THE ROLE OF LUNAR ASTRONOMY IN THE EXPLORATION AND DEVELOPMENT OF THE MOON

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1. Introduction

The idea of using the Moon as a location for astronomical facilities is of long standing. Robert S. Richardson, a former Mount Wilson astronomer, wrote a piece, "Astronomical Observations from the Moon", in 1947 [1] wherein he demonstrated a sound grasp of the advantages to be gained from a lunar site, but some of his concerns show how far the relevant technology has advanced in 50 years.

"But the polar axis would *not* be directed toward a point near Polaris. The axis of the moon is oriented so that it points 23o from Polaris toward the constellation of Draco. There is no bright star conveniently at hand to serve as the lunar Polaris; in fact, the best astronomers can do in this respect is the fifth magnitude star, 36 Draconis. The moon's axis of rotation points to within 10 .5 of 36 Draconis.

The moon's axis describes a circle in the sky around 36 Draconis, but instead of having a radius of 230.5 it is only 1° .5. The motion is much faster, however, the north celestial pole of the moon completing a circuit in 18.5 years instead of 26,000 years. This raises difficulties that never have to be taken into consideration in the operation of a terrestrial telescope."

Or, again:

"A pendulum clock which keeps accurate time upon the earth would lose at an alarming rate upon the moon, since the acceleration of gravity there is one-sixth that upon the earth. The pendulum instead of requiring one second in which to make a swing would now require 2.5 seconds. To make the clock keep time as before the length of the pendulum would have to be drastically shortened--from 39.1 inches to 6.5 inches.

Instead of using pendulum clocks, the lunar astronomers might prefer timepieces which are operated by the vibrations of a quartz crystal. These quartz crystal clocks are independent of gravity and fully equal in accuracy to the best pendulum clocks."

Indeed, the Moon provides an airless, seismically stable platform on which to mount instruments. However, large temperature swings, dust, and, above all, the difficulty of climbing down the Moon's gravitational well (compared to residence in free space) counterbalance these advantages [2].

The objective of this paper is to assess the potential of the Moon as a venue for conducting investigations in astronomy. The assessment falls naturally into two cases: 1) where the emplacement of a facility is done solely through robotic means, and 2) where the agency of human effort is employed on the Moon. Considerable thought has been given, particularly in the last 15 years, to the possibilities for lunar astronomy and the associated designs. Hence, the approach, here is to draw upon this accumulated store, some portion of which is indicated in the next section.

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2 . Approach

a. Existing Proposals

Concepts for use within the scientific portion of the assessment will be restricted, for reasons of economy, to four workshops/symposia conducted by NASA and a report from ESA'S Lunar Study Steering Group.

"Lunar Bases and Space Activities of the 21st Century" [3]
Washington, D.C.
October 29-31, 1984

"Future Astronomical Observatories on the Moon" [4]
Houston, Texas
January 10, 1986

"Physics and Astrophysics from a Lunar Base" [5]
Stanford, California
May 20, 1989

"Astrophysics from the Moon" [6]
Annapolis, Maryland
February 5-7, 1990

"Mission to the Moon "
"Europe's Priorities for the Scientific Exploration and Utilization of the Moon" [7]
1992

A supplementary source is given by the report [8, 9] of NASA's Lunar Observatory Steering Group, whose deliberations took place in 1994. See also the bibliography given by Linebaugh, in [6].

A taxonomy to facilitate discussion will be based upon, at the coarsest level of classification, the four channels -- electromagnetic waves, gravitational waves, cosmic rays, neutrinos -- through which astronomical information might be collected. ("Cosmic rays" represents the more general category of "tardyons", e.g., meteorites, muons, and solar-wind particles would fall into this genus.) The taxonomy does not account for several investigations in fundamental physics, such as proton decay, for which one can consult the references.

One could instrumentally categorize the next tier of classification by wavelength range (for electromagnetic investigations) or by scientific discipline, e.g., studies of planetary atmospheres, and, in fact, the references used here employ both schemes, which are not, of course, independent approaches. To avoid complex mechanics, this survey will go from the quadrapartite categories directly to the finest level of classification, the individual proposal: there are about 120 of them.

b. Principles of Assessment

The question "What is the best set of astronomical investigations to be carried out from the lunar surface?" is not a well-posed question because boundary conditions have not been established. For example, if lowest total cost were to be the major driver, than (in the absence of a lunar base built for other purposes) certain robotic emplacements of instruments would be indicated. If lowest marginal (incremental) cost for a certain established lunar base were the requirement, another recommendation would be forthcoming. Then there is a set of scenarios which center upon highest scientific value compared with results achievable from Earth or from free flyers. One could also construct proposals for best science from the Moon given a certain allocation of cash.

