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A LONG-RANGE PROGRAM IN SPACE ASTRONOMY

Position Paper of the Astronomy Missions Board

July 1969

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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PREFACE

The Astronomy Missions Board was established by the National Aeronautics and Space Administration by charter in September 1967 to assist in an advisory capacity in the planning and conduct of all NASA missions to create and operate astronomical experiments in space. The scope of the Board's activities includes: development and review of the scientific objectives and general strategy for space astronomy and associated ground-based astronomy; the formulation of guidelines and specific recommendations for the design of space astronomy missions, and for the various experiments and auxiliary equipment to be developed and used on these missions; the continuing examination of policies relating to the operation of these space observatories once they have been made operational and are available for observations by the scientific community. The work of the Board encompasses the many aspects of space astronomy including direct observations of electromagnetic radiation from astronomical sources, cosmic-ray particles and the supporting research that is necessary, but its scope does not include the study of the Moon and planets from close vantage point or study of the Earth.

The Astronomy Missions Board is presently composed of 18 members of the scientific community with a wide diversity of interests and experience. They are drawn largely from universities, but include members from national laboratories (see appendix for a list of members of the Board and its panels). The Board's activities are supported and supplemented by seven panels and two ad hoc working groups to whom specific areas of responsibility are assigned. The panel compositions are similar to that of the Board itself and involve an additional 31 scientists. This wide membership provides a broad representation of current thought in space astronomy both directly through its membership and from the wider astronomical community by means of letters and discussions.

The activity of the Board has been intensive. With few exceptions, it has met monthly for 2 days at locations appropriate to its current activities. In addition to extensive deliberations and discussions, the meetings have included reports and résumés from NASA personnel about matters such as the current status of projects then underway, present NASA plans for the future, technical reports on areas of special relevance, and budgetary aspects of current and planned programs. The panels have met several times during the past year and have taken the opportunities for obtaining firsthand information about the activities in space astronomy at various NASA centers relevant to their particular fields of interest. Again, briefings as to technical capabilities and current planning were obtained and the panels prepared detailed programs and recommendations for activities in their areas.

An important continuing activity of the Board is the presentation of specific recommendations to the Associate Administrator of NASA. Many of these recommendations have been ad hoc answers to questions raised by NASA, while others have been of a more general nature and have, in most cases, been incorporated into the body of this report. Many of these ad hoc recommendations were for the purpose of assisting NASA to optimize a low-level program, and should not be construed as approval of such a program by the Board or the scientific community.

The Board has created a long-range national program for space astronomy—including discussions of the major problems of astronomy and astrophysics, an observing program describing the next important measurements from space, and examples of the instruments, spacecraft, and missions needed to make those measurements. Specific mission descriptions are not intended as concrete definitions of future missions, but as part of an exemplary program which is used to establish the best current balance between the subdisciplines. The plan contains sufficient mission priorities and interdependences on which to base AMB advice to NASA at various foreseeable levels of effort, and should enable NASA management to assess the impact on scientific progress of the various future options available to them. The purpose of this position paper is to describe the long-range plan as it appears in July 1969.

Past experience has shown that astronomy is a field full of surprises and the unexpected, and it would be extremely shortsighted to expect this report to remain up to date for very long. This report is not intended to be a static document. It is, rather, a working paper to be updated and altered continuously by the Board as technical capabilities change and scientific opportunities and priorities evolve. Nevertheless, it seems appropriate to publish this version of the position paper, just as it was submitted to NASA as part of the fiscal year 1971 budget planning cycle, in order to acquaint a wide community of astronomers, astrophysicists, physicists, and other interested scientists with the workings of the Astronomy Missions Board, as well as with the national space astronomy program. NASA and the Astronomy Missions Board hope in this way to continue to improve the mechanisms by which the NASA space astronomy program can get the best assistance from, and give the most help to, the entire community of astronomers and space physicists. From time to time, as the extent of the revisions makes a major part of this work obsolete, the Board will again publish an updated position paper.

