19 July 1968, Volume 161, Number 3838 SCIENCE

Astronomical Research with the Large Space Telescope

A space telescope of 120-inch aperture would be uniquely important for solving problems in astronomy.

Lyman Spitzer, Jr.

Space research promises to advance the study of astronomy in profound and fundamental ways. Exploration of the moon and the planets with flyby spacecraft, with automated landing equipment, and finally with manned space vehicles will obviously give a wealth of information that could scarcely be obtained in any other way. The discovery and analysis of x-ray sources in the sky by means of detectors on sounding rockets has already opened up a basically new and fascinating branch of astronomical research. Spectroscopic analysis of ultraviolet light from the sun and measurement of energetic particles and magnetic fields in interplanetary space have enormously increased our understanding of physical processes in the solar atmosphere and in the interplanetary medium.

Observations with large optical telescopes in space, designed to detect and analyze the faint light from remote stars, nebulas, and galaxies, also promise to have a revolutionary impact on astronomical research. Because of the size and complexity of the necessary equipment, this field has developed slowly. Even with small telescopes on sounding rockets, precise pointing toward stars other than the sun is technically difficult, and not until 1965 was this stabilization sufficiently precise to yield ultraviolet stellar spectra with enough resolution to show the strong absorption lines. In principle, however, the ability to make observations from above the atmosphere should greatly increase the effectiveness of an optical telescope; the absence of an atmosphere, with its strong absorption at wavelengths shorter than 3000 angstroms and longer than 10,000 angstroms, permits extension of the wavelength range into the ultraviolet and the infrared, and the absence of scintillation and image motion caused by atmospheric irregularities makes it possible, in principle, to obtain diffraction-limited imagery, with a resolution limited only by the aperture of the telescope and the wavelength of light. While, in ground observation, high resolution may be achieved for bright stars and planets through the use of various sophisticated techniques, there appears little prospect that this objective can be achieved for faint objects, which must be observed for long periods of time with telescopes of large aperture.

The long-range research potentialities of large optical telescopes in space were considered by a group of astronomers in 1965 at the Woods Hole Summer Study, organized by the Space Science Board of the National Academy of Sciences (*1*). A central conclusion of the Working Group on Optical Astronomy was as follows:

> We conclude that a space telescope of very large diameter, with a resolution corresponding to an aperture of at least 120 inches, detecting radiation between 800 Å and 1 mm, and requiring the capability of man in space, is becoming technically feasible, and will be uniquely important to the solution of the central astronomical problems of our era.

Essentially this same group (*2*) was asked by the Space Science Board in 1966 to constitute a committee of the Board for continuing studies of this powerful instrument, which has come to be referred to as the Large Space Telescope (LST). This LST Committee has devoted most of its efforts to a detailed consideration of the astronomical research that could be carried out with such an instrument. A series of conferences were held with other interested astronomers, and a report, "The Scientific Uses of a Large Space Telescope," has been prepared. Here I summarize the salient features of this report (*3*).

Performance of the Large Space Telescope

Before considering how astronomy could profit from use of the LST, let us review the technical performance characteristics that might be expected for such an instrument. Basically, a space telescope, like a telescope on the ground, is simply a large concave mirror that reflects light to a sharp focus, where it is analyzed by any of a variety of instruments, including precise photometers, spectrophotometers, polarimeters, and image recorders such as photographic film or a television camera. To achieve a long focal length without excessive telescope length, a conventional two-mirror system, of Cassegrain type, is likely to be used, with a secondary convex mirror reflecting light back through a hole in the primary mirror to a focal plane a short

The author is Charles A. Young Professor of Astronomy at Princeton University, Princeton, New Jersey, and director of the Princeton University Observatory.

distance behind the primary. With an optimum choice of aspheric surfaces on the two mirrors, such a system can give diffraction-limited images over an angular field several minutes of arc in diameter. With aluminum coatings on the two mirrors, and with thin overcoats of lithium fluoride, reflection coefficients as great as 60 percent can be obtained at wavelengths as short as 1000 angstroms, and coefficients greater than 90 percent, at wavelengths in the visible and far-infrared regions of the spectrum. Thus a space telescope of this relatively conventional optical design could be used to concentrate electromagnetic radiation at wavelengths between 1000 angstroms and 1 millimeter, the shortest radio wavelength readily accessible from the ground. Photons of wavelengths between 912 angstroms, and at about 50 angstroms in the soft x-ray region, are strongly absorbed by interstellar hydrogen atoms.