Since possible criteria and the set of possible lunar-base designs (including the null design of no lunar-base substrate) are so extensive, only a few cases can be considered. Specifically, they are: 1) the lowest absolute cost (for a single mission), 2) being competitive with free flyers with a series of missions, and 3) best science from the Moon given a comprehensive lunar base. Items 1 and 2 are treated in the next section , while 3 is addressed in "Human-Assisted Emplacements". But only a scientific panel, representative of the community and functioning within a specific program environment, could make valid judgments regarding individual proposals. The present "selections" must be regarded only as illustrations.

3. Robotic Emplacements

In recent years, the frequency of flights within NASA has increased significantly, driven in no small part by competitions conducted through the "Announcement of Opportunity" (AO) mode. Thus, the Discovery (planetary science), MIDEX (astrophysics and space physics), SMEX (astrophysics and space physics), and Earth-science lines have kept proposers busy in thinking of new ideas. Yet, to date, no astronomy-from-the-Moon proposal has emerged at the head of a competition.

Perhaps the scale of resources is inappropriate; one might require more than the AO-route allows (on the order of $100m-$200m) in order to land on the Moon and take advantage of its benefits. (Just as space-based astronomy costs more, generally speaking, than ground-based astronomy but has desirable benefits for certain types of investigations.) But even the larger (proposed) astrophysical projects such as SIRTF, SIM, and NGST will be space based.

Of course, these considerations do not prove that there is no niche for low-end lunar-based astronomy, only that the case is not an easy one to make and that comparison with the free-flyer option is an important factor in evaluating any lunar proposal. A study [1 O] conducted by The European Space Agency is a case in point; they found a certain lunar interferometer would be a more expensive undertaking than its free-flyer counterpart. However, there is an ameliorating factor when considering investment in facilities at the lower end of the cost scale (typically, robotic emplacements). These facilities need not pay for themselves on the basis of only scientific return; under certain circumstances, they can also function in the site-testing mode, as has classically been done in astronomy in evaluating mountain-top locations for seeing. On the Moon, one would be assessing "seeing" too, as affected by thermal loads and scattered light, for example. See [2], and its related pieces, for a catalog of factors which should be considered in a program of evaluation for the lunar environment. In addition to site testing, one could test designs for facilities, such as the ability to withstand large thermal swings and the susceptibility to contamination from lunar dust, etc. The New Millennium Program of NASA is conducting a series of flights for technology validation while returning important science.

a. Single Missions

An illustrative case is furnished by considering a lunar low-frequency radio array [1 1]. When this scientific proposal was being developed at JPL for a recent application, it appeared that implementation as a constellation of free-flying spacecraft was more cost effective than the original proposal (in [11]) of a lunar-based array. An option to hard land the array on the lunar surface was considered, but the shock of a several-thousand-g impact was considered too risky, even for the simple dipole antennas (and associated equipment). Nevertheless, the Moon would present advantages over free space for the low-frequency investigation: 1) shielding from radio signals from Earth if placed on farside, and 2) relief from the necessity of having to maintain the compactness of the free-flying constellation of spacecraft; the configuration tends to disperse rapidly under differential solar pressure and requires propulsive action to maintain its integrity.

The scientific objectives for such an array might be (from [9]):

The frequency range below about 30 MHz is unexplored with high angular resolution due to the opacity of the Earth's ionosphere. An interferometric array in space providing sub-degree angular resolution images would allow a wide range of problems in solar, planetary, galactic, and extra galactic astronomy to be attacked. These include the evolution of solar and planetary radio bursts (including auroral kilometric radiation (AKR) from the Earth), scintillation caused by turbulence in the interplanetary and interstellar media, the distribution of diffuse ionized hydrogen in our galaxy, the determination of spectral turnover frequencies and magnetic field strengths in galactic and extra-galactic radio sources, statistical tests of radio-source unification theories at frequencies where radiation is expected to be completely isotropic, searches for “fossil” radio galaxies which are no longer detectable at higher frequencies, and searches for new sources of coherent radio emission. In addition, it is likely that completely unexpected objects and emission processes will be discovered by such an instrument, as has often happened when high-resolution astronomical observations become possible in a wide new region of the electromagnetic spectrum. The window from about 30 kHz to 30 MHz spans three orders of magnitude in frequency, wider than the infrared window opened by IRAS and ISO or the ultraviolet window opened by IUE and EUVE. It represents the last region of the spectrum which is inaccessible from Earth and still largely unexplored.

To make the lunar option more attractive, one might turn to technology in order to find inexpensive ways to place undamaged packages for the array on the surface: improved hardening or landing techniques. The option would be made much more attractive if a low-cost way of establishing communications between Earth and lunar farside could be devised. (A low-frequency array on nearside is not without value; Earth’s radio noise is diminished by the inverse-square effect.)

A second candidate for robotic emplacement is an interferometer operating at optical frequencies. Baselines can be achieved which would be infeasible with a unitary structure in space. However, separated interferometers (at optical frequencies) are planned for an upcoming flight within NASA’s New Millennium program, so it is possible that this potential lunar advantage will not persist.

