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OVERVIEW OF LUNAR-BASED ASTRONOMY

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Time Scales

Barring the collapse of high-technology civilization, extensive settlement and utilization of the Moon will certainly occur. The only question is the timing. An Apollo-scale effort could result in setting up an initial lunar base within a decade. More realistically, lunar base development should and presumably will follow that of Space Station, and both of these developments will surely have funding constraints preventing them from progressing at the fastest possible rate. Thus, 15 to 20 years is a plausible target, at least for the Western World, for establishing our first and initially very small permanently manned lunar facility. However, such activities tend to exponentiate, and it is reasonable to expect that by 40 or 50 years hence, there will exist substantial scientific and industrial facilities on the Moon. These next four and a half decades happen to cover the effective working lifespan of astronomers currently getting their Ph.D.'s. They also carry us to the extreme range of reliability of my crystal ball. Accordingly, most of what follows will deal with this coming long generation — the only one we can directly influence and define with any plausible assurance. (As with any crystal ball gazing, the ideas expressed represent a personal viewpoint with which the reader may well disagree.)

In this frame of reference, I visualize lunar astronomy as having four major phases, compressed but analogous to those experienced in the development of the Americas.

First is the pioneering stage, during which nearly all the effort is spent on simply getting there and building survival facilities, with extremely limited resources available for other activities. This stage is likely to occupy most of the decade until around 2010 and can feature only simple scientific equipment which is easily carried, installed, and operated.

Next comes a period of initial settlement, when access has become fairly easy and enough infrastructure exists to allow the beginning of concentration on using the environment. On the Moon, this period could well occur in the decade around 2010-2020 and might be characterized by the installation of several relatively substantial astronomical facilities, but essentially everything needed would still have to be brought from Earth at great cost.

Third is the time of consolidation, featuring routine low-cost access, significant population, and some local facilities for manufacturing. Given a reasonable pace of lunar development, this phase could begin to become real in the period around 2020-2040. It would open up new kinds of opportunities for astronomy, including not only larger units manufactured on Earth but also some usage of local resources.

Eventually will come the phase of maturity, when there will be substantial self-sufficiency and when lunar civilization will begin its own evolution in parallel with that of Earth. Here, speculation can be cheerfully unfettered, because few of those who now believe themselves qualified to speculate will be around to blush. Nevertheless, I do not intend to speculate.

These phases offer a framework in which to place plausible sequences and rough estimates of time scale for lunar astronomical facilities.

The Lunar Environment for Astronomy

The Moon offers both significant advantages and drawbacks for astronomy. Recognition of these characteristics can clarify the objectives toward which developments should be directed and can help to inhibit premature or excessive selling of lunar developments on the basis of astronomy.

Lunar Advantages and Opportunities

Some advantages and opportunities of the lunar environment for astronomy are discussed in the following paragraphs.

Vacuum.- For all practical purposes (other than perhaps low-frequency radio astronomy), the Moon has an excellent vacuum. Its tenuous atmosphere acts as a collisionless gas, with the molecules traveling in ballistic trajectories. The total nighttime surface concentration of known species (hydrogen, helium, neon, and argon) is only about 2×10^5 molecules cm^{-3}, with daytime concentrations substantially lower because of heating and escape of gases. These values are characteristic of the Earth's atmosphere at upper ionospheric heights and constitute an ultrahigh vacuum in laboratory terms. The lunar surface thus offers a splendid environment for diffraction-limited imagery, for phase-coherent interferometry, and perhaps for detectors using naked cathodes. It also offers the prospect of indefinitely long lifetimes for reflective or transmissive coatings on optical elements.