For an ideal optical system, with a mirror of radius a, the first dark ring around the image of a point source, observed with light of wavelength λ, has an angular radius of 0.61 λ/a radians. For a 120-inch (3-meter) telescope and light of 5000-angstrom wavelength, this radius is 0.04 second of arc; ideally, 84 percent of the light at this wavelength falls inside this circle. Actually, photographic images obtained with ground-based instruments normally have a radius about ten times this, or a diameter of about 1 second of arc. Sharper images have been obtained with ground-based instruments either visually or with very short photographic exposures, but one can generally not count on these for systematic research programs on faint objects. The combination of high spatial resolution and wide wavelength coverage constitutes the essential advance in capability offered by the LST.

To realize and make effective use of this capability would require a large engineering effort. To achieve nearly the ideal resolution possible, the surfaces of the two mirrors should not deviate from their ideal shape by more than $\lambda/50$ root mean square; careful control of the thermal design would be required to achieve this objective. The pointing of the telescope should be held steady during an exposure of several hours, with angular deviations from the mean direction preferably not exceeding a tenth of the resolution, or 0.004 second of arc for imagery at 5000 angstroms with a 120-inch telescope.

Studies for the National Aeronautics and Space Administration, together with test data and flight results obtained from the Stratoscope and Orbiting Astronomical Observatory programs, indicate that these objectives can be met with present techniques for an orbital telescope in the 40-inch range, and probably also for an instrument of roughly 120-inch aperture. The extensive equipment required can be visualized as a permanent space observatory. To ensure reliable operation, the installation would have to be manned at relatively frequent intervals. Discussion of the many engineering problems involved in designing and orbiting such an installation is beyond the scope of this article; it is assumed here that feasibility has been sufficiently indicated to warrant detailed discussion of ways in which the LST might be used scientifically.

The LST could be placed either in an orbit around the earth or on the surface of the moon. The cost of launching, maintaining, and resupplying such an installation would be least in an orbit relatively near the earth's surface at an altitude of some 500 kilometers. In such an orbit most objects are occulted by the earth for an appreciable fraction of each 100-minute orbital period. A higher orbit or a location on the moon would offer some advantages for more continuous observation, especially for longer exposures, but it is not clear whether these advantages would be worth the greatly increased cost.

One basic operating characteristic of any telescope is the faintness of a star that can be detected with a given exposure time. A fundamental limit is set by the number of photons available. From a star of stellar magnitude 24 (about the faintest so far detected from the ground), about 20 photons per second, with wavelengths between 4500 and 5500 angstroms, strike a telescope mirror of 120-inch diameter. Some 10 percent of these can be reliably detected photoelectrically. Hence, with an exposure time of 2 hours, from a star 1/100 as bright as this (that is, of magnitude 29), 140 photon pulses would be counted, providing a detectable signal with a measurement accuracy of 10 percent (0.1 magnitude), if the background noise were sufficiently low. On the earth, the permanent airglow form the night sky, which is equivalent, under good conditions, to the brightness of one star of magnitude 22 per square second of arc, masks such very faint stars, since the stellar images are about 1 square second of arc in diameter. With a 120-inch space telescope the image area would be about 0.005 square second of arc; since in space the sky is less bright by about one stellar magnitude (or a factor 0.4) than the sky as seen from the earth's surface, the diffuse sky light within an area equal to the stellar image would be about equal to the light from a 29th-magnitude star. Thus the limit imposed by the sky brightness is much less important in space than it is on the earth, thanks largely to the much sharper angular concentration of a stellar image obtainable in space. With a photoelectric image tube and either photographic recording or electrical recording as in the case of television cameras, stars as faint as magnitude 29 should be detectable by the LST, with exposure times of some 5 to 10 hours or less.