The scientific objectives for such an array might be (from [9]):

The Moon is an especially attractive location for optical interferometry, because the lunar surface provides a stable observing platform where the images are free of atmospheric distortions. By “optical “ we mean the broad spectral window from the ultraviolet to the infrared where imaging arrays are available as the detectors.

There are many applications in astrophysics and planetary science where major breakthroughs would result from interferometric imaging with very high resolution, say in the range 1 to 0.1 milliarcsecond. Two outstanding examples would be the formation of planetary systems, where images of the thermal emission from protoplanetary disks around young stellar objects could depict the process of planetary formation; and quasars and active galactic nuclei, where images could show the structure of the central engines that power these beasts.

Interferometric imaging would require the emplacement of dozens of telescopes. An intermediate step towards an imaging interferometer would be an astrometric interferometer, where three telescopes would suffice. With astrometric precision in the 1 to 0.1 microarcsecond range, a variety of fundamental questions in astrophysics and planetary science could be addressed. For example, an optical interferometer could search hundreds of nearby stars for evidence of low-mass companions. This would address issues such as the role of binaries in star formation (more than half of stars end up in binaries), and the puzzle of why the frequency of companions appears to drop off precipitously just at the substellar dividing line (there are no confirmed brown-dwarf companions to stars). Pushing to iower-mass companions, the same instrument could be used to search for planetary systems orbiting nearby stars.

A logical first step toward establishing more powerful interferometers on the Moon would be the lunar emplacement of two small robotic telescopes and the demonstration that fringes could be achieved.

A design for a lunar-farside scientific station incorporating both of these types of facilities (LF and optical interferometer) was done as the International Space University's 1991 design project [12]. (Astronauts were postulated to set up the optical facility.)

Other investigations have been proposed (see [9]) for low-cost robotic emplacements - UV and IR telescopes in particular -- but it is difficult to see how they could be competitive in cost with free flyers. Thus, it is necessary to devise another approach if robotic emplacements are to have a chance to flourish on the Moon, and this is done below.

b. <u>Dependent Missions</u>

Here, the central idea is to offset the cost of robotic lunar emplacements by utilizing partial inheritance of physical assets from one mission to the next; this strategy would increase the science-per-dollar. The "dependence", then, is that of one investigation upon either temporal predecessors (still scientifically functioning or not) or contemporary emplacements. Since the temporal case probably presents the greatest engineering challenges (and the lowest cost profile), only it will be treated here. The subject is presented in [13], and just an abstract of that material is given.

There are two principal issues which must be addressed: 1) Is it reasonable to expect that schemes for effective inheritance can be formulated? and 2) Can engineering systems survive on the Moon for meaningful periods of time, particularly with a diurnal thermal cycle of about 300°K at the equator. (Polar regions have a smaller cycle, 20"K or less.)

There are two parts to issue 1): designs for reusability (the "inheritance") and the economics of reusability. The first part is basically a question of connectivity and will only be addressed by listing some functional examples: instrument change-out; instrument augmentation; inherited rover services; passive thermal control (shade!); inherited data systems; inherited power systems.

The second part, economic considerations, is summarized in Figures 1 and 2 (from [13]) and subsequent text.

