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INSTRUMENTS AND TECHNIQUES

# New Frontiers of Astronomical Technology

## Technological developments challenge the astronomer, both from the ground and in space.

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The principal tool of the astronomer, the telescope, is basically an instrument designed to gather the light of stars and other celestial objects and focus it with precision. Most celestial objects are intrinsically very luminous objects, but they appear faint because of their great distances from us. The brightest star, Sirius, with an intrinsic luminosity 28 times that of the sun, is approximately 10,000 million ($10^{10}$) times apparently fainter than the sun. The faintest object detected with the 200-inch telescope, of 23rd magnitude, is another 10,000 million ($10^{10}$) times fainter. The faintness and small angular size of celestial objects (other than the sun and moon) set the unusual characteristics of astronomical instrumentation and research.

Very little astronomical work is done today by looking through the telescope, except as this is incidental to the setting of the telescope on the desired region of the sky. In recent decades the astronomer has worked principally with the photographic process to determine the positions, motions, and brightnesses of celestial objects. The photographic process still represents a method of information retrieval unrivaled for pictorial display, as is evidenced by the photographs from the 120-inch Lick and the 200-inch Palomar telescopes, shown in Figs. 1–4. The most efficient emulsions, however, utilize only 1 percent of the incident light. In recent years certain astronomical observations, particularly those of the brightness of stars, have been made with greater precision and light efficiency by using photomultiplier cells such as the RCA 1P21 and EMI.

The principal auxiliary instruments currently used by astronomers are the direct photography plateholder, the photoelectric photometer, and the spectrograph. A spectrograph can reveal many interesting properties of a star, such as temperature, mass, chemical composition, atmospheric structure, multiplicity, motion toward or away from the observer, and, indirectly but effectively, the absolute luminosity and hence the distance and even the age of the star. Other kinds of special equipment have been devised from time to time to measure special properties such as polarization of starlight and magnetic fields of stars.

Since the turn of the century the astronomer has pushed the telescope close to its maximum useful size. Four telescopes with aperture sizes of 100 inches or more have been successfully built. The 100-inch on Mt. Wilson was completed in 1919 and, in the hands of Hubble and Baade, did much to revolutionize astronomy. This was followed by the 200-inch on Mt. Palomar, completed in 1947, and by the 120-inch on Mt. Hamilton, in 1959. The fourth, of 104-inch aperture, is now being placed in operation in Russia. A giant of 240-inch aperture is reported under design by the Institute of Optics in Leningrad.

Each new and larger telescope costs much in return for a relatively small gain in distance reached and in new knowledge. In line with the times, we must look for a "new frontier" to explore and develop (*1*). Thus, we can look for new methods enabling us to make better use of the starlight that is collected by our terrestrial telescopes, and we can also look to the new field, so challenging to astronomers, opened up by the development of aerospace technologies.

### Atmospheric Effects

Telescopes have always operated under the handicap of an atmosphere that is opaque to most electromagnetic radiation, and that is constantly in motion. The various turbulences always present in the atmosphere are accompanied by thermal differences that make it impossible to focus a telescope to its theoretical angular resolution. In addition, the sky background is far from dark. Even in the absence of moonlight and far from the light of cities one can easily read the large-headline type of a newspaper by the light of the night sky. From the surface of the earth the stars are seen projected upon this faintly luminous background. It is this diffuse light of the night sky, in fact, that sets the limit in faintness to which a telescope can reach.

The light of the night sky is from several sources, both terrestrial and extraterrestrial. The lower atmosphere of the earth scatters starlight (7 percent). The upper atmosphere contributes the airglow, or permanent aurora, as it is

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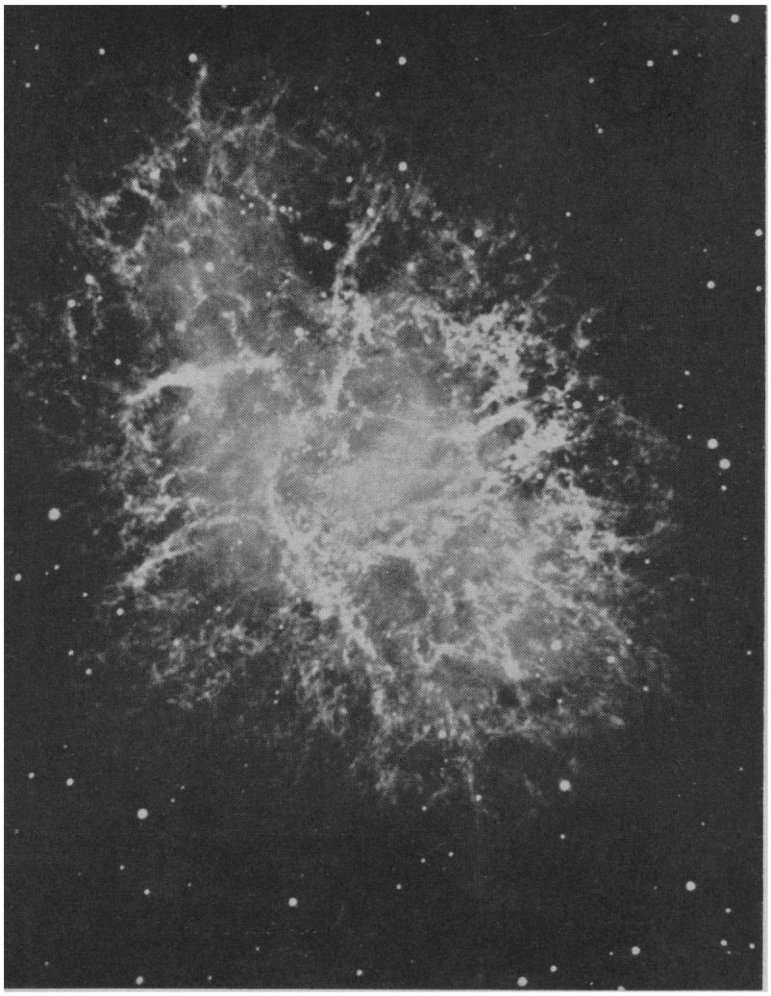


