ASTROPHYSICS FROM THE MOON

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1. Introduction

The moon offers mixed blessings as a site for astronomical observatories, and some of these are presented in Tables I and II (see the paper by Smith for a more complete discussion). The advantages are so strong that they make the moon a unique site for certain kinds of observatories, particularly those which feature very large telescopes or interferometric arrays of large dimensions, and those that require a presence beyond the screening effect of the earth's magnetic field. More than one hundred scientists gathered at Annapolis, Maryland for a Workshop on Astrophysics from the Moon (Feb. 5–7, 1990), and discussed these questions in considerable detail (Mumma and Smith 1990). The objective was to examine the astrophysical frontiers of the 21st century, and to identify those which require the presence of astrophysical observatories on the moon for their successful address. The scope of the Workshop was defined to include all areas of space astronomy. It was assumed that the base program of space astronomy will have been completed prior to the emplacement of lunar-based observatories, thus that the four Great Observatories, the Solar and Heliospheric Observatory, the Orbiting Solar Laboratory, the Coronagraphic Imaging and Astrometric Telescope Facility, and the Earth-Orbital Planetary Telescope will all have been accomplished. The Workshop participants tried to look beyond the scientific objectives to be addressed with those Earth-orbiting facilities to the next generation of scientific frontiers, which are associated with the very small, the very distant, and the very faint. This paper summarizes some of the ideas presented there, but these are presented in much greater detail in the published Proceedings (Mumma and Smith 1990).

2. The Principal Themes

Five great themes of fundamental importance emerged from the discussions. They are:

- *How do Stars and Planetary Systems Form?*
- *Are There Earth-like Planets among the Nearby Stars?*
- *Do Life and Intelligence Exist Elsewhere?*
- *What's Happening in Our Sun and Other Stars?*
- *What Happened in the Early Universe?*

Y. Kondo (ed.), Observatories in Earth Orbit and Beyond, 381–390.

TABLE I
Advantages of the moon as an astronomical site

Ultra-High-Vacuum –	Effectively no Atmospheres	
	Perfect Transmittance; Diffraction Limited Imaging	
	Dark Sky – No Scattered Light – Daytime as well as Night Observing	
		Very Small Solar Elongation Possible (Few Solar Radii)
	Cold Sky – Thermal Infrared Background Limited by Zodiacal Emission	
		Radiative Cooling of Telescopes for Infrared Observations
	No Wind – Permits Simplest "Sunshade" Domes, and Lightweight Telescopes	
High-Lunar-Mass		
	Enormous Moment Of Inertia	
		Easy Pointing of Massive Telescopes – Completely Smooth Tracking
	Small Gravity	
		No Co-Orbiting Dust or Debris in Field-of-View of Telescopes
		Dropped Tools and Parts Easily Retrieved
		Easier Working Environment Than Zero-G
		Biologically Friendlier than Zero-G
	Unlimited Mass Available for Shielding Humans and Sensors From	
		Radiation of Solar Storms and Galactic Cosmic Rays
	Vast Area/Dimensionally Stable Real Estate for Interferometers	
Small-Sidereal-Rate -	500 Times Smaller than Leo	
	14 Day (or More) Availability of Source	
		Long Uninterrupted Observations of Variable Phenomena
		Long Integrations on Faint Sources
	Slowly Changing Thermal Environment	
		Permits Excellent Dimensional Stability
"Ultimate" Telescopes Probably Possible Only on the Moon		
		Giant Filled-Apertures; Large Interferometers; Far-Side Radio Receivers

TABLE II
Disadvantages of the moon as an astronomical site

Lack of Solar Power During Lunar Night	
	Requires Enormous Batteries, and Doubled Solar Array Size, or
	Radioisotope Thermal Generators for Small Observatories,
	Nuclear Power Stations for Large Observatories
High Radiation Background - Increased Detector Noise	
	Meters of Rock Needed to Match Shielding Effect of Earth's Magnetic Field
	Extractable Resources are Available for Shielding
Expensive to Operate Human-Tended and -Emplaced Observatories	
	Soft Landed Automated Observatories are Much Cheaper
	Free-Flyers are Much Cheaper (Even HST!)
	Unmanned Cargo Ships are Needed to Relax Safety-Driven Telescope Costs
Day-Night Cycle Limits Efficiency of Single Observatory to 50%	
	Requires two Antipodal Observatories if 100% of Sky must be available 100% of time
	If Equatorial, each Achieves 50% Duty Cycle on the Entire Sky
	If Polar, each Achieves 100% Duty Cycle on Half the Sky