Galaxies and the Universe

While the LST would have important uses in many branches of astronomy, in the study of objects outside our own galaxy the capabilities of this instrument seem particularly well matched to the scientific requirements. The nature, extent, and destiny of the vast universe in which we live have engrossed man for thousands of years, but only now is there reason to hope for meaningful answers. In particular, bringing all galaxies in the universe effectively ten times closer than they can be brought by ground-based instruments promises to provide the information needed to answer some of these most basic questions in astronomy.

More specifically, research on other galaxies is designed to resolve the following two central problems:

1) What are the large-scale characteristics of the universe—its geometry, homogeneity, size, and curvature? What have these characteristics been in the past? What will they be in the future?

2) What is the structure of galaxies, and how do these systems evolve with time?

Investigations of these two central questions are somewhat intertwined, but the two areas of research are distinct in principle. In the first, the spatial distribution and velocities of the galaxies are investigated, without regard to their structure. In the second, the individual galaxies are analyzed. In both these investigations the high resolution and broad wavelength range of the LST could be of crucial importance.

The velocities of galaxies can be determined from the Doppler shifts of the lines in their spectra, which can be obtained with large instruments on the ground, such as the 200-inch Hale telescope on Mt. Palomar. To establish the distribution of galaxies in space, however, requires a knowledge of their distances, which are much more difficult to determine. In principle, the distances can be measured in two ways—either photometrically, from the apparent brightness of an object whose absolute luminosity is known, or geometrically, from the angle subtended by an object of known size. Most distance determinations of galaxies have been based on the photometric method, the brightness of individual stars being used for very close galaxies and the brightness of an entire galaxy, for more remote systems. The absolute luminosities of some individual stars can be determined rather accurately, especially in the case of the brilliant Cepheid variable stars for which the luminosity is strongly correlated with the period of variation. Hence distances determined from stellar photometry are relatively trustworthy. Galactic luminosities, on the other hand, are difficult to determine, and distances determined in this way may be subject to substantial errors.

One powerful capability of the LST would be that it could detect Cepheid variables, and measure their luminosity, at a distance of 10^8 light-years, ten times the distance at which such variable stars can be measured from the ground. At this distance of 10^8 light-years the velocity due to the expansion of the universe is believed to be roughly 3000 kilometers per second, sufficiently large to be relatively unaffected by random galactic motions. Thus the Hubble constant, H (the ratio between the expansion velocity and the distance) could be determined very precisely with the LST. The greatest distance at which Cepheid variables can be measured from the ground is not much more than 10^7 light years, and at this distance the expansion of the universe is largely masked by random local velocities. According to the "big-bang" theory, the time $1/H$ is proportional to the time since the "creation" or starting point of the expansion. Since the constant of proportionality in this relation depends on the structure of the universe, comparison of a precise value of $1/H$ and the ages of the stars should give basic information about the nature of the universe.

Distance measures for galaxies farther away than 5×10^9 light-years would give the large-scale curvature of the universe. In particular, nonlinearity in the velocity-distance relationship at great distances depends on the radius of curvature. The LST could be of vital importance in determining the distances of the most remote galaxies. The accuracy of values obtained photometrically would be improved by measurement at infrared wavelengths, since measurement in the visible region of the spectrum involves uncertain corrections for the red shift that results from the large velocity due to expansion at great distances. Also important would be the ability to obtain measures of the angular diameters of galaxies from detailed luminosity profiles. The turbulence of the atmosphere, with resulting fluctuations in the seeing, and fluctuations of the airglow make it quite impossible to obtain such measures from the ground for galaxies some 5×10^9 light-years away (angular size, at most 1 second of arc), and complicate such measurements for closer systems. The higher resolution and fainter, more stable brightness of the sky background in a space telescope should make measurement of angular diameters from the LST quite feasible. Similarly, for systems within about 10^9 light-years, the angular diameters of hydrogen-emitting regions, which would be measurable with the LST, could provide a good determination of distance, with probably much less scatter than is associated with photometric measurement of distances of individual galaxies.

