Scientific Uses of the Large Space Telescope

Ad Hoc Committee on the Large Space Telescope,
Space Science Board, National Academy of Sciences,
National Research Council

ISBN: 0-309-12363-1, 56 pages, 8 1/2 x 11, (1969)

This free PDF was downloaded from:
http://www.nap.edu/catalog/12399.html

Visit the National Academies Press online, the authoritative source for all books from the National Academy of Sciences, the National Academy of Engineering, the Institute of Medicine, and the National Research Council:

- Download hundreds of free books in PDF
- Read thousands of books online, free
- Sign up to be notified when new books are published
- Purchase printed books
- Purchase PDFs
- Explore with our innovative research tools

Thank you for downloading this free PDF. If you have comments, questions or just want more information about the books published by the National Academies Press, you may contact our customer service department toll-free at 888-624-8373, visit us online, or send an email to comments@nap.edu.

This free book plus thousands more books are available at http://www.nap.edu.

Copyright © National Academy of Sciences. Permission is granted for this material to be shared for noncommercial, educational purposes, provided that this notice appears on the reproduced materials, the Web address of the online, full authoritative version is retained, and copies are not altered. To disseminate otherwise or to republish requires written permission from the National Academies Press.

THE NATIONAL ACADEMIES
Advisers to the Nation on Science, Engineering, and Medicine

Scientific Uses of the Large Space Telescope

AD HOC COMMITTEE ON THE LARGE SPACE TELESCOPE
SPACE SCIENCE BOARD
NATIONAL ACADEMY OF SCIENCES–NATIONAL RESEARCH COUNCIL

NATIONAL ACADEMY OF SCIENCES
WASHINGTON, D.C.
1969

Available from
Space Science Board
2101 Constitution Avenue
Washington, D.C. 20418

PREFACE

The Committee on the Large Space Telescope was appointed by the Space Science Board of the National Academy of Sciences to consider the scientific functions and the practical feasibility of placing in orbit around the earth or, conceivably, on the surface of the moon, a diffraction-limited optical telescope with a nominal aperture of 120 in. The Committee is a continuation of the Working Group on Optical Astronomy, one of the working groups organized by the Space Science Board to carry out at Woods Hole, Massachusetts, during the summer of 1965, a study of the nation's long-range space program.*

While the Committee has given thought to the engineering aspects of such a complex facility, its principal responsibility has been to isolate the astronomical questions whose solutions depend on the Large Space Telescope (LST). To assist in this task, three conferences were held, each devoted to topics in astronomy most likely to require the telescope and each attended by a number of invited astronomers specializing in those fields.

Meeting on Galaxies and the Universe, and on Interstellar Matter (California Institute of Technology, July 18 and 19, 1966): J. L. Greenstein, Mt. Wilson and Palomar Observatories; T. D. Kinman, Lick Observatory; C. R. Lynds, Kitt Peak National Observatory; E. E. Salpeter, Cornell University; A. R. Sandage, Mt. Wilson and Palomar Observatories; M. Schmidt, Mt. Wilson and Palomar Observatories; G. de Vaucouleurs, University of Texas; and A. E. Whitford, Lick Observatory.

Meeting on the Solar System (University of Arizona, December 7, 1966): W. A. Baum, Lowell Observatory; J. W. Chamberlain, Kitt Peak National Observatory; G. P. Kuiper, University of Arizona; T. C. Owen, Illinois Institute of Technology; D. G. Rea,

---

*The working group's report, a substantial portion of which is devoted to the Large Space Telescope concept, is published in *Space Research: Directions for the Future,* Report of a Study by the Space Science Board, Woods Hole, Massachusetts, 1965, NAS-NRC Publ. 1403 (Nat. Acad. Sci. - Nat. Res. Council, Washington, D.C., 1966), pp. 147-175.

University of California, Berkeley; J. D. Strong, The Johns Hopkins University; and J. A. Westphal, California Institute of Technology.

Meeting on the Stars and Other Problems (Harvard College Observatory, March 6 and 7, 1967): W. P. Bidelman, University of Michigan; G. R. Burbidge, University of California, San Diego; G. H. Herbig, Lick Observatory; K. A. Strand, U. S. Naval Observatory; B. Stromgren, Institute for Advanced Study, Princeton; P. van de Kamp, Sproul Observatory; G. Westerhout, University of Maryland; and C. A. Whitney, Smithsonian Astrophysical Observatory.

The present report is largely an outgrowth of these conferences and represents the ideas and suggestions of many astronomers. Following the conclusions of the study and of the performance characteristics of the space telescope, four chapters treat the scientific investigations particularly appropriate to the telescope.

The Space Science Board is grateful to the panel members and specialists who contributed to this study. The Board acknowledges with appreciation the support of the National Aeronautics and Space Administration, which helped to make this study possible.

H. H. Hess, *Chairman*
Space Science Board

CONTENTS

SPACE SCIENCE BOARD

H. H. Hess, *Chairman*

Luis W. Alvarez
Allan H. Brown
Loren D. Carlson
John W. Findlay
Herbert Friedman
John S. Hall
Francis S. Johnson
William M. Kaula
Donald B. Lindsley
Gordon J. F. MacDonald
Nicholas U. Mayall
Courtland D. Perkins
Richard W. Porter
William W. Rubey
Leonard I. Schiff
James A. Van Allen
Wolf Vishniac

G. A. Derbyshire, *Executive Secretary*

AD HOC COMMITTEE ON THE LARGE SPACE TELESCOPE

L. Spitzer, Princeton University, *Chairman*

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
W. G. Tifft
University of Arizona
F. L. Whipple
Smithsonian Astrophysical Observatory

E. R. Dyer, National Academy of Sciences, *Secretary*
(through March 1968)
B. N. Gregory, National Academy of Sciences, *Secretary*
(from April 1968)

Invited Participants from National Aeronautics and Space Administration

J. E. Kupperian
L. Roberts
N. G. Roman

Chapter 1

CONCLUSIONS

Based on its study of the scientific potential of the Large Space Telescope (LST), the Ad Hoc Committee on the Large Space Telescope arrived at four major conclusions:

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.* The sharp images--less than 0.1 sec of arc in diameter--provided by the telescope would yield a limiting visual magnitude of about 29 for stellar photometry; this magnitude is about a hundred times fainter than any that can be observed from the ground. This capability should permit photometric determination of distances of galaxies with a precision sufficient to yield the scale and curvature of the universe; measurements of diameters of H II regions and galaxies would give independent checks. Studies of the content and structure of galaxies at different distances and hence at different epochs would give information on the evolution of galaxies.

2. *In many other fields of astronomy, also, the LST would give important and decisive information.* Ultraviolet and infrared spectroscopy, combined with high spatial resolution and large collection area, would render a variety of major problems accessible to solution. For example, measurements of ultraviolet absorption lines provide a thousandfold increase in sensitivity for detecting interstellar matter, and the LST could for the first time measure the density, composition, and physical state of the gas within the galactic halo, which is likely to play an important part in the dynamical history of our own galaxy. Also, measurement of infrared emission could locate and analyze contracting gas clouds where stars are presumably being born, thus elucidating this early stage in stellar evolution. Ultraviolet stellar spectra obtainable with the LST could yield basically new information on highly evolved stars, such as supernovae and hot white dwarfs, as well as on coronal and chromospheric activity in a wide variety of stellar types.

3. *An efficient space astronomy program cannot be carried out by the LST alone. A continuing series of smaller telescopes is also required.* Some astronomical problems, such as the size and structure of the universe, can be solved only by the LST. Other problems, such as the ultraviolet luminosity of hot stars and the chemical composition of local interstellar gas, can be handled by instruments with apertures of from 30 to 60 in. These smaller telescopes and sounding-rocket instruments would provide important research programs to be followed up with the LST and would free this powerful facility to carry out those observations for which it is unique. Apart from the engineering desirability of gaining experience in the special problems of space telescopes by launching smaller instruments before building the large one, the scientific need for a continuing series of smaller space telescopes should be an overriding requirement in setting the pace of the LST effort.

4. *The most effective utilization of powerful space telescopes requires a substantial increase in the number of ground-based instruments.* To choose suitable objects for observation by the LST requires many preliminary observations of such phenomena as the red shift and other characteristics of different galaxies and the spectral types and colors of wide classes of stars. Information for the southern hemisphere of the sky is particularly fragmentary; if the LST were available today an appreciable fraction of its time would probably be allocated to observations on the Magellanic Clouds and other southern stars and galaxies, some of which could be observed well enough and much more economically from the ground but have not been because the large ground-based telescopes that could provide such observations have not existed. Moreover, for spectroscopic observations in visible light, a large instrument on the earth's surface is generally preferable to a space telescope. Ground-based and space astronomy, including research with x rays, γ rays, and radio waves as well as with solar, stellar, and nebular light, form a single discipline and will best advance together. A proper balance among the various techniques and investigations in this unified discipline should be provided, both in scientific effort and in funding. Facilities for ground-based astronomy should be at least doubled--the cost would be a small percentage of that of the LST program--thus greatly increasing the value of the space astronomy program both by improving scientific insight and by avoiding space observations that could have been made from the ground.

Chapter 2

PERFORMANCE CHARACTERISTICS OF THE LARGE SPACE TELESCOPE

The Large Space Telescope (LST), like a large telescope on the ground, would be a general-purpose optical facility, designed to collect photons from some direction in the sky and bring them to a focus where they could be analyzed. For full effectiveness the LST should satisfy the following four requirements:

Wavelength Range The LST should gather light effectively over the largest possible range of wavelengths. This requirement is of particular importance for a space telescope, since analysis of photons with a wavelength less than 3000 A or between 10000 A and 1 mm is one of the main objectives in placing a telescope above the atmosphere, which absorbs most of such photons.

Imagery The image of a point source should be nearly as sharp as is permitted by the finite wavelength of light and held steady with respect to the photon-analyzing instruments. The field of view over which good images are obtained should be as wide as feasible. Sharp imagery is the second main objective in placing a telescope above the atmosphere, whose motions and thermal microstructure corrugate the wavefront, with a resultant loss of phase coherency, together with spreading and distortion of the image.

Instrumentation A wide variety of photon-analyzing instruments, including cameras, image tubes, photometers, and spectrophotometers, should be usable. The necessary environmental conditions for using such instruments should be obtainable, for example, low temperature, thermal stability, and some shielding against background radiation.

System Effectiveness The accessibility, operability, reliability, and flexibility of the telescope, its scientific instrumentation, its other components in space, and its technical and scientific support on the earth's surface should be such that the most significant data can be obtained without appreciable loss in precision, quantity, or variety, during perhaps several decades or more, with resupply and maintenance.

Each of these requirements is discussed in detail below.