Dark, cold sky.- The tenuous atmosphere, the lack of appreciable magnetic field, and the apparently very low ion density in the lunar ionosphere all should conduce to an effective absence of airglow. Accordingly, the lunar night sky should be about four times darker than is typically experienced at Earth-based observatories, and spectra will be free of the degrading contamination of sky emission lines. If telescopes are appropriately shielded from direct and reflected sunlight, even the daytime sky should appear amply dark for many kinds of observation. The sky will be even darker than seen from near-Earth orbit, because of the absence of spacecraft-type glow and of the very high terrestrial airglow. For wavelengths at which thermal background is important, the nighttime temperature of an entire system which is well insulated and shielded from the ground can easily be held to a deep cryogenic state even without special cooling. This advantage could lead to superb infrared (IR) performance.

Stable inertial platform.- It is expensive and difficult to aim and guide instruments from free-flyers which lack anything solid to push against. The Moon offers the advantages of space observing along with the simplicity and economy of terrestrial telescope mountings. In addition, separate structures firmly rooted in the lunar surface should be almost absolutely stable in their relative positions and orientations for indefinitely long times. Lunar seismic activity is orders of magnitude less than that of the Earth. Any differential effects between interferometer structures caused by expansion and contraction of the lunar surface between day and night will not only be exceedingly small but can be completely eliminated by putting foundations at a depth of several meters, where the regolith is essentially immune to the diurnal thermal wave. Solid-body tides caused by the Sun have amplitudes of centimeters, but their lunar-diameter wavelength guarantees that any differential tilt effects between line-of-sight interferometer elements will be only second order, and any changes of path length will be of even lower order yet.

Proximity of people and support facilities.- Although nearly all lunar astronomy will involve remote and automated equipment, the immediate proximity of people, service gear, cryogenics, etc., for operation, maintenance, and modification will prove advantageous for many kinds of programs.

Rotation.- The lunar rotation allows properly located observatories to view essentially all the sky. The slow rotation produces nights lasting for 2 weeks and thus permits extremely deep exposures on very faint sources or the very long uninterrupted time series on variable objects which are so necessary to permit solution for complex periodicities.

Avoidance of Earth.- The Earth and/or its human activities enhance the noise background at nearly all wavelengths of observation. The Moon is sufficiently far away that even the Earth-facing side is fairly well quarantined, and the back side is the only place in the universe which is never exposed to Earth. This latter factor is likely to become of absolutely crucial importance when later generations of radio astronomers face the challenge of building ultimately-low-noise systems for purposes of science and probably of the search for extraterrestrial intelligence (SETI).

Low gravity.- When the day finally comes for erection of very large structures on the lunar surface, the 1/6g will appreciably simplify engineering problems compared with their Earth-based counterparts. Also, the lunar gravity will continuously clean out contamination, which is unfortunately not the case for orbiting stations.

Readymade landforms.- The smooth and symmetrical bowls of some lunar craters, coupled with the low gravity, suggest that, someday, construction of Arecibo-type antennas as large as perhaps 10 km in diameter should be feasible.

Raw material.- The Moon offers an inexhaustible supply of raw material. Unprocessed, it serves for shielding people and some kinds of equipment against cosmic rays. When processing facilities are in place, locally produced metals, ceramics, fibers, etc., will greatly reduce the dependence on Earth for supply. This factor will become important should very-large-scale engineering of astronomical facilities be undertaken.

Drawbacks of the Lunar Environment

Some drawbacks of the lunar environment for astronomy are discussed in the following paragraphs.

Cost.- At present, it costs several hundred times as much to put a given astronomical facility in Earth orbit as to build it on the ground, and — certainly in the early years — it will cost at least a further factor of 10 to put it on the Moon. Shipping costs in the range of $\$10^5$/kg suggest that during the pioneering and early settlement stages, any lunar astronomical instruments should be relatively simple and lightweight, be of high scientific importance, and require the lunar location for feasibility or cost-effectiveness.

Gravity.- Although low, the lunar gravity is still present and will be an increasingly important cost driver as the sizes of lunar instruments grow.

Vacuum.- Though indispensable for many kinds of astronomy, the lunar vacuum environment will render many kinds of human construction and operation activities exceedingly cumbersome, dangerous, and expensive. During at least the pioneering and settlement phases, this factor will require a very high degree of terrestrial prefabrication of astronomical equipment destined for the Moon. For larger scale construction, robots will certainly be required.