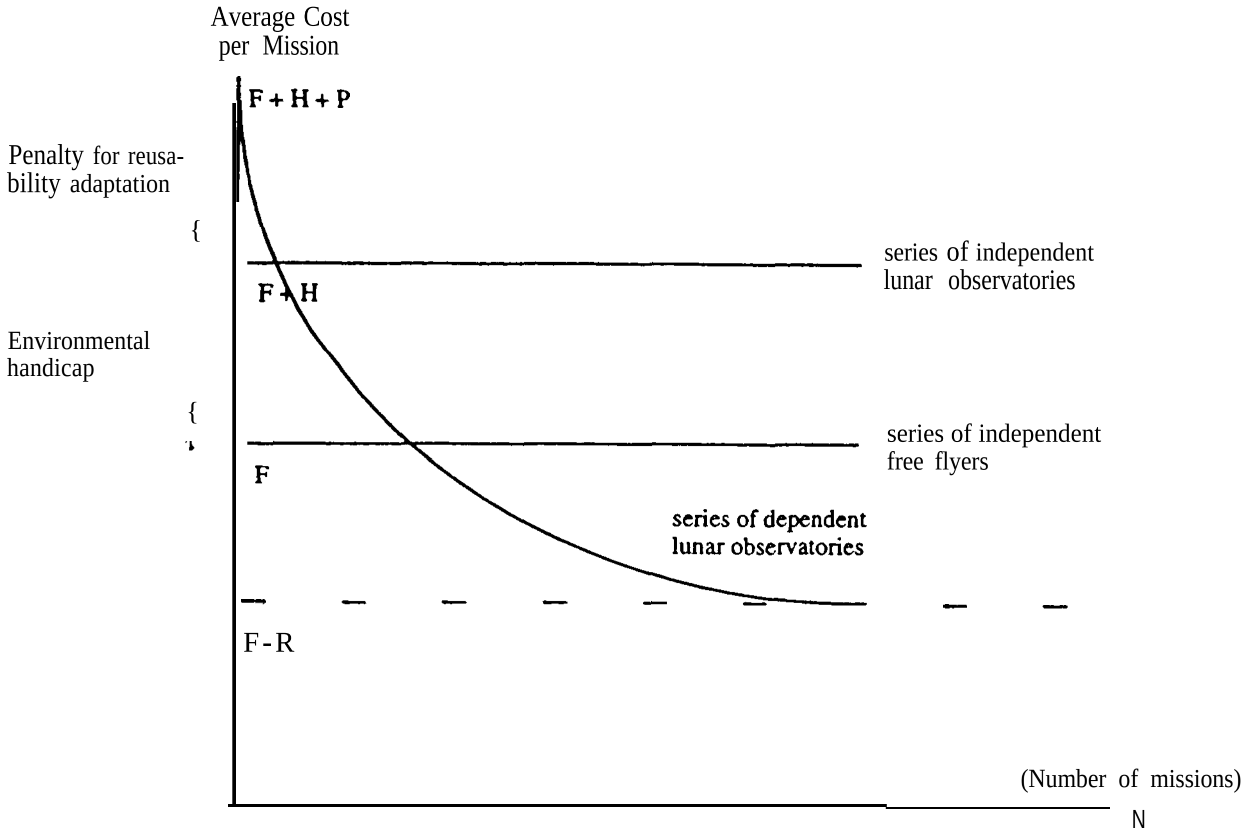

Figure 1. If assets from previous lunar observatories can be (partially) reused by subsequent observatories, the cost per investigation will decrease. The curves are idealized in many ways including, for convenience, representation of the reusable case by a smooth curve rather than a chain of step functions. The horizontal asymptote accounts for the facts that there are always costs associated with a mission and that emplaced assets eventually break down or become obsolete.