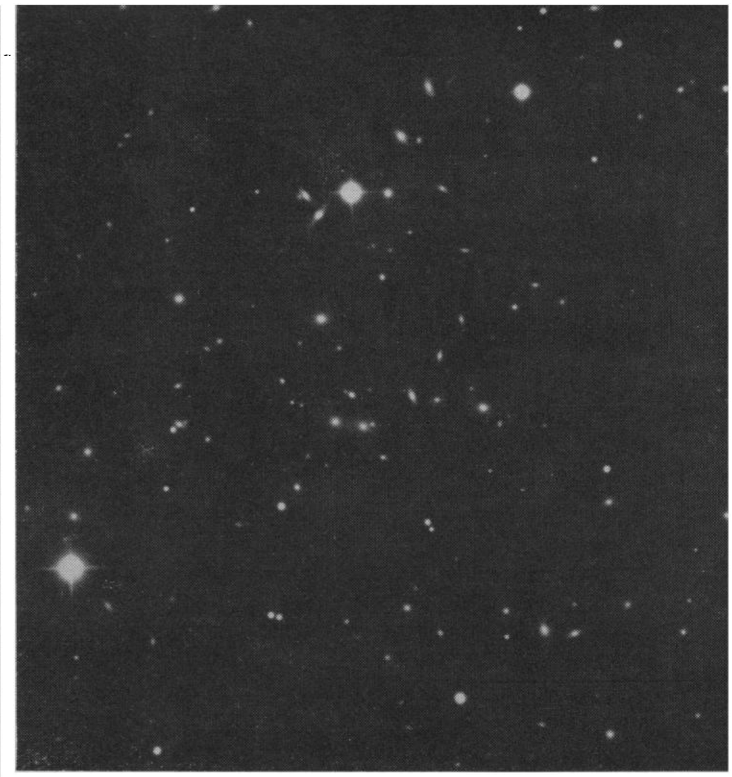
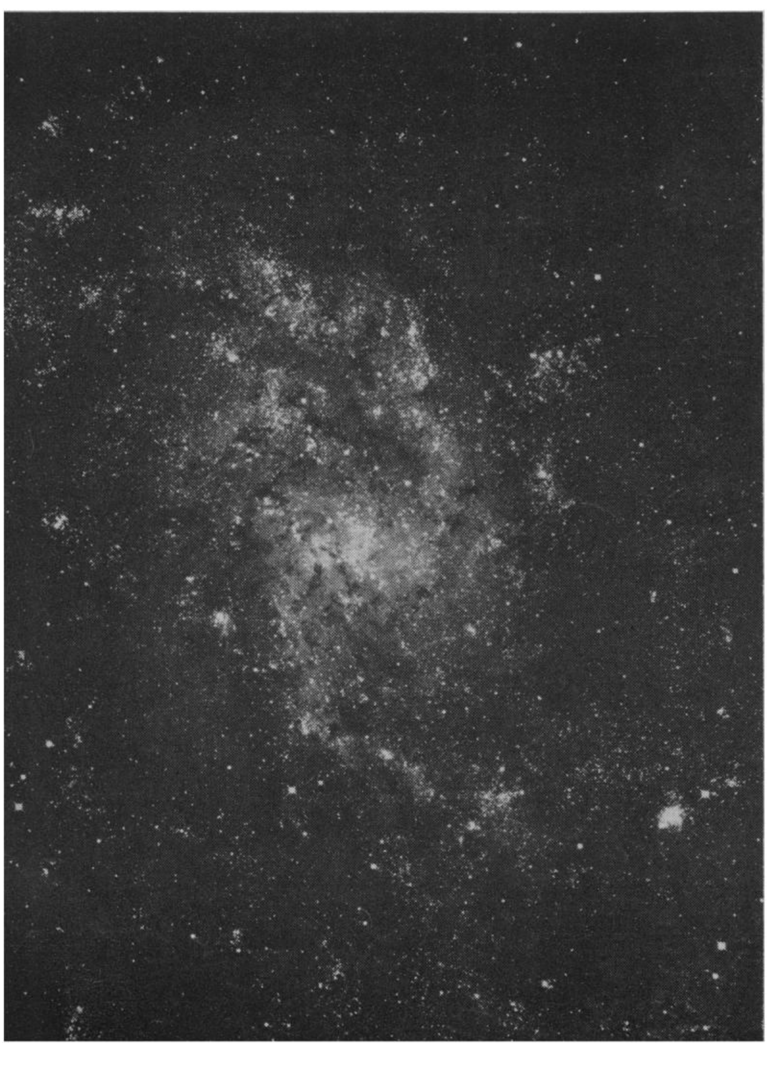
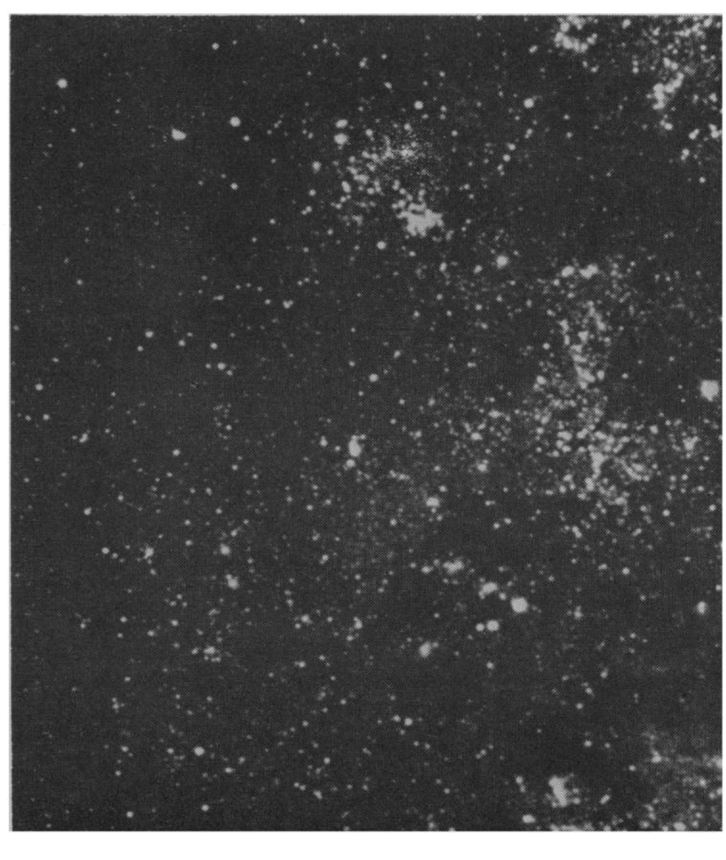