The detailed reports on the subdisciplines of space astronomy, authored by the panels and endorsed in substance by the Board, will be found in Part II. Part III describes how the panels' programs were evaluated, and how parts of them were combined into long-range plans at two levels of effort—a minimum balanced program and an optimum program—both of which do not attempt simply to do everything suggested by the subdisciplines, but rather emphasize research on those problems judged astrophysically most important by the greatest consensus of the Board.

A summary of the position paper and key features of the long-range plan will be found in Part VII.

FOREWORD

The Astronomy Missions Board advises the National Aeronautics and Space Administration (NASA) through the Associate Administrator, Dr. Homer E. Newell, on the present and future of the national space astronomy program. The Board has developed a position paper which recommends to NASA an integrated space astronomy program for the Seventies. The position paper was received by NASA on July 5, 1969. Because of current widespread interest this paper is being published in its original form without any evaluation or comment by NASA beyond this statement. While NASA will be guided by the recommendations in this paper, publication of this document by NASA is in no sense either an endorsement of its contents or a commitment on the part of NASA to undertake to carry out all or any part of the proposed astronomy program.

CONTENTS

INTRODUCTION

The ability to mount astronomical instruments on observing platforms high above the Earth's atmosphere is the latest and most decisive in a series of technological developments that have stimulated the recent fantastic growth of astronomy. Astronomers are now able to observe the sky in ways they could only dream of less than 30 years ago. In those days, the known spectrum of radiation reaching the Earth's surface was only slightly broader in wavelength than the visible spectrum, 4000–7000 Å, because the Earth's atmosphere blocks out most of the shortwave radiation emitted by the Sun and the stars, and a good part of the infrared as well. Moreover, there was little reason to suspect that any significant number of astronomical bodies were radio emitters, and Jansky's early apparent observations of radio waves from the Milky Way aroused little interest among astronomers.

With observations restricted to a small fraction of the electromagnetic spectrum, a large part of astronomical research was concerned with the collection of data that could not be well understood. Astronomers could hope to deduce the physical nature only of objects emitting purely thermal radiation at a temperature of a few thousand degrees so that most of their radiated energy was radiated in the form of visible light. Very hot or very cold objects or those that gave off exotic, nonthermal radiation were beyond understanding. Then, one by one, the other regions of the spectrum began to be exposed. First the cosmic rays provided the first clue to high-energy processes in the universe. Next radio astronomy came to fruition, revealing both high-energy and nonthermal phenomena on a grand scale, notably the quasars and pulsars. Finally, the space program is bringing into view the ultraviolet region of the spectrum between 3000 and 300 Å, and X-rays and gamma rays at still shorter wavelengths.

No longer may theories be proposed that cannot be tested because key parts of the spectrum are inaccessible. On the contrary, it is now possible to devise and carry out decisive experiments to test almost any hypothesis in astrophysics, which is one of the reasons why more and more physicists now look upon astrophysics as the most interesting and exciting branch of physics.

Space astronomy offers two kinds of challenges. First, a great many well-defined scientific problems can now be solved by multiwavelength experimental approaches, and second, many unexpected discoveries are sure to be made as they always are when a new region of the spectrum is first explored or when a new instrument of unprecedented power is put into operation. The recent history of astronomy is full of examples of such unexpected discoveries. For example, the first radio and X-ray sources were both discovered accidentally and many of the recent discoveries of strong emitters of infrared radiation could not have been predicted in advance.

Telescopes in space have other important advantages beyond their capacity to intercept radiation that cannot penetrate the atmosphere. Thus, Earth-based telescopes must look through columns of turbulent air which severely degrade the images they produce. A telescope of 120-inch aperture above the Earth's atmosphere has 10 times the resolving power of the 200-inch telescope on Mount Palomar operating under the best atmospheric conditions. Because of the very small image sizes that are possible with telescopes in orbiting observatories, a space telescope 120 inches in diameter should be able to detect stars 100 times fainter than the faintest detectable from the Earth. Data on such faint objects are critical for settling major questions in cosmology, such as whether the universe is infinite or not.