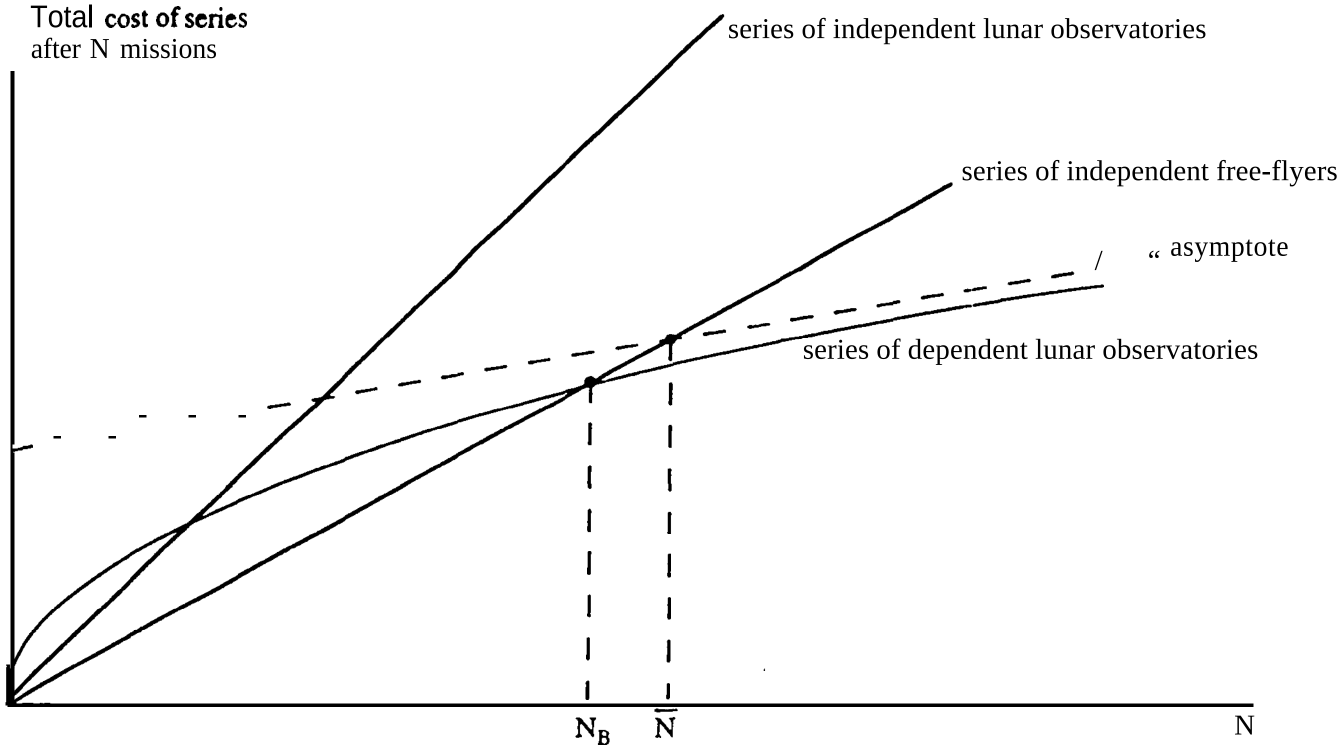

Figure 2. Integration of the curves of Figure 1. The point N_B is the "break-even" number; if N_B or more partially reusable missions are flown, the total cost for the series will be less than for a similar series of independent free flyers. See equation (8) for $\bar{N}$.

The assumptions inherent in these figures are:

(1) N is treated as a continuous quantity rather than assuming discrete (integer) values as it does in reality.

(2) The cost, F, of free-flyer missions is the same for each mission in the series. This need not be the case, since free flyers could also utilize a reusability strategy (robotically implemented or through the aid of astronauts). However, there are certain scenarios where the Moon does appear to have an advantage over free flyers. For example, as mentioned above, multiple spacecraft formations (as in interferometric arrays) tend to disperse over time due to differential solar radiation pressure on the individual vehicles. Another example is given by that uniquely two-dimensional creature, the lunar (or planetary) rover, whose three-dimensional analog is, in many ways, more complex. Also, the repetitive lunar-station to Earth-station link geometry makes the reuse or communications equipment attractive. Finally, repetitive Sun and lunar-station geometry facilitates planning for the use of (predecessor flight-system) shade patterns for (successor) thermal control.

(3) The cost, F+H, of a series of independent lunar observatories, with the same scientific scope as their free-flyer counterparts, is the same for each mission in the series and, also, is H dollars per mission more than a free-flyer: the lunar handicap (gravity well, etc.).

(4) In the steady state, reusability could drive the cost per mission to as low as $R > 0$ dollars below free flyers.

(5) There is a penalty of P dollars per mission in order to equip the system for reusability.

(6) The cost per reusable mission decreases by a constant fraction, k, of the span between top cost (F+H+P) and bottom cost (F-R) for a reusable observatory.

(7) Monetary inflation is O over the time span considered.

With C' denoting the cost per mission and subscripts R, F, I denoting reusable lunar mission, free flyers, and independent lunar missions, respectively, then,

$$C'_R(N) = (H+P+R)\exp(-k(N-l)) + (F-R) \quad (1)$$

$$C'_F(N) = F \quad (2)$$

$$C'_I(N) = F+H \quad (3)$$

describe Figure 1. Integration of (1) through (3) provides the analytical description of Figure 2 (with C, no prime, denoting the cumulative cost for the series).

$$C_R(N) = [(H+P+R)/k](1-\exp(-k(N-l))) + (F-R)(N-1) + F+H+P \quad (4)$$

$$C_F(N) = FN \quad (5)$$

$$C, (N) := (F+H)N \quad (6)$$

The break-even point for lunar investment occurs when

$$C_F(N) = C_R(N). \quad (7)$$

A figure of merit (an approximate version of equation (7)) is obtained by solving for the intersection $\overline{N}$ of C_F (N) and the straight-line asymptote to C_R (N) :

$$\overline{N} = (H+P+R)(1+1/k)/R. \quad (8)$$

The smaller that $\overline{N}$ is, the better. Some tabular results give a feel for the quantities involved. The cost unit is taken to be F = 1.

Parametric Case	H	P	R	k	$\overline{N}_B$	$\overline{N}$
1.	0.25	0.25	0.5	0.1	19	22
2.	0.10	0.10	0.5	0.1	10	15
3.	0.10	0.10	0.5	0.2	5	8

Table 1. Examples of break-even points N_B in terms of model parameters. For $\overline{N}$, the figure of merit, see equation (8).

It seems reasonable, from programmatic and engineering institutions, to require $N_B \leq 5$. Thus, for one launch per year, the break-even point N_B would be reached in five years. Of course, there are many tradeoffs to be conducted, but this constraint on N and inspection of Table 1 shows that cases 2 and 3 exemplify viable parametric values. Of course, no evidence has been presented to show that such parametric values are attainable. One might also consider some elements of a dependent series of missions to fall under “site testing” or “design prototypes”, as mentioned previously. These investments in technology have not been included in the economic analysis above, but such provision would not be difficult and would strengthen the lunar case in the competition with free flyers.

With regard to survivability on the Moon, much needs to be done to understand the range of possibilities, but there are some grounds for optimism based upon analysis of Apollo-12-retrieved parts from Surveyor 3 (after some 32 lunar day/night cycles): see [1 3]. In addition, Pathfinder operations on Mars in 1997 are giving us experience with 70° K thermal cycles, which would be achievable at selected places on the Moon.