Fig. 1 (top left). Crab Nebula, M1, in red light, taken with the Lick Observatory 120-inch telescope, 3 November 1959. Exposure, 30 minutes; 103aE2 + R61 plate and filter. [N. U. Mayall] Fig. 2 (top right). Region in Corona Borealis taken with the Palomar 200-inch telescope. Each of the diffuse or elongated objects is a separate galaxy. Exposure, 30 minutes; 103a-O plate. Fig. 3 (bottom left). Galaxy M33 in Triangulum, in blue light, taken with the Lick Observatory 120-inch telescope. 17 September 1960. Exposure, 30 minutes; 103a-O plate. [S. Vasilevskis] Fig. 4 (bottom right). Region at center left of Fig. 3, showing resolution of the galaxy into stellar images. The small images are of approximately ¾ second of arc diameter.





sometimes called (40 percent). Both of these components will be eliminated in light viewed through a telescope located more than 500 miles above the earth. The remaining light comes from interplanetary, stellar, and interstellar sources. The interplanetary light comes from the scattering of sunlight by meteoric dust and gas in the solar system; it is known as zodiacal light (average, 20 percent). It usually appears brightest in late twilight or early dawn, as a hazy band of light stretching outward from the sun along the ecliptic. The stellar light (20 percent) comes from faint stars and galaxies that are not resolved by the telescope as individual stars, since only the relatively infrequent high-luminosity stars can be seen separately as stars, even those in our own Galaxy. The last component, of interstellar origin, arises from the scattering of starlight by interstellar dust and gas (13 percent). Interplanetary, stellar, and interstellar light sources will still limit the operation of a telescope at orbital altitude.

The total brightness of the night sky in its darkest regions, as seen through a large telescope, is approximately equal to a brightness of one 20th-magnitude star per square second of arc. It is obvious, therefore, that we cannot tolerate many square seconds of arc in our detector when we wish to observe a 23rd-magnitude star. When a 23rd-magnitude star is observed with one of the very large telescopes, the detector records approximately one photon count per second. Since the error of an observation consisting of $N$ events is equal to $N^{\frac{1}{2}}$, one must collect photons for 167 minutes to measure the brightness of such a star to an accuracy of 1 percent. With so few quanta from celestial sources, the astronomer has four means of making gains: (i) increase the size of the telescope mirror; (ii) increase the efficiency of the detector; (iii) decrease the aperture (sky noise) at the detector; and (iv) place the telescope above the atmosphere.

The first alternative—building larger telescopes—has been considered. While it is within the scope of present-day technology to build a 400-inch telescope, the cost would be in the vicinity of $40 million and the benefits are doubtful because of the limitations imposed by atmospheric "seeing," unless a site with exceptionally fine seeing could be found.

The effects of the terrestrial atmosphere on an incoming beam of starlight in the wavelength region of light transmitted by the atmosphere are twofold: (i) time fluctuations in the intensity of the wave front arriving at a given point at the telescope aperture, and (ii) time fluctuations in the direction of arrival of the wave front. The first effect is called scintillation and is readily seen with the unaided eye as twinkling. The second effect is usually referred to as "seeing," since it affects the ability of a telescope, especially a large one, to focus sharply. Both effects are caused by the presence of irregularities in the index of refraction of the atmosphere.