Such considerations suggest a fascinating possibility. If the universe has an observably small radius of curvature, say about 5×10^9 light-years, the apparent diameters of objects at much greater distances should be observed to increase with increasing distance. Thus the plot of apparent diameter versus red shift should have a minimum, reached at a red shift, $\Delta\lambda/\lambda$, which depends on the average density of matter in the universe, and which is about unity if the gravitational energy is equal, and opposite, to the kinetic energy of expansion. A measurement of this effect would provide convincing proof of the overall curvature of the universe and would give directly values for both the radius of curvature and the corresponding density of matter.

Research on the second problem, the structure and evolution of galactic systems, would evidently be much advanced by the resolution capability of the LST. For example, compact nuclei are believed to be responsible for much of the explosive activity observed in galaxies, including the high luminosities observed from quasars, the high excitation observed in Seyfert galaxies, and the outward-streaming filaments of gas observed in a variety of systems. At least in the closer systems, the structure of galactic nuclei should be observable with the LST. A system 1 light-year in radius could be at least partially resolved even at a distance of 3×10^6 light-years; several dozen galaxies lie within about this distance. Some of the most active galactic nuclei are apparently much more luminous in the far-infrared, at wavelengths longer than 10 microns, than in the visible spectrum, and for detection and spectroscopic study of such systems even at very great distances the LST could be particularly useful.

Evolution of galaxies through time should produce measurable differences between systems some 5×10^9 light-years away and those close at hand, since the light from these remote systems started out toward the earth some 5×10^9 years ago, when the universe was perhaps half as old as it is now. The LST would permit examination of the structure of these remote systems, which, on pictures taken from the ground, appear only as tiny formless blobs.

Research on galaxies with the LST would not be a quick program, especially since exposures of several hours on many different objects would be required; it would be several years at least before any conclusive results could be obtained. However, it seems clear that the amount of detail visible in these stellar systems could be vastly increased with such an instrument. Surprises would doubtless turn up, perhaps fundamentally altering our viewpoint, but even the foreseeable results promise to add very greatly to our general knowledge of the universe.

Gas between the Stars

Interstellar matter is believed to play a major role in the evolution of a galactic system. Groups of new stars form from interstellar clouds, and massive old stars, in which heavy elements have been produced, explode as supernovae, ejecting their material back into interstellar space.

To study these phenomena the density, velocity, composition, and physical state of the interstellar gas must be determined. Important results have been obtained from measures of the radiofrequency line at 21-centimeter wavelength produced by neutral hydrogen atoms, and, in the visible spectrum, of absorption lines produced by neutral sodium (the D lines at 5890 and 5896 angstroms) and ionized calcium (the K and H lines at 3934 and 3969 angstroms). However, these lines are relatively weak; the oscillator strength for the 21-centimeter line is less by a factor of 10^{-12} than that for normal, "permitted" lines in the visible spectrum, and neutral Na and singly ionized Ca^+ are both relatively scarce, since the more highly ionized Na^+ and Ca^{++} predominate over neutral Na and singly ionized Ca^+, because of the very low electron density in intersellar space. The ultraviolet absorption lines of the abundant elements are very much stronger. For example, the O I line at 1302 angstroms will have an easily measurable equivalent width if the chemical composition of the interstellar gas is similar to that of the sun, and if the amount of interstellar gas in the line of sight is some 10^{-8} gram per square centimeter, which is about 10^{-3} as much as the amount needed to produce either observable absorption in the Na and Ca^+ lines or detectable emission in the 21-centimeter line of hydrogen. Most elements produce no interstellar absorption lines in the visible spectrum, since almost all atoms are in the ground level in interstellar space and a photon energy of more that 4 electron volts (corresponding to a wavelength of less than 3000 angstroms) is needed to excite atoms in permitted transition from the ground level. Hence the interstellar gas can be detected and analyzed from above the atmosphere with sensitivity greater by three orders of magnitude than that for ground-based observations.