The scientific consequences, of, say, a 5-or-so term sequence of dependent missions would be to extend from LF radio and optical interferometry arrays to include infrared and ultraviolet telescopes in the 1 m or greater class, with significant applications as outlined in [9]:

UV Astronomy

Two separate, stand alone, instruments have been suggested for the initial emplacement: a transit telescope with a fixed declination and a conventionally pointed telescope. The prime objective of the transit telescope would be a deep UV survey. This survey, although somewhat limited in sky coverage, would give statistical descriptions of, for example, the morphology of distant galaxies, or regions of recent star formation identified from the presence of hot, young, UV bright stars. Studies of variable objects such as active galactic nuclei or chromospherically active stars on time scales of one month (the repetition period of the survey), could also be conducted. An interesting avenue of study has been identified for the pointed telescope: stellar seismology using precision photometry. Precision photometry has become a relatively routine procedure for ground-based, automatically operated telescopes in the visible region. Aside from the ability to observe in the UV, which is intrinsically more variable than the visible, these observations would benefit from the long uninterrupted observation periods (up to two weeks) which are possible from the lunar surface but not from low Earth orbit. These observations would provide insight into seismic vibration of stars, convectively-driven oscillations, and the presence of star spots. On longer time scales, they would provide data on magnetic cycles of other stars analogous to the sunspot cycle of our own star.

IR Astronomy

Requirements of low cost, low mass and remote, non-serviceable operation for the next generation of lunar instrumentation drive the design of an infrared observatory to the simplest kinds of usable instrumentation. A useful and important observational program that can be carried out with this kind of “suitcase science” includes deep, very wide area surveys at wavelengths from 1 to 10 microns. This wavelength range is easily accessible from the Moon with a low-mass observatory, and there are no planned space observatories with the capability to survey more than a few hundred square degrees of sky to a significant depth over this band.

Very wide area surveys can be used to attack a wide variety or problems. All-sky surveys which address new wavelength regions or previously unachieved sensitivities or higher spatial resolutions have always been priceless sources of scientific data. The very low sky background of a lunar observatory and the high spatial resolution attainable with a 1 meter diameter telescope with no atmospheric distortion would allow a significant improvement in sensitivity *over* planned Earth based surveys from 1 to 2.5 microns. The large amount of observing time available with a long-life facility would allow surveys to cover much more sky at high sensitivity than will have been possible with precursor space IR observatories. The unbiased nature of all-sky surveys is a powerful aid in the statistical interpretation of results, and the inclusion of very large areas allows detection of rare phenomena. All-sky surveys are an archival snap shot of the universe which becomes an essential data point in the investigation of time varying phenomena such as proper motions of stars, detection of Kuiper belt objects, motions of interstellar clouds and stellar dust shells, variability of stars, and search for supernovae, to name a few..

Some specific goals of a near infrared wide area survey would be:

1. Study of low-mass stars and , possibly, brown dwarfs.
2. Study of newly formed and forming stars.
3. Search for and potential measurement of "dark matter" in galaxies and clusters of galaxies.
4. Study the birth and evolution of normal galaxies.
5. Understand the role of ultraluminous and hyperluminous galaxies in the early evolution of galaxies.
6. Measure the spatial correlation of high redshift galaxies to study large scale structure in the universe.

Many more problems could be attacked as well. To be sure, the currently planned space infrared observatories will address many of these problems and will make great strides toward their solution. But, a deep all sky survey will allow follow up work for more complete verification of results and can approach some problems, such as the mass and spatial distribution properties of low mass objects in the Galaxy and detection of very large scale structures in the universe, with much greater thoroughness than the currently planned restricted area surveys.

All observations from a survey instrument such as this might not necessarily be confined to wide area surveys. Smaller surveys to greater depth than the main survey might be performed, and maximum sensitivity observations of individual objects could be done as well.

4. Human-Assisted Emplacements

If a lunar base, with humans, is established on the Moon, a large number of astronomical investigations is potentially feasible. Which ones should be, in actuality, undertaken depends upon scientific priorities, budgets for the investigations, and the nature of support available from the lunar base. In the absence of details for these areas, a broad brush will be applied to list some reasonable candidates. The discussion will be done in terms of four channels for information: electromagnetic waves; gravitational waves; cosmic rays; neutrinos. The overall context is established by the compilations which were identified in Section 2.

The basic advantages of the Moon for robotically-placed investigations carry over for the present case: a clean electromagnetic environment on far side; a stable platform for arrays; near vacuum conditions. In the present case, one assumes that the gravity-well access problem and thermal cycling have been substantively ameliorated due to the existence of a (relatively) extensive transportation system and the ease of employing effective thermal-control measures, respectively.