Research has now established that

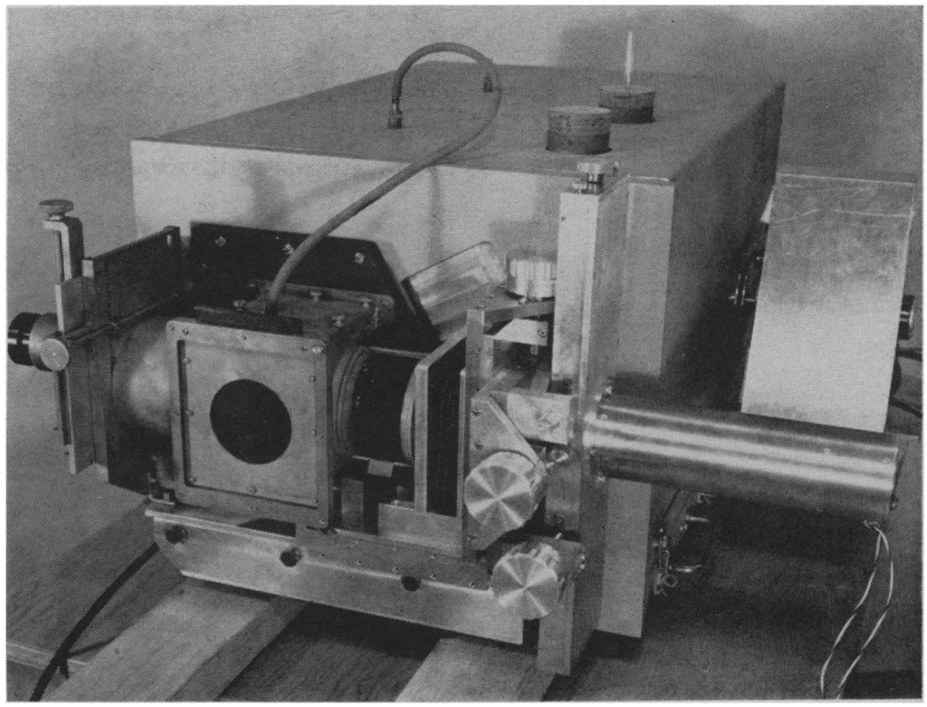


Fig. 5. Image orthicon camera developed by Livingston at Kitt Peak National Observatory. The orthicon is located inside a refrigerated box, with various test and operating auxiliaries on the front face.

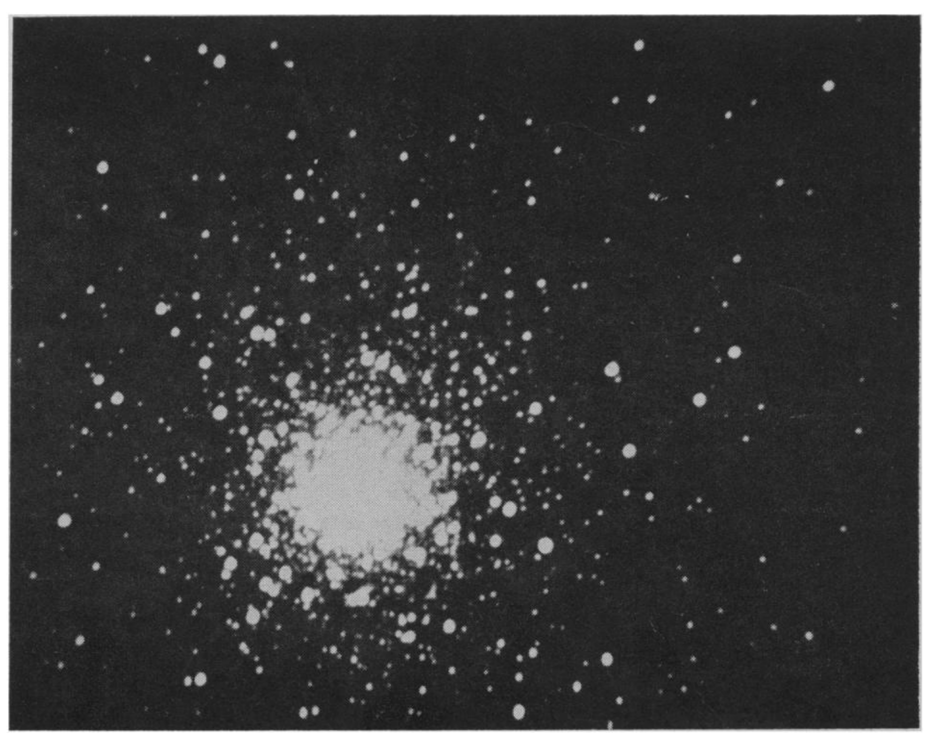


Fig. 6. Globular star cluster M3 in yellow light, taken at Kitt Peak 19 March 1961 with a GL-7629 image orthicon. Exposure time, 8.5 sec. [Livingston]

