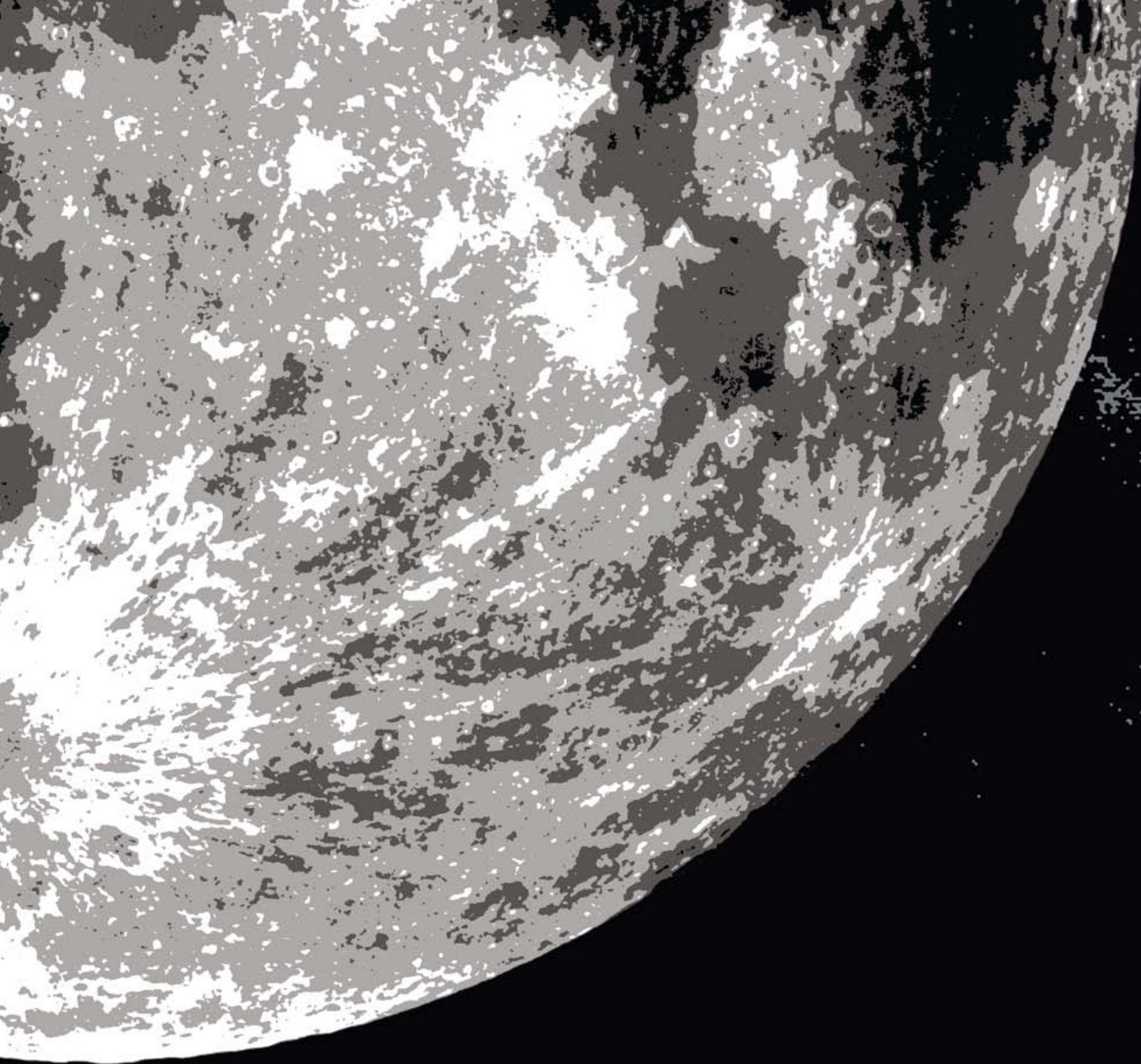

AStROPHYSICS

ENABLED BY THE RETURN TO THE

MOON

A Brief Summary of Highlights Based on the Workshop held at

SPACE TELESCOPE SCIENCE INSTITUTE

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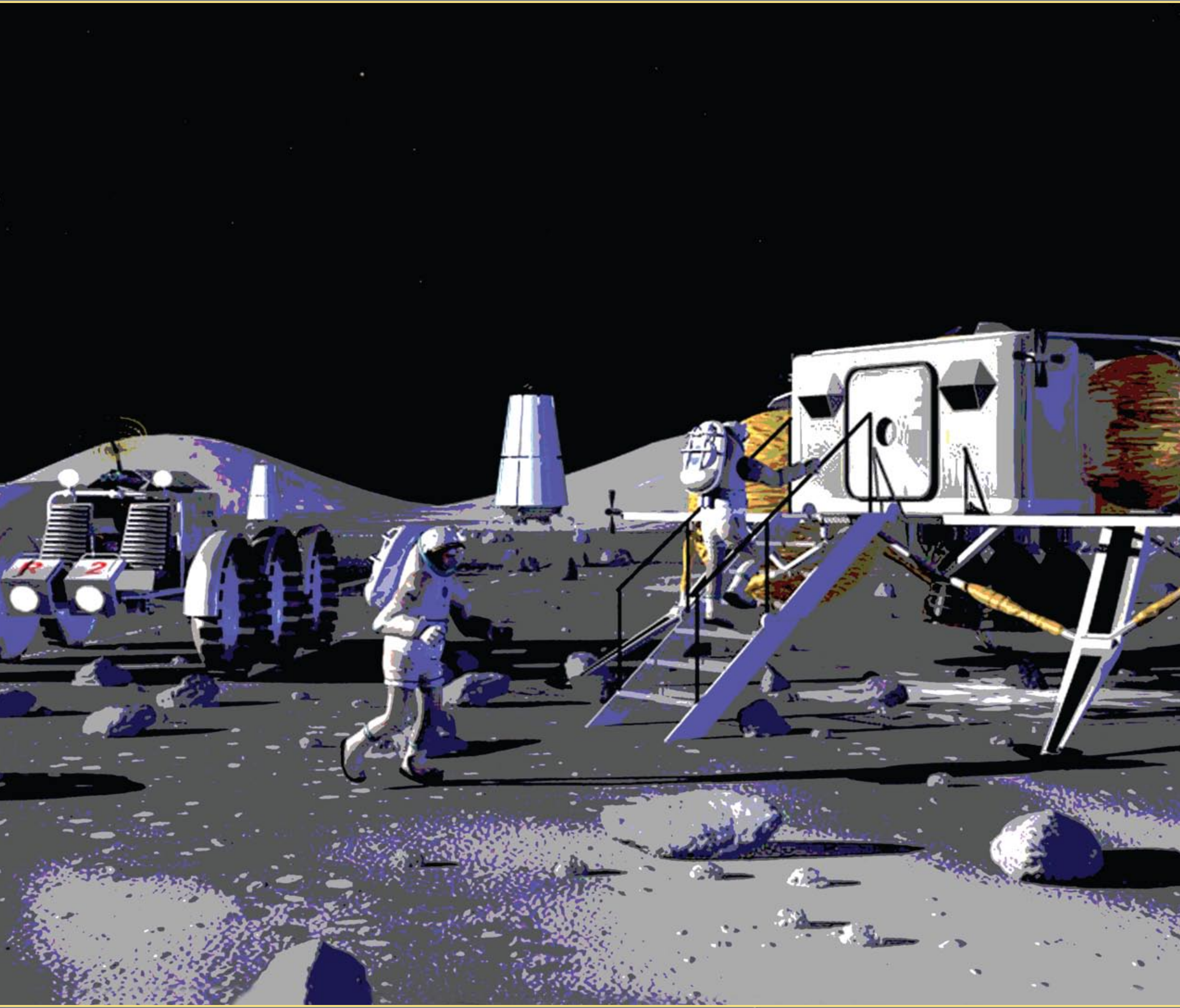
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CONTENTS