To fully appreciate the unique contribution of space research in reaching otherwise inaccessible information about our universe, we should survey the great problems before us in modern astronomy, and determine for each case just what observations ought to be made next. This is how each of the reports of the subdisciplines (Part II) begins. Among the problems they examine are:

The quasars and the violent explosive events in the nuclei of galaxies which share many properties with those most distant objects known to man;

the strange problem of the million-degree temperatures in the solar corona surrounding the—astronomically speaking—cool surface of the Sun (a few thousand degrees) when, as every schoolboy knows, heat flows from hot to cold places and not the other way around;

the possibility that astronomers may be witnessing in some clouds of dust surrounding a certain star the formation of a system of planets like our own;

the mysterious pulsars, whose unnatural sounding rhythm led the first astronomers detecting them to catalog them as LGM 1, LGM 2, etc., where the LGM stood for "little green men";

- the puzzling situation in the interstellar medium where OH molecules (two-thirds of a water molecule), at temperatures hundreds of degrees below freezing (on Earth), are sending us brilliant maser beams of radiation, brighter than the radiation from any normal thermal source with a temperature of trillions of degrees; and
- the most recent discovery of organic molecules existing in cold interstellar space—perhaps the simplest building blocks of life were not formed in early geological evolution but were created as part of the same process that formed the stars.

We conclude here with brief discussions of two challenging problems in modern astrophysics, and especially note the interplay between new techniques in widely separate subdisciplines.

One of these problems, the microwave background, is concerned with beginnings, with the cosmological question of the ultimate origin and fundamental forces that govern the evolution of the universe. The second example, the Crab Nebula, is related to endings, to the termination of the life of a star which apparently dies—contrary to T. S. Eliot's despairing poetic prediction—with a bang, not a whimper.

THE CRAB NEBULA: SUBJECT OF ALL DISCIPLINES

The Crab Nebula is now recognized as one of the most remarkable objects in the entire sky, combining the attentions of nearly every modern astronomical discipline, both spaceborne and ground based, observational and theoretical. The scribes of the Sung dynasty described it as a "guest star" that appeared on July 4, 1054, and in recent times the combined efforts of astronomers and scholars of Chinese history finally showed that the nebulosity known as M1 (object no. 1 in Messier's catalog of 1742) was indeed the remnant of the stellar explosion of 1054. The event was no ordinary nova (for "new" star) outburst, but an example of the much rarer supernova explosion, only three of which have been observed in our galaxy in the last thousand years. As a star exhausts its nuclear fuel, it cannot keep from collapsing under its own gravity. A complex series of events, whose details are still not completely understood, leads to a rapid collapse, followed by a violent explosion, during which the supernova releases more energy in 1 year—10^{52} ergs—than it had given off in its entire lifetime as a star. Theorists have predicted for many years that the residue might include a neutron star—a star so compressed that atoms lose their individuality, their nuclei and electrons merge, and the resulting state is best described as continuous nuclear matter. These neutron stars would be only 10 km or so in diameter, but would be extremely dense, with 1 cc weighing a billion tons or so. This corresponds approximately to the entire material of Manhattan Island, rock, buildings, and all, compressed into the volume of a thimble.

The combined efforts of radio, optical, and X-ray astronomers over the past 20 years have shown that the remnants of this incredible energetic explosion provide fascinating new ideas of the complexity of our universe. The optical astronomer sees a faintly glowing nebulosity, interlaced by a delicate network of red filaments that are expanding at a rate of 1000 km per second. In the center is a faint star, unlike any known stellar types. The light from the continuous part of the nebulosity was found to be strongly polarized, and by combining this information with the intense radiation seen by the radio astronomers, it became clear that the nebulosity is not just a glowing mass of hot gas, but a relativistic gas, composed of electrons whose energies exceeded 100 billion electron volts (and with velocities near the speed of light, the relativistic limit), an energy greater than that produced by any accelerator in operation on the Earth. The electrons emit radiation by the process known as synchrotron emission (like that given off by synchrotron accelerators), which requires that the relativistic gas be permeated by a magnetic field weak by terrestrial standards, but fabulously energetic when it extends over a region light-years in extent.