With human assistance (and low-gravity), the Moon also offers the opportunity to establish very-large serviced structures, e.g., Arecibo-like antennas, for astronomical investigations. Such structures are notoriously difficult to place in space as free flyers. No attempt will be made to perform engineering trades (including cost) between space and the Moon as a venue for large structures; it will just be assumed that the potential exists for them to prosper on the Moon, other environmental factors permitting. (A similar assumption was made with respect to the large -- geometrically -- radio and optical arrays described in Section 3.)

a. Electromagnetic Waves

X-ray and Gamma-ray Facilities

A representative summary is contained in Peterson [1 4]. Scientific objectives (see Table 1 in [14]) include, for x-rays: normal stars; supernova remnants; collapsed objects; normal galaxies; AGNs (Seyferts & QSOs); clusters; cosmology, while for gamma rays: solar flares; nucleosynthesis; collapsed objects; active galaxies; QSOs; gamma-ray bursts.

With so much real estate available, both sensitivity and resolution can be pursued. For example, long-baseline systems might achieve resolution on the order of 0.01 arc seconds for X-ray investigations.

Peterson envisages a “Lunar Transient Observatory” which would not only monitor gamma-ray (*per* se) bursts but also make simultaneous measurements in the IR, UV, and X-ray regions of the spectrum. This kind of facility shows the use of the Moon to good advantage: a variety of instruments placed on the surface and not constrained by packaging problems associated with free flyers.

Optical Facilities

Optical interferometers have been discussed under “robotic emplacements” and the concept is, of course, easily extensible to larger and more capable arrays. One idea [7, pp. 40-50] proposed by A. Labeyrie is the Lunar Optical Infrared Synthesis Array (LOISA) consisting of 15-33 1.5 m telescopes. This, or other implementations, could address an impressive set of scientific questions in astrometry including, e.g., parallaxes of Cepheids and the structure of evolving objects such as represented by the motion of spiral arms of our Galaxy. One could also, for example, image surfaces and envelopes of stars. Additional topics include: imaging of accretion phenomena; imaging of interactive binaries; imaging of active galaxies and quasars; imaging of gravitational lensing.

The classical (large) filled-aperture telescope is a natural candidate for lunar residence. An example of a multispectral facility is given by Illingworth [15]. This passively-cooled, diffraction-limited telescope would have enormous capabilities from detection of Earth-like planets to the study of the structure *of* distant galaxies (z > 1). Spectroscopy of faint objects would, of course, be facilitated by the large aperture.

Radio Facilities

Long baseline interferometry would be a natural candidate for investigations in the radio portion of the electromagnetic spectrum. In addition, a large, monolithic structure, similar to the Arecibo telescope, has been proposed by Drake [16]. The support structure would be supplied by a suitable lunar crater or valley. The absence (by design) of changing gravity loads and the absence of wind loads leaves only thermal influences as a source of change for the telescope's geometry. Reflector diameters of 30-90 km are envisaged by Drake

b. Gravitational Waves

Although sensible designs can be produced for lunar-based instruments (see [17]), it does not seem likely that, at least in the near term, the Moon will play a significant role in this channel of information.

c. Cosmic Rays

Cherry [18] points out some advantages of using a lunar location for particle physics and cosmic-ray studies:

1. Near vacuum implies lack of secondary particles and lack of attenuation.

2. Access for low-energy particles due to the Moon's dilute magnetic environment.

3. Possibility of large (area, volume) detectors.

4. Use of *in situ* materials.

A considerable variety of investigations has been conceived (see, also, the "Session on Cosmic Ray Physics" in [5], pp 29-52).

More generally, the Moon, as a storage device for several species -- cosmic rays, solar wind -- communicated through the "tardyon channel" will undoubtedly offer rewards to a suitably equipped human detector-browser, the analog of the field geologist on Earth. The lack of an atmosphere and of significant weathering yield advantages with regard to receipt and preservation. Beyond the scientific realm *per se,* it has been proposed that deposits of helium-3 on the Moon could be used to produce substantial amounts of energy.

d. Neutrinos

The response, from segments of the neutrino-physics community has been, as with the case of cosmic-ray investigation, to produce a rather diverse menu of possibilities (see "Session on Neutrino Physics" in [5], pp. 53-142).

The use of the entire Moon as a neutrino detector (Wilson, [19], which is just one approach) and the lack of a lunar atmosphere (cosmic rays interacting with the Earth's atmosphere produce a diffuse background of neutrinos) point to aspects of the Moon that lend themselves to utilizing this channel of information.

Scientifically, a high energy (1 to 1000 TeV) probe into our Galactic center is envisaged by Wilson. Learned [20] seconds the use of the Moon for high-energy (TeV) neutrino astronomy: "it seems possible that the future of very high energy neutrino astronomy is on the Moon".