EXECUTIVE SUMMARY

- The Workshop *Astrophysics Enabled by the Return to the Moon* has identified a few important astrophysical observations that can potentially be carried out from the lunar surface. Most promising in this respect are:
  - (i) Low-frequency radio observations from the lunar far side, to probe structures in the high-redshift ($10 \lesssim z \lesssim 100$) universe and the epoch of reionization; and
  - (ii) Lunar ranging experiments, to test a certain class of alternative theories (to general relativity) of gravity.
- A few smaller and more limited in scope experiments have been suggested. These included:
  - (i) A small telescope to observe the Earth, for a better characterization of Earth-like planets;
  - (ii) A calorimeter for the study of intermediate-energy cosmic rays; and
  - (iii) A small, far-UV telescope to examine the structure and composition of the hot Galactic medium.
- The ideas of external occulters for observations of Earth-like planets, and of liquid mirrors for deep-field observations, should be further examined.
- At the same time, the Workshop highlighted the fact that observations from free space (and in particular from Lagrange points) *offer the most promise for significant progress in broad areas of astrophysics*. Given the impressive capabilities of the proposed Vision for Space Exploration (VSE) infrastructure, every possible effort should be made for the VSE not to preclude—*but rather to enable*—future observations from free space.

1. INTRODUCTION

The Workshop *Astrophysics Enabled by the Return to the Moon* was organized by the Space Telescope Science Institute (STScI), in collaboration with the Johns Hopkins University, the Association of Universities for Research in Astronomy, and NASA. The decision to hold the meeting was in direct response to the encouragement by the NASA Administrator to provide scientific input to the VSE, which envisions the return of humans to the lunar surface by 2020. Unlike a few previous meetings and studies that mostly concentrated on observatory concepts and on sites, the STScI Workshop focused primarily on the *science*. The broad goal of the Workshop has been to identify *key questions* in astrophysics, and to critically examine whether the proposed return to the Moon can, either directly or through the capabilities developed by the VSE, provide opportunities for significant progress toward answering those questions. Accordingly, the Scientific Organizing Committee of the Workshop identified four topics that are widely believed to pose intriguing astrophysical challenges for the next two decades. These are (in no particular order):

A WHAT IS THE NATURE OF THE DARK ENERGY THAT IS PROPELLING THE COSMIC EXPANSION TO ACCELERATE?

B ARE THERE EXTRASOLAR HABITABLE PLANETS AND, IN PARTICULAR, IS THERE EXTRATERRESTRIAL INTELLIGENT LIFE?

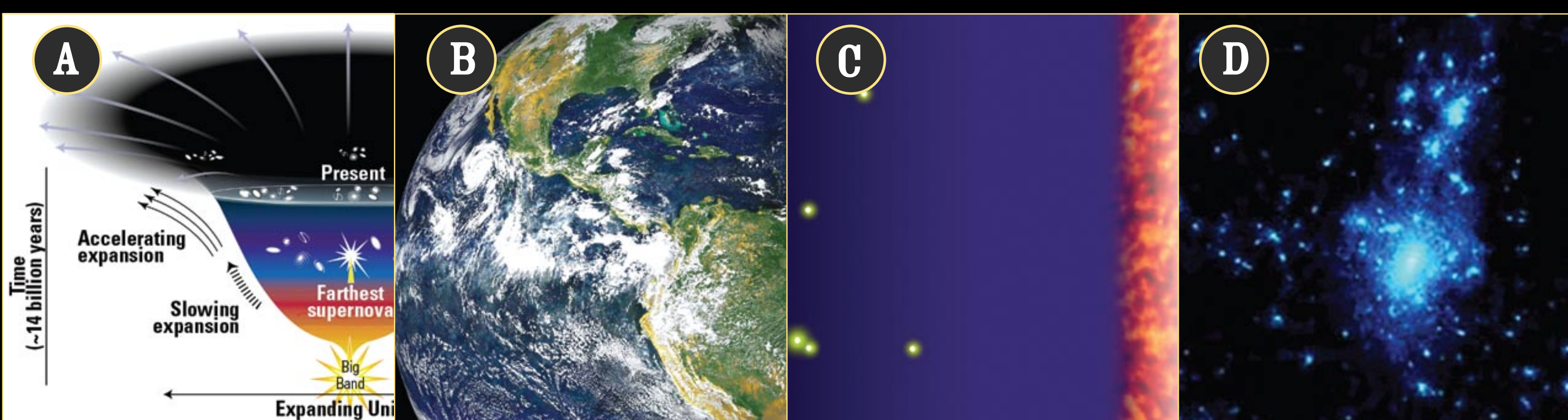
C WHICH ASTRONOMICAL OBJECTS AND WHICH PHYSICAL PROCESSES WERE INVOLVED IN THE "FIRST LIGHT" IN (AND THE RE-IONIZATION OF) THE UNIVERSE?