The advent of space technology brought forth the new field of X-ray astronomy, and after the initial discovery of Scorpio XR–1, the first X-ray star, the next object to be observed clearly as an X-ray emitter was the Crab Nebula. The X-rays might be generated by a "cool" gas at a temperature of a million degrees Kelvin—a substrate mingled with the relativistic gas—or by the relativistic electrons themselves. The evidence now favors the latter choice, but this implies many more energetic electrons, and at energies of 10 000 billion to a hundred thousand billion electron volts, which radiate so strongly that a new supply must be furnished continuously.

New surprises were in store for the astronomers, however, when an entirely new class of object—the pulsar—was discovered by radio astronomers two years ago. The first of these remarkable objects was observed to emit sharp radio pulses every second or so, with clocklike regularity. One of the suggested mechanisms that would explain the observations invoked the rotation of a neutron star as the means of controlling the pulse rate, although the means of producing the radio pulses themselves remained unclear.

Within a year, a pulsar was discovered within the Crab Nebula, and in many respects the Crab Pulsar has proven to be the most promising key to the puzzle. Its repetition rate is 30 times per second—much faster than the typical pulsar—and the rapid rate can best be understood, it appears, by assuming that we are indeed observing a rapidly rotating neutron star. The optical astronomers quickly discovered that the peculiar star at the center of the Crab was indeed the pulsar, flashing in the visible as well as in the radio part of the spectrum. Space astronomy has now further extended the observations, for the X-ray astronomers have shown that approximately five percent of the X-rays from the Crab are pulsed in synchronism with the light and radio pulses.

The space observations have special significance because of the need for powerful energy sources to explain the source of X-ray emission. A hundred times more energy is emitted in the X-ray spectrum than in the visible, and the total rate of energy radiated by the Crab Pulsar must be over 100 times the rate of energy radiated by the Sun.

The combined X-ray, radio, and optical observations all support the model of the Crab Nebula being energized by a rotating neutron star. According to one theory, the rotation of the neutron star at 30 times per second results from the collapse of the original star, and the conservation of angular momentum. The collapse also compressed the normal magnetic field previously present in the star, to a value of a trillion gauss. Calculation then indicates that the huge electric field induced by the rapidly rotating magnetized star accelerates particles that drag the magnetic field with them, emitting synchrotron radiation as they go. In this way one accounts for the magnetic fields and relativistic particles observed in the nebula. Moreover, the process extracts energy and angular momentum from the star at a calculable rate, which agrees with the observation that the Crab Pulsar period is lengthening on a time scale of a thousand years.

Thus the discovery of a neutron star at the center of the Crab may solve several problems concerned with the energization of the nebula itself. More important, perhaps, it demonstrates the close relationship between the formation of neutron star and the explosion of a supernova. It will be of great interest to see whether all supernovae produce a pulsar (neutron star) to play a clocklike dirge during the final stages of evolution—the magnificent death throes of a star, or whether some lead to a relativistic collapse to a gravitational singularity, a lump of matter so highly condensed that no radiation of any kind (and hence no information) can escape from its gravitational pull—"black holes" of the universe into which things may enter, but from which nothing ever returns.

THE COSMIC MICROWAVE BACKGROUND

The abundance of the chemical elements, and an unexplained discrepancy in the performance of a satellite communication system, unexpectedly prove to be closely related to the deep question of the origin and evolution of the universe. George Gamow and his coworkers showed theoretically 20 years ago that if the universe began as an initially compact mass of hot matter (the "big bang" theory of cosmology), they could explain some of the observed element abundances. A further consequence of the theory, not entirely appreciated at the time, was the lingering effect of the blast of gamma rays that would have been present in the initial fireball.