Dust.- The Apollo astronauts found electrostatically clinging lunar dust to be a nuisance. If carelessly splashed around delicate or sensitive equipment, dust might prove to be a significant problem. However, the fear that naturally saltating dust would soon coat anything on the lunar surface seems not to be realized, because the three U.S. lunar laser reflectors which have lain open on the lunar surface for the past 15 years have yet to show any measurable loss of reflectivity.

Ionosphere.- The actual electron density in the lunar ionosphere (poorly known) could be a limiting factor for very low frequency radio astronomy from the Moon and might possibly prove to be a noise source for some kinds of detectors.

The Competition

Surface

As noted previously, for the next several decades, it is likely that attempting an astronomical observing program from the Moon will cost at least a thousand times more than it would to set up the program on Earth. In other words, if it is possible at all — even with great difficulty — to do the work from the Earth's surface, this will normally remain the preferred approach.

Space

Advantages of locating an astronomical facility in space rather than on the lunar surface are discussed.

Cost.- Once again, at least until we reach the consolidation phase of lunar utilization, the expense of performing space-based astronomy from Earth orbit rather than from the Moon will be about an order of magnitude less. Until this ratio changes, experiments and observations which can be done from Earth orbit will continue to be concentrated there. What might change this? The development of very-low-cost orbital transfer vehicles (e.g., solar sails, nuclear or solar-electric propulsion, oxygen supply from the Moon) will help. Invention of a practicable lunar landing system not requiring retrorockets would be a great step forward. Exotic lunar takeoff systems not requiring rockets (e.g., electromagnetic launchers) will be important. Such systems will presumably be available someday, but for the next 20 to 30 years, only improved orbital transfer vehicles appear promising. During this period, any substantial lunar astronomy facilities should be only those which uniquely require the Moon and which can afford to be there.

Advantages of orbital space over the lunar surface.- Compared with lunar basing, location in Earth orbit offers at least one immediate and two major general advantages for astronomical instrumentation.

First is a question of timing. We already can work effectively in Earth orbit, whereas it will be at least 15 to 20 years before any significant instrumentation can be built on the Moon. This fact gives a great head start for evolving technology and for accomplishing science and undoubtedly will have some inhibiting effect on planning and resources which might otherwise go into developing lunar facilities.

More fundamentally, the lack of gravity loading means that orbiting structures of virtually any size can be built from exceedingly lightweight, low-cost materials, and, with prefabrication, the assembly of these structures in space will be easier than with the more elaborate construction equipment and techniques required in a gravity field. Normally, the larger the structure, the greater the gain will be from constructing it in free space. Secondly, for interferometer systems not requiring continuous structure, arbitrarily large baselines are possible in principle, and ingenious techniques are being developed for baseline monitoring and stationkeeping. In general, lunar astronomy will likely be limited to structures of only modest size and baseline compared to those which will be built in free space. (Arecibo-type antennas may be an exception to this principle.)

Lunar Astronomy

In light of all the factors discussed previously, what kinds of developments should we be planning and dreaming about for lunar-based astronomy, at least during the first three phases of lunar exploitation? The remainder of this symposium deals with this question in detail, so I only note here some of the possible high spots. I also specifically omit high-energy physics and astronomy, leaving these fields to the experts and to whatever case they can make for putting such facilities on the Moon rather than in orbit.

Pioneering Phase

I am aware of only four proposed astronomical facilities which appear to satisfy all the criteria of being scientifically important and needing the Moon, while also being both affordable and probably more cost-effective than any other approach, during the pioneering initial Moon-base phase. These are

1. A very large, very low frequency radio interferometer, with tiny antenna elements simply laid out on the lunar surface

2. One (later a set of) extremely lightweight, small (~40-cm class) telescope(s) equipped with high-quality photometers and spectrographs to study submillimagnitude and meter-per-second stellar seismology for long uninterrupted runs on each star

3. A modest (3-m class) cryogenic IR/submillimeter antenna system in a shielded place on the Moon which may well prove cost-effective compared with the expense of building and free-flying such a system in Earth orbit and keeping it cold over very long periods of time

4. In the later stages of this phase, an ultraviolet (UV)/optical interferometer of substantial (kilometers) baseline (This may well be the only project of such high scientific importance, which is also uniquely feasible on the Moon, as to be something of a science driver for the lunar base.)