5. A Note on the Astronomical Use of Other Solar-System Bodies

In the course of examining possibilities for robotic and human-assisted emplacements on the Moon, certain general factors have emerged which show to advantage the properties of natural surfaces (not blanketed by an atmosphere) for locating astronomical facilities. In particular, the stable geometry facilitates accumulation of dependent astronomical facilities and also provides the opportunity for a human base, with its attendant advantages for supporting construction and maintenance. Also, for some investigations, the location of the Moon, outside the magnetosphere, has advantages.

Thus, a few notes are appropriate to see if the lunar case can be generalized to other solar system bodies: planets and natural satellites without atmospheres; some comets and asteroids. These remarks will truly be "notes", with little attempt to rationalize what program or mission setting might enable utilization of these other sites.

Using a very coarse classification, one can consider near-Earth asteroids, main-belt asteroids, and "other" (particularly objects in the outer solar system).

Near-Earth asteroids are generally easier to light upon than the Moon's surface; they do not present the gravity-well problem associated with that more massive body. However, for very long baseline operations, they are geometrically deficient and, quite significantly, one cannot be assured of stable rotational behavior.

Knowledge of the spin rates and orientations of axes of asteroids is growing rapidly: through analysis of light curves (e.g., G. De Angelis [21]) and, for closer asteroids, radar observations (Hudson & Ostro [22]). Small bodies are candidates for chaotic dynamical behavior, so one would have to design an investigation that would be compatible with stochastic variations in pointing (perhaps changeable on the time scale of several days).

Main-belt asteroids are not, energetically, as accessible as the previous class, but they could be serendipitous sites, depending on a program of exploration, and the larger asteroids would have relatively stable rotational properties.

As one goes further from the Sun, the zodiacal emission becomes less onerous with respect to astrophysical observing. For example, over a broad range of wavelengths, that emission is 30-100 times fainter at 3 AU than at 1 AU. A wide range of astrophysical investigations would benefit from this reduction.

Thus, one might consider locating facilities on icy satellites of the outer planets (but the larger ones have significant gravity wells, like the Moon, and the Jovian system is plagued by radiation problems) or Pluto. Perhaps more intriguing would be a facility on a Centaur: an object with semimajor axis between Jupiter and Neptune. However, in addition to their great distance, one must beware of possible eruptive behavior (but see Brown & Luu [23] for some comfort with regard to Centaur 1995 GO). *Caveat transgressor'.*

6. Conclusions & Comments

a. conclusions

1. The Moon has some attractive features which would benefit certain astrophysical investigations: practically no atmosphere; radio quiet zone on far side; seismically quiet; "the Moon is not space" (i.e., it is a convenient haven for storing assets); removed from much of the magnetic & charged particle entanglements of Earth.

2. The principal drawbacks of the Moon are its significant gravity well and, in many regions, extreme diurnal thermal cycling.

3. A low-frequency radio investigation is a leading candidate for robotic emplacement. Small optical interferometers and UV and IR telescopes (on the order of 1 m) could do significant science from the Moon but would have a difficult time in being economically viable on their own. However, additional justification would be supplied by employing them to site test with respect to various lunar environmental factors (seeing, contamination, effective horizon) and as test beds for design (thermal cycling etc.).

4. Robotic emplacements of astronomical facilities are generally more expensive than their free-flyer counterparts, but the advance of technologies may tend to close the fiscal gap.

5. A dependent series of robotic emplacements might be able - to share facilities -- if one solves problems of connectivity and survival under thermal cycling -- so as to reduce costs, increasing the science-per-dollar to a figure competitive with corresponding free flyers.

6. There is a large corpus of attractive scientific proposals which might be implemented if human assistance is provided, presumably from a larger lunar base. Such investigations would take advantage of the natural advantages (see 1) which the Moon provides. In particular, massive structures -- optical or radio -- would be well suited for a lunar location. Cosmic rays (and other tardyons) and neutrino investigations also hold promise for a lunar setting.

7. The economics of the marginal cost of astronomical facilities associated with a human lunar base are not clearly understood, but again the challenge is to be cost effective compared to free flyers. There are some indications that this is a difficult challenge to meet, but it is not implausible that very large astronomical facilities, e.g., Arecibo-like but multikilometer-scale radio telescopes, might be more cost effective if built on the Moon.

8. Small bodies in the Solar System have attractive attributes for locating astronomical facilities. Smaller asteroids have correspondingly small gravity wells, and near-Earth asteroids are energetically accessible. Certain objects in the outer solar system would lie beyond much of the obscuration due to zodiacal dust; but some of those objects have eruptive propensities, at least at certain times. Small

objects can have significantly variable rotational properties: rate and spin-axis direction.

b. Comments

1. A continual flow of proposals increases the likelihood of finding some which might fill lunar niches.

2. If dependent emplacements are to be considered, designs for connectivity and data on survivability (particularly under diurnal thermal cycling) should be pursued.

3. The economics of astronomical facilities attached to larger lunar bases needs to be better understood.

4. If asteroid locations are to be further considered for astronomical investigations, science and mission scenarios are necessary before viability can be assessed.

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