Wavelength Range

With a conventional Cassegrain system, using a large concave primary mirror and a convex secondary mirror, the wavelength response is determined entirely by the reflection coefficient of the coating used on the mirror surfaces. Standard aluminum coatings normally have reflection coefficients greater than 85 percent for visible light and increasing reflection at longer wavelengths. An aluminum oxide layer which forms on the coating reduces the reflection coefficient at wavelengths below 1600 A; an overcoating of LiF, however, can yield a coefficient of about 60 percent down to about 1000 A. Thus it seems clear that the LST could concentrate photons effectively over the wavelength range from 10^{-5} to 10^{-1} cm.

Photons between 900 and 1000 A can be observed with a telescope of the sort envisaged here, but with existing metallic coatings the optical efficiency at 900 A may be as low as 1 percent. Grazing-incidence optics, which are required for x rays, can be used for this range but their very small field makes such systems unsuitable for the longer wavelengths. The telescope need not be sensitive at wavelengths shorter than approximately 900 A, since any photons from outside the solar system in the wavelengths between 912 and approximately 100 A are probably absorbed by interstellar hydrogen.

If the telescope were in an orbit at low altitude (approximately 500 km), the reflecting surface might be degraded by oxygen-atom bombardment, resulting in increased small-angle scattering and loss of reflectance in the ultraviolet. Frequent recoating would then be required. The likelihood of damage by meteoroid particles appears negligible, at least over a span of several years.

Imagery

To give diffraction-limited images, a telescope must satisfy several successive requirements. (a) Reflecting surfaces must not deviate from their ideal shape by more than $\lambda/50$ rms, where λ is the wavelength of light. The successful polishing and testing of the 36-in. Stratoscope II mirror suggest that even larger optical systems can be made diffraction-limited. (b) Thermal distortions in space of the reflecting surfaces must be negligible. Analysis indicates that if fused silica is used for the mirror disk, distortions can be kept to acceptable levels (Spitzer and Boley, 1967); use of new types of glass having lower coefficients of expansion or of complex servo systems to maintain the figure of the primary reflecting surface would further reduce the thermal problem. (c) The orientation of the telescope must be held fixed with respect to the apparent position of the objects being observed. For a circular aperture of radius a the angular radius of the first dark ring of the diffraction pattern is $0.61\ \lambda/a$ rad, giving 0.04 sec of arc at 5000 A for a telescope of 120-in. (3-m) aperture. To take pictures with no significant degradation below the diffraction limit, pointing should be steady to within a tenth of this diffraction radius, or 0.004 sec of arc. For comparison, Stratoscope II, a 36-in. balloon-launched telescope, has demonstrated a pointing stability better than ±0.03 sec of arc rms for periods of several minutes during a flight. There seems to be no fundamental reason why diffraction-limited performance by a large space telescope should not be possible during exposures of several hours, or even days. If the telescope is in a low-altitude orbit, a long exposure would generally be interrupted by occultation behind the earth; however, the source could be reacquired on the next orbit and the exposure resumed.

Given an ideal circular aperture of uniform reflectance, 83.8 percent of the radiant energy appears inside the first dark ring of the diffraction pattern. One may assume that at the focal plane of the LST at least 70 percent of the radiant energy would fall within this circle.

The amount of radiation reaching the focal plane at a large angular distance from a point source is determined partly by scattering from the optical surfaces and the sides of the telescope tube and partly by the wings of the diffraction pattern. It is believed that with suitable shields and baffles scattered light from the sun and the earth can be made negligible provided that the instrument is not pointing closer than either approximately 45° to the sun or approximately 15° to the limb of the earth. Thermal emission from the primary and secondary mirrors, which is a limiting factor in the far infrared, will be limited by the low emissivity of the mirrors (less than 0.02), and by the relatively low mirror temperature (200 to 250 K in a low orbit, and perhaps substantially lower in a high orbit).

The size of the angular field is limited by the optical aberrations of the primary-secondary combination. With a Ritchey-Chrêtien system, coma is absent, and the size of the field is limited by astigmatism. With a 120-in. telescope and a primary focal ratio of about *f*/5, diffraction-limited images should be obtainable over a slightly curved field about 10 min of arc in diameter. For many scientific purposes very small fields are adequate; a field diameter less than 1 min of arc will include most of a distant galaxy. For other purposes, it would be desirable to record as large a field as practical.

Instrumentation

Light reaching the focal plane of the LST can be reimaged on a wide variety of light detectors and analyzers; in the reimaging, the focal ratio can be modified to provide a beam compatible with each particular detector and analyzer.

Image tubes and television cameras may be used to photograph restricted portions of the sky at highest resolution, down to the faintest magnitudes. To match the present spatial resolution of these devices, equivalent focal ratios between *f*/100 and *f*/200 are appropriate, in order that the diffraction-limited imagery not be degraded significantly by the finite resolving power of the detector.

In some cases where high resolution is required over a larger field, direct photography in a faster light beam (*f*/10 or *f*/20), using large, very-fine-grained film plates with very large data-storage capacity, may be advantageous despite the much longer exposure times required. Electronography might make it possible to store the same information on a smaller photographic area with a shorter exposure time. However, radiation damage to film is a serious problem, especially in a low orbit, where protection from energetic protons might require prohibitive amounts of shielding. Television cameras, with electrical readout, can operate without difficulty between occasional bursts of energetic particles and are likely to be the primary imaging detectors used in a space telescope.

Photometers with filters and wide-band scanning spectrophotometers may be employed to analyze the light focused by the telescope. For wavelengths between 3000 and 11000 A, photocells need to be refrigerated for low dark count, with temperatures below -30°C. For detectors used further in the infrared, lower temperatures are needed, with liquid helium cryogenics required for very long wavelengths. Special photometers may also be used to measure polarization.

Spectrophotometry with high spectral resolution can be carried out with single-channel detectors, such as a single photomultiplier tube, or with multichannel detectors, such as image tubes, television cameras, and possibly photography. For stability during a long exposure, the temperature of such an instrument must usually be constant to within better than $1^{o}C$.

An absolute pointing accuracy at least as good as 1 sec of arc is required of the LST. If photomultiplier tubes are used for the photometry of very faint stars, an accuracy of 0.1 sec of arc may be needed to center the image in a very small entrance aperture (see Appendix A). As noted above, pointing direction must be steady to within about 0.004 sec of arc during each astronomical exposure to prevent degradation of high-resolution imagery. The time required to shift from one star to another in an entirely different region of the sky should be less than 10 min and preferably about 5 min, including time for acquisition and fixing on the new star. In a low orbit, this short acquisition time would permit almost constant use of the telescope despite the fact that the earth occults most stars for about 30 of every 100 min.

Stabilization and pointing within an error of at most 5 sec of arc over 10 min of time should be attainable with the telescope's inertial guidance system. Presumably the method of fixing on offset guide stars, which has been used successfully on Stratoscope II, would be employed for finer absolute pointing accuracy and for stabilization during an exposure. Instruments using narrow entrance slits and apertures and requiring an initial telescope setting with an uncertainty of less than 1 sec of arc may provide their own guidance error signals, with starlight reflected from slit jaws, for example.

System Effectiveness

Spacecraft systems, such as power supplies, data storage units, and transmitting equipment, as well as components of the telescope itself, must be extremely reliable over a long period of time to permit continuous and efficient operation of the scientific instrumentation and transmission of high-quality data to earth. In view of the cost and magnitude of the initial installation, the telescope must be capable of full operation for many years.

To meet these requirements, manned servicing of the facility seems unavoidable. The presence of man, at least at intervals, appears essential for three major functions: initial alignment, adjustment, and checking of the telescope and of the scientific and support equipment; maintenance of the equipment, including periodic inspection and repair; and modification of the system, particularly replacing and updating the instrumentation as the scientific program demands. Astronauts might also participate on occasion in the scientific operation of the equipment, although under most circumstances the telescope would probably be programmed by direct control from the earth. It is desirable that the facility be capable of unmanned operation for many months; it might be manned only at regular intervals.

If man is considered essential to the long-term operation of the LST, the telescope should be designed so that all its components can be maintained, repaired, or replaced in orbit. Further, since activity, particularly precision work, is extremely difficult in a space suit, the chamber containing most of the astronomical instrumentation should probably be capable of pressurization so that astronauts can make instrumental modifications and adjustments in a shirt-sleeve environment. A manned space station nearby, with full life-support equipment, would probably be required also.

An efficient ground installation would be essential to effective use of the LST. Most, if not all, of the telescope's observational sequences would be controlled from the ground necessitating, for example, "quick-look" analysis by scientists of data that may affect subsequent programming. The monitoring analysis and programming of the spacecraft systems will be a complex engineering task. Scheduling of scientific investigations will require careful organization, since the number of different possible programs and users would be very great and the total telescope time requested would probably very much exceed the time available.

A fundamental prerequisite for effective use of the LST is an active program of ground-based astronomy. As shown in succeeding sections of this report, the LST could provide the answers to many of the central questions in modern astronomy. However, observing time on such an instrument would necessarily be limited, and ground-based equipment must be relied on for the broad advance of astronomy as a whole, which is required to point out the most interesting questions and to provide the LST with problems best suited for this unique instrument. Thus to achieve the fullest return on the large investment required by the LST, a substantial expansion of ground-based facilities is required.

Observational Improvement Attainable

The limiting magnitude capability of the LST and the necessary exposure or integration times both for photoelectric photometry and imaging are discussed in Appendix A. The general conclusions are summarized here.

The limiting magnitude gains of a space telescope can be understood on simple qualitative grounds. The image sizes recorded on long exposures made from earth are usually limited to a diameter of about 1 sec of arc. Thus a typical star image occupies about 1 (sec of arc)^2 in the sky. The dark night sky seen from earth has a photographic brightness of 22.2 mag (sec of arc)$^{-2}$, and stars of magnitude 23 or fainter can be detected with the best ground-based instruments. The star image obtained with the LST would have a diameter rather less than 0.1 sec of arc and an area less than 1/100 the area of the same star seen within the atmosphere. Also, the sky in space is darker because of the absence of terrestrial airglow and may be taken as about 23 mag (sec of arc)$^{-2}$. If the effective image diameter is taken to be 0.08 sec of arc, the image area is about 0.005 (sec of arc)^2 and the magnitude of an equal area of the sky, about 29. Extraordinarily faint objects are thus accessible to study by the LST.

With conventional photography, stellar sources at a limiting magnitude (m_ℓ) of approximately 28 could be acquired by the LST in 24-hr exposures. Using image-tube techniques, this time should in principle be reduced by a factor of about 10. Even assuming restriction by filters of the wavelength band, image-tube exposures should rarely exceed 5 to 10 hr to reach stars of magnitude 29. Thus, given plausible advances in image-tube and television-tube technology, there is no insuperable barrier to carrying out significant extragalactic investigations on a number of such faint stars when these are of crucial importance.