After the elements stopped forming, at a time when the universe would have been about 3 days old in the simplest cosmological model, the radiation began to degrade in energy, and should still be observable today. Gamow's colleagues estimated in 1949 that the cosmological red shift would have transformed the gamma rays in energy all the way through the electromagnetic spectrum to radiofrequencies, and the sky should today appear to have a uniform brightness of a "blackbody radiator" at a temperature of about five degrees Kelvin (°K).

Four years ago two radio astronomers, Penzias and Wilson, showed that a previously discarded discrepancy in the observed noise from a very-high-sensitivity receiving system at the Bell Laboratories was indeed real and was observable no matter what direction in the sky they pointed their antenna. The apparent brightness of the sky at 7-centimeter (microwave) wavelength, when all corrections for the Earth, the atmosphere, and the galaxy had been applied, was measured to be about 3.5° K. Since then, measurements at many wavelengths between 3 mm and 70 cm have established that the spectrum is very accurately that of a blackbody radiating at a temperature of 2.7° K, and measurements in many directions confirm that it is a true isotopic cosmic background. Thus, the prediction of Gamow's theory was verified, and the range of acceptable cosmological models was greatly reduced. The steady-state theory, which envisioned a universe whose appearance never changes, with new galaxies constantly forming from new matter in the void left by the expanding system of old galaxies, cannot explain the new observation without additional hypotheses, such as a new class of radio sources far exceeding the number of galaxies. The radio evidence at present surely favors the big bang theory, but cosmological problems are notoriously slippery, and new observations are certainly needed to cross-check the new ideas.

If this cosmic microwave background radiation is a true "blackbody" at 2.7° K, it should have its peak intensity at a wavelength of one millimeter and fall off rapidly at shorter wavelengths. Unfortunately, the Earth's atmosphere is opaque at this and shorter wavelengths, so it is difficult to verify the predicted decrease in intensity by ground-based measurements. Upper limits have been deduced at several wavelengths near one millimeter by observations of the state of excitation of interstellar molecules, and these suggest a fall in intensity, but the method is indirect. Several groups are therefore undertaking direct observations at millimeter wavelengths from balloons or rockets. One preliminary rocket observation had indicated that, to the contrary, there is a component of radiation at one millimeter which is almost 100 times stronger than a 2.7° K blackbody. If the observations of interstellar molecules are correct, the radiation observed by rockets must be locally produced.

The question of the ultimate origin and grand scheme of the universe is so important that one should be driven by only the utmost decisive evidence to acceptance of a particular cosmological model. The evidence for the "big bang" is mounting, but the final evidence is not in hand. Only through a combination of all the threads of observational evidence can the scientist be convinced. The choice of a particular theory for the origin of our universe has tremendous implications for many other astrophysical problems at the frontier of study, such as the nature and distribution of quasars, the origins, distribution, and dynamics of the high-energy cosmic rays, the abundance of the elements, and in particular the relative amounts of different isotopes. Those abundances must be determined more accurately in a variety of different astronomical objects. To be sure, our present best measurements of the helium abundance in the oldest stars support the cosmologies that are consistent with the cosmic microwave background, but the abundance determinations, in many instances, are still subject to large uncertainties.

Moreover, because of its great energy density, which exceeds that of other known sources, the microwave background may have had profound effects on the evolution of galaxies. For example, density fluctuations which would otherwise have collapsed gravitationally to form galaxies may have been prevented from doing so by radiation pressure, and relativistic electrons ejected by distant quasars are rapidly decelerated by Compton collisions with microwave background photons. Examples such as these emphasize the importance of this new cosmological phenomenon.

The quest for the solution of the basic cosmological problem remains a difficult one, but the discovery of the cosmic microwave background has added new impetus and excitement. It permits us to look directly at radiation created when the universe was just a few days old, and allows us to surmise conditions in this most early history of the universe.

VII

SUMMARY

The Astronomy Missions Board (AMB) was established by the National Aeronautics and Space Administration in the fall of 1967 and charged with the creation of an exciting, significant, and forward-looking long-range program in space astronomy. The Board was asked to formulate the major unsolved problems of astronomy, to define the measurements from space that would assist in their solution, and to specify the types of instruments, spacecraft, and missions needed to perform the required measurements.