D HOW DID GALAXIES AND THE LARGE-SCALE STRUCTURE OF THE "COSMIC WEB" FORM?

Speakers were encouraged to examine these questions from the perspective of research opportunities enabled by the VSE. In addition, a few speakers were specifically invited to examine the question of whether the capabilities developed by the VSE offer clear advantages in terms of observatory locations, new telescopes or new technologies, that could advance broader swaths of astronomy and astrophysics. This brief summary of highlights from the Workshop is organized as follows: In Section 2, I present what I regard as the key points of the discussion concerning the above four scientific questions. In Section 3, I give a concise description of the consensus emerging from the examination of broad astrophysical research enabled by the VSE.

All the presented talks can be found at:

WWW.STSCI.EDU/INSTITUTE/ITSD/INFORMATION/STREAMING/ARCHIVE/AERM

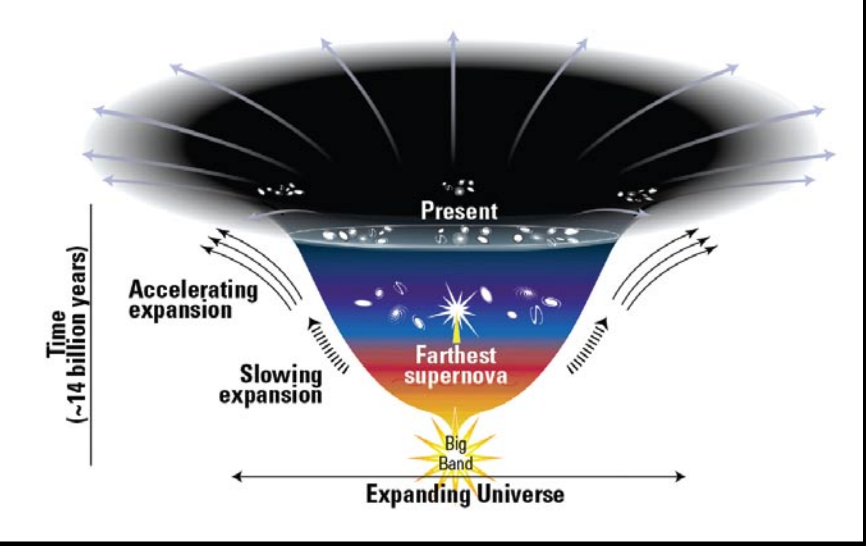


2. POTENTIAL OPPORTUNITIES FOR MAJOR SCIENCE QUESTIONS

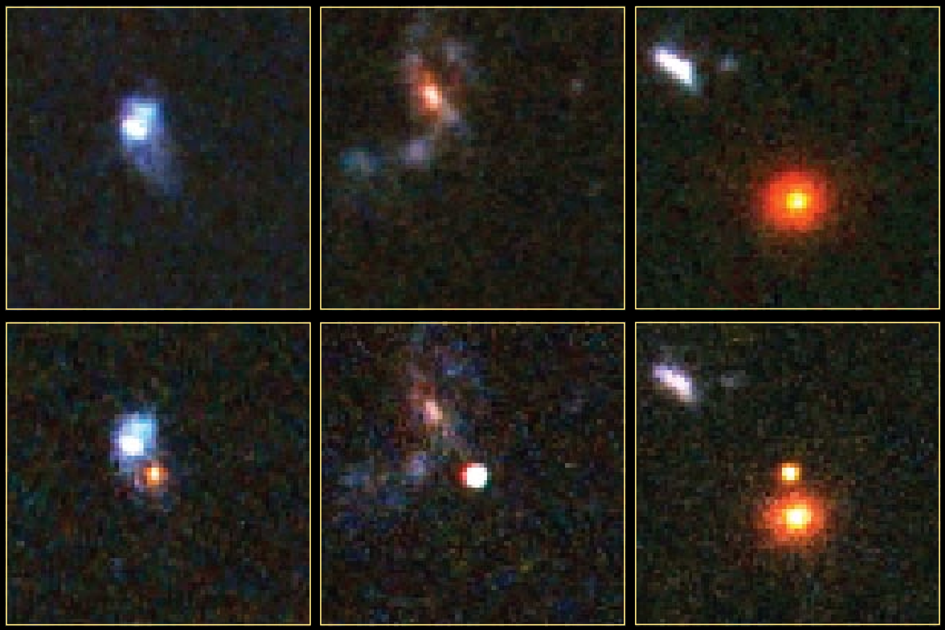
Each of the four major science questions (that were formulated in the Introduction) was addressed by several experts. The following summary is not intended to represent a comprehensive review of these topics, but rather a short restatement of the main points.

2.1 The Accelerating Universe

In 1998, two teams of astronomers working independently discovered that the expansion of the universe is accelerating, as if propelled by the repulsive force of some "dark energy" that permeates all space and operates on the largest cosmological scales. Since then, observations of high-redshift supernovae, of the cosmic microwave background, of baryon oscillations, and of the Integrated Sachs-Wolfe Effect, and of X-ray clusters, all seem to indicate that about 70% of the energy density of the universe is in the form of dark energy. Theoretical models attempting to explain the nature of this dark energy or of the cosmic acceleration generally fall into three classes:



A schematic representation of the history of cosmic expansion.