Photomultiplier measurements of the faintest objects would be impeded by the dark count, which even for the quietest tubes now available amounts to some 3600 counts hr^{-1}, about 50 times the signal from a star of magnitude 29 during the same time. In addition, the aperture diameter for a photoelectric measurement would probably have to exceed the image diameter of 0.08 sec of arc by a substantial margin. Nevertheless, even assuming present dark counts and an aperture diameter of 0.4 sec of arc, a photometric accuracy of some 10 percent could be achieved with an integration time of 3 hr on an object of magnitude 27 (see Table A1, page 45). If image tubes of sufficient linearity and precision can be developed, the use of photomultipliers may become unnecessary.

Reference

Spitzer, L., and B. Boley, J. Opt. Soc. Amer. *57*, 901 (1967).

Chapter 3

EXTERNAL GALAXIES AND THE UNIVERSE

Although major uses for the Large Space Telescope (LST) exist in nearly all branches of astronomy, such an instrument may well play its most important role in extragalactic research.

The ultimate goal of astronomy is to comprehend the large-scale structure of the universe--its size, form, age, and evolution. Much progress toward first-order solutions has already been made using earth-based telescopes, and much more is possible; but the problems inherent in working through the atmosphere nevertheless set some limits to extragalactic observations. The brightness of the night sky produced by terrestrial airglow and the variability of this brightness interfere with the measurement of faint sources; atmospheric absorption blocks ultraviolet and infrared wavelengths which contain important information relevant to the energy distribution and evolution of galaxies. But the most serious restriction is that of angular resolution, normally limited to about 1 sec of arc for long exposures made from the earth's surface. Definitive answers to cosmological questions may depend on data from sources near the fringe of the observable universe at distances greater than 2×10^9 pc, at which galaxies approximately 10,000 pc in diameter subtend less than a second of arc as seen on the sky. An increase in linear resolution by a factor of 10 leads to a hundredfold increase in the resolvable information from any area of the sky, and if we extrapolate from our experience with objects nearby, it is in this range that some of the details of greatest interest are to be found.

For example, the high resolution specified for the LST--on the order of 0.04 sec of arc--would open up study of the fine structure of bright galaxy nuclei. It would allow observation of the brightest individual stars, clusters, H II regions, and other objects in selected galaxies out to nearly 10^8 pc. It would make possible detailed study of the internal distribution and indirectly perhaps also of the dynamics of matter in both normal and abnormal types of galaxies out of the tens of thousands available from space. Such information, of great intrinsic interest especially in unusual cases, such as the apparently exploding galaxy M82, may also have cosmological relevance.

The capability of the LST to detect and measure stars of apparent magnitude 28 to 29 should permit checking and refining the luminosity calibrations of certain objects which are fundamental to the near and intermediate distance scales. Direct intercomparison of many distance indicators, faint as well as bright, among a substantial number of galaxies will considerably enhance the accuracy and confidence in the distance-scale work. With local galaxies, it will also be possible to study relationships of the important horizontal branch stars to the main sequence. At intermediate distances, where the brightest individual stars or nebulae can still be resolved, a large number of galaxies of all types would be accessible to the LST for further checks and calibrations of their brightest stars, H II regions, novae, cepheids, and the like. It would no longer be necessary to depend so substantially on what may be a local supercluster of galaxies for this intermediate-distance step. The assumption of homogeneity of content of galaxies, while no doubt a reasonable first approximation, should be tested as carefully as possible to the greatest attainable distance in various directions.

Such research on galaxies at high angular resolution with the LST would be relatively slow. In comparison with the 200-in. ground-based telescope, the LST would receive only about half as many photons per second and, with its tenfold higher resolution, would divide these photons among a hundred times as many picture elements. Fortunately, with the use of image tubes, at least ten times more sensitive than photographic film, the exposure times required to achieve limiting magnitudes with the LST should be within an order of magnitude of the 30 min typically used for direct photography at the prime focus of the 200-in. (see Appendix A). Over a period of years, a substantial number of galaxies could be observed with this resolution, and stars in the outlying regions of galaxies, where overlapping of stellar images should be unimportant, could be detected to magnitude 28 or even 29.

Several kinds of information to be derived from the extragalactic program are discussed below.

Expansion of the Universe

Although the basic constants of physics are now known to many significant figures, the fundamental values corresponding to the large-scale structure of the universe are uncertain even in the first significant figure and, in the case of mean density, even as to order of magnitude. The most important of these cosmological parameters, the Hubble constant, H, represents the apparent rate of expansion of the universe as determined by the red shift of galaxies. Over the last several decades, both major and minor corrections have been made in the value assigned to H, the net effect being a reduction by more than a factor of 5 from Hubble's older value of 530 km sec^{-1} Mpc^{-1}; even today H remains uncertain within perhaps 50 percent, although work in progress with the 200-in. may be able to establish at least the local value of H to better than 10 percent.

A principal application of the Hubble parameter follows from its inverse--a number having the dimension of time--which measures some characteristic interval associated with the expansion of the universe. Although the current value of $1/H$ (10^{10} yr) is close to the age of the oldest known objects in the universe, the uncertainty in H remains serious. For example, an important test of the "big-bang" theory of the creation of the universe is the relation between $1/H$ and the ages of the oldest stars. Also, as cosmology becomes increasingly an exact science, we can be certain that theorists will demand the second and then higher significant figures in so fundamental a constant as H, both in order to discriminate among models and to use the numerical value in calculating associated parameters of interest.

Even assuming that H is isotropic, at great enough distances and therefore far enough back in time a deviation from linearity of the velocity-distance relation should appear as a result of acceleration or deceleration in the expansion of the universe. Some cosmologies also predict a departure from linearity apart from any effects of time. Observation of the fundamental parameter, q, which measures this nonlinearity, is thus central in distinguishing among models of the universe. To the distance limit of several billion parsecs set by ground-based observations of giant galaxies, it will be difficult indeed to measure q within 10 percent accuracy. The use of such special objects as quasistellar sources (quasars), which may be more distant, depends on highly uncertain calibrations. With a large, high-resolution instrument in space, the velocity-distance relation for galaxies can be extended to more distant objects and made more precise for the closer objects, thus yielding improved values for both H and q.

Complicating the determination of H, q, and other basic parameters are systematic changes in the brightness and color of galaxies due both to their red shifts and their evolution in time (at greater distances we see galaxies in earlier stages of evolution); corrections must therefore be applied to the observed magnitudes. These corrections must now be determined from theoretical models bearing on origin and evolution of galaxies coupled with careful ground-based spectrophotometry covering the entire range of accessible wavelengths. Relatively small orbiting telescopes will add the important ultraviolet energy distributions for nearby bright elliptical galaxies. Such techniques will probably suffice for the first-order assault on the cosmological problem, out to red shifts $z(=\Delta\lambda/\lambda)$ between 0.5 and 1. But attempts to study relatively normal giant galaxies out to $z = 2$ or farther will almost certainly require the LST for detailed information on the ultraviolet spectra of objects at intermediate distances. (Indications of peculiar ultraviolet effects in the nuclear regions of relatively normal galaxies nearby are already coming from the small instruments on the first successful Orbiting Astronomical Observatory.)

A further potential complication to brightness measurements of distant galaxies comes from the possible existence of absorbing material diffusely distributed between galaxies or in fainter intervening galaxies. Such absorption is virtually certain to decrease with increasing wavelength and may therefore be detected by comparing photometric measurements made over a wide range of wavelengths from the ultraviolet to the infrared. Again, the faintness of the sources, their extended spectral range, and their small angular scale make the LST the most appropriate tool for this work.

The previous discussion has emphasized luminosity and red shift as the principal distance parameters. It seems unlikely that cosmologists will rest content with conclusions based solely on these, when independent distance determinations of galaxies can also come from refined measurement of diameters. As one example, the largest H II regions in galaxies appear to have a rather small range in their true sizes; when this function has been more fully calibrated over a wide variety of galaxies nearby, measurements of angular diameters will permit this distance criterion to be used on objects as far away as several hundred million parsecs. A much larger step should follow if it proves possible to measure the effective angular diameters of the galaxies themselves, corresponding to a metric diameter as measured, for example, by the photometric contour at the half-power level. To utilize diameters of galaxies as indicators of distances, one must calibrate precisely the luminosity profiles of typical galaxies. Because of terrestrial airglow and its rapid variations, the extremely low surface brightness of the outer fringes of galaxies cannot be measured very accurately from the ground. In the case of very faint, distant galaxies, the entire galaxy shrinks to an apparent size such that atmospheric turbulence ("seeing") wipes out the image structure. The high resolution of the LST together with the low surface brightness and unvarying transparency of the sky in space should permit effective utilization of this second index of distance. At still greater distances, the diameters of clusters of galaxies may prove useful.

Density of Matter in the Universe

An important class of problems is based on the large-scale effects of gravity. In several different ways these effects suggest the presence of very substantial amounts of undetected matter. On the largest scale, the general theory of relativity asserts that the mean curvature of space and hence the volume of the universe depends on the average density of matter. If the present value and interpretation of the Hubble parameter can be trusted, the "radius of the universe" implies a mean density of perhaps 10^{-29} g cm^{-3}. But the most careful attempts by astronomers to determine the visible matter yields observed mean densities in the range of only 10^{-30} to 10^{-31} g cm^{-3}. A similar deficiency appears in studies of the masses of some clusters of galaxies, where arguments based on the virial theorem require the presence of at least ten times the amount of visible matter in order to account for the observed velocities in a stable configuration. The well-known Oort limit, with its 50 percent deficiency of visible matter (sufficient to produce the measured vertical components of velocity with respect to the galactic plane) may be another example of the same effect. Rather than reject basic theories and assumptions, many astronomers have preferred to postulate that as much as 90 to 99 percent of the matter of the universe may so far be undetected. Several suggestions have been put forth to account for this "missing matter." Some of it, for example, could be in the form of faint galaxies and intergalactic stars: the intergalactic volume, if populated with less than 10^{-4} the mean density of matter in our galaxy in the neighborhood of the sun, suffices to account for the difference. Successful detection and study of such galaxies and stars may prove to depend on the dark sky and high resolving power available to the LST, although to be sure such detection would normally be only a by-product of other investigations. Alternatively, large amounts of diffuse gas may account for undetected matter. Detection of such gas by its emission or particularly by its absorption of light from relatively faint background sources is likely to need the wavelength range available from space and the power of a large telescope-spectrograph combination, although an instrument of smaller aperture than the LST might be adequate for this purpose (see Chapter 5).

According to general relativistic models of a curved universe, the effective (although not the isophotal) angular diameters of galaxies should cease to decrease with increasing distance, and rather should increase again slowly at distances larger than the radius of curvature. The red shift, z, corresponding to a minimum angular diameter, varies with the density of matter in the universe (Sandage, 1961; Zeldovitch, 1965), and equals approximately unity if the gravitational potential energy is equal and opposite to the kinetic energy of expansion. Quantitative information on this effect could yield directly the radius of the universe and provide a direct determination of the mean density of matter, two results of profound significance.