TABLE III
A subset of lunar-specific observatories

- Observatories Required by Scientific Considerations
  - Large Aperture UV/Optical/IR Telescope
    - Detection of Earth-Like Planets, and Search for Exobiology
    - Formation And Evolution of Stars, Galaxies, Quasars, and Structure in Early Universe
  - IR and Sub-MM Interferometers
    - Study of Forming and Evolved Planetary Systems
    - Structure and Processes in Galactic Nuclei and Quasars
  - Optical Interferometer
    - Imaging Nearby Stars
    - Distances and Distance Scales
  - Large Aperture X-Ray and Gamma-Ray Telescopes
    - Stellar Accretion Disks
    - Physics Of Neutron Stars and Black Holes
  - 2-Meter Class UVOIR Telescope for Solar System Studies
    - Origin of Solar System; Compositions of Comets and Asteroids
    - Time Variable Phenomena in Planetary Atmospheres
- Observatories Required by Human Safety Considerations
  - Solar Flare Network
    - Flare Physics and Prediction
    - "Early" (Few-Minutes) Warning of Life Threatening Flares for Humans on Moon and Mars
  - Mars Telescope(s) – Continuous Support of Mars Expeditions
    - Two Low Latitude UVOIR Telescopes – 2-Meter or Larger
      - Study Mars Atmosphere in Detail Throughout at Least One Solar Cycle for Enhanced Forecasting
      - Derive State of Atmospheric Waves and Dust Storms Related to Safe Aerobraking and Accurate Landing

Each theme requires one or more observatories on the moon for its successful address and, in several cases, a given observatory could address more than one theme.

The Workshop of course did not exhaust all possible areas of astronomy and astrophysics. A different set of participants might well have added or stressed other topics (e.g. black holes) out of the rich array of problems waiting to be solved. But we believe any workshop on the subject would agree that the conclusions reached at Annapolis include some of the most important problems, and that these clearly demonstrate the instrumental developments needed to tackle them. In the next sections we examine these themes in slightly greater detail.

3. How do Stars and Planetary Systems Form?

We still do not understand how stars and their systems of planets form, nor do we have a clear understanding of the processes that occurred during the formation of our solar system. Yet there are many young stars in the Taurus-Auriga complex, the nearest star-forming region, and about half of those younger than three million years show clear evidence that they possess nebular-presumably pre-planetary-disks some tens to hundreds of astronomical units in size. The inner regions nearest the star are the sites of mysterious processes which energize stupendous amounts of gaseous material into organized bi-polar outflow along the axis of rotation of the newly forming stellar-planet ary system. We do not yet understand the processes that drive these flows, the mechanism for transporting mass inward toward the star while momentum is transported outward, or the details of formation of planets and comets within the system.

The elemental compositions of the planets preserve the record of fractionation processes in our solar system, while the chemical and mineralogical signatures in cometary material preserve a record of the transition region between unmodified interstellar composition and the chemically equilibrated material of the inner solar nebula. We are beginning to learn how to read this record for comets in their active phase, and will do so using space – as well as Earth-bound observatories in the next decade. However, none of the planned Earth-orbital observatories can observe comets at small solar elongations when they are most active.

A 2-meter class dedicated UVOIR telescope is needed. It requires low temperature optics, a cryogenic focal plane, and a satisfactory solar occulting screen.

It could also provide detailed studies of time variable phenomena such as chemically and temporally variable jetting from individual vents on the cometary nucleus and dynamical and interactive processes in other planetary atmospheres, including wave phenomena and weather on Mars in support of eventual human exploration there.

