Astrophysics from the Moon

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The surface of the moon would be an excellent location for astronomical telescopes, and, if a lunar base were to be established, the construction and maintenance of instruments would become feasible. The prospects are reviewed, with particular attention given to large optical aperture-synthesis instruments analogous to the Very Large Array of the National Radio Astronomy Observatory. Typical parameters for a particular system are presented.

THE EXPANSION OF OBSERVATIONAL POWER HAS ALWAYS been a central theme in the advance of astronomy since the time of Galileo, whose telescope launched a new era in instrument development that advanced sensitivity and angular resolution far beyond the levels obtainable with the unaided human eye. For the largest ground-based telescopes of today, however, there remains the barrier of Earth's atmosphere, whose turbulence limits angular resolution to a half second of arc or slightly better at even the best locations and whose absorption features in the infrared and ultraviolet domains of the spectrum limit the wavelength range over which measurements can be made. In our own time, the development of artificial satellites freed astronomers from Earth's atmosphere, but the constraints of telescope weight, size, complexity, and cost remain barriers to technical creativity. Angular resolution is still subject to the diffraction limits imposed by the wave nature of light, and an optical telescope capable of a resolution of 1 milliarc sec at a wavelength of 0.5 μm would need to have a diameter of about 100 m.

Proposals for establishing a lunar base have been put forward recently (*1*), and enough preliminary studies have been carried out to demonstrate that such a base could provide support for astronomical instruments of great power (*2–6*). This review examines some of these possibilities, many of which were raised in these references, with particular emphasis on aperture-synthesis arrays that would improve angular resolution to the level of a few microarc seconds. The moon has many favorable qualities as a spacecraft, because it is a stable platform with an enormous moment of inertia, rotating far more slowly than Earth, with a well-determined ephemeris. The only conceivable mode of catastrophic instrument failure would be a meteorite strike, but the probability is small and not very different from the case for Earth orbit. Indeed, the chance of a collision with space debris in Earth orbit is probably far more severe than for meteorite damage on the moon. There are, nevertheless, several possible objections that must be addressed. Lunar dust might be a problem, the lunar surface might not be able to support a telescope structure, "moonquakes" might disturb the instruments, gravitational deflection might distort the instruments, and heat radiation and scattered light might cause trouble.

Enough is known about the mechanical properties of the lunar soil to demonstrate that the lunar surface is a competent base for supporting telescopes and other instruments. Results of the Apollo drive-tube core sampling (*7, 8*) showed that, after the first few centimeters, persistent hammering was required to reach a depth of 70 cm. Mitchell *et al.* (*8, 9*) concluded that the mechanical properties of the lunar soil are remarkably similar to those of terrestrial fine silty sands, although the lunar soil is more cohesive, and the strength of the lunar soil at a depth of 2 m is considerably greater than the average strength near the surface. The loads to be borne will be relatively light because of the low lunar gravity. The lunar atmosphere is negligible, with an optical depth below that of the interstellar medium (*10, 11*).

Seismic activity should present no threat. Immediately after the Apollo seismometers were deployed, snapping and popping of the lander module under thermal stress gave a false alarm, but it is now clear that the moon is seismologically quiet. The average lunar seismic activity observed is 10^{-7} of that measured on Earth (*12, 13*).

Lunar dust could be troublesome, but it is cohesive, and the many photographs of astronaut footprints show crisp outlines. When dust is kicked up, it travels in ballistic orbits, so it does not go far; astronauts will certainly have to exercise care in servicing a lunar-based telescope. The lunar dust sticks tenaciously, so critical bearing surfaces would have to be protected, but, because of the near-vacuum condition, all the lubricated bearings would have to be sealed anyway. Optical surfaces would need to be treated carefully, as on Earth. After 20 years, the lunar laser retroreflectors show no evidence of major deterioration (*14*). The lunar dust problem, nevertheless, should be treated with respect.

Background light and heat from the lunar surface must be dealt with, but extensive heat shielding should be possible on the moon, and a large heat sink is close at hand. In some respects, there are similarities between having a telescope at a lunar base and having one in geosynchronous orbit, where shielding against sunlight has to be provided continuously. Costs of transport to geosynchronous orbit are nearly as great as costs of transport to the moon, however, and there would surely be advantages to having the lunar base personnel close at hand.