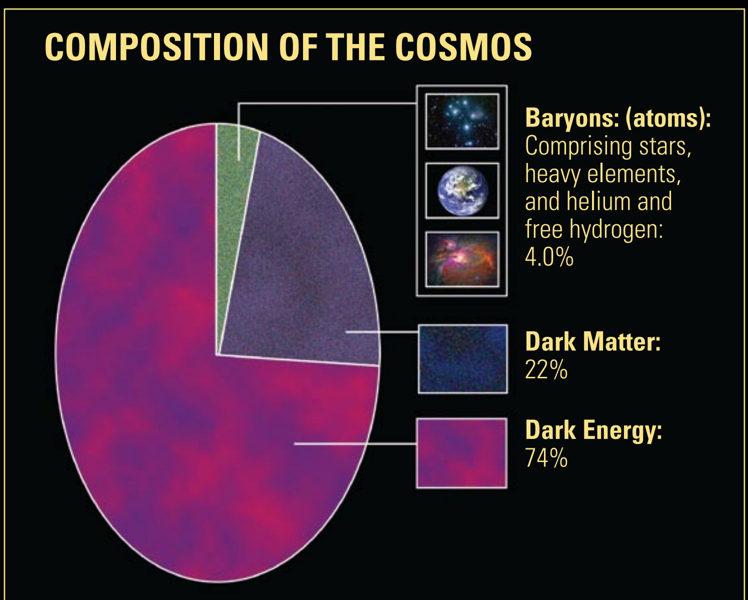


This image shows the discovery by *HST* of three distant Type Ia supernovae.

1. Models in which the dark energy is associated with the physical vacuum (Einstein's famous "cosmological constant").
2. Models in which the dark energy is associated with some scalar fields (dubbed "quintessence fields").
3. Models in which there truly is no dark energy, but where the theory of gravity (general relativity) needs to be modified.

2.1.1 Observations Related to Dark Energy

Given the relative dearth of information about the nature of dark energy, recent observations have concentrated on attempts to determine its equation of state, expressed by the relation between its

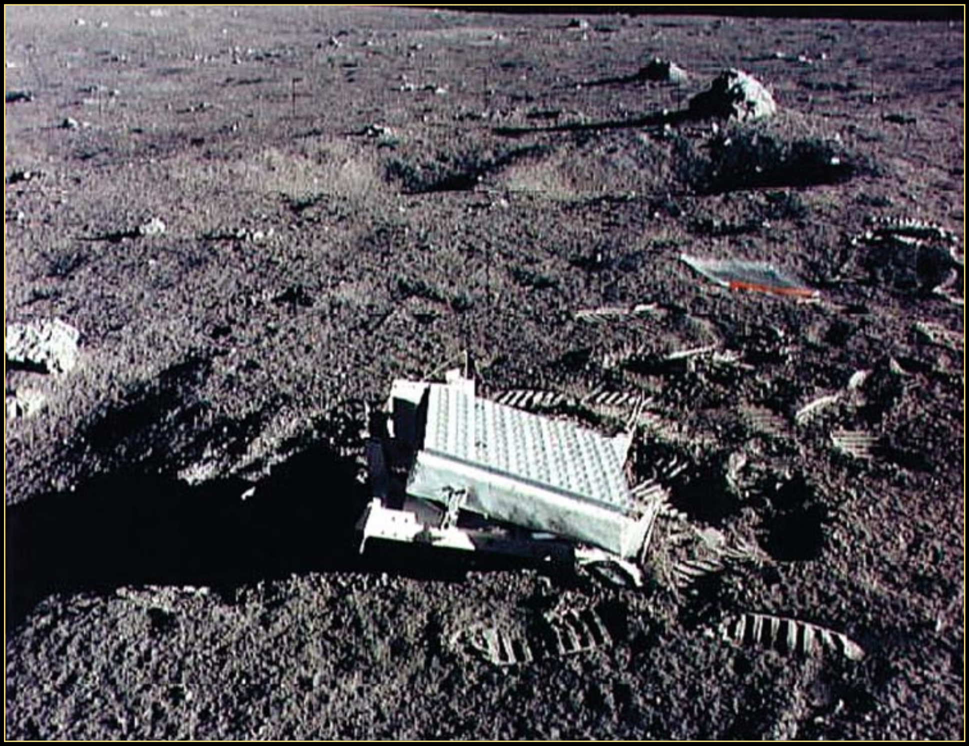


A schematic representation of the components of the energy density of the universe.

density and pressure, $p = w\rho$. In particular, vacuum energy is characterized by a constant value $w = -1$, while quintessence fields could have redshift-dependent values of w (the fact that the universe is accelerating implies that presently $w < -1/3$). Type Ia supernovae (SNe Ia) have proved to be one of the best tools for measuring the rate of cosmic expansion, because they are very bright (and hence can be seen to high redshifts), and their luminosities are well calibrated (and hence their distances can be determined). In order to beat down potential systematics, a sample of a few thousand of well-observed SNe Ia needs to be assembled. The best tool towards this goal appears to be *a modest-sized space-based telescope with a wide field of view*. The same telescope can be used to observe baryon oscillations that can also help constrain cosmological parameters. *The lunar surface is not perceived as offering any advantages over free space for these observations, while it has some clear disadvantages* (*e.g., power, thermal loading, dust*).

2.1.2 Observations Related to Alternative Theories of Gravity

There exist theories that propose to explain the observed acceleration by modifying gravity on scales comparable to the cosmological horizon, $r_c \simeq cH_0^{-1} = 10^{28}$ cm (where H_0 is the Hubble constant and c is the speed of light), without any need for dark energy. These theories predict



The existing retroreflectors on the lunar surface.

the existence of corrections to general relativity inside a scale r_* given by $r_* = (r_c^2 r_g)^{1/3}$, where $r_g = 2GM/c^2$ (where G is the gravitational constant, and M is the mass of the astrophysical object). Most importantly, however, *these theories predict an anomalous perihelion precession* (*the perihelion advance per orbit*) *of the lunar orbit*. The theoretical prediction for the precession is $\delta\phi = 1.4 \times 10^{-12}$. *Measurements of the lunar precession with this accuracy are definitely achievable by lunar ranging experiments*. The accuracy of the current laser lunar ranging experiment that uses

The lunar ranging experiment.

the retroreflectors placed on the Moon by Apollo astronauts reaches $\sigma_\phi = 2.4 \times 10^{-11}$, with no anomalous precession detected at this accuracy. *The return to the Moon is likely to allow for the placing of a carefully designed array of transponders that is expected to lead to a tenfold improvement in the accuracy.*