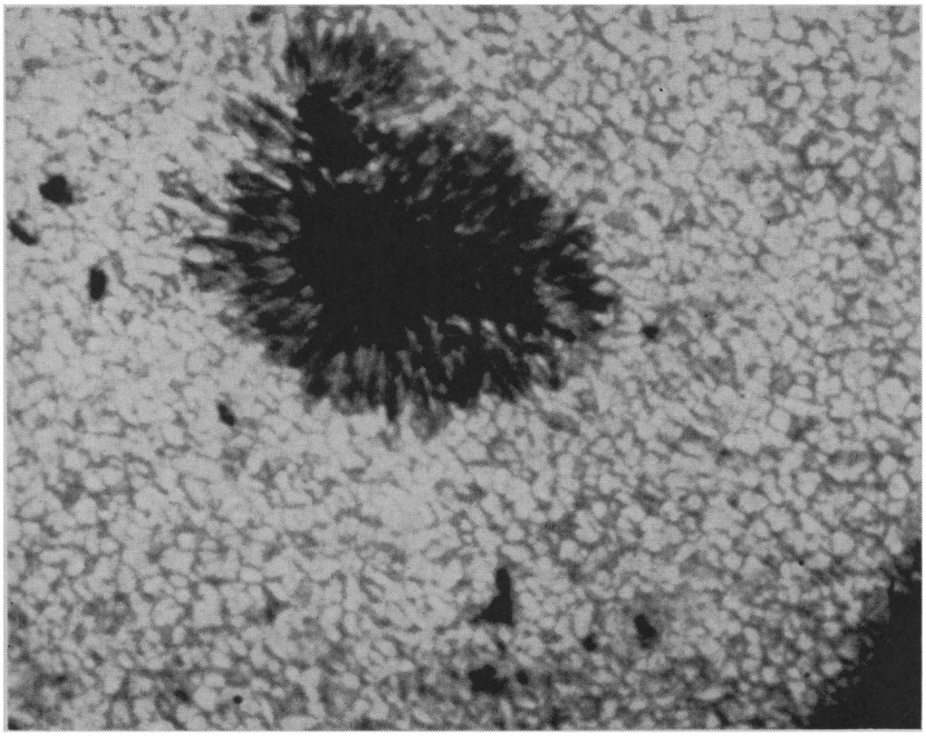


Fig. 7. The sun, taken with the Stratoscope I system from an altitude of 80,000 feet; the theoretical resolution of the telescope was attained.

scintillation effects arise high in the atmosphere, while the major seeing effects arise close to the ground. To minimize these seeing effects, telescopes are now located, at no small inconvenience, on the summits of mountains in relatively undisturbed air. In the best sites, the average seeing-image diameter, for a large telescope, is between 1 and 2 seconds of arc. Upon rare occasions the minimum seeing-image diameter may approach 0.3 second of arc; however, this is still much below the theoretical resolving power of a large instrument. As a consequence, a very large telescope can produce only a larger picture of the same blurred celestial objects. Under these conditions the telescope only gathers more quanta per unit time, and the gain in signal to noise ($N^{1/2}/N$) is proportional to the linear aperture of the telescope. Since the cost varies nearly as the 2.8th power of the aperture, the cost in terms of information gain is very high.

## Detector Efficiencies

The second possible means of making gains is that of increasing efficiency in the detection of photons. The photographic process has for many years been the chief detection method in astronomy. The process has a wide dynamic range, but relatively low fidelity as far as intensity registration is concerned. The quantum efficiency of a photographic emulsion is low, ranging from 0.1 to 1 percent for the optimum use of the fastest emulsions. The dynamic range and information retrieval of the photographic emulsion are remarkable. One photograph may record star images over a range of 20 magnitudes ($10^8$) and also record a million information elements per square centimeter. Information densities up to five million per square millimeter are possible under laboratory conditions.

Improvement in the quantum efficiency of a detector thus promises a greater gain than does an increase in the size of the telescope, for the same expenditure. There is little basis for hoping that there will be large improvements in the photographic process itself, since individual silver grains are quite good detectors. The quantum efficiency required for a single grain to be developable, in terms of absorbed photons, is 25 percent; however, a single grain has a low absorption cross section. Moreover, one developed grain does not provide a detectable quantity. Only when groups of 20 to 100 grains are developed does one find a star as an entity on the background of random developed "noise" produced by fog-grain clumpiness.

In recent years much effort has been devoted to the utilization of the high quantum efficiencies (approximately 20 percent) of the photoelectric detector. The photomultiplier is a commercially available device of high efficiency that has been widely employed in astronomy and particle physics. The internal amplification of this device ($10^7$) produces a measurable pulse for each photoelectron emitted from the cathode. The cathode will occasionally eject a thermal electron spontaneously as a consequence of the low work function of the cesium-compound emitting surface. These thermal electrons produce what is called the dark current, which adds a noise background to the signal. A good photomultiplier at room temperature will have a dark current of 10 to 20 electrons per second per square centimeter of photo-cathode surface. Because the dark-current emission of electrons is temperature-dependent, the astronomical use of photomultipliers is almost always at low temperatures. At Dry-Ice temperature (−80°C) a good photomultiplier will have a dark current of 0.1 to 0.5 electron per second per square centimeter.

The photomultiplier is an excellent detector for the observation of a single object at a time. The output current is accurately linear over a wide range of intensities; hence, brightness can be measured with high precision. In practice, the photoelectric photometer attached to a telescope isolates a single small region of the sky, containing the object, by means of a small diaphragm. In order to reduce the noise background of the sky in observing a faint object, this diaphragm is kept as small as the stellar seeing disk and guiding accuracy of the telescope will permit. Diaphragms as small as 0.1 millimeter have been used, but with brighter objects it is convenient to use a diaphragm as large as 5 millimeters in diameter.

The photomultiplier, while very sensitive, has a slow information-recovery rate. At the faint limit of the 200-inch telescope, Baum (of Mt. Wilson and Palomar Observatories) has spent an entire night measuring a 23rd-magnitude star in three broad wavelength bands. To use a single photomultiplier to successively examine more than a few hundred information elements to that faintness is, therefore, out of the question. If, for example, the photomultiplier is 100 times more efficient than a photographic emulsion, then one could retrieve information for 100 picture elements in the time required for a photograph. In other words, one could not effectively exceed the information-recovery capability of a photographic emulsion with a scanning photomultiplier if many elements must be scanned. Nevertheless, when the ultimate in accuracy is desired, a photomultiplier is often used, even if it is somewhat slower than a photographic plate. On the other hand, if one could use the sensitivity of the photo-cathode in an imaging device, much gain would result.