The acceleration of gravity at the moon's surface is one-sixth of the terrestrial value, and on the whole the effect should be beneficial, since it cleans up residual gases, seats bearings, and should make easier the design of gas compressors. Gravitational deflection is no longer a limitation, even for terrestrial telescopes. The most complete compensation, used generally for large radio telescopes, is the principle of homology, first formulated by von Hoerner (*15*). It appears that thermal deformation, and not gravitational deflection, is the principal limitation for large, precise structures. The art of building servocontrolled telescopes is also advancing rapidly. Laser beams can be used to measure the configuration of critical points on a structure, and active structures can maintain that configuration. The Mark III stellar interferometer, an astrometric interferometer on Mount Wilson (*16*), is an example of a working astronomical instrument that depends on the reliable functioning of an extensive laser metrology system.

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Sensitivity and Angular Resolution

The thrusts for greater sensitivity in detecting faint objects, higher angular resolution to see their detailed structure, and broader spectral coverage have been continuous themes in astronomy, with advances generally coming through technical development. Space technology opened up the x-ray, ultraviolet, and far-infrared spectral domains. Electronics and computer technology have aided both the expansion of radio astronomy and the improvement in the sensitivity of optical telescopes, and the sensitivity is now close to the quantum limit with modern charge-coupled device arrays (CCDs). Similar improvements are now under way for infrared astronomy. Many of the most interesting objects are faint, however, and, once detectors have reached their limit, ever-larger telescopes must be built. Several ground-based instruments in the 8- to- 10-m size range are under way, and these set the scale for the desirable collecting area of optical and infrared telescopes of the future. A recent workshop (*17*) examined the future directions of next-generation space telescopes and concluded that planning should start for either a 10-m telescope in high Earth orbit or a 16-m telescope at a lunar base. Such a telescope would cover the ultraviolet, visible, and infrared domains and would be of such a size that it would probably be assembled in situ. The proximity of a lunar base would be a clear advantage in this respect.

Improving angular resolution raises a different set of considerations. The Hubble Space Telescope was designed to reach a resolution of 50 milliarc sec at a wavelength λ of 0.5 μm (*18*), but there are a large number of important astronomical questions that will require larger advances in angular resolution. Radio interferometry, for example, has shown that there are interesting structures associated with quasars and active galactic nuclei (AGN) in the milliarc second range. A synthesis of the radio, optical, and x-ray observations leads one to expect still more compact structures at the nuclei of these ill-understood objects. A more general view of angular resolution requirements is shown in Fig. 1, which was developed in the course of a National Research Council study (*18a*). The shaded zones indicate the sizes and distances characteristic of many classes of astronomical objects. In this representation, the locus of constant angular size is a diagonal line, and it is immediately evident that the angular size range from a milliarc second to a microarc second opens up a dramatic new set of frontiers. At a wavelength of 0.5 μm, the aperture size would have to be about 100 m to achieve a resolution of 1 milliarc sec, and the aperture size goes to 100 km for a resolution of 1 microarc sec. A single aperture is therefore out of the question, and aperture-synthesis methods must be used, extending the established radio methods to much shorter wavelengths. The LOUISA Workshop (*6*) examined the problems of building arrays on the moon in some detail.