To some extent this ability to detect the presence of very small amounts of interstellar gas can be exploited by smaller space telescopes. However, the LST, with its large photon-collecting area, could undertake research programs which are not feasible with smaller instruments. With a photoelectric image tube and exposure time of about an hour, a 120-inch telescope could obtain an ultraviolet spectrum of a 10th-magnitude blue star with the resolution of 0.1 angstrom needed for weak interstellar lines. Such a star would be at a distance of several thousand light years from the earth, the exact distance depending both on the absolute stellar luminosity and on the amount of obscuration produced by small solid particles or dust grains in the line of sight. Measures on such distant stars could yield far more detail on the galactic distribution and dynamics of the interstellar gas than can be obtained in any other way.

One of the significant problems that could be investigated with such equipment is the galactic corona or halo, the envelope of gas that extends thousands of light-years above and below the galactic plane. Present information on this subject is fragmentary; a few high-velocity clouds have been observed, from weak 21-centimeter emission and from Ca^+ line absorption. This gas may originate from intergalactic material falling into our own system or from gas shot out of the nucleus of our galaxy. Confinement of cosmic rays in this galactic halo has been suggested, but this possibility remains speculative for lack of data. Measurement on such physical quantities as the ionization and temperature of the gas, which are believed to be profoundly affected by the energetic particles in the cosmic radiation, and the detailed velocity distribution of different clouds of gas would open up essentially a new field of research.

The motions of gas in spiral arms, which may have an important effect on the structure of these features, could also be investigated with the LST. An intrinsically bright star with an apparent magnitude of 10, the limiting magnitude, as noted above, for spectroscopic observation with the LST, might be some 10,000 light-years away. This distance is great enough so that stars in other spiral arms, in addition to the local arm in which the sun is situated, could be observed with the LST, and the gas in these arms could be analyzed in detail. One outstanding problem, which is evidently vital to our understanding of the way in which spiral arms form and are maintained, is the ratio of gas densities between and inside the arms; whether this ratio is as high as a few percent or possibly very much less would perhaps be revealed by LST observations.

The infrared capabilities of the LST could also contribute significantly to research on interstellar matter. Extended infrared sources or infrared nebulas have been observed through available infrared windows in our atmosphere. Some of these sources are believed to be contracting interstellar clouds about to condense into a multitude of new stars. Both the resolution capability of the LST, which would give a beam of 1 second of arc at a wavelength of 10 microns, and the large collecting area for photons, which would facilitate detailed spectrophotometry, should be useful in analyzing the way in which stars form from interstellar clouds.

Solar System

For systematic study of the planets and their satellites the LST would be a most useful instrument. Even for Mars and Venus, the two planets that have been reached by planetary probes, a 120-inch telescope in orbit around the earth could yield systematic and continuing data not obtainable in any other way, except with special observatories orbiting around the planet of interest. The telescope's resolving power of 0.04 second of arc would give resolution of surface detail ranging in size from 8 kilometers on Venus to about 700 kilometers for Uranus and Neptune.

Continuing observations of the cloud systems on these planets could open up a new field of research in planetary weather. This possibility would be enhanced by spectroscopic observations with high frequency resolution and high spatial resolution as well. For example, variation of the planetary radiation, including various absorption lines, very near the edge of the planetary disk would give detailed information on the distribution, with height, of various atmospheric constituents. In addition, the temperature of the Martian atmosphere, as a function of position and height, could be determined from emission profiles of molecular lines in the infrared, such as the 15-micron band of CO_2, with high spatial and spectral resolution. Changes of these distributions with time, together with changes in apparent cloud structure shown in high-resolution images, would provide observational data needed for a detailed analysis of planetary meteorology.