Structure and Evolution of Galaxies and Quasars

In this brief survey, galaxies have so far been emphasized as tools. But their intrinsic properties form the subject of one of the most interesting and important branches of astronomy. Among such studies appropriate to the LST is that of improved classification. Correct face-on classification requires some 10^3 picture elements in an image. With resolution approaching 0.04 sec of arc, galaxies less than 2 sec of arc in diameter could be analyzed, making it possible to classify accurately any reasonably oriented nondwarf galaxy as far away as 1000 Mpc and to investigate the uniformity of galaxy types out to great distances. Evolutionary effects in galaxies may be most clearly manifest in transient outer structures which are fundamental in classification.

In stellar astronomy it has been found that the maximum of the luminosity function--the number of stars per interval of absolute magnitude (intrinsic brightness)--continues to shift toward fainter magnitudes in step with our ability to detect and study fainter stars. There are suggestions that the same may be true of galaxies--that the really abundant systems are those of small populations and low surface brightness. While the LST would presumably not devote much time to the discovery of such subdwarf galaxies, it would be expected to encounter some in the course of other work and to provide detailed data for selected members of the class.

Galactic nuclei appear to be extremely compact, energetic, and fundamental structures; in many cases their radii are too small to be measured but may be only a few parsecs or less. Nuclei and nuclear regions frequently appear to play a basic role in driving and controlling the structural pattern, streaming of matter, excitation conditions, and perhaps even the overall stability of some galaxies. In particular, violent processes play a dominant role in the nuclei of radio, Seyfert, and compact galaxies. Until these nuclei can be studied and understood in detail, important factors controlling the evolution of many galaxies may remain uncertain.

Filamentary structures of considerable variety are associated with unstable galaxies, radio sources, and some quasars; under high resolution these structures should illuminate the role of magnetic fields in galaxies and the mechanisms controlling violent ejection from them. Somewhat less violent are the "active" nuclei in which unusual conditions of high excitation (Seyfert) or perhaps star formation (blue nuclei) exist. Variability has been detected in the optical radiation from the nuclei of some of these objects. All these nuclear phenomena represent reactions to special conditions which must be accounted for in any definitive theory of the structure and evolution of galaxies.

The quasars and more recently the pulsars have provided the most remarkable unexpected discoveries in recent astronomical history. Major tasks for the LST would include the high-resolution study of the spatial structure of quasars and their surroundings and the analysis of their spectra from far ultraviolet to far infrared. If, as some astronomers suggest, these objects are at only medium distances, then their physics--presumably involving immense gravitational fields--is of the highest interest and importance. The discovery of true intergalactic absorption lines would provide unambiguous evidence on the distance of these sources; the search for such absorption, if not already found by the time of the LST, could be one of the major contributions of the LST. If, indeed, the great red shifts of quasars prove to be accurate indicators of distance, these objects would presumably be the most luminous in the universe and should eventually provide data for understanding some of the most difficult physical and cosmological problems. The high luminosity in the far infrared of at least some quasars (Low and Kleinmann, 1968) may enhance the usefulness of the LST in analyzing these objects, even at the very greatest distances. (The pulsars, although within our own galaxy, are almost certainly too small for any degree of angular resolution, but the faint limiting magnitude of the LST should permit optical detection of other members of the class that are now invisible to us.)

Finally, the most important applications of the LST may be to classes of objects now quite unknown, as was the case with the 200-in. telescope and the discovery of quasars or with large radio telescopes and pulsars. For example, x-ray telescopes are detecting what appears to be a rich array of high galactic-latitude, possibly extragalactic, sources of an unknown nature. As another example, some radio source fields appear to be entirely empty, to the present magnitude limits reached by large telescopes, yet something must be there. Indeed, the LST should constitute so long a step over the 200-in. that we can be confident of its ability to provide the data needed for solving a number of radically new problems.

Summary

Many astronomers believe that at least the most basic first-order cosmological questions are currently being answered by ground-based radio and optical studies, especially those using the immense power of the 200-in. telescope. There is strong evidence (e.g., Sandage, 1968) for this point of view; several more ground-based telescopes of the 200-in. (5-m) class and at least one in the 10-m class are most urgently needed to pursue the large body of extragalactic work that depends primarily on the ability of a telescope to collect photons. But the resolution limits set by the earth's atmosphere appear to be well short of permitting ground-based study of details of relatively normal objects and processes in the range $z = 1$ to 2, where effects of space curvature and of the early history of the universe become pronounced. Indeed, these studies of detail will utilize the resolving power and limiting magnitude of the LST to the very limit. But its ability to achieve more than 100 times the angular information density of the 200-in. telescope, and to detect and measure stars and starlike objects at nearly ten times the distance, should prove invaluable for markedly extending the accuracy of the ground-based cosmological studies. If historical experience is a reliable guide, the LST will reveal both unexpected modifications required in our picture and radically new kinds of objects in the universe.

References

Low, F. J., and D. E. Kleinmann, "Infrared Observations of Seyfert Galaxies, Quasistellar Sources, and Planetary Nebulae," Proceedings of the Conference on Seyfert Galaxies and Related Objects, Astrophys. J. *73*, 868 (1968).
Sandage, A., Astrophys. J. *133*, 355 (1961).
Sandage, A., Observatory *88*, 91 (1968).
Zeldovitch, Ya. B., Advan. Astron. Astrophys. *3*, 241 (1965).

Chapter 4

SOLAR SYSTEM

Knowledge of planetary atmospheres and surfaces will have been greatly advanced by spacecraft observations by the time launching of the Large Space Telescope (LST) is feasible. Nevertheless, certain aspects of planetary study are particularly well suited to the capabilities of the LST and are likely to justify its use in this field. Even Venus and Mars, for example, our nearest planets and the objects of extensive investigation, will probably require high-resolution observations extending over planetary seasons and the solar cycle to complement the information gained by direct exploration and to follow up results obtained by flybys and orbiters. The value of space telescope observations of the more distant members of the solar system, such as Mercury, the major planets, asteroids, and comets, follows from the difficulties associated with exploratory missions to these objects; several decades may elapse before probes will be sent to these distant bodies with the sophisticated instrumentation required for direct imagery or spectral studies.

Direct Imagery of the Planets

The LST would be useful for the study of broad-band images of solar system objects because of its gain in resolving power over ground-based telescopes. With a resolving power of 0.04 sec of arc, the linear scale, h, of the smallest detail distinguishable on the surface of various bodies at their closest approach to earth is:

Planet		h (km)	D/h	Planet	h (km)	D/h
Mercury		18	260	Jupiter	120	1180
Venus		8	1500	Saturn	250	480
Mars		11	610	Uranus	550	90
Asteroids:	Ceres	27	26	Neptune	870	54
	Eros	2	8	Pluto	1100	5

The net amount of detail or information contained in the image of a body of diameter D is measured by the number $(D/h)^2$, which for the LST is about 100 times that of images obtained by telescopes on the earth's surface. Polychromatic images having this high information content should make significant contributions to the following studies.

Physiography of Objects Having Little or No Atmosphere If Mercury has a crater-saturated surface similar to that of the moon, the resolving power of the LST could distinguish several hundred craters over the planet's surface, as well as other features; however, Mercury is so close to the sun that observing it with the LST might require either that this instrument be placed on the moon or that an occulting disk be used in orbit. In the case of Mars, the high angular resolving power of the LST would allow photometric and polarimetric study of small-scale surface features as a function of wavelength, phase, and time. Similar but less detailed data could be obtained for some satellites, such as Ganymede, for which the expected number of resolvable surface features is approximately ten. Such observations would provide information on the surface topography and on the composition, texture, and thermal inertia of surface materials.

Structure and Time Variations of Clouds in Planets with Atmospheres Such observations would provide a basis for constructing the synoptic meteorology of planetary atmospheres. The emphasis given to observations of Mars would be determined by the extent and completeness of surveys made by other spacecraft. If the LST can observe an object as close to the sun as Venus (possibly just after sunset or before sunrise), high-resolution pictures in the ultraviolet may indicate the nature of the markings seen in existing photographs. The cloud formations of Jupiter are of great complexity and variety and are little understood today. The distribution in height of clouds may be determined by analysis of images obtained over wide wavelength ranges and in narrow passbands within CH_4 bands of various strengths. Similar information on the other major planets is highly desirable.

Atmospheric Limb Effects Information on the distribution with altitude of the absorbing and scattering components of a planetary atmosphere may be obtained by photometric and polarimetric measurements close to the limb of the planet, using the high angular resolution of the LST.

Measurement of the Diameters and Photometric Properties of Minor Bodies in the Solar System: Pluto, Planetoids, and Satellites The largest asteroid, Ceres, presents a maximum disk of only 0.8 sec of arc. Disks with diameters > 0.04 sec of arc at opposition--there are about 400 of them--will have magnitudes brighter than 12.5 and can be measured from the LST. In addition to measurements of diameter, the telescope may usefully measure the albedo, polarization, and phase function of selected objects to obtain information on surface texture and composition.

Spectral Analysis of the Planets

The value of the LST for studying the composition and physical structure of planetary atmospheres arises from the accessibility of the entire spectrum, with a spectral resolution limited only by detector sensitivity. The high angular resolving power of the LST provides a means of studying extreme limb effects, which yield critical data on the height distribution of absorbing and emitting gases. The ultraviolet spectrum of the planets contains information related to their upper atmospheric layers. An OAO-class instrument can obtain some of this information from the integrated light of the entire planet. The study of the spatial distribution of the atmospheric emissions and their variations with time will, however, require the larger angular scale and light-gathering power of the LST. Infrared observations have the greatest interest for the study of the structure of planetary atmospheres and surfaces. This structure has been partially explored by observations in restricted spectral bands, never completely free of atmospheric absorption. Beyond 24 μm, the absorption by the pure rotation band of terrestrial water vapor is complete, and much of the proper emission spectrum of the major planets falls in this region. Infrared studies will require the use of cryogenically cooled detectors in conjunction with a variety of ancillary equipment, such as broad-band radiometers and high-resolution spectrometers and interferometers. Such measurements are likely to require human attention in the LST.

Among the most interesting planetary problems that could be attacked with the spectroscopic equipment of the space telescope are the following.

Detection and Distribution of Constituents over the Disks of Mars and Venus Although short-term observations of this kind will undoubtedly be made by planetary probes, they can be supplemented and extended in time by the LST, e.g., observations could be made over an entire Martian year of the global distribution and circulation of carbon dioxide and water vapor. Sporadic gaseous emanations from the solid crust of Mars, if found, could also be studied by the LST. As the planetary exploration program advances, we may expect to uncover a variety of problems regarding the atmospheres of the terrestrial planets that could be studied most easily from the LST because of its versatile instrumentation, its availability, and the impracticality of repeating a planetary mission to clarify a small but important point. Planetary probes and the LST should complement each other, just as ground-based, balloon, rocket, and satellite studies all play an important role in increasing our understanding of the earth and its atmosphere.