ASTRONOMY AND SPACE RESEARCH

Astronomy has a far greater potential for advancement by the space program than any other branch of science. Telescopes working on the surface of the Earth can only observe those portions of the electromagnetic spectrum that penetrate through the Earth's atmosphere, chiefly those of visible light, and radio waves in the band from a few millimeters to about 20 m in wavelength. Astronomical instruments located in space can now reach the remaining regions of the electromagnetic spectrum. Thus, by coordinated programs of observation, in which the same object is observed over the entire range of the electromagnetic spectrum by telescopes in space and on the ground, the most fundamental problems of astronomy may be brought within range of solution.

The new multiwavelength approach to astronomy requires the combined efforts of scientists working in many fields of the natural sciences, since radically different experimental and theoretical techniques are needed to observe and interpret radiation from different parts of the spectrum. In order of decreasing energy, the principal subdivisions of the spectrum are: gamma rays, X-rays, ultraviolet radiation, visible light, infrared, and radio waves. The measurement of particles and magnetic fields in space has also come to be recognized as a major tool for the exploration of the universe. The acquisition of the data alone involves the application of talent from many different branches of experimental physics and engineering. Moreover, the data are of keen interest not only to astronomers but to research workers in many branches of theoretical physics, chemistry, mathematics, geology, and geophysics, and perhaps also biology. Thus, the multiwavelength approach is also a multidisciplinary approach and space astronomy is an activity that promotes the unification of science.

Because of the specialized nature of the instrumentation employed in different spectral regions and the special requirements of solar and planetary observations, the Board carries on its work with the aid of seven specialized panels, each concerned with a different subdiscipline of astronomy: solar, planetary, particles and fields, X-ray and gamma-ray, ultraviolet, infrared, and radio. In addition, several working groups are engaged in studying the needs of supporting research and technology, complementary ground-based research, education and training of scientific manpower, and the role of man in space astronomy.

THE MAJOR UNSOLVED PROBLEMS IN ASTRONOMY

Each of the seven panels began its work by formulating the major questions it was seeking to answer by the application of its special techniques and by showing how space astronomy could make unique contributions to their solution in the next 10 years. Full discussion of these scientific questions will be found in the reports of the panels and only two examples will be given here.

The Crab Nebula is a fine example of the usefulness of space observations. This enormous cloud of glowing gas, left over from the explosion of a star in A.D. 1054, radiates in all regions of the spectrum from long radio waves to X-rays. Close to the center of the nebula is a pulsar which may be a neutron star, in which matter is compressed to a density of about 10 billion tons per cubic inch, probably resulting from the collapse of the central core of the exploding star. The pulses have now been observed in radio waves, visible light, and X-rays. Taken together, the combined observations show that the total rate of energy radiated by the pulsar is over 100 times greater than that radiated by the sun, despite the fact that the pulsar is only 6 miles or so in diameter.

A second set of measurements suggests that we may be able to observe the cosmic fireball that occurred at the beginning of the expansion of the universe. Radio-astronomy measurements made on the ground at many wavelengths between 3 mm and 79 cm have shown that space is filled with blackbody radiation with a temperature of about 3° K. Such a background of microwave radiation was predicted by George Gamow to arise naturally from an early hot phase in an evolving universe, and if the radiation is indeed found to have a cosmological origin it would provide strong evidence in favor of an evolving model of the universe and against steady-state models in which matter is being continuously created. The peak intensity of the microwave background occurs at a wavelength of about 1 mm. Since the Earth's atmosphere is opaque at this and shorter wavelengths, it has been impossible with ground-based equipment to verify whether the intensity at shorter wavelengths does indeed decrease as predicted. As a fundamental cosmological phenomenon, the microwave background has a high priority for study from space.