In order to interpret the fossil record of our solar system, it is essential to identify the physical and chemical processes occurring in pre-planetary disks elsewhere, and to relate this record to current models of formation for our own solar system. For example, it has been suggested that giant gaseous planets form outside the distance where water ice is stable and can be carried in the solid phase into the cores of proto-planets. We also have models for the temperatures, densities, and chemical abundances in the main stellar nebula and in giant planet sub-nebulae for newly forming systems, and these models badly want testing.

The spatial scale of interest is initially 1 astronomical unit (au), later 0.1 au. The available tracers are the spectral signatures of gaseous species, particularly carbon monoxide (CO) and water (and many other species), and of condensed phase matter such as water ice (and other volatile ices), organic grains, and silicious grains. The pre-planetary disks exhibit enormous optical depths in the visible and infrared regions, but become optically thin at sub-millimeter wavelengths. Fortuitously, both CO and water have strong lines in this region, indeed the 557 GHz line of water should be an excellent probe of water in the low temperature regions of the outer disk (beyond $\sim$ 5 au), while the higher excitation lines of water and CO provide important probes of temperature and density in the warmer inner regions. Several low excitation lines of CO can be sensed from the earth's surface, and important preliminary studies will be carried out with interferometric arrays now under construction or in the planning phase, but many important spectral lines are obscured by heavy extinction in the Earth's atmosphere. Ground-based observations of normal water are hopeless, for example.

Observations from space are required, and the aperture diameter must be at least

24 km (at 600 μm wavelength) in order to achieve spatial resolution of 1 au at the 140 parsec distance of the nearest star-forming region. An interferometric array is indicated, and it must be located on the moon to ensure the required dimensional stability and pointing precision. An initial configuration might be remotely deployed, then connected by humans.

4. Are There Earth-like Planets Among The Nearby Stars?

It is now within our ability to directly detect – if they exist – planets similar to those in our solar system, but around the nearby stars. Though giant planets similar to Jupiter will of course be much more conspicuous, the Holy Grail is to detect Earth-like planets. The discovery of even one other planet with size and atmosphere similar to Earth would have profound implications. We are confident that planets from Earth-like to Jovian size can be detected and studied, using instruments of the kinds discussed in this volume. While present and near-term searches may achieve indirect detection of a few Jovian-class planets, direct detection and study of all planets down to Earth-class planets is the real goal, and it is a challenging one. At visible wavelengths, the contrast ratio between a star and an Earth-like planet shining by reflected light is about 10 billion, but in the infrared, where the planet shines in its own thermal radiation, the ratio is about 100,000, a much more favorable value. The diffraction disk of the star is much larger in the infrared, but it is easier to reduce light scattered from the telescope mirror. Thus, on balance, it is probably easier to detect Earth-like planets in the thermal infrared.

The instrumentation to detect Earth-like planets must be based on the moon. Two approaches have been examined: a large filled aperture "conventional" telescope of the 16-meter diameter class, and an interferometric array of comparable total collecting area.

The collecting area is a consequence of the faintness of Earth-like planets and the need to examine a significant number of nearby stars in a reasonable time. When seen at infrared wavelengths from a distance of ten parsecs, the Earth returns only about 50 photons each second to a square meter of collecting area. Thus telescopes several hundred square meters in area are needed to collect sufficient photons for detecting and characterizing the planet. Low temperature optics are required, and they must be located in space, in order to eliminate background emission from both the telescope and the atmosphere. The telescopes are very large, have high mass, and require precise pointing which in turn requires an exceptionally stable platform. This stability is probably not possible to provide in Earth orbit, but is obtained simply for lunar based telescopes by virtue of the moon's enormous moment of inertia and excellent dimensional and seismic stability. Such instruments would have to be assembled on the moon, and maintained from a lunar base. It is certain that both concepts require extensive technical study, and in both cases the critical areas of work are well defined. Detailed studies of these concepts should begin immediately.