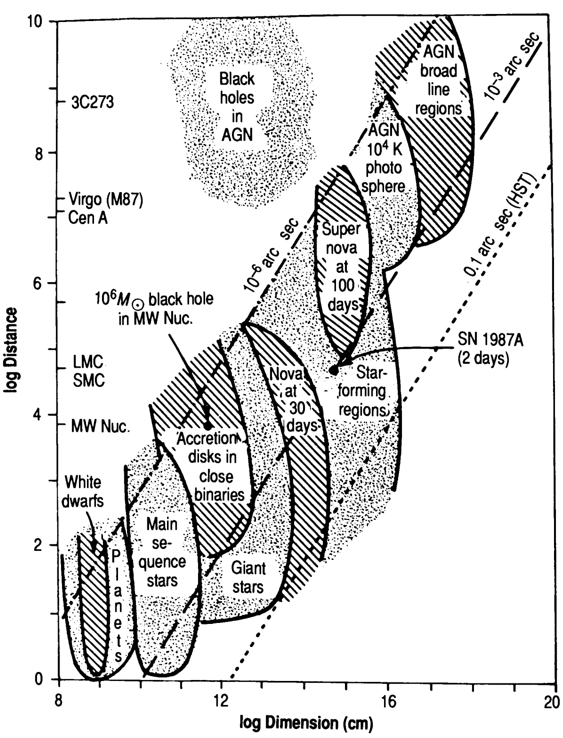

Fig. 1. Characteristic dimensions and distances of astronomical objects. Constant angular size is shown by the diagonal lines; LMC, large Magellanic cloud; SMC, small Magellanic cloud; MW, Milky Way; and HST, Hubble Space Telescope. [Adapted from (*18a*) with permission of the National Academy Press]

The central idea of aperture synthesis is rooted in the dualism of the Fourier transform, a theme that underlies so many innovative fields of modern science. If an astronomical source is reasonably compact, its angular brightness distribution can be described with sufficient accuracy in Cartesian coordinates (x,y) (using the small-angle approximation). The brightness distribution will be a function of frequency, ν, and so the specific brightness $B_\nu(x,y)$ gives complete information on the source [strictly speaking, there may be polarization, so there are actually four functions, $B_\nu^{(i)}(x,y)$, representing the Stokes parameters or their equivalents]. Any physical measurement is an average of $B_\nu(x,y)$ over frequency, solid angle, and time, and the astronomical task is to interpret this estimated specific brightness distribution. Any physically reasonable brightness distribution, however, has a Fourier dual, $\tilde{B}_\nu(u,v)$, in an appropriately defined set of dual coordinates (u,v):

$$B_\nu(x,y) \rightleftharpoons \tilde{B}_\nu(u,v)$$

The dual representations $\tilde{B}_\nu(u,v)$ contain all the information of the original brightness distribution, but in a less intuitive form.

A radio example of a Michelson stellar interferometer is schematized in Fig. 2. Here, a pair of radio telescopes are fixed on a given point in the sky, and a radio source is allowed to drift through their diffraction pattern. The fringe spacing in angle is $1/\tilde{D}$, where $\tilde{D}$ is the interferometer baseline length, measured in wavelengths, projected on a plane perpendicular to the line of sight. The Fourier transform connection follows directly. The projected baseline $\tilde{D}$ (measured in units of wavelength) defines the dual coordinate system (u,v). The amplitude and phase of the quasi-sinusoidal fringe pattern is proportional to the Fourier transform $\tilde{B}_\nu(u,v)$ of the source brightness distribution. This means that, with enough interferometric spacings in the (u,v) plane, the complete Fourier transform can be built up, and by Fourier inversion the actual brightness distribution $\tilde{B}_\nu(x,y)$ can be recovered. The angular resolution is limited only by $\tilde{D}_{max}$, the maximum baseline length.

The generalization to an array of telescopes follows directly. If there are N elements in an array, there are $N(N-1)/2$ possible pairs of elements, and each pair is a Michelson interferometer giving a fringe visibility V_{ij} for the ith and jth elements. One thus obtains a set of values for the Fourier transform, which may be extended by continuing observations over time, using Earth's rotation to change the lengths of the projected baselines. A comprehensive monograph on aperture synthesis has been written by Thompson, Moran, and Swenson (*19*), referred to henceforth as TMS.

Synthesis Arrays, Optical and Radio

The Very Large Array (VLA) of the National Radio Astronomy Observatory is the prime example of an aperture-synthesis array (*20*)