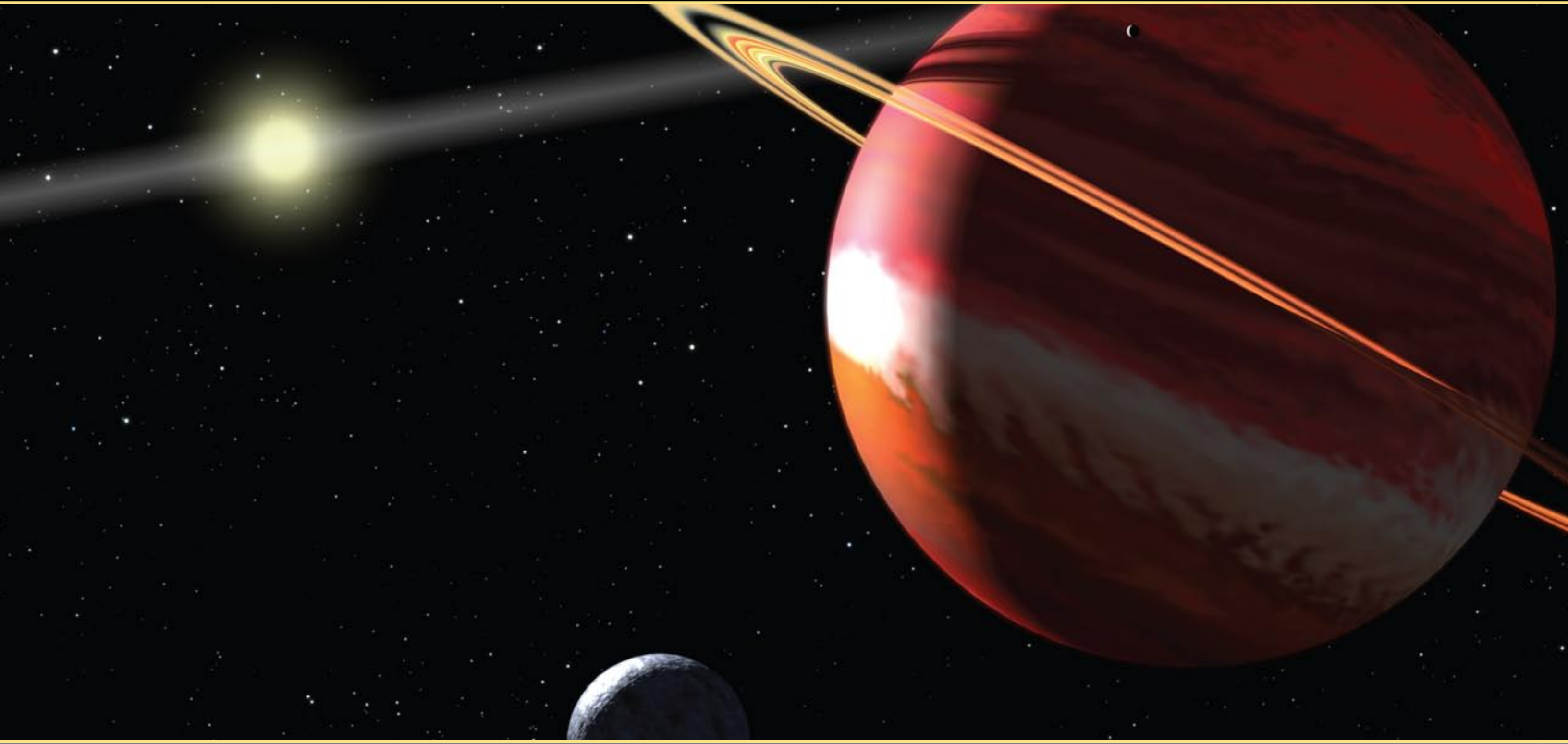
I should also note that it may be possible to use the laser communication developed for the lunar base for the same type of measurements.

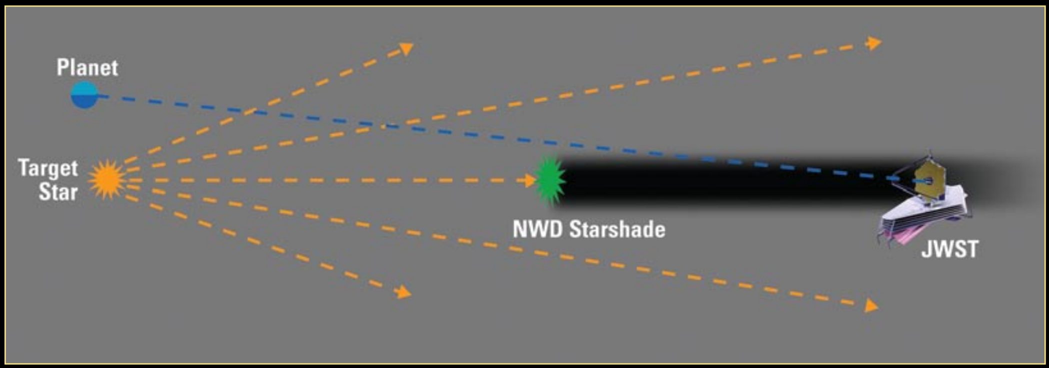
2.2 Extrasolar Planets and Life

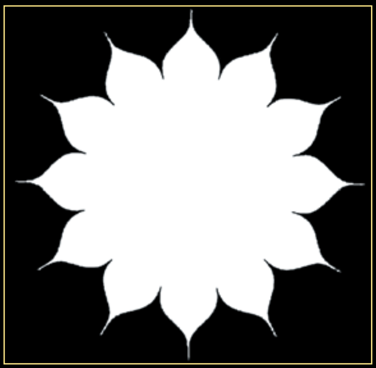
More than 200 extrasolar planets around normal stars have been discovered since 1995. The main techniques for discovering planets have been radial velocity measurements, photometric transits, and photometric monitoring of microlensing events. The lowest-mass extrasolar planet discovered to date is of 5.5 Earth masses. In one transiting planet (HD 209458b), the presence of sodium, hydrogen and carbon in the atmosphere has been established.