5. Do Life and Intelligence Exist elsewhere?

We still know of only one planet on which living things exist, yet several lines of evidence suggest that life may be harbored in many places. The fossil record shows that, at least on Earth, life began almost as soon as conditions permitted. Twenty years of molecular astronomy have demonstrated that many of the pre-biotic molecules thought necessary for the spontaneous origin of living material are found in dense molecular cloud cores, which evolve into new stars, many of which are undoubtedly surrounded by young planetary systems. The discovery of organic grains (CHON), formaldehyde, and complex hydrocarbons in comet Halley demonstrated for the first time that cometary nuclei contain these pre-biotic substances. Cometary planetesimals must be enormously abundant in the cooler regions of proto-planetary nebulae, hence their impacts on young planets must also be numerous. Recent theoretical work argues that a significant portion of the delivered material survives the impact process without significant chemical modification, allowing the surfaces of all young planets to receive pre-biotic material in enormous quantities. The discovery that disks and clouds of debris in fact do orbit many of the nearby stars is a strong indication that all these processes are relatively common. It thus seems plausible that living organisms may exist on at least some other planets.

Life has modified our atmosphere in fundamental ways – indeed the presence of enormous quantities of free oxygen is a consequence of the presence of terrestrial life. Likewise, the presence of abundant methane in an otherwise oxidizing atmosphere is a direct consequence of biological processing of carbon. While the atmospheres of the giant planets in our solar system contain copious methane, and the atmosphere of Mars contains trace oxygen and ozone, only Earth's atmosphere contains both oxygen and methane in significant quantities. Thus, a major objective in exobiology is to characterize the atmospheres of extra-solar planets, and to identify those which have been modified by the presence of life. This can be accomplished by spectroscopy at thermal infrared wavelengths, where the principal biologically-connected gases all have strong characteristic absorption bands. Ozone (a tracer for oxygen), methane, ammonia, water, and carbon dioxide can all be detected at thermal infraredwavelengths, using spectroscopy. *A large aperture telescope having several hundred meters collecting area is required, to identify biological modification of Earth-like planets, and it must be instrumented with low resolution spectrometers (spectral resolving power ≈ 100) n the wavelength region 6–15 μm.*

It must feature low temperature optics and cryogenically cooled detectors, be located in space, and have exceptionally precise pointing stability. It seems necessary to locate it on the moon.

Though a successful search for extra-terrestrial biology may require the study of a large number of stars, discovery of life would be profoundly significant. Far more significant yet, but presumably vastly more rare would be the discovery of extra-terrestrial intelligence. A crude feeling for detection probabilities follows from knowing, for example, that the terrestrial atmosphere has testified to biological modification for billions of years, but the evidence of an intelligent presence has only been detectable remotely for less than 100 years. Even supposing human technical capability to extend for another 10,000 years, the remote detection of biology through atmospheric evidence would still be favored in the ratio of 100,000 or so. This greatly over-simplified argument suggests that comparably larger samples of stars must be examined to provide a comparable probability for the successful detection of intelligence. The Search for Extraterrestrial Intelligence (SETI) is presently conceived as a search for radio emissions. Its detection sensitivity and completeness are severely limited by natural atmospheric emissions and opacity, and by artificial noise sources associated with human activities. The lunar far-side is the quietest zone in near-Earth space and would provide a unique location for large radio antennae, or arrays. This would provide commensurate improvements in detection sensitivity and in the range of available frequencies. The potential benefits seem clear, but there has been no critical and broad evaluation of the potential of the lunar far-side for SETI.

6. What is Happening in our Sun and in Other Stars?

We have never seen a picture of a star other than our sun. Moreover, essentially all that we know of solar physics and processes is based on a single temporal snapshot in the 4.5 billion-year life of this ordinary star. We do n ot know whether predictions derived from present conditions are representative of future development or not, but we do know that some aspects of the sun have changed significantly during recorded history – for example that sunspots virtually disappeared for a period of time 300 years ago known as the Maunder Minimum. No one knows why this happened. Our theory of the internal engine that drives the sun predicts a certain flux of neutrinos which exceeds the detected flux by a major factor. We do not know whether this represents some basic flaw in our understanding of the interior processes, of neutrino physics, or of some other missing factor. While many stars are variable in their energy production, the sun does not seem to vary much, but we also know that the Earth has experienced major climatic changes which may have been in part caused by changes in the annual insolation. One way of gaining insight into our sun is to investigate processes occurring in other stars. Stars of similar age and mass, or of similar mass but a range of ages, are of obvious and direct interest, but the sample should also include a range in mass and age beyond the sun's so that true comparative solar-stellar physics may begin.