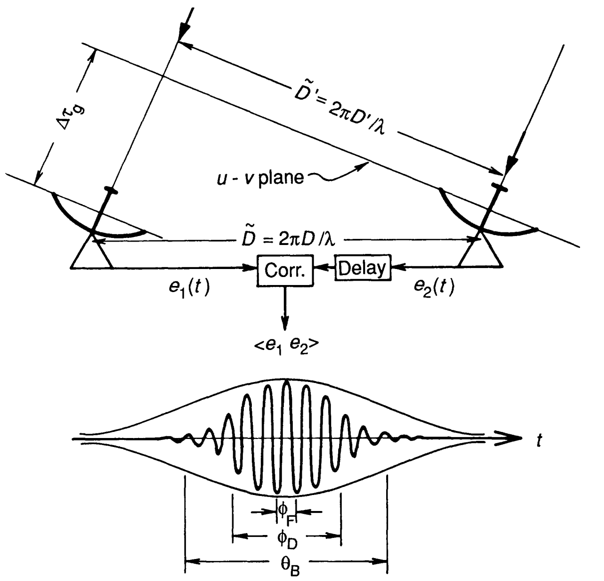

Fig. 2. Idealized radio version of a Michelson stellar interferometer. The angular spacing ϕ_F of the fringes is determined by the projected spacing $\tilde{D}'$, and the modulation in angle is determined either by the coherence length (the inverse bandwidth) or by the diffraction pattern θ_B; e_1, signal from antenna 1; e_2, signal from antenna 2; $\Delta\tau_g$, arrival time delay. [Adapted from (*24*) with permission of the author]

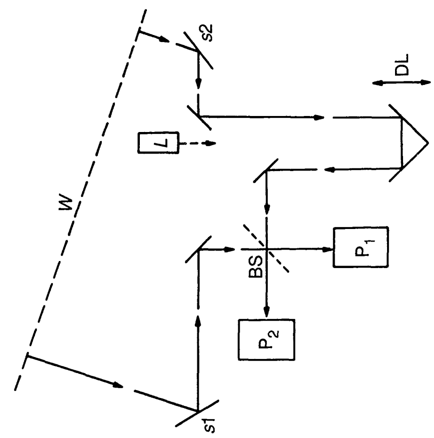

Fig. 3. Simplified optical version of a Michelson stellar interferometer. A delay line DL is moved on a transport *L*, and the two beams are combined on photodetectors P_1 and P_2 through the beam splitter BS, from which fringe amplitude and phase are derived; *W*, wavefront.

and may well be a prototype for a lunar array built for infrared and optical wavelengths. The instrument is composed of 27 separate radio telescopes, and the signal from each telescope is sent to a central station, where the signals are divided 26 ways and combined pairwise in individual correlators. These form 351 separate Michelson interferometers, each giving one value of the Fourier transform of the source brightness distribution. Computer reduction of the data follows. The 27 antennas are deployed along three arms of a wye, and the antennas can be moved into configurations of various sizes, depending on the maximum (or minimum) angular resolution desired. Data from different arrays can be combined in the computational process to give a wider range of angular coverage (and, in general, maps of higher quality).

The Fourier conversion of the data to a map is accomplished by software routines, described in TMS (*19*). Self-calibration procedures allow aperture-synthesis maps to be improved in fidelity, since the number of constraints from the observations exceeds the number of degrees of freedom (*21*). The spectacular synthesis maps of the radio galaxy Cygnus A (*22*), and the supernova remnant Cassiopeia (*23*), with dynamic ranges of 10,000:1, are examples of the state of the art.

Aperture-synthesis arrays in the radio and optical domains obey the same principles (in this discussion "optical" will refer to the spectral range from the infrared to the ultraviolet). Even though the optical signals have to be treated as discrete photons, the classical wave description can be used for the wave function (*24*). The signal-to-noise considerations are different, because radio observations are limited by internal thermal noise that obeys Rayleigh statistics, whereas most optical observations will be limited by photon shot noise. This means that the radio signal-to-noise ratio will be proportional to the array area, whereas in the optical case this ratio will be proportional to the square root of the array area.

Another distinction arises from quantum considerations. Radio arrays generally convert the incoming signal to an intermediate frequency (IF) by heterodyning with a local oscillator signal that is distributed from a central station. Unfortunately, heterodyning is impractical in the optical domain unless the sources are intense, and astronomical sources seldom are. The reason is fundamental: every amplifier must generate noise or it would violate the second law of thermodynamics (*24*), and in particular the classic Bohr explanation of the interferometer paradox would be violated (*25*). This means that the equivalent of approximately one photon per hertz of bandwidth is generated at every amplifier input, with disastrous results at optical frequencies. Optical aperture-synthesis arrays must rely on direct optical relay; the division between use and nonuse of heterodyning probably falls at wavelengths between 50 and 100 μm.