### Electronic Imaging Devices

The electronic image tube is currently under intense development as the first device to challenge seriously the information-retrieval properties of the photographic emulsion. The simplest form uses an electrostatic (or magnetic) lens to re-image accelerated photoelectrons upon a recording surface. Some of the earliest image tubes have used a phosphor as the recording screen, which in turn is photographed. This device was used by Krassovsky (of the U.S.S.R.) in 1950 to observe the infrared air-glow spectrum, a task impossible with the photographic emulsion because of its very low sensitivity in the 10,000-angstrom region. In recent years Hall and Ford (of Lowell Observatory) have used similar techniques with success; however, the phosphor is an inefficient intermediate medium.

Lallemande (Observatorie de Paris), Hiltner (Yerkes Observatory), and Kron (Lick Observatory) have in recent years successfully eliminated the phosphor by imaging the photoelectrons directly upon the photographic emulsion. The reduction in contamination of the photo-cathode by the photographic plate was one of the difficult problems faced in this technique; however, the device is now in a semioperational state. Recent research at Lick Observatory with the Lallemande-type tube on the 120-inch telescope has yielded new observational results and a net speed gain of about 30 times that of a photographic plate. A modification by Hall (Lowell Observatory) and by Hiltner (Yerkes Observatory), using thin film windows of mica or aluminum oxide to lessen the contamination, has shown encouraging results. In these tubes the photographic plate is placed in contact with the thin window to minimize electron scattering by the window.

The image orthicon is a different approach to the development of a more sensitive image tube, and this technique has been pioneered by Livingston (Kitt Peak National Observatory), DeWitt (Vanderbilt University), and Spalding (General Engineering Laboratories, Schenectady) (Fig. 5). Their developments are based upon the high sensitivity and integrating properties of certain new types of image orthicons. The promise of this type of image tube is shown in the short-exposure photograph of a star cluster (Fig. 6) taken at Kitt Peak by Livingston. The use of these scanning systems is especially attractive for future applications, since electronic processing and information retrieval by telemetry are possible.

A vast military technology has developed for infrared detection (1 to 20 $\mu$), which has not as yet been fully applied to astronomy. Strong (Johns Hopkins University) and Kuiper (University of Arizona) have pioneered in the astronomical application of infrared techniques, and Sinton (Lowell Observatory) has extended this work, but much remains to be explored. The principal reason why infrared techniques have not been used more in astronomy is that the atmospheric transmission is highly variable in these spectral regions and detectors are inefficient to the extent that only the most luminous objects are within reach of a large telescope.

### Stratospheric Telescopes

The third possible means of improving the operating efficiency and research potential of a telescope is to improve seeing conditions, thus decreasing the seeing image of the celestial object and, in effect, increasing the resolution of the telescope. Much effort was expended in selecting the location of the Palomar and Kitt Peak observatories to find a site with the best possible seeing conditions. It does not appear that much can be gained in this respect in locating future telescopes as long as the terrestrial atmosphere is involved, although an exceptional site might provide conditions twice as good as those at existing sites. Only when one can place his telescope above the atmosphere does the theoretical resolving power of a telescope become attainable.

Balloon-borne telescopes offer the possibility of a major increase in the resolution of a telescope. At altitudes of approximately 80,000 feet there is essentially no seeing disturbance, even from direct sunlight on the telescope. While visual observations have been made from balloons by Dolfuss (Observatorie de Paris), the first successful demonstration of high-resolution photography was made with the 12-inch Stratoscope I system by Schwarzschild (Princeton University). This unmanned photographic telescope has taken superb direct photographs of the sun, achieving the full theoretical resolution of the telescope (Fig. 7). The same balloon-borne stabilized platform has been flown by Newkirk (High Altitude Observatory), with a coronagraph to study the outer corona.

At the present time the 36-inch Stratoscope II system, also developed by Schwarzschild, is nearing completion (Fig. 8). This instrument is large enough to permit observation of planets, stars, and nebulas, and it is designed to

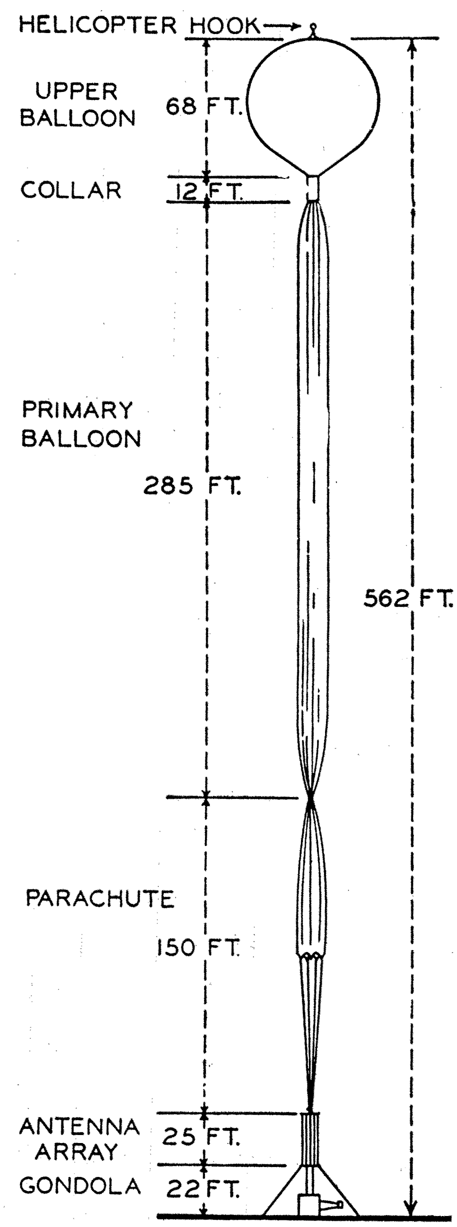



Fig. 8. The Stratoscope II system, which will carry a 36-in. telescope to 80,000 feet for night observations.

