—or any other major university center—without a struggle.

I hope that Caltech will, by its past performance, justify its share in the future expansion in exciting new areas of astronomy. But we should not forget the benefits to scientific enterprise of institutions based on private funds, to some degree independent of federal funding. The existence of the Hale Observatories—the largest privately operated optical astronomy observatories in the world—attests the value of such institutions. There remains an interesting challenge to the private sector in helping *one* outstanding center of excellence survive, independent of the vagaries of federal funding. Auxiliary devices required by our large telescopes are not beyond the resources of individual donors; instrument costs range from extremely expensive to modest; new research in the infrared is relatively inexpensive; theoretical astrophysics costs no more than the salaries of the young men involved, and the use of a computer. The opportunities in the next ten years are clearly unparalleled, and I hope that Caltech will remain central to the production of those new developments in astronomy which so enormously enlarge the horizon of man.