Otherwise, even though the appearance of the optical components may be dissimilar, there is an exact analog to the radio case. The Naval Research Laboratory–Massachusetts Institute of Technology–Smithsonian Astrophysical Observatory Mark III interferometer (*18a*) has demonstrated the principles and has the necessary phase stability, and there seem to be no insuperable barriers to developing the techniques for a lunar-based optical array. The general concept of an optical interferometer is schematized in Fig. 3, which contains all of the elements of Fig. 2 with most of the optical components left out for simplicity. The incoming signals at apertures *s*1 and *s*2 are combined by imaging the apertures onto photodetectors P_1 and P_2, with an adjustable delay line DL to equalize the path lengths (a small, rapidly oscillating DL, not shown, is also present to modulate the detected signal and permit the extraction of a value for the fringe visibility). The two detected signals determine the amplitude and phase of the complex fringe visibility (*26*). The beam splitter BS is an optical analog of the hybrid junction known to microwave engineers as a "magic T."

Array Configuration

The VLA configuration, a wye with antennas spaced in increasing steps along each arm, was arrived at empirically. More recently, Cornwell (*27*) has proposed an array that he calls a "crystalline array," derived from the use of an entropy-like measure of array quality, which is maximized by a Monte-Carlo numerical procedure. The constraints are that *N* elements must lie within a fixed area, and the solutions always converge to location on a circle, with the elements unequally spaced. The resulting *u–v* coverage is quasi-crystalline in appearance, and, the larger *N* can be, the more complete is the Fourier coverage for a given configuration.

The choice of configuration is governed by practical considerations. The wye arrangement of the VLA has a significant operational advantage, since rails were the most practical ways to transport the 170–metric ton antennas. The lunar optical array does not necessarily have the same needs, since the elements would be relatively light, and, if power and data can be transferred by light beam or another inexpensive and flexible method, the elements can be transported by trucks to their stations. The circular "Cornwell array" is probably preferred. The trade-off between simplicity (fewer elements) and snapshot quality (many elements) remains to be studied.

In principle, single-mode optical fibers might be used to transmit from the telescopes to the correlator, but direct beam transmission is simpler and less lossy. Two limitations exist: the curvature of the lunar surface and beam spreading from Fresnel diffraction. Both transmitting and receiving optics would have to be at least 2 m above a plain, at 5-km separation, to be mutually visible. Fresnel diffraction will cause the beam to spread, so the aperture of the relay optics must be sufficiently large. For example, at a wavelength of 0.5 μm, a 10-cm beam has a near-field range of 10 km, good enough for an array of 5-km radius. Beam spreading is more severe at longer wavelengths in the infrared and could be the limiting factor on array size unless single-mode fibers can be used.

The Array Elements

The two-element optical interferometer shown in Fig. 3 can be generalized to the N-element case. The apertures s_i are telescopes that produce collimated quasi-plane waves that travel through DLs (one per telescope) that equalize the path delay. At the central correlator, the beams are each split $N - 1$ ways, so that all possible pairs can be cross-correlated to give the set of $N(N - 1)/2$ values of the source Fourier transform. Since this is just a set of complex numbers, the results can be averaged and stored for later numerical reduction. The basic elements, then, are the telescopes, the DLs, and the central correlator.

The first element, the telescope, need not be very different from an Earth-based telescope in concept, although innovative designs may prove attractive. Telescopes designed for the moon should be much lighter than their terrestrial counterparts, since modern large terrestrial telescopes are already using mirrors of low mass. As an example, the cellular mirrors now being cast at the University of Arizona have a filling factor of only 20%, and 5% should be possible (*28*). A 4-m mirror could therefore have a mass of only 500 kg. This means that a terrestrial telescope, following the empirical rule that the total mass is about eight times the mass of the mirror, could have a mass of 4 metric tons or so. The lunar telescopes can be lighter, because lunar gravity is only one-sixth that of Earth, and simple scaling laws can be used to estimate the mass of a "conventional" lunar telescope. For conventional materials, and if gravitational deflection is used as the constraint, the total mass of a lunar 4-m telescope should be about 1 ton. The weight on a lunar transporter, or on its mounting hard points, would be only about 370 pounds. Segmented telescopes of the Keck telescope type might well be a good way to go, particularly for telescopes of larger sizes.