Determination of Local Temperature Profiles on Mars and Venus The determination of temperature profiles of various regions of the terrestrial planets is of interest as a basis for analysis of their atmospheres. This information can be derived from high-resolution emission profiles within strong bands of a major atmospheric constituent, such as the 15-μm band of CO_2. Here, too, the LST and planetary probes can supplement each other.

Energy Balance of the Major Planets One of the most important current questions in planetary astronomy is whether the energy emitted by the major planets derives entirely from solar radiation or arises in part from internal sources. The solution of this problem requires the measurement of the energy distribution in thermal spectra extending well beyond the 24-μm limit set by terrestrial water vapor absorption. Limb effects, both polar and equatorial, in the thermal emission are also critical to the solution of this problem. Hence the LST is needed with certainty for examining Uranus and Neptune and probably Jupiter and Saturn as well.

Over-all Composition of the Major Planets Determination of the abundance ratio of helium to hydrogen on Jupiter will increase our understanding of the processes that led to the formation of the solar system and of chemical elements in general. The most direct method of determining this ratio by remote sensing is from the shape of the emission spectrum, which is also needed for establishing the thermal balance, as described in the preceding paragraph. Model atmosphere calculations (Trafton, 1967) show that the color index defined in terms of intensities at 14 and 50 mμ differs by one magnitude between an atmosphere composed of pure hydrogen and one containing equal amounts of hydrogen and helium.

Comets

We can only speculate today on the reasons that the comets, in sharp contrast with the planets, are loosely bound conglomerates of matter populating a region around the sun that has linear dimensions two orders of magnitude larger than that occupied by the planets. It has long been realized that this dichotomy in the state of aggregation of matter in the solar system holds important clues to the nature of the processes by which the solar system was formed. A comet approaching the inner regions of the solar system in a nearly parabolic orbit is believed to be a remnant of the primordial matter that formed the solar system, and its composition and structure are thus of the greatest interest in relation to the history of the solar system.

It should be realized that an *in situ* study of a comet by means of a probe raises a variety of nearly insurmountable difficulties. The most fundamental is that, in general, it is not possible to determine cometary orbits from ground-based observations, prior to launching a ballistic probe, with the accuracy needed for a close intercept. Even assuming that the problem of the long lead times for launching can be solved and that a large midcourse guidance capability becomes available, we would still have encounters with extremely high relative velocities, which would necessarily imply the probing of only a small region of the comet for a very short time. While observational restrictions would probably prevent observations on any object at a very small angular distance from the sun, the capability of the LST should make possible a full set of observations on the variety of phenomena taking place in a large comet as it comes in from far out in the solar system. These processes are at present only poorly understood, in part because of insufficient angular resolving power and the limited spectral range available for observation. The following specific problems could be studied.

Structure of the Cometary Nucleus Since we do not know the size of a single cometary nucleus, a measurement of the angular dimensions of the nucleus or nuclei by means of direct images obtained through suitable filters would be of interest. Such images would also provide brightness measurements at various wavelengths and thus an indication of the composition. A physical understanding of the observed fission or splitting in cometary nuclei may well require the observing potential of the LST.

Nature of the Gas Flowing from the Nucleus through the Coma to the Tail Spectroscopic analysis of molecules and atoms streaming out from a comet is critical to an understanding of cometary structure. Research in the visible should be supplemented by observations in the ultraviolet and infrared. For example, measurement of emission lines in the ultraviolet can furnish information on the abundance of O I, C I, and C II. Certain molecules (Swings, 1965) can also best be detected in this wavelength range; detection and measurement of H_2 emission are of particular importance. Infrared spectra may yield data on the intermediate molecules (Swings, 1965) resulting from the gradual disruption of the parent gases H_2O, NH_3, and CH_4. This spectroscopy can be carried out to some extent by smaller space instruments, but the large light-gathering capacity of the LST would be important for detailed analysis.

Thermal State of Constituent Solids and Gases Radiometer and spectrophotometer measurements in the infrared will provide brightness temperatures and energy-level populations, essential for understanding the photochemical processes described in the preceding paragraph and the absolute size distributions of particles.

References

Swings, P., Advan. Space Sci. Technol. *7*, 393 (1965).
Trafton, L. M., Astrophys. J. *147*, 765 (1967).

Chapter 5

INTERSTELLAR MATTER

The diffuse material between the stars is of interest for several reasons. New stars are believed to form in the tenuous clouds of gas and dust within a galaxy. Old stars, in which heavy elements have been produced by nuclear transformations, can eject a large fraction of their mass back into interstellar space, changing the chemical composition of the gas. Thus the interstellar gas plays a major role in the evolution of stars and galaxies, and detailed information on the physical state of the gas and how this gas condenses to form new stars is vital to an understanding of galactic evolution.

In addition to this cosmogonic role, the interstellar medium is characterized by a variety of interesting physical processes, whose understanding should enhance our knowledge of nature's laws. In particular, the dynamics of extended clouds of ionized gas, permeated with a magnetic field, is a subject whose analysis presents both physics and astronomy with an outstanding challenge and whose practical application (in controlled release of fusion energy, for example) could be immense. Finally, if intergalactic matter can be detected and its density measured, information on the mean density of matter in the universe, a datum of fundamental cosmological significance, will have been obtained.

The LST would be of central importance to research on interstellar matter in its capability both for high-resolution imagery and for spectroscopy in the ultraviolet and infrared. Specific research programs along these lines are discussed below.

Ultraviolet Absorption Lines

Because of the very low gas density and very low radiation intensity in interstellar space, atoms and molecules are almost always in their ground states. Hence, interstellar absorption lines are produced only by atoms and molecules in their ground states. Since permitted transitions from the ground state up to excited levels normally require more than 4 eV of energy, the wavelengths of the radiation absorbed in such transitions are normally shorter than 3000 A. As a result, the interstellar absorption lines of the most abundant elements, H, C, N, O, Mg, Si, and S, all lie in the ultraviolet and can be observed only with telescopes above most of the earth's atmosphere. Similarly, the Lyman absorption bands of H_2 extend from 1108 A to shorter wavelengths.

Research carried out on the interstellar lines of Na and Ca^+ in the visible has given substantial information on the velocities of the interstellar clouds. However, these atoms are too scarce to give measurable absorption in the more tenuous clouds, and lines from a wider variety of atoms would give information on electron density, ionization level, and chemical composition.

The interstellar ultraviolet lines provide an enormous increase in sensitivity for this research over the lines used hitherto. To produce measurable absorption in a strong resonance line requires about 10^{13} atoms cm^{-2}, but since Na and Ca are relatively scarce and are mostly ionized to Na^+ and Ca^{2+}, about 10^{19} hydrogen atoms cm^{-2} in the line of sight are required if the Na and Ca atoms, assumed to be present in the same relative abundance as in the sun, are to produce measurable interstellar lines in visible light. About the same amount of hydrogen is needed to produce measurable emission or absorption in the 21-cm line. By contrast, the OI line at 1302 A will have an easily measurable equivalent width (about 0.05 A) if the number of neutral hydrogen atoms in the line of sight is only 10^{16} cm^{-2} and the oxygen-to-hydrogen ratio has its usual value of 1 to 1000. Thus measures in the ultraviolet provide an increase in sensitivity by three orders of magnitude in the detection of interstellar gas.

The magnitude of stars that may be examined for interstellar lines in the ultraviolet can be determined from experience with the Mt. Wilson 100-in. telescope, where a spectrum of a star of magnitude 5.0 can be obtained in about 3 hr with a resolution of about 0.1 A (dispersion of some 3 A/mm). Measurements under these conditions (Rogerson *et al.*, 1959) show a loss of light at the slit of about 3.2 magnitudes at the 50-μm entrance slit. Essentially all the light should go through the entrance slit of a space telescope spectrograph. Use of a photoelectric image tube instead of photographic film yields an additional gain of about 2.5 magnitudes. The stellar flux in the ultraviolet per angstrom unit is about 2 magnitudes greater than in the visible, but selective interstellar extinction will reduce the ultraviolet flux, and we neglect this difference. Thus a 120-in. telescope in space should obtain a spectrum of a tenth-magnitude star, with a resolution of about 0.1 A, in about an hour. If 2 magnitudes of extinction are assumed in the visible, and an absolute magnitude of -5, a star of the tenth magnitude would be at a distance of 4000 pc. An early-type Population II star, on the horizontal branch of the Hertzsprung-Russell diagram, might have an absolute magnitude of 0; at high latitudes, where the extinction is small, such a star would have an apparent magnitude of 10 at about 1000 pc.

This computed performance of a high-resolution spectrometer represents a very marked improvement over present instruments on ground-based telescopes. A similar improvement may be anticipated for ground-based instruments during the next few years. Spectroscopic research with image tubes or with photoelectric scanning at high spectral resolution is beginning at several observatories. Loss of light at the slit can be reduced by use of either an image slicer or an interferometer. At the Mt. Wilson Observatory a gain of 5 magnitudes was achieved by using the coudé spectrograph as an order-isolation monochromator, with a very wide entrance slit, and a Fabry-Perot interferometer with photoelectric scanning.

The relatively high resolution of 0.1 A is required to resolve the different components of an interstellar line produced by different interstellar clouds, or to detect lines produced by very tenuous clouds or by relatively scarce atoms in normal clouds. However, the stronger interstellar lines produced by the more abundant elements can be examined with much less resolution. Even for a star as close as 30 pc the average number of oxygen atoms in the line of sight should be 10^{17} cm^{-2}, and the corresponding equivalent width of the strong ultimate line at 1302 A should be 0.5 A. With a resolution of 1 A, ultraviolet spectra of B stars in regions relatively free of extinction should be obtainable on stars down to the fifteenth magnitude with an exposure time of about an hour. Many stars in the Magellanic Clouds could be measured at this dispersion.

Some of the scientific programs that could be carried out with the LST, by measuring interstellar absorption lines, are discussed below.

Intergalactic Medium According to the usual cosmogonic theories, the density of intergalactic matter should be about 10^{-29} g cm^{-3}, corresponding to a hydrogen density n_H, of about 10^{-5} atom cm^{-3}. Attempts to measure the density of neutral hydrogen present have yielded conflicting results, with an upper limit of 6 x 10^{-11} atom cm^{-3} found (Gunn and Peterson, 1965) from the weakness of intergalactic L-α absorption in the red-shifted spectra of the quasi-stellar radio source 3C9; on the other hand, absorption of 21-cm radiation from the Fornax cluster of galaxies has been interpreted (Koehler, 1966) as indicating an intergalactic hydrogen density of about 4×10^{-7} atom cm^{-3}. More definite results on this problem would be of fundamental interest.