yield a guidance accuracy of 0.1 second of arc over extended periods. The size and complexity of this instrument are such, however, that a sizable support operation is required for launching and recovering the telescope. It is to be hoped that, as balloon-borne telescopes are developed, a permanent facility will be established so that astronomers can work with such instruments without the prodigious effort in systems development now required of individual astronomers.

Balloon astronomy, like the rocket astronomy of the last decade, can be viewed as an interim step, preliminary to the establishment of more permanent observing stations above the atmosphere. From a vertical rocket probe one can glimpse the sky for only a few minutes on a flight, and at present, the number of such flights is limited to three to six per year. In the case of balloons, one can expect observation time of a few hours per flight in three to six flights per year. The cost per hour of observing is indeed high, but the return is also high, since the results of these operations will point the direction of research with subsequent satellite telescopes.

## Space Astronomy

The use of rockets in the last decade has led to the development of instruments to observe the sun spectrographically from the 3000-angstrom atmospheric cutoff into the x-ray region. The beautiful far-ultraviolet spectra and Lyman-$\alpha$ photographs of the solar disk obtained by Tousey and his group (Naval Research Laboratory) are well known. The short observation time available on these flights has led to major advances in instrument technology. The development of the successful Aerobee pointing control by the Upper Air Laboratory at the University of Colorado, and the subsequent evolution of stabilized pointing systems, made it possible to use the entire period of flight above the atmosphere for observation. The parallel development of spectrometers, image-forming spectrometers, special detectors, and filters has progressed rapidly to a point where it is now possible to observe stars and nebulas. In a recent series of flights by Boggess (NASA) in 1960, observations of stars were made, for the first time, with multicolor broad-spectral-region detectors. A subsequent flight by Stecher and Milligan (NASA), on 22 November 1960, with spectrometers designed by the University of Rochester, yielded for the first time stellar spectral energy distributions below 3000 angstroms. The photograph of the spectrometer used on this flight (Fig. 9) illustrates the design problem posed by the weight and space limitations of rocket astronomy.

The initiation of the Orbiting Astronomical Observatories (OAO) program by NASA now gives ground for hope that the astronomer will soon have telescopes of considerable size in orbit, providing extended periods of observation. The most obvious gain to be had from a space telescope is, of course, accessibility to the ultraviolet. The short-wavelength region is of great interest to the astrophysicist. In fact, the absorption cross sections become so large that it appears that even the dilute interstellar atomic hydrogen must certainly be opaque, over stellar distances, to radiations of wavelength shorter than 912 angstroms. In the infrared one expects only very weak interstellar absorption because of the presumed scarcity of molecules. If detector technology permits, the study of stars and of the interstellar medium in the infrared may bring surprising results.

A less obvious advantage—one that cannot be realized without further technological development—is greater resolving power. An orbital telescope can work at the theoretical resolving power of the optical system, since no seeing disturbance is present. Nidey and I (Kitt Peak National Observatory) have made system studies for high-resolution orbital telescopes. Given sufficient guiding accuracy, one could use diaphragms of very small angular size and increase the star-to-sky signal by many magnitudes.