Settlement Phase

The settlement phase should open up possibilities for developing sites remote from the initial lunar base (which will probably be Earth-facing). If these new sites included startup polar and far-side stations, they would permit the beginning of initially small and specialized observatories capable of taking advantage, respectively, of fully continuous monitoring of certain objects and of the radio quiet of the lunar far side.

A UV/optical interferometer with more and larger elements will become feasible; also, one or more lightweight general-purpose telescopes of the several-meter class may prove cost-effective. By this time, free-flying observatories of modest size will still cost at least several hundred million dollars, and it may become possible to build, ship, erect, and operate comparable telescopes on the Moon for significantly less cost than for their free-flying counterparts.

Consolidation Phase

In the consolidation phase, the overall state of lunar development and robotics should have reached the point at which quite substantial systems can be contemplated. These systems may include more conventional radio interferometers with baselines of hundreds of kilometers and optical interferometers with baselines of tens of kilometers; even the construction of Arecibo-type antennas may be possible. And it is likely that radio observatories of ultimate low-noise performance, for science and for SETI, will be in operation.

Conclusions

By the mid-21st century, it is reasonable to expect that astronomy should have developed several major domains, each with its areas of technical preeminence or cost-effectiveness.

1. Ground-based work will continue, because of its accessibility, its convenience, its economy, its established funding, its continued effectivity, and because of the fact that for some important purposes such as spectroscopy, many kinds of photons can be collected almost as well on the ground as anywhere.

2. Earth-orbital work will remain useful, primarily for convenience of access in constructing and operating very large space systems, but can be expected to have migrated largely to orbits near geosynchronous in order to avoid debris in low orbits and the inconvenience of 90-minute days.

3. Deep-space studies will feature not only probes but extensive systems for extremely-long-baseline (many astronomical unit) studies at wavelengths from gamma rays through visible and IR out to radio.

4. Finally, lunar astronomy will have found important permanent applications along lines such as are discussed in this symposium and, no doubt, others quite unsuspected by us today.

PART II
HIGH-ENERGY, OPTICAL, AND INFRARED TELESCOPES

In part II of these proceedings, ideas for individual lunar-based telescopes at the shortest x-ray and gamma-ray wavelengths, at optical and infrared (IR) wavelengths, and also for high-energy cosmic rays are described. P. Gorenstein leads off with a discussion of the advantages of the Moon for x-ray astronomy. He concludes that large-area detectors connected to long-focal-length telescopes will provide superior signal-to-noise ratios and resolution compared to any high-energy-photon observatories that can be practically placed in Earth orbit. J. Linsley reviews the state of cosmic-ray physics in the second paper of part II and concludes that the nonexistent lunar magnetic field, the low lunar radiation background, and the lack of an atmosphere on the Moon provide an excellent environment for the study of high-energy primary cosmic rays. H. S. Stockman, in the third paper, considers the growth of space observatories, especially at optical wavelengths, during the next several decades. He concludes that large-aperture optical telescopes on the Moon, possibly constructed of lunar glasses, will be very competitive with and in some instances superior to Earth-orbiting telescopes. An innovative idea for an optical interferometer is proposed by B. Burke in the fourth paper. Many of the workshop participants viewed this proposal as the single most important advance in astronomy for the 21st century, in that it would best utilize the remarkable stability of the lunar surface. In the final paper in part II, D. Lester describes the manner in which infrared astronomy could benefit from a lunar base. He concludes that the low lunar vacuum and massive thermal shielding provide an opportunity for simple, but very sensitive, large-area IR detectors that are passively cooled.