Absorption measurements in L-α radiation could be carried out on neighboring galaxies. High resolution is unnecessary since the line is broadened by the expansion of the universe; as a result of this expansion, the only advantage of the more distant, fainter sources over the closer, brighter ones is that the intergalactic density was presumably greater at an earlier epoch. The brighter, nearer galaxies that could be observed in the ultraviolet with the LST have the advantage that more accurate photometry is possible when a greater number of photons are received. If the density of neutral hydrogen in the neighborhood of our own galaxy is actually as great as 10^{-7} cm^{-3}, measurements of galaxies with the LST should quickly confirm it, since the optical thickness in L-α at wavelengths between the red-shifted line in the galaxy observed and the λ1216 A line in our own galaxy should be large. Such measurements must be made of objects more distant than 2×10^{7} pc to shift the intergalactic absorption away from the L-α absorption in our own galaxy, which even at high galactic latitude will produce an absorption line several angstroms wide. If essentially all the intergalactic hydrogen is ionized, optical measurements will, of course, be unable to detect it directly.

If an appreciable number of atoms heavier than hydrogen and helium are present in intergalactic space, they also can produce appreciable absorption even though several times ionized. An intergalactic density of about 10^{-11} cm^{-3} is required to produce perceptible optical depth in a strong resonance line between the sun and a galaxy a few magaparsecs distant. If the intergalactic hydrogen density is in fact 10^{-5} atom cm^{-3}, and if the abundance of carbon relative to hydrogen exceeds 10^{-6}, the intergalactic C IV lines at 1550 A could be detected, provided that the carbon is not more highly ionized than C IV (ionization potential 64 V). The O VI ion (ionization potential 128 V) may be abundant even if most of the carbon atoms have lost more than three electrons each, and the O VI lines at about 1035 A might be looked for.

Galactic Corona The possibility that gas extends thousands of parsecs above and below the galactic plane has been discussed by many authors. Observational evidence for such a galactic corona is fragmentary, and the possible physical conditions in such a gas are conjectural. Interstellar clouds having only 10^{-3} as much material as those now analyzed could be detected by ultraviolet spectroscopy with a resolution of 0.1 to 1 A; the LST could make such measurements on stars several kiloparsecs from the galactic plane.

If the O I absorption produced by a single cloud is to be distinguished from the broad absorption feature produced by the O I atoms in the galactic plane, large Doppler shifts, exceeding 100 km sec^{-1}, are required; such shifts are expected in the galactic corona. If the coronal gas is highly ionized, as suggested by some astronomers, the absorption lines of C IV, N V, or O VI may be measurable.

Two types of stars far from the galactic plane could be used for spectroscopic investigations of the coronal gas. Some O and B stars of Population I are "runaways" with velocities up to 100 km sec^{-1} that take them far from the galactic plane. Spectra of several such stars down to about the eighth apparent magnitude have been used (Münch and Zirin, 1961) to investigate high-velocity clouds of Ca II in the corona, and many more should be readily observable down to the tenth magnitude, the practical limit for 0.1 A resolution spectrophotometry with the LST. The distance limit of 4000 pc found above for O and B stars of this magnitude is conservative in this case since there may be relatively little extinction away from the galactic plane. On the other hand, it is not certain that stars of this type will be present so far from the galactic plane. In any case, a closer net of stars would be provided by the horizontal branch Population II stars, which for the same limiting apparent magnitude may be 1000 pc away.

Among the topics that may be investigated in this way are: density of the gas in the galactic corona; density fluctuations and velocity distribution of the clouds; electron density, as determined from ionization equilibrium; and chemical composition. Such physical topics as inflow of gas from intergalactic space or the galactic nucleus, and the role played by the coronal gas in the evolution of the galaxy, could be explored.

Large-Scale Structure of Gas in the Galactic Disk Because of the thousandfold increase in sensitivity that it provides over either 21-cm or visual absorption line data, ultraviolet spectrophotometry from space vehicles promises to open a new field of research in the study of interstellar absorption lines produced by gas in the galactic disk. Much of this work can be done with smaller space telescopes than the LST. In particular, ultraviolet spectra of the brighter stars of types O and B within 500 pc of the sun can be analyzed at high resolution with an instrument of 40-in. aperture.

The LST would enable us to extend this type of analysis to far greater distances, to other spiral arms, for example, at 4000 pc from the sun. With somewhat lower resolution, even greater distances can be reached, with the limit set primarily by extinction in the galactic disk of gas. Thus the density, chemical composition, and velocity field could be analyzed in other spiral arms and perhaps also in the gas between the arms.

The study of inhomogeneities in the interstellar medium should yield important information on the origin of spiral arms and on the over-all dynamics of the interstellar gas. At the present time, detailed information on the structure of the interstellar medium is so fragmentary that theories on these topics are necessarily speculative.

The study of molecular hydrogen is likely to play an important part in these studies. Theoretical estimates now suggest that the density of molecular hydrogen is low but still measurable with high resolution. Detailed information on the local density and temperature of the neutral hydrogen gas can be obtained from the ratios of different lines in the Lyman bands.

High Spatial Resolution

Structure of Expanding Gas Shells Ejection of gas is a fairly common stellar characteristic. In the extreme case of a supernova of Type I the velocity of ejection may be as great as 20,000 km sec^{-1}; in a planetary nebula this ejection velocity is a few tens of kilometers per second. Both these objects produce conspicuous nebulae that show fascinating detail. With the LST, finer detail in such nebulae could be resolved; on a nebula 1000 pc away, a spatial resolution of 40 AU would be possible, which is ten times that obtainable by the best present spectrographs. In addition, the LST may be able to detect nebulae around other stars believed to eject matter. The more massive stars are believed to eject a significant fraction of their mass during some stage of their evolution, and spectrographic evidence indicates that this process is particularly strong from the supergiant stars of types O and M. We cannot predict what results such high-resolution pictures will yield.

Structure of Prestellar Systems Particularly dense gas clouds such as the Orion nebula are believed to be the birthplace of stars; detailed analysis of the structure of these regions may indicate how stars are formed. Spectroscopic analysis of individual small filaments and structures to give information on their velocity and physical state should aid materially in the study. The LST should be able to perform such observations on the brighter nebulae; in the Orion nebula, which is at a distance of about 500 pc, structures only 20 AU in diameter should be resolvable. High-resolution studies should be made of dark clouds such as globules and elephant trunks. Very small globules or protostars might be detected against the bright background provided by a diffuse or reflection nebula.

Extinction by Interstellar Grains

Small solid particles, or grains, are believed to affect the dynamics and evolution of interstellar gas. Measurement of the selective extinction produced by such grains, as a function of wavelength and direction of polarization, gives information on the sizes and physical constitution of these particles. Measurements at wavelengths between 900 and 3000 A are certain to greatly improve our knowledge on these subjects and, as in the case of the interstellar gas, the LST would be able to extend measurements to very distant stars. Small space telescopes should be used to provide the bulk of the information needed.

Infrared Capabilities of the Large Space Telescope

Earth-based observations through the available infrared windows in our atmosphere have shown that extremely bright infrared objects exist relatively near the sun. The extended infrared sources, or infrared nebulae, are thought to be contracting interstellar clouds already starting to form stars at their centers. Pointlike sources have also been discovered, some of which may be individual protostars and preplanetary systems. Since these sources are probably of relatively low density, they are treated in this section. Further study of these infrared objects at all available wavelengths may be expected to advance our knowledge materially in two fundamental areas of astronomy--stellar evolution and the origin of the planetary system.

Since infrared techniques as applied to astronomy are undergoing rapid change, it is difficult to assess the role of the LST in these investigations. In particular, it may be that ultimate sensitivity in the infrared will be attained by a relatively small-aperture space telescope cooled in its entirety to 20 K or lower, with detectors operating at 0.1 K. This type of specialized instrument may well be able to answer such questions as: How many prestellar or preplanetary systems are there in our galaxy? How are they distributed? What are their total luminosities? How rapidly do they evolve? Assuming that this smaller telescope is built first, what contribution would the LST make? The most immediate answer to this question is that the high angular resolving power of the LST combined with a detecting system of good sensitivity would allow an attack on such problems as angular diameters and limb darkening as a function of wavelength for the suspected preplanetary systems, detection of individual preplanetary condensations, and changes with time of the resolved structural features produced by energy fluctuations in the protostar or by evolutionary changes. In this context it should be noted that the diffraction-limited performance contemplated for the LST would be an important asset at infrared wavelengths even though at 10 μm, for example, the beam diameter would be increased to approximately 1 sec of arc. As shown by experience with radio telescopes, information well below a tenth of the beam diameter can be recovered if the beam pattern is stable, accurately measured, and free of sidelobes.

The full power of infrared spectroscopy has still to be applied to astrophysical problems. However, it can be expected that through the application of multiplexing and Fourier spectroscopy techniques, rapid advances will be forthcoming.

The infrared spectra of some of the brightest sources probably will be observed with space telescopes of intermediate size. The large collecting area of the LST will be needed for the study of most sources. The very small interstellar extinction in the far infrared should make it possible to observe with the LST infrared sources throughout the galaxy, as indicated recently by the observations of the galactic center at 2.2 μm (Backlin and Neugebauer, 1968).

The interstellar grains are of great astrophysical interest since they play an important role in both stellar and galactic evolution. With space telescopes operating in the far infrared it may be possible to observe the thermal radiation of interstellar grains heated by nearby stars. The constitution of the interstellar grains would also be clarified through the absorption features they may produce in the spectra of distant sources.

References

Backlin, E. E., and G. Neugebauer, Astrophys. J. *151*, 145 (1968).
Gunn, J. E., and B. A. Peterson, Astrophys. J. *142*, 1633 (1965).
Koehler, J. A., Astrophys. J. *146*, 504 (1966).
Münch, G., and H. Zirin, Astrophys. J. *133*, 11 (1961).
Rogerson, J. B., L. Spitzer, and J. Bahng, Astrophys. J. *130*, 991 (1959).

Chapter 6

STARS

Both in astrometry and in spectrophotometry the LST could significantly advance the study of individual stars in our galaxy. Resolution of close binaries would markedly increase information on stellar masses, and photometry in the ultraviolet and infrared would aid in determining the bolometric luminosity. In addition, ultraviolet spectroscopy might yield information on the composition of faint early-type stars, as, for example, in globular clusters, and on chromospheric and coronal activity in a wide variety of stars.

Stellar Masses

The masses of stars are derived from the orbits of binary systems. It has long been a matter of concern that so much of astrophysics, particularly the theory of stellar structure and stellar evolution, depends on a very small number of accurately known masses. The mass-luminosity relation is defined by less than 100 stars whose masses are known to an accuracy within 12 percent. Increased accuracy would be most desirable; we take 6 percent as the desirable precision for determination of stellar masses. Since the relative error in mass is three times the relative error in parallax, the distance must be known with an accuracy of 2 percent. Similarly, the velocity change in orbit must be measured with 2 percent accuracy, if it is used instead of a measured parallax.