The foregoing are only two examples of the many astronomical mysteries that can be cleared up by the methods of space astronomy. The most pressing of these problems form the basis for the design of a long-range program. A much longer list of problems is given in the subdiscipline reports of part II. They are representative of the many well-defined scientific problems which can now be solved by the multiwavelength approach.

A second major justification for space astronomy consists of the many unexpected discoveries that are sure to be made, as they always are, when a new region of the spectrum is first explored or when a new instrument of unprecedented power is put into operation. The recent history of astronomy is full of examples of such unexpected discoveries. For example, the first radio and X-ray sources were both discovered accidentally, and many of the recent discoveries of strong emitters of infrared radiation could not have been predicted in advance.

PREPARATION OF THE LONG-RANGE PLAN

Once the scientific problems had been formulated, each panel considered how its special techniques could be applied to acquire knowledge in an orderly, systematic fashion by a series of space missions involving equipment of increasing size and sophistication. Each panel was in fact asked to draw up so-called minimum and maximum programs, the former being defined to proceed at the minimum rate necessary to attract and retain the interest of the leading workers in the field. Conversely, the maximum program was designed to proceed at the fastest possible rate consistent with available scientific and technical manpower. The full Board accepted the judgment of each panel as to the order in which they should be flown. But the rate at which each of the panels' programs was recommended for implementation was decided by the Board, after examining carefully the competing claims of the separate panels.

In effect, the Board decided the percentages of the budget to be allocated to each of the subdisciplines in a given year. In fact, two such programs are presented in this report. The first is a so-called minimum balanced program, which recommends an annual expenditure of $250 million for an average year in the mid-1970's (fiscal years 1974 to 1976 time period). The Board believes that this is the minimum figure at which viable long-range programs in all of the subdisciplines can be supported. The second, or optimum program, calls for an average annual expenditure of $500 million during the same period and is envisaged as the optimum program that can be supported with available manpower. Both the optimum and minimum balanced program cost figures do not include provision for the cost of the largest instruments, among them a 120-inch diffraction-limited telescope for optical stellar astronomy, which are planned for a National Astronomical Space Observatory (NASO) envisaged for the early 1980's.

SOME NEW DIRECTIONS

Comparisons with the current NASA space-astronomy program reveal some of the new directions which will be required to implement the AMB plan. Perhaps the most significant change is an increased effort in X-ray and gamma-ray astronomy. Less than 10 percent of the current NASA effort, X- and γ-ray astronomy amounts to about a quarter of the AMB program, which assigns approximately equal levels of effort to optical, solar, and high-energy astronomy. The increase needed in the minimum balanced program is a major start in fiscal year 1971 on a new spacecraft with the pointing, telemetry, and general sophistication of an Explorer-class spacecraft but with a payload size capable of carrying large area X-ray detectors, spark chambers, and Cerenkov telescopes, as well as particles and fields experiments in the 1- to 5-ton range. Also included is the adaptation of a future OAO spacecraft or an equivalent vehicle to carry a state-of-the-art stellar X-ray imaging instrument comparable to existing solar instrumentation. Later, stellar imaging X-ray telescopes of about 1-m aperture, 10-meter focal length will be required.

The optical ultraviolet astronomy program has as a mid-1970's goal observations requiring the equivalent of a 1- to 1.5-m telescope with diffraction-limited performance, as an essential intermediate scientific and technological step toward the 3-meter large space telescope of the 1980's. This could be achieved either through a new spacecraft design or by upgrading an evolutionary OAO program. Also possible would be an early developmental model of the 3-meter telescope, structurally similar but with degraded pointing, mirror quality, etc. providing performance equivalent to a 1.0 to 1.5 meter diffraction-limited telescope.

The infrared astronomy program has a most pressing need for research and development of detectors and small cooling systems which will permit infrared observations with much greater efficiency, as is commonplace at both shorter and longer wavelengths. Such advances could continue the present high rate of discovery of new classes of astrophysical phenomena from the ground and from airplane observatories.