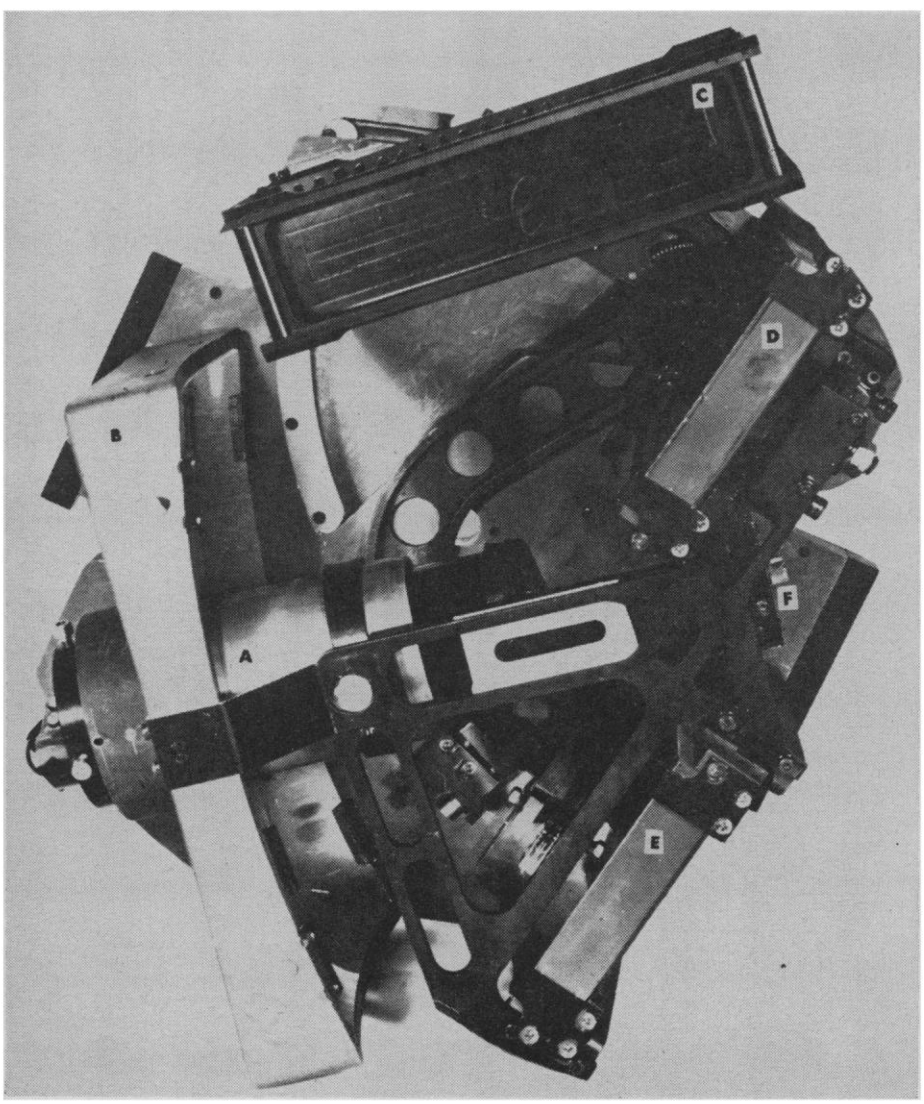


Fig. 9. The NASA–University of Rochester objective grating spectrometer for use in an Aerobee rocket. *A*, photocell; *B*, paraboloid; *C*, sky baffle; *D* and *E*, gratings; *F*, secondary.

If television devices of sufficient information-handling capability become available, then high-resolution photographs of the planets and other celestial objects can be obtained. While we do not now know of many crucial astrophysical problems that depend primarily upon higher angular resolution for their solution, the attainment of this resolution may of itself open new research fields. Even satellite observations in the visual region may prove attractive, in conjunction with observations in the other spectral regions. This possibility exists because an orbital telescope would enable the astronomer to plan and make a special observation, such as an observation of time-variable phenomena, at a predetermined time or for long periods of time, since neither weather nor considerations of daylight would interfere. Once per revolution of an OAO telescope a star will be occulted for 45 minutes, but as second-generation telescopes are developed, especially if they are placed in high-altitude orbits, observations of most celestial objects will be uninterrupted.

## Space-Telescope Problems

The principal problem that must be solved if space telescopes are to be effective is that of information retrieval. That telemetry will be exclusively employed seems certain, since recovery of packages of data might well be prohibitively expensive and hazardous. A large number of information elements are contained in an astronomical photograph such as Fig. 3. A higher resolution, and consequently more information elements per square second of arc, will make the information retrieval problem even more formidable. The solution may lie in either of two directions. In the direct method, a slow-scan televison link and a high-sensitivity integrating image orthicon would be used. While Vidicon-type television tubes have been used in rocket and satellite instrumentation, they are relatively insensitive and could be used only for lunar and planetary work. "Ruggedized" image orthicons are under development for use in rockets and satellites. In the indirect method an intermediate recording surface, such as a photographic or xerographic film, would be used, and the picture would be subsequently transmitted by Vidicon or line-scan techniques.

In the design of satellite telescopes and instruments new boundary conditions are encountered. Two serious ones, aside from weight, are the low reflectivities of reflecting surfaces in the ultraviolet and the opacity of all transmission materials. The designer is, therefore, limited to the very few reflecting surfaces compatible with the design specifications. This requirement makes it mandatory that more sophisticated aspheric systems be utilized, in spite of attendant manufacturing problems. In space optics use may also be made of unconventional mirror materials. The lifetime of a space telescope is so short in comparison to that of a terrestrial telescope that optical stability of several months may be sufficient for the mirror materials.

The design of an orbiting telescope poses three major problems not encountered in designing terrestrial telescopes.

The launching *g* forces in particular are an example. During the launch into orbit a telescope may be subjected to vibration of approximately 5 to 10 *g*'s over a frequency range of 5 to 1500 cycles per second. As a consequence, either the engineer must find a design that will preserve optical collimation or the astronomer will have to realign his optical systems after the telescope arrives in orbit. The lack of proper optical collimation could seriously degrade the performance of a space telescope.

The second major problem in the design of the space telescope is that produced by its thermal environment while in orbit. Sunlight will intermittently illuminate one side or the other of the space craft. This variable heating will produce a large and changing temperature gradient between the outer skin of the space craft and the telescope optical system. It will be necessary to keep the thermal gradient small in the optical system if high-resolution performance is to be obtained.

The third problem area, one common to all orbital instrumention, is that caused by prolonged operation of moving parts in the hypervacuum of space. The list of problems can easily be extended as one looks closer into the actual design of a space telescope.

## A Lunar Observatory

There has been considerable speculation concerning the ultimate location of a space telescope. The inaccessibility of an orbiting telescope, for purposes of repair or for modification of the onboard experiments, would be a severe handicap. The establishment of a manned lunar base could considerably change this picture. If such a base should be established, we may be certain that a large lunar telescope would be constructed. While the erection of a lunar telescope would be an exceedingly expensive and challenging problem, the proposal is perhaps no more farfetched than the establishment of a great research facility at the South Pole, such as now exists, would have seemed a century ago (*1*).

### Note

1. This article is contribution No. 11 from the Kitt Peak National Observatory.