Stars having separations of 0.1 sec of arc should be "well separated" by the LST. Not only could the pair be photographed free of photographic defects, but each component could be placed separately on the slit of the LST spectrograph. Spectroscopic resolution is taken to be 0.1 A with a limiting magnitude of 10 (see Chapter 5).

Spectroscopic Binaries All spectroscopic binaries with periods greater than one year should be checked to see if they can be resolved by the LST. Of particular interest are systems in which the velocities of both components have been measured and for which the mass ratio is therefore known. A carefully planned program for photographing such a system several times during one orbital period would yield the inclination, i, with relatively little observing time; knowledge of i gives the stellar masses immediately, provided that the mass ratio of the two components is known. A rough survey reveals 12 systems that should be resolvable by the LST and for which reliable orbits could therefore be determined over a period of about 5 years.

Astrometric Binaries In these systems one component is so much brighter than the other that the duplicity is revealed only by the brighter star's "wobble" as it moves across the celestial sphere. A study of the μ Cas would be very rewarding, since this pair is definitely a system of Population II, the only one so far known. An analysis of the perturbed orbit of μ Cas reveals that its companion must be greater than 1 sec of arc away, and Δm is ≤ 4. This system could be resolved by a diffraction-limited space telescope with an aperture of 40 in. or more. Similar arguments hold for BD + 66°34. The following is a provisional list of such systems:

μ Cas (Pop. II)
BD + 66°34
ζ Cnc A,B,C
BD + 20°2465
Ci 2354
ζ Aqr
61 Cyg

At least ten other systems are suspected, some of which should doubtless be confirmed shortly.

Even binaries with separations as low as 0.05 sec of arc should appear double with the LST, although precise measurements may be difficult.

Eclipsing Binaries Both the period and inclination of an eclipsing binary are known; but since the parallax usually cannot be determined with sufficient accuracy, spectroscopic determination of the velocity change of each component is required to yield the two masses. In an extensive list (Wood, 1963) containing 42 binaries, only 12 meet even our arbitrary minimal 12 percent accuracy in the masses. In principle, the velocity curves of the other 30 can be obtained from the ground, especially if the efficiency of the instrumentation is improved with the use of photoelectric image tubes. A space telescope may be needed, however, to measure the spectra of both components if they are of different spectral types and one component is appreciably fainter than the other in visible light;

the brightness ratio may be reversed in the far ultraviolet or far infrared.

Stellar Luminosities

A star's luminosity is computed from the distance to the star, the radiant flux reaching the earth, and the magnitude of the interstellar extinction. Observations from space telescopes can, in principle, make a central contribution to such observations.

Present-day parallaxes are determined with a probable error of 0.003 sec of arc (0.001 sec of arc with great effort), corresponding to an accuracy of 6 percent at a distance of 20 pc. This limit is set in part by the resolution, in part by distortions in the emulsion, and in part by seasonal, night, and other effects. A gain in accuracy would be obtained from the tenfold decrease in angular image diameter provided by the LST. Although the telescope should probably not devote much time to parallax research, a relatively small number of observations of a few particularly important standard stars would markedly improve knowledge of the star's distance and luminosity. Precise measurements of the apparent separation of close visual binaries whose scale has been determined from spectroscopic observations can also be used to give accurate parallaxes. Precise knowledge of stellar luminosities as determined from accurate parallaxes is likely to become increasingly important as the theory of stellar structure becomes more detailed and exact.

The radiant flux and the resulting bolometric magnitude of a star must be studied with a space telescope, if a large portion of a star's energy is radiated in the vacuum ultraviolet or far infrared. Detailed measurements on a number of stars in the same region of the sky can establish the selective extinction and, presumably, the total extinction as well. Smaller space instruments, even sounding rockets, can perform the bulk of these measurements for the brighter stars. However, the fainter stars, such as those in globular clusters, require a space instrument with the light-gathering power of the LST.

Stellar Spectra

An important aspect of stellar evolution research is the determination of the abundances of the elements in various stellar types and populations. In early-type stars, the abundance determinations today depend in large measure on subordinate high-excitation lines, for which fundamental physical data are mostly lacking and which are extremely sensitive to temperature. A larger number of lines, covering a wide range in excitation and ionization but including specifically the resonance lines, are accessible to ultraviolet observation; they are needed both to define more precisely the physical conditions in stellar atmospheres and to determine abundances. Again, much of this work could be started with smaller instruments. However, the light-gathering power of the LST is required for detailed ultraviolet spectrographic analysis of the highly evolved blue stars in the galactic halo and in globular clusters and of the unevolved main sequence of this old population. Abundance determinations for hot stars of various ages in neighboring galaxies would also require the large collecting area of the LST.

In addition to its use in abundance determination, the LST would open up a new field of research on the outer atmospheres of the stars situated above the layers responsible for the normal absorption lines. The chromosphere and corona of the sun, where deviations from thermal equilibrium are large and transient disturbances may become dominant, have been studied for many years, but corresponding information about stars is fragmentary. The existence of extended envelopes around some early-type stars has long been known from ground-based observation of certain emission and absorption lines in their spectra. Similar information for some late-type supergiant stars has been obtained from absorption lines, particularly in eclipsing variables and in wide binary systems. Recent rocket observations of stellar spectra in the ultraviolet (Morton, 1967) have suggested that ejection of matter from early-type stars is a more general phenomenon than had been thought. Partly because of the role that mass loss plays in stellar evolution, and partly because of increasing physical interest in nonthermal processes in astrophysics, a study of the emission and absorption lines produced by these outer stellar layers would be a major problem for space astronomy. As in interstellar space, the more abundant atoms in these outer layers absorb and emit primarily in the ultraviolet, and the chromospheres, coronas, and mass loss can be detected with much greater sensitivity by ultraviolet measurements at high spectral resolution than by data in visible light.

A fundamental goal is the evaluation of the stellar input into the interstellar medium in the form of chromospheric or coronal emission of particles and of photons. The ultraviolet spectrum of the sun provides us with a surprisingly large value of the radiated flux from a corona that is much less active and dense than that of a late-type, young, main-sequence star. The ultraviolet flux from supernovae is completely unknown and will require a large telescope to observe; such observations should help us to evaluate the total energy that supernovae radiate and which in some theories is 1000 times greater than that found in visual light.

While smaller space telescopes can be used for this research with the brighter early-type stars, the large aperture of the LST is likely to be required for cooler main-sequence stars which are intrinsically very faint and also for hot but faint degenerate stars. A study of the Mg II emission lines in both giants and dwarfs should give information about the chromospheres of such stars along the main sequence. Similarly, ultraviolet observations of highly evolved stars could indicate the presence of neighboring clouds of gas, either ejected from these stars or falling into them. Recent investigations indicate that any central stars identifiable with x-ray sources, providing an energy input for the observed bremsstrahlung spectrum, must be very faint; similarly, any stellar objects associated with pulsars must apparently be fainter than approximately the twentieth magnitude. The largest feasible space telescope is probably required for any ultraviolet spectrophotometric observation of these exciting objects, even if most of their energy lies in the ultraviolet.

High-resolution monochromatic imagery could be an important tool in such investigations. It might permit direct observation of stellar envelopes in the radiation from Mg^+ ions at 2800 A, for example, especially in stars of later spectral types, as well as study of mass exchange of double-star systems and halos around long-period variable stars. In the far infrared, stellar envelopes have been detected from the ground and could be mapped if imaging techniques were available at these wavelengths.

Stellar Evolution

Despite extensive theoretical work, the final stages in stellar evolution are far from clear. To understand these processes better, the extreme faint end of the stellar luminosity function must be observed, including low-mass stars late in their gravitational contraction and cooling phases and very cool white dwarfs. Only the relatively bright objects in these classes can be reached by ground-based telescopes.

A more fundamental observational question is whether stable neutron stars exist. These objects presumably have a diameter of only a few kilometers. If their surface temperatures were similar to that of the sun, they would have absolute magnitudes near +30--even if they were as close as 10 pc, such intrinsically faint stars would be at or beyond the detection threshold of the LST and clearly beyond the scope of lesser instruments. But during at least part of their cooling time, the surface temperature would be far higher than the sun's. Thus, if neutron stars do exist and if ways can be found to identify them, such as by binary or proper motions or by x-ray effects, a few may lie in the apparent magnitude range 25 to 29 within which some astrophysical studies of this remarkable state of matter could be made using the LST.

References

Morton, D. C., Astrophys. J. *147*, 1017 (1967).
Wood, F. B., in *Stars and Stellar Systems*, Vol. 3, p. 377, Univ. Chicago Press, Chicago, Ill. (1963).

APPENDIX A

Limiting Magnitudes and Exposure Times

The performance of a space telescope, in terms of its ability to detect faint objects in a given amount of time, depends on several factors including the number of photons received per second from the object, the background noise that tends to obscure the wanted signal, and the properties of the optical train and of the detector used. Full discussions of these topics appear elsewhere (Baum, 1962); here a brief and simplified treatment for the Large Space Telescope (LST) will be presented. The performance of an ideal detector, with no background noise, is considered first; subsequently the performance to be expected if photoelectric tubes and photographic plates are used is discussed very briefly.

Performance with an Ideal Detector

We consider the detection of light from a faint object, which is taken to be a point source. Let n photons per second reach the telescope per unit area per second. If a is the radius of the primary mirror, $\pi a^2 n$ photons will be intercepted per second. Of these photons we assume that a fraction, q, are detected. When account is taken of light losses in the telescope, of obscuration by the secondary mirror and its supports, and of the fractional quantum efficiency of the detector, the value of the overall efficiency factor, q, cannot greatly exceed 0.1 in present systems and is often much smaller. The signal, S, received during time, t, equals the total number of photons detected, and is given by

$$S = \pi a^2 nqt. \qquad (1)$$

In the absence of interfering background either from the sky or the detector, the accuracy with which starlight is measured is limited only by the shot noise of the signal; this mean noise level, N_S, equals the rms fluctuation of S, equal to $S^{\frac{1}{2}}$. If we let ζ denote the photometric accuracy desired, we have

$$\zeta \equiv \frac{N_s}{S} = \frac{1}{S^{\frac{1}{2}}} = \frac{1}{(\pi a^2 nqt)^{\frac{1}{2}}} \,. \tag{2}$$

For a bandwidth of 10^3 A centered at 5000 A and a star of visual magnitude 0, n equals (Code, 1960) approximately 1.1×10^6 photons $\mathrm{cm}^{-2}\ \mathrm{sec}^{-1}$. It follows from Eq. (2) that if t equals 2 hr, if a equals 1.5×10^2 cm, and if q equals 0.1, then a photometric accuracy of about 8 percent could be obtained on a star of magnitude 29, with a signal of about 140 photons detected during this time period. In the absence of any interfering background or other noise, clearly a 120-in. telescope either in space or on the ground could detect very faint stars with reasonable exposure times.