Observations of astrophysical objects in the longwave radio portion of the spectrum with the minimum angular resolution required to distinguish individual sources may require an antenna made of wires surrounding an enormous area 6 miles in diameter. However, a remote possibility of making similar observations by "supersynthesis" interferometric techniques must be studied before this large electronically filled aperture is initiated.

The continuing need for observation of the solar surface with an effective angular resolution of 5 arcsec will require the development of a ground-controlled solar spacecraft with the instrumental sophistication of the ATM–A. This spacecraft may evolve through a series of upgraded missions to achieve effective 1 arcsec performance by the late 1970's, or an entirely new 1 arcsec spacecraft will be needed. This, too, is an essential scientific and technological step needed to acquire solar observations with spatial, spectral, and time resolution intermediate between the ATM–A and the 0.1 arcsec solar telescopes of the National Astronomical Space Observatories of the 1980's.

Observations of the planets from Earth orbit will be accomplished with the instruments of the planned OAO's and a Small Astronomy Satellite optimized for planetary observations.

The acquisition of data on cosmic-ray particles and fields in the interplanetary medium requires a careful programing of small fractions of the missions to the planets, and the joint use of the "heavy Explorer" spacecraft for high-energy astronomy.

An important element in the balanced acquisition of essential astrophysical data in the AMB plan is the continuing requirement for the smaller space experiments—the aircraft, balloons, rockets, and small Explorer-class satellites. Though less dramatic and unimposing by their nature, they have a great potential for economic and timely measurements of important data that can complement the other space-based and ground-based wavelength observations.

An essential part of the AMB endeavor to project the level of space astronomical research as far as possible into the future was an assessment of the availability and enthusiastic interest of excellent people—scientists and supporting specialists, including several engineering and technical groups skilled in the measurement of astronomical radiation. Continuity, breadth, and active competition for flight opportunities among these groups must be maintained by a strong NASA program in Supporting Research and Technology (SR&T).

Both SR&T and NASA's Advanced Research and Technology (AR&T) program must press forward to develop essential instrumentation such as lightweight optical mirrors, improved X-ray reflectors and detectors, X-ray photometric standards, electronic imaging systems, improved grating technology, infrared sensors, and small cryogenic systems, devices which will be useful in ground-based observatories of the future as well as space experiments. Support is also essential for the experimental and theoretical research in related areas of atomic and nuclear physics that will insure progress in analyzing the new observations resulting from these technological advances.

In a properly integrated program of federally supported astronomy, NASA should have a responsibility to support particular ground-based instruments, especially those which are most closely and directly related to NASA's mission. Specific instruments, which are of comparable expense to some spacecraft and might be defended as separate line items in the NASA budget, should include special-purpose monitoring telescopes of intermediate (60- to 100-inch) aperture, large optical telescopes in both hemispheres, and a large steerable paraboloid radio telescope.

The Astronomy Missions Board believes that the long-range program described in this position paper fully complies with NASA's request for the creation of a worthwhile and imaginative long-range program in space astronomy. It includes a careful assignment of priorities and balanced allocation of resources in order to optimize scientific progress on such problems as the origin of the universe, the course of stellar evolution including the ultimate destiny of the Sun and solar system, the existence of other planetary systems, some of which may support other forms of intelligent life, and other problems with deep philosophical significance which are of great interest to everyone and are therefore properly supported by public expenditure. The Board proposes this program to NASA and to the country with its unanimous and enthusiastic endorsement. We believe that the program is one in which scientists from many disciplines will want to participate, and that its implementation will result in a vast accumulation of new and fundamental scientific knowledge.

Finally, we again wish to point out that we regard this report as an ongoing working paper to be reviewed and then revised and updated as necessary, so that it always reflects the best judgment of the scientific community and the march of scientific discovery.

Appendixes

ASTRONOMY MISSIONS BOARD BIBLIOGRAPHY

APPENDIX A

MEMBERS OF THE ASTRONOMY MISSIONS BOARD

DR. LEO GOLDBERG, *Chairman*
Director, Harvard College Observatory
Chairman, Department of Astronomy
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DR. BERNARD F. BURKE
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