High-precision transit observations require photometric errors smaller than ~10^{-4}. Space-based transit-search missions such as *KEPLER* have been designed with that goal in mind. The actual *imaging* and characterization (e.g., in terms of bio-signatures) of Earth-like planets will require extraordinarily high-contrast (~10^{-10}) imaging of objects that lie only a fraction of an arcsecond away from the host star, and even more challenging spectral capabilities. *The two solutions that have been proposed until recently envisage space-based telescopes*, either equipped with an internal coronograph or performing nulling interferometry by formation-flying telescopes.

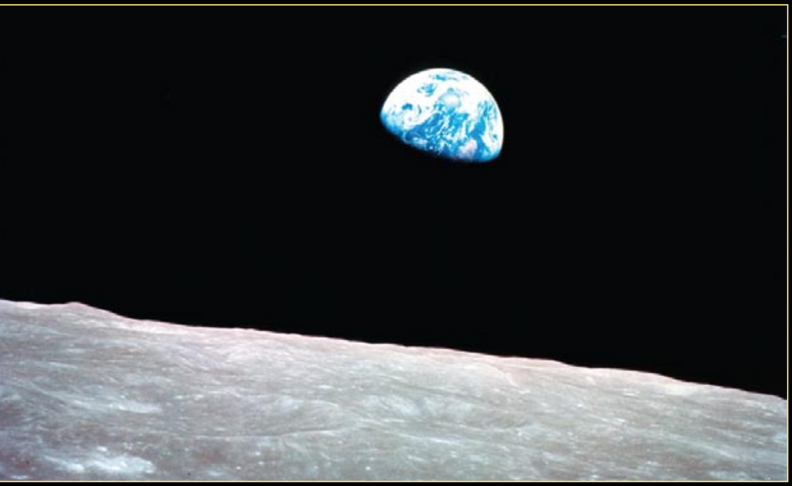
The idea of an *external occulter* was presented at the Workshop. The carefully designed flower-shaped occulter is a simple, deployable sheet about 30 meters in diameter. The occulter must be at a large distance (~20,000 km) from the telescope, *but it can be used with planned telescopes*







External occulter throws deep shadow over JWST, but allows planet light to pass.



Earth viewed from the surface of the Moon.

such as JWST. Astronauts could, in principle, rendezvous with the occulter when it runs out of fuel, to allow for new lines of sight. A collection of formation-flying large telescopes operating in a phased array would be needed to obtain a resolution of a few hundred kilometers.

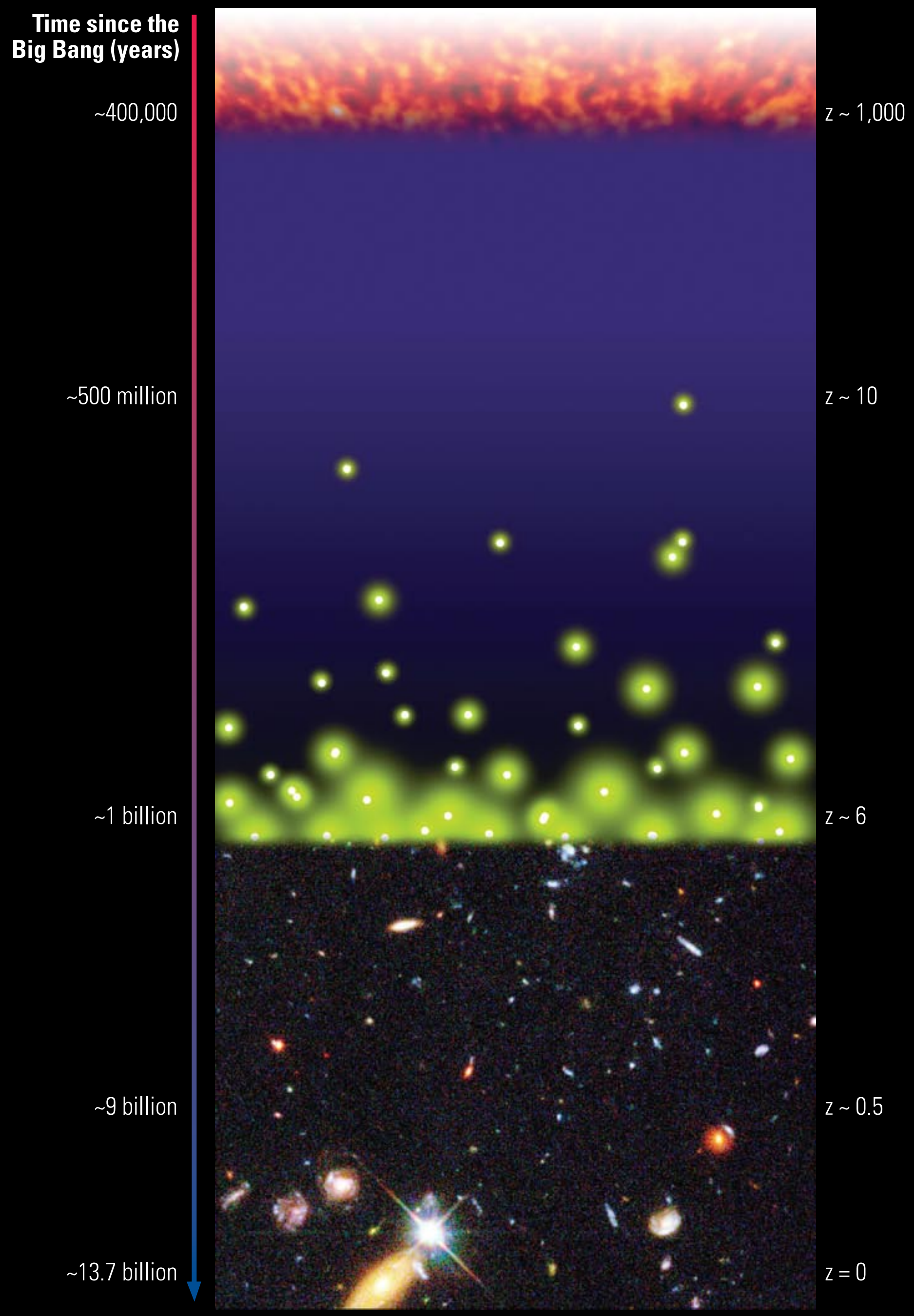
Positioning the telescopes on the lunar surface (with the occulters in orbit) would pose serious difficulties due to the Moon's rotation. It would require delay lines that are hundreds of kilometers in length. However, given the potential availability of a predictable infrastructure, this level of challenge may not be inappropriate for a scientific endeavor that is more than two decades into the future. Still, high-precision formation flying in space may prove to be the lesser challenge.