The surface detail on Mercury would be of particular interest. If the history of that planet has been similar to the history of the moon, several hundred craters should be detectable on Mercury with the LST. The number of craters observed might give important information on the early history of the solar system, especially on the number of meteors and asteroids in the solar system relatively close to the sun. In order to photograph a planet so close to the sun without excessive heating of the instrument, special arrangements would probably be required to keep the LST in shadow during the observations. Surface details on the larger asteroids and on the satellites of Jupiter would also be interesting.

Conclusions

The programs outlined above represent some of the exciting astronomical problems suggested for the LST. This great instrument could be of central importance not only in the study of cosmology and the other areas described above but in many additional areas of astronomy, including cometary research, studies of stellar evolution, and the determination of stellar masses and distances.

Experience indicates that some of the most exciting results obtained in a space program are likely to be those which had not been foreseen. Improvement of observational capability by an order of magnitude, both in spatial resolution and in photon-gathering capacity at ultraviolet and infrared wavelengths, is bound to lead to unexpected results in the study of the heavens.

While the LST would be an extremely powerful tool, its efficient utilization would require active astronomical programs both with other, smaller space instruments and with ground-based facilities. Orbiting telescopes with apertures of 30 to 60 inches and smaller instruments launched in sounding rockets can be used for a variety of important astronomical problems, such as determination of the ultraviolet luminosity of hot stars and the chemical composition of the interstellar gas within several hundred parsecs. Quite apart from the engineering desirability of launching smaller space telescopes before building the large instrument, the astronomical requirement for a continuing series of smaller space telescopes should be an overriding consideration in setting the pace of the LST effort.

Similarly, the LST must rely heavily on ground-based research both in selecting objects to observe and in interpreting the results. For example, the red shifts and other characteristics of different galaxies and the spectral types and colors of wide classes of stars would have to be observed from the ground before LST time could be allocated intelligently. Particularly for the southern hemisphere of the sky, such information is now fragmentary; if the LST were available today, an appreciable fraction of its time would probably be used in making observations of southern stars and galaxies, some of which could be made about as well (and much more economically) from the ground as from space. Moreover, for spectroscopic observations in visible light, a large instrument on the earth's surface is generally preferable to a space telescope. Ground-based astronomy, including research with x-rays, γ-rays, and radio waves as well as with solar, stellar, and nebular light, forms a single discipline, and will best advance together. A proper balance between the various parts of this unified discipline should be provided, both in scientific effort and in funding. For a small percentage of the cost of the LST program, the facilities for ground-based astronomy could be doubled. Such a step would increase both the value and the efficiency of the space astronomy program.

In summary, the following four conclusions may be drawn:

1) The LST would make a dominant contribution to our knowledge of cosmology—to our understanding of the content, structure, scale, and evolution of the universe.

2) In many other fields of astronomy, also, the LST would give important and decisive information.

3) An efficient space astronomy program cannot be carried out by the LST alone. A continuing series of smaller space telescopes is also required.

4) The most effective utilization of powerful space telescopes requires a substantial increase in the number of ground-based instruments.

Notes

1. *Space Research, Directions for the Future* (Space Science Board, National Academy of Sciences–National Research Council, Washington, D.C., 1966), pt. 2.
2. Members of the LST Committee are as follows: A. D. Code (University of Wisconsin); L. W. Fredrick (University of Virginia); F. J. Low (University of Arizona); G. Münch (Mt. Wilson and Palomar Observatories); H. J. Smith (University of Texas); L. Spitzer (Princeton University), *chairman*; W. G. Tifft (University of Arizona); and F. L. Whipple (Smithsonian Astrophysical Observatory).
3. Much of the concluding section of this article is taken directly from the committee report.