The next element to consider is the delay line, DL. Large arrays present a real engineering challenge, since the "throw" of the DL must be of the order of magnitude of the diameter of the array if full rotation synthesis is desired. A maximum array diameter of 10 km, therefore, requires a 10-km maximum delay, although multiple-pass reflection delays would reduce the required motion. One would probably mount the DL on an optical bench, which would in turn be carried by a transporter. In operation, the transporter would position itself and orient the optical bench, and the delay carriage would then be adjusted to give the correct time delay. Designing the DL and its transporter may be the most challenging engineering task in the system.

Finally, the correlator must be considered. The best low-loss beam splitters are refractive, and with a simple dispersion corrector a 2:1 frequency coverage is achieved (*26*). The incoming beam must be split $N - 1$ ways, and, if this is done in binary steps with refractive beam splitters, the number of telescopes would be $2I - 1$, where I is an integer. This means that arrays of 9, 17, and 33 elements are a natural choice for the number of elements in the system. A single $N - 1$-times beam splitter is conceivable, in which case there can be any number of elements. The Mark III correlator (*16*) has been cited as an example, but the dispersed-fringe approach of Stachnik and Labeyrie (*29*) is an alternative approach.

Science and Practice

Figure 1 implies that there are many potential scientific problems that might be addressed by a large aperture-synthesis array, and three of these, in very different fields, will be presented here. To start with, the scale of the instrument should be set. Telescope elements of roughly 4-m aperture, whether intended for infrared or for visible-ultraviolet wavelengths, have properties that can be estimated with some confidence. The DL designs are less well defined, since the wavelength domain determines the mirror size, and the acceptable path loss (and bandwidth) determines the number of passes light beams will make between the central station and the delay unit. For the purposes of argument, let us postulate that an array of 17 telescopes, each of 4-m diameter (mass of 1 ton each) will be put in place on the moon and can be deployed on concentric circular arrays ranging from a diameter of 100 m to one of 10 km. Two telescope transporters, at 0.5 ton each, would be needed. Delay lines with a 10-m throw and with integral transporters will also be postulated; these could have multiple, hydraulically activated feet of the sort used to stabilize modern cranes. A rough mass estimate of the unit projects a mass of 2 tons per DL; telescope plus DL would have a combined mass of 3 tons. The central correlator might have a mass of 2 tons. The total mass estimate, therefore, comes to 53 tons, and, like all arrays, the system could come into service gradually, as more elements are transported and assembled. The characteristics of the "straw-man" system are impressive: a total collecting area equal to that of a 16-m telescope, with the capability of determining spectra as well as brightness distributions of faint objects.

Brief examples of its capability can be cited in three very different areas of astronomy: stars, quasars, and planetary searches. A fifth magnitude star of the solar type delivers a total of about 10^{10} photons per square meter per second, and so about 4×10^{14} photons would arrive in one 200-s integration time. If the overall efficiency of the system were as small as 0.01, there would be 4×10^{12} photons detected in this time, or 3×10^{10} per correlator, far more than enough to give an acceptable estimate of all 156 fringe amplitudes. A solar-type star at a distance of 10 pc would subtend an angle of 1 milliarc sec, so at a wavelength of 0.5 μm the 10-km array would give a 10^4 pixel view of the star with its sunspots and chromospheric features. Closer stars, such as Alpha Centauri, subtend an angle ten times as large, and a hundred times as many resolution elements, a total of a million pixels or so, would be obtained at visible wavelengths. At the Lyman alpha hydrogen line, the resolution would be four times as great. An entirely new field of stellar astronomy would open up.

Another example can be cited, in a very different field. Quasars and their close relatives, AGN, are still ill-understood objects. The power source may be a massive black hole accreting matter, attended by entirely new physical processes. Radio astronomers, using very-long-baseline interferometry (VLBI), have shown that the radio jets can exhibit transverse velocities that appear to exceed the speed of light (*30*). The general scale of phenomena, as currently understood from optical spectroscopy and radio work, is represented in Fig. 4,

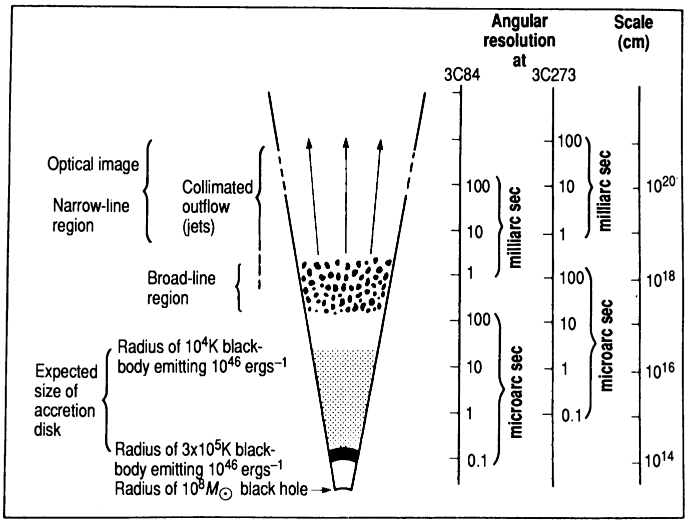

Fig. 4. Schematic structure of a quasar. The angular scales are shown for the quasar 3C273 and the active galaxy 3C84; the linear scale is also shown on the far right. The structure is correct only to order of magnitude and is adapted from the model of Rees (*34*).

which shows the angular size of key regimes. An array having a resolution of 5 microarc sec (10 km diameter and 0.25 μm wavelength) clearly reaches into new territory for both examples given, the relatively nearby radio galaxy 3C84 (Perseus A) and the first known quasar 3C273 (redshift = 0.16). A large number of quasars and active galaxies would be accessible because of the great collecting area.

A third example, touching an entirely new frontier and pressing the instrument to its limits, could have a powerful impact on the world of science: the detection of planets in other solar systems and the determination of their chemical composition. The possibilities of both optical and infrared detection were examined in a lively exchange (*31*), which can be summarized as follows: not only Jupiter-like planets, but Earth-like planets can be detected. Optical detection requires a stellar coronagraph and an apodizing mask, as part of the telescope system, to suppress the light of the star. Even with these precautions, in order to distinguish the planet from the star, the optical surfaces must be of extremely high quality, but, if the system requirements could be met, the oxygen A band at 0.76 μm could be detected. Infrared detection is probably somewhat easier, since the contrast between star and planet is more favorable. The wavelength range 5 to 15 μm contains absorption lines of ozone, carbon dioxide, ammonia, water, and methane, so a rich set of possibilities awaits the observer. Approximately two dozen stars of stellar type in the solar neighborhood could be examined for planets varying in size from that of Earth upward. Participants at the recent TOPS Workshop (*31*) concluded that the infrared domain, in particular, offers attractive possibilities for detecting planets and studying their atmospheric characteristics. If an earthlike planet were to be detected and if its atmosphere (like that of Earth) showed a rich oxygen content far from chemical equilibrium, there would be strong grounds for inferring the presence of life (*32, 33*).

There are other classes of high-resolution instruments that are well suited to a lunar location. A submillimeter array, for example, was mentioned as a possibility in the "90-day" report (*1*) and is probably the most conservative of the possible arrays. The water vapor in Earth's atmosphere causes almost complete blockage at submillimeter wavelengths shorter than 600 μm, but in regions where stars are forming now the preplanetary disks that are known to be a frequent occurrence should exhibit interesting structure in both the water bands and the atomic lines that occur between 100 and 600 μm. When the first giant planet forms, there are reasons to expect that its location will be determined by the water-ice phase transition. A linear resolution of 0.1 astronomical unit has been suggested as a worthwhile goal (*31*), and, since the nearest zone of star formation, the Taurus-Auriga complex, is about 140 pc away, a submillimeter array about 20 km in diameter is indicated. As with the optical array, a variety of smaller diameter rings would be needed to study a wide variety of molecular phenomena in the interstellar medium.

Concluding Comments

The examples given in the previous section of possible applications of a lunar-based array in studying stars and quasars and searching for life represent only a few of the many new directions that could be opened up with a lunar-based telescope. Expansion of angular resolving power by a factor of 10^5 beyond current Earth-bound practice would surely result in unexpected discoveries and would provide new insights into the nature of the universe, and other classes of astronomical instruments would surely be similarly productive. The design studies to date have been highly preliminary, and the 17-element array of 4-m telescopes that I have outlined here can only be taken as an illustrative example at this stage. New ideas for precise, superlight large telescopes, designed expressly for the benign lunar environment, must be explored and would be of direct use for single-telescope projects on the moon as well. Various approaches to the DL problem must also be examined.

Nearly every class of astronomical instrument that might be emplaced on the moon would depend on the astronauts who would assemble, adjust, and maintain the equipment. Whether this is done by direct manipulation either within an assembly bay inside the lunar habitat or out in the open, or by robot manipulators controlled from within the habitat, the systems must be thought out with care. Assembly by astronauts on the moon would require designs that minimize hazard and maximize ease of assembly, but these requirements, thoughtlessly applied, could have a disastrous effect on costs. In all probability, the design teams will need to include scientists, engineers, and astronauts working in concert, rather than in compartments. Finally, flexibility rather than rigidity will be needed in applying rules to actual situations. There will surely be a learning process that will take place as use of the new environment that the moon can offer increases. The lunar base will be a fragile outpost and must be built well, but in that building process it must accommodate the reasonable expectations of science.

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Research Articles

Spacing Differentiation in the Developing *Drosophila* Eye: A Fibrinogen-Related Lateral Inhibitor Encoded by *scabrous*

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In the development of multicellular organisms a diversity of cell types differentiate at specific positions. Spacing patterns, in which an array of two or more cell types forms from a uniform field of cells, are a common feature of development. Identical precursor cells may adopt different fates because of competition and inhibition between them. Such a pattern in the developing *Drosophila* eye is the evenly spaced array of R8 cells, around which other cell types are subsequently recruited. Genetic studies suggest that the *scabrous* mutation disrupts a signal produced by R8 cells that inhibits other cells from also becoming R8 cells. The *scabrous* locus was cloned, and it appears to encode a secreted protein partly related to the β and γ chains of fibrinogen. It is proposed that the *sca* locus encodes a lateral inhibitor of R8 differentiation. The roles of the *Drosophila* EGF-receptor homologue (DER) and *Notch* genes in this process were also investigated.

THE STRUCTURE AND FUNCTION OF MOST MULTICELLULAR organisms depends on the differentiation of the cell types in an appropriate spatial organization. In some cases, it may be that the organization is determined by an invariant pattern of cell divisions. In others the organization is determined by induction, a process by which uncommitted cells are instructed to adopt a particular fate by another cell type. In a spacing pattern, some cells from a field of equivalent precursor cells become different from their neighbors, forming a spaced array of determined cells (Fig. 1). Which cells are chosen depends not on lineage or induction, but on the distance separating the differentiating cells, an indication that spacing patterns may result from competition; for example, the first of a set of equipotent cells to attain some developmental threshold inhibits the progression of others, giving rise to a mixture of determined and undetermined cells (Fig. 1).

Examples of spacing patterns are found in the development of many organisms. In insects, neuroblasts arise from the neurogenic ectoderm separated by undifferentiated cells that later make epidermis (*1*). Other examples include the pattern of sensory bristles in insects (*2*), determination of the anchor cell and the ventral uterine precursor cells in the nematode *Caenorhabditis elegans* (*3*), the differentiation of heterocysts in the nitrogen-fixing alga *Anabaena* (*4*), and the pattern of stomata on the leaves of higher plants (*5*). In vertebrates, the patterns of hair and tooth development may be examples of spacing patterns. Inhibitory mechanisms have been proposed to account for regeneration in Tubularia (*6*), vertebrate organ growth (*7*), and cell differentiation in the vertebrate retina (*8*). The wide phylogenetic distribution of spacing patterns suggests that competition and inhibition may be a common mechanism whereby

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