On a very different scale, it has been suggested that a small telescope on the Moon could perform automatic photometry, spectroscopy and polarimetry of the Earth in the visible-near infrared. The goal would be to *characterize unambiguously the time-dependent signature of a life-bearing planet for future terrestrial-planet-finding telescopes*.

2.3 Probing the Epoch of Reionization and beyond

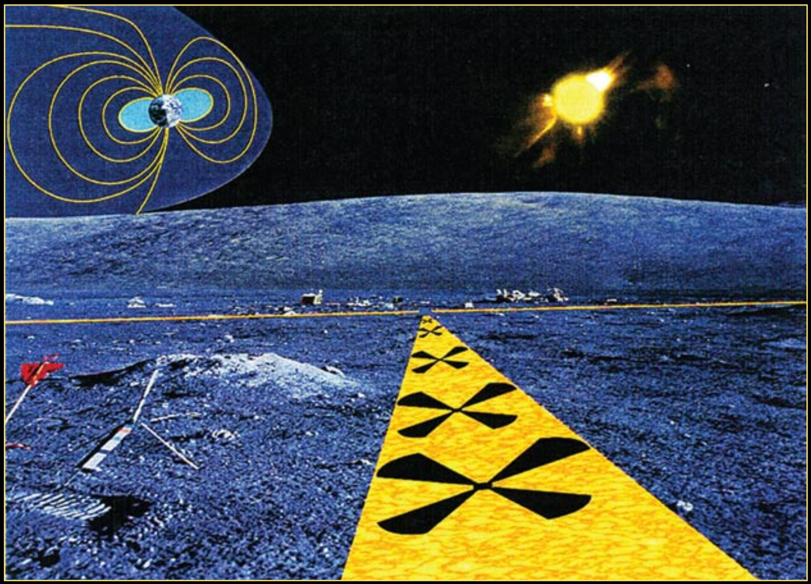
Observations of distant quasars by the Sloan Digital Sky Survey (from the ground) and of the Cosmic Microwave Background (CMB) by the *WMAP* satellite (from the Sun-Earth Lagrange point L2) have shown that the universe was reionized between redshift 13 and 6. This represented a dramatic phase change in cosmic evolution. Observations of the redshifted 21-cm emission of neutral hydrogen could probe scales smaller than those accessible to CMB measurements, at redshifts $10 \lesssim z \lesssim 100$. Note that the scale of ionized bubbles towards the end of reionization is about 10 Mpc in physical scale and the fluctuations are at about 10 mK. A combination of 21-cm observations with observations by *JWST* (albeit, probably not on a large fraction of the sky) will allow for an even more complete picture, since the infrared galaxies at $z > 6$ are expected to be anticorrelated with the 21-cm brightness, because of the reionization. While a few interesting experiments to observe the high-redshift 21-cm emission are currently under construction on the ground (in places ranging from the Netherlands and West Virginia to China, to western Australia), the Moon offers some very clear advantages:

1. The far side of the Moon is expected to have very little radio frequency interference (RFI). It is also blocked from the Earth's auroral emission.
2. Unlike the Earth, that has an ionospheric frequency cutoff (at ~10 MHz), the Moon is expected to allow measurements at lower frequencies (note that 10 MHz corresponds to z = 140). The very low frequency science (0.1–10 MHz) is in fact between the ionospheric cutoff and the heliospheric/Galactic free-free cutoff.



A schematic representation of the cosmic ionization history.

3. On the Moon there is no ionospheric distortion at higher frequencies, which leads to better imaging and sensitivity.
4. On the far side of the Moon there are no disturbances expected from weather, animals, or other human activities, to observatories with large collecting areas, operating over long periods of time.



A potential low-frequency radio telescope on the Moon.

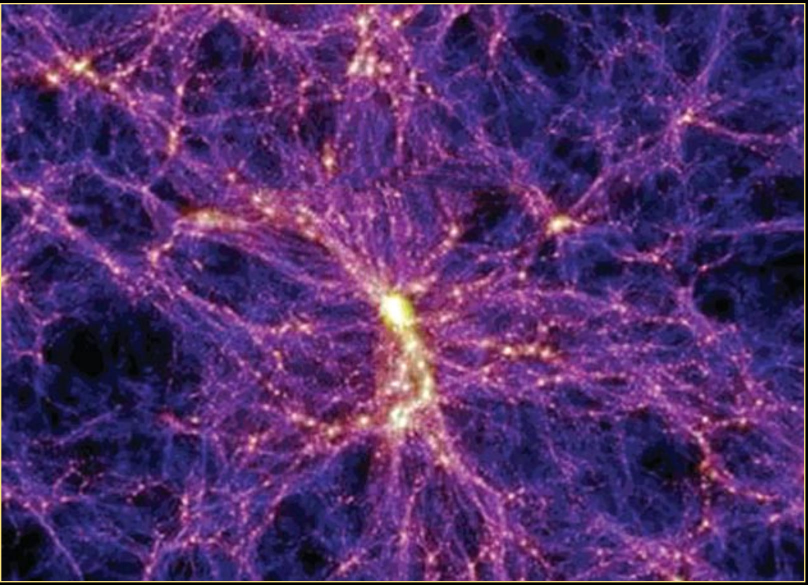
Since low-frequency radio telescopes consist of very simple, lightweight arrays of dipoles (that could even be "printed" onto flat sheets which could be rolled up), the deployment of such telescopes should be relatively easy. Consequently, while clearly there are still many aspects to be examined (e.g., the lunar ionosphere, the Galactic synchrotron emission), *low-frequency radio observations from the Moon's far side appear to provide a very promising opportunity to examine the epoch of reionization and especially beyond.* The experience that will be gained in the near future from the ground-based observations will occur at just the right time to inform the lunar experiments.