We must begin a program of comparative solar-stellar physics, and this requires observations of the surfaces of other stars on spatial scales similar to that obtained for the sun. For our sun, the best ground-based observing conditions provide optical image quality of about 0.4 arc-seconds, or a linear resolution on the surface of about 300 km at visible wavelengths. Correction of atmospheric errors might improve this to about 150 km, but further improvement requires space observatories. The nation's plan for solar physics includes the Orbiting Solar Laboratory (OSL), which features a one-meter diameter telescope instrumented at ultraviolet-optical-infrared (UVOIR) wavelengths. OSL will achieve about 50 km resolution on the sun's disk at visual wavelengths.

For stars, we ultimately wish to achieve resolutions comparable with the best solar images, or about 150 km. Imaging of nearby stars with this spatial resolution requires angular resolutions in the micro-arc-second range, which at optical wavelengths corresponds to an aperture diameter of 125 km. Interferometric observatories are mandated, and these will need to be based on the moon. They must be based in space in order to escape the limiting atmospheric effects of airglow and turbulence. The observations require low fringe drift rates which imply extreme dimensional control and stability. The needed pointing and tracking precision require a stability and predictability of baseline which cannot be achieved in free space, but which is easily achieved on the moon. This system is the ultimate objective toward which initial and intermediate systems must grow, but a start can be made with 2-meter class telescopes and 100-meter baselines. The dedicated 2-meter class telescopes identified for planetary, stellar, and galactic astronomy might form the elements of an initial simple array for this purpose.

A particularly compelling case is made for a network of dedicated free-flying spacecraft, spaced in solar longitude, to provide predictive and alerting capability for life-threatening solar flares.

These occur relatively often, and the greatly enhanced solar wind they produce could be fatal for unprotected humans. Improved understanding is clearly needed, since at present we are unable to predict when a flare will erupt or whether the particles emitted from it will hit the Earth-moon system. This becomes doubly important for areonauts enroute to Mars, and while they are on the surface of that planet, with its only tenuous atmosphere and tiny magnetic field.

7. What Happened in the Early Universe?

There is a crisis in cosmology, which suggests that our present understanding of processes in the early universe is fundamentally flawed. Measurements of the cosmic background radiation demonstrate the absence of large-scale fluctuations at times corresponding to red shifts of $z < 15$. However, the earliest quasars appear only a bit larger in time, at red shifts of $z \approx 5$ and already exhibit a solar abundance of elements, implying the existence of an earlier generation of stars. Thus, stars and galaxies must have existed near $z \approx 15$ or even earlier, yet we see no evidence of them in the cosmic background radiation. Furthermore, recent measurements of galaxy-pair correlations, based on a deep red-shift survey, suggest that the clumping and voids ("bubbles") seen on the local scale extend to at least 1000 mega-parsecs, or about 3.3 billion light years, and thus that the occurrence and scale-size of these voids appears to be cosmogonic and fundamental. The nature of the voids present in the large scale structure is poorly known at present, but can be addressed by absorption spectroscopy of quasars and galaxies. In addition, the "hidden" mass required to close the universe has not yet been found, even though several lines of evidence suggest that it must exist.

Investigation of the formation and evolution of stars and galaxies in the epoch $5 < z < 15$ requires photometric and spectral observations of quasars and early galaxies in the 0.75–10.4 micrometer wavelength range.