A fundamental source of background noise that cannot be entirely eliminated is the light received from the sky, including diffuse galactic light, zodiacal light, and for telescopes on the earth's surface, the airglow. We shall assume that the ideal detector is sensitive only to photons within a cone of half-angle α, or of solid angle $\pi\alpha^2$. Let b denote the average number of photons $\mathrm{cm}^{-2}\ \mathrm{sec}^{-1}\ \mathrm{sr}^{-1}$ received from the sky background. Within a circle of angular radius, α, on the sky the background signal, B, received by the detector is

$$B = \pi^2 \alpha^2 a^2 bqt. \tag{3}$$

This unwanted background can be subtracted out to yield the desired stellar signal, but the fluctuations of B increase the total noise. Hence the photometric accuracy, ζ, now becomes

$$\zeta = (B + S)^{\frac{1}{2}}/S, \tag{4}$$

where S represents the signal from the star only, and $B + S$ is the total number of photons detected. When S is substantially less than B, ζ varies inversely as the stellar brightness, and the exposure time, t, required to achieve a given precision, ζ, increases as $1/n^2$ with decreasing n.

The stellar magnitude at which B equals S may be computed from the known value of b, which at good observing sites on the earth's surface can be as small as one star of visual magnitude 22.2 (sec of arc)$^{-2}$. Hence for earth-based telescopes, for which the effective image area during periods of good seeing corresponds to about 1 (sec of arc)^2, B equals S for a star of magnitude approximately 22, and fainter stars can be detected and measured only at the cost of substantially longer exposures than would be predicted from Eq. (2). For the LST, the radius of the first dark ring is 0.04 sec of arc at 5000 A, and the area within this circle is 0.005 (sec of arc)^2. In addition, the sky brightness above the atmosphere is reduced by the absence of airglow, the reduction amounting to as much as 1.3 magnitudes at the ecliptic poles (de Vaucouleurs, 1958), far from both the zodiacal light and diffuse light from the galactic disk. As a typical sky background in space we shall take 23 mag (sec of arc)^2, giving equal B and S for the LST with a star of about the twenty-ninth magnitude. On the average, and with an ideal detector, measurements of stars even somewhat fainter than the twenty-ninth magnitude should be possible with the LST.

Performance with a Photomultiplier Tube

In practice, measurements with present photomultiplier tubes fall below the ideal performance described above in two respects. First, the dark current of the tube gives an additional unwanted output, which we denote by D pulses within the time, t. While the average dark current can be subtracted out, the fluctuations in this dark current produce added noise, and the photometric accuracy, ζ, now becomes

$$\zeta = (B + D + S)^{1/2}/S. \qquad (5)$$

With present phototubes, D/t is rarely less than 1 count sec^{-1} corresponding to a value of 7200 for D within a 2-hr exposure, far exceeding the count of 140 obtained during this time interval with a 120-in. telescope and a twenty-ninth magnitude star. This value of D equals the signal from a star of magnitude 24.7, and for fainter stars substantially longer times are required than Eq. (2) would predict. If filters are used to restrict the bandwidth to less than 1000 A, the necessary exposure times are further increased.

In principle, it seems entirely possible that photoelectric tubes can be designed to have much lower dark counts. The size of the stellar image is very much smaller than the photocathode area of most modern tubes; with a much smaller photocathode, the contribution of thermionic emission to D should be correspondingly reduced. Cosmic rays and trapped energetic particles can produce substantial dark counts, but these could be discriminated against by particle detectors and anticoincidence circuits similar to those used in cosmic-ray research. Whether

D can be reduced below the signal from a twenty-ninth magnitude star is uncertain.

Second, the amount of skylight measured by the photocell is generally much greater than the skylight within the stellar image area, since the defining aperture placed at the focal plane of the telescope normally has a radius substantially greater than the image size. For telescopes on the earth's surface, this aperture has generally been made at least 7.5 sec of arc in diameter, to ensure that all the starlight will be admitted despite seeing fluctuations. For a space telescope, the distribution of light over the image is presumably relatively constant in time, but the fraction of light passing through the aperture will be constant only if the image is accurately centered. To achieve accurate centering, one can imagine that a photograph of the local star field is taken first (possibly with an integrating image tube) and that a small differential offset is then used to center the star in the entrance aperture for the phototube. We shall assume that even with this technique the minimum diameter of the entrance aperture cannot be made less than 0.4 sec of arc, five times the diameter of the first dark ring. With this aperture, the signal, *S*, equals the sky background, *B*, for a star of magnitude 25.5.

A comparison between the LST and the 200-in. Hale telescope at Mt. Palomar on the basis of the above figures is given in Table A1, computed from Eq. (5) with ζ equal to 0.1. It should be emphasized that both the dark count and the entrance aperture diameter assumed for the LST are somewhat uncertain. The figures for signal and sky for the Hale telescope assume an atmospheric extinction of 0.25 mag. For an earth-based telescope, the fluctuation of the sky background may considerably exceed the assumed values because of the spatial and temporal variations of the airglow; hence, for 10 percent accuracy longer integrating times may be required than are shown in Table A1.

Evidently, precise photoelectric measurements by the LST at the twenty-seventh magnitude and fainter would require both a lower dark count and a smaller entrance aperture than assumed in Table A1. Photoelectric image tubes, discussed below, should be able to reach fainter stars than can a photoelectric cell; these tubes may have sufficient linearity of response to give stellar magnitudes directly, without the use of a photomultiplier tube.

TABLE A1 Comparison of Large Space Telescopes and Hale Telescope Photoelectric Photometry

	Large Space Telescopes	Hale Telescope
Diameter		
Of primary	305 cm	508 cm
Of entrance aperture	0.4 sec of arc	7.5 sec of arc
Signal, S/t	$8.0 \times 10^{(9 - 0.4m)}$ sec^{-1}	$18 \times 10^{(9 - 0.4m)}$ sec^{-1}
Sky background, B/t	0.63 sec^{-1}	1000 sec^{-1}
Dark count, D/t	1 sec^{-1}	1 sec^{-1}
Computed Magnitudes		
Signal = Sky	25.4 mag	18.1 mag
Signal = Dark	24.8 mag	25.6 mag
Integrating Times for 10 Percent Accuracy		
M = 21	3.3 sec	19 sec
23	27 sec	14 min
25	6.5 min	3.6 days
27	3.0 hr	

Performance with Imaging Techniques

The limiting magnitude obtainable for different exposure times with photography or image tubes depends heavily on the properties of the film or tube used and on the parameters of the telescope. The best performance is, of course, obtained if the telescope is optimized for the particular characteristics of the recording system used. We shall not attempt a complete discussion but give only a rather crude calculation of the type of performance that may be anticipated, based on a comparison with the 200-in. Hale telescope.

At the prime focus of the 200-in. (*f*/3.67), a 30-min exposure on a 103a-O emulsion, with a filter (GG13) cutting off radiation short of 4000 A, is fogged by skylight to a density of 0.6 (A. R. Sandage, informal communication). Since the sky brightness amounts to 22.2 mag (sec of arc)$^{-2}$, the same intensity will be received by the LST from a star of magnitude 28.0 if this image is assumed uniform over a diameter of 0.08 sec of arc; this diameter corresponds to the first dark ring of the diffraction image at 5000 A. Hence if reciprocity-law failure is ignored, an assumption which begins to be valid for sensitized emulsions, and if the photographic density in the LST stellar image is to be 0.6, the exposure time equals 30 min multiplied by the ratio of the square of the *f* numbers for the two instruments.

The LST image must not be smaller than the resolution element of the photographic emulsion. We shall consider here an *f*-number of 25 for the LST, which gives an image diameter of 30 mμ. To achieve the greatest resolution, a slower focal ratio is likely to be necessary, but *f*/25 might well be suitable for the practical detection and measurements of faint stars. With this focal ratio, the exposure time becomes 30 min x $(25/3.67)^2$, or 23 hr. The density in the sky fog will be substantially less than 0.6, since as we have already seen the sky brightness in space is less by about a magnitude than that observed from the earth's surface. The limiting magnitude, m_ℓ, may somewhat exceed 28 on such an exposure, since even such a small stellar image can presumably be detected with a photographic density less than 0.6. For a star of magnitude 29 the sky brightness in the stellar image is about equal to the stellar image brightness, and an exposure time of about 3 days is probably adequate to detect such stars. For comparison, the limiting magnitude obtainable on a 200-in. photograph described above is 23.5; the images are about 100 mμ in size and contain sufficient information so that a star image 1.3 mag fainter than the light from the sky in the same area can safely be distinguished.

An exposure time of 3 days would be nearly prohibitive for most programs proposed for the LST, and reciprocity failure would be difficult to eliminate for such long exposures. However, with use of photoelectric image tubes a reduction in exposure time by an order of magnitude or more should be possible. With this technique the detection of stars down to magnitude 28 to 29 should be possible with exposure times of 2 to 7 hr or less, respectively. This performance begins to approach that of the ideal detector discussed above. Exposure times on diffuse sources such as nebulae and distant galaxies, which are only slightly brighter than the night sky, would also be in the range of a few hours. Appreciable resolution might be lost with an image diameter of 30 mμ, and slower focal ratios would probably be used for some objects.

Evidently the effective use of image tubes would be of crucial importance in the utilization of the LST to observe faint objects of all kinds. At least two types of tubes are in development and early use. One makes use of photographic recording of a photoelectric image, either by direct impact of the electrons on a nuclear emulsion (electronography) or by photographic recording of an image produced on a phosphor; the other type makes use of an integrating television tube with electric readout. Important advantages seem to be offered by tubes of the latter type. They do not require frequent human access for film reloading or recovery, and they are not subject to degradation by occasional exposure to penetrating radiation, which will fog photographic emulsion. For example, during passage through the South Atlantic anomaly, where trapped energetic particles are present even at altitudes of several hundred kilometers above the earth's surface, a television tube can be turned off, while protection of a photographic film or plate may require prohibitive amounts of shielding. This advantage of integrating television tubes over all photographic detectors may prove decisive for many space applications. Preliminary tests of one such television tube (Lowrance and Zucchino, in press) indicate a performance level which begins to approach that required for space-astronomy application, with integrating times of more than an hour possible without excessive background noise.

References

Baum, W. A., in *Stars and Stellar Systems*, Vol. 2, p. 1, Univ. Chicago Press, Chicago, Ill. (1962).
Code, A. D., in *Stars and Stellar Systems*, Vol. 6, p. 50, Univ. of Chicago Press, Chicago, Ill. (1960).
Lowrance, J. L., and P. M. Zucchino, Advan. Electron. Electron Phys. (in press).
de Vaucoulers, G., Astrophys. J. *128*, 486 (1958).