2.4 The Assembly of Galaxies and Large-Scale Structure

The studies of galaxy and large-scale structure formation, of black hole formation, of chemical evolution, of the properties of the intergalactic medium, and the determination of cosmological parameters from galaxy distributions, are all key ingredients of the new, precision cosmology. Suffice it to note that the large-scale structure is a tracer of dark matter, and that the intergalactic medium is the dominant reservoir of baryonic material and its evolution is directly related to galaxy formation, to realize the importance of these studies for cosmic evolution. The observations necessary for all of these topics, however, will generally require large, free-space-based telescopes, in the IR-optical-UV-X–ray regimes. *The lunar surface, while clearly offering advantages over terrestrial sites, has essentially no additional advantages over free space, but obvious disadvantages* (*e.g., engineering uncertainties, dust*). In fact, any complex observatories (e.g., with many moving parts) are at a disadvantage on the lunar surface compared to free space. *Consequently, the general consensus is that the often "photon-starved" observations of cosmic structures should be performed from free space.*

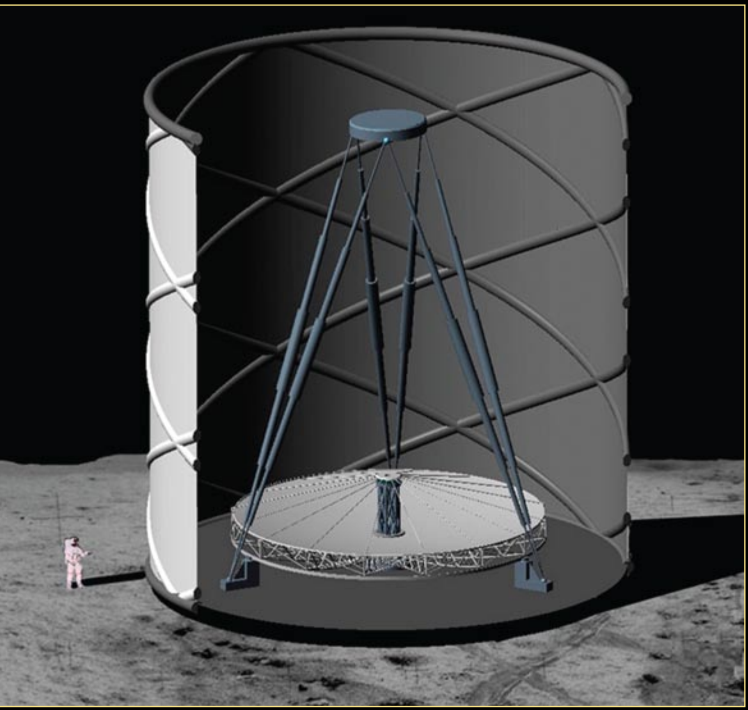
Nevertheless, a suggestion was presented for a small, far-UV telescope on the lunar surface to map the hot (~10^5–10^6 K) gas in our own Milky Way Galaxy through observations of the key ionization stage of oxygen—O VI.

I should note that the angular sky coverage desired for the science (as well as for dark energy observations) is larger than what would likely be available to a fixed liquid mirror telescope (see §3.1).



Structure of the cosmic web and the intergalactic medium can be best studied by ultraviolet spectroscopy from L2.

3. OTHER POTENTIAL ENABLING BY THE VSE



A schematic of a potential liquid mirror telescope at the lunar pole.

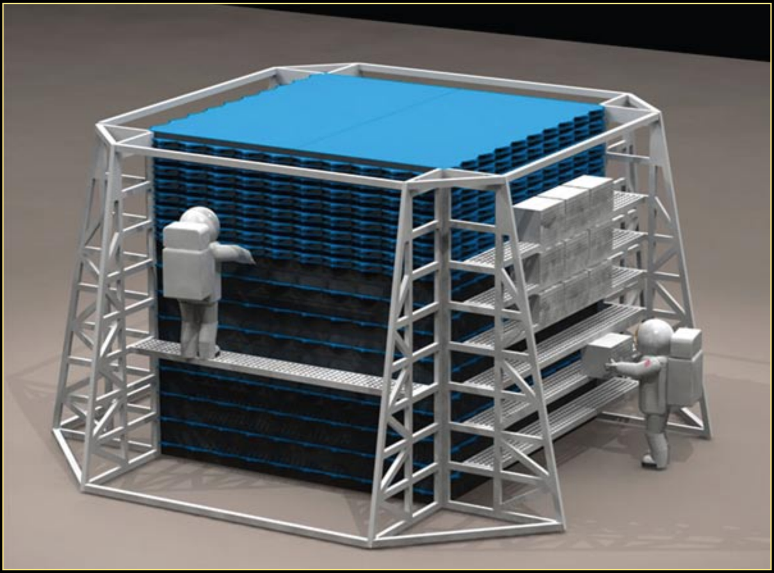
There are other opportunities that will potentially be enabled by the VSE. I would like first to mention briefly two specific experiments that were presented at the Workshop. Then I will discuss more general capabilities enabled by the VSE *infrastructure*.

3.1 Liquid Mirrors

Liquid mirrors are relatively easily transportable, and can be constructed quite cheaply. Working prototypes (using mercury) have been built on the ground, and fluids that may be suitable for the lunar surface have been identified. The claim is that dust can be easily collected from the surface of the mirror and that the mirror can be recoated, if necessary. However, these processes definitely require further study, as do the effects of impact by micrometeorites, and issues related to supporting and spinning the mirror. A liquid-mirror-based, near IR (1–5 μm) telescope (perhaps as large as 100 m in diameter) could, in principle, be placed at the lunar pole, to use the lunar rotation for very deep observations of a narrow circular ring. Clearly, more experience with such telescopes would be required before their feasibility on the lunar surface can be adequately assessed.

I should also note that the Large Magellanic Cloud dominates the sky for a fixed south-pole telescope (of any type) on the lunar surface, making the north pole preferable for extragalactic research.

3.2 A Lunar Cosmic Ray Calorimeter