A large filled-aperture telescope of the 16-meter class would meet these needs, but it must be in space to achieve diffraction limited imagery, full wavelength coverage, and sensitivity limited only by the natural background imposed by the zodiacal *light. In turn, the low temperature and the extreme pointing stability required of this immense and high-mass telescope speak for its presence on the moon.*

Along with photometry and spectroscopy, ultra high spatial resolution will be needed for many key investigations. Imaging the structure and kinematics of active galactic nuclei and quasars is basic to understanding their physics and evolution, but requires far higher angular resolution than can be achieved with filled aperture telescopes. The core activity of galactic nuclei and quasars is most significant on spatial scales below 0.1 parsec. A 16-meter telescope, if diffraction limited at 2 μm wavelength, could achieve angular resolution of 0.03 arc-seconds, but this corresponds to a spatial scale of 0.1 parsec at a distance of only 0.7 mega-parsec. Micro-arcsecond angular resolution is needed to map structure with a resolution of 0.1 parsec at a distance of several thousand mega-parsecs. Lunar-based interferometric arrays with 500 km baseline (at 2 mm wavelength) would achieve this resolution.

8. Environmental and Site Considerations

Two environmental aspects requiring further study include the nature of the surface thermal environment, and the effects of cosmic and solar particulate radiation on instruments, particularly on solid-state detectors and electronic components. Because the moon lacks a strong magnetic field, the particle flux at the lunar surface is much greater than in low-earth orbit and may require burial or heavy shielding of detectors. The high daytime temperatures at low latitudes present a potential problem for unprotected telescopes and instruments, particularly those operating in the thermal infrared and sub-millimeter region, and those requiring active cooling. It appears that simple "sunshade" shielding techniques can be devised for such telescopes and instruments, but the problem requires detailed study.

Candidate sites for initial observatories should be evaluated on the basis of visibility of the celestial sphere, dynamic accessibility for spacecraft landings and rendezvous with lunar transportation nodes or transfer vehicles, trafficable and workable terrain and geological/geophysical interest. A network of 5 sites would be ideal: two at the poles and three at the equator, 120 degrees apart. A minimum of two antipodal sites is needed for support of human exploration of Mars For a single initial site, the NE flank of the Orientale Basin at 80 degrees W longitude on the equator was suggested as a promising candidate. While maintaining line-of-sight communications with the Earth, this site would also permit access by tele-robotic vehicles to the lunar far side for emplacement of radio astronomy instruments, and is of considerable geological interest.

One concept that seems important is the need for site-testing telescopes, to be landed at prospective sites for lunar observatories in order to establish basic feasibility from the perspective of radiation background, thermal factors, achieved operating temperatures, and a host of other practical engineering details.

These should surely precede a final commitment to an individual site. Also, while the Annapolis workshop stressed major instruments and far-reaching programs which require a presence on the moon for successful accomplishment (cf . Table III for a partial listing), several authors have argued for a suite of lesser instruments which may be able to compete scientifically and cost-effectively with their earth-orbital counterparts. The future will determine whether the advantages of the moon will in fact carry over into a much wider range of usage, including a possibly large number of instruments of nearly all sizes and kinds. But whether or not this occurs, the Annapolis Workshop demonstrated that some of the most fundamental goals of astronomy are unlikely to be achieved without lunar basing and the magnificent astronomical instruments which this alone will make possible.

9. Conclusion

In addition to the fundamental themes outlined in this summary, many innovative and useful ideas and concepts were advanced at the Annapolis Workshop, and are described in individual papers and in the Summaries of the Scientific Working Sessions (Mumma and Smith, 1990).

It is clear that the astrophysical frontiers of the 21st century will require very large filled-aperture telescopes and interferometric arrays of many kilometers dimension for their successful address. These must be located in space, and the requirements of accurate and stable pointing alone require that they be placed on the moon. There is yet another important reason for placing them on the moon, namely the need for human interaction with – and tending of – these sophisticated and complex instruments. Compared with free space, the moon presents a familiar environment for humans. Tools stay where they are put, dropped parts fall to the ground for easy retrieval, and the body experiences gravity, thereby avoiding the deleterious health effects of prolonged exposure to zero-g, and there is ready shelter from cosmic rays and solar storms.

Many astrophysical objectives of the 21st century require lunar-based observatories for their full realization, and we should insert these scientific objectives as requirements to be met by a program of renewed human exploration and exploitation of the moon.

Reference

Mumma, M. J., and H. J. Smith: 1990, *Astrophysics from the Moon, AIP Conf Proc.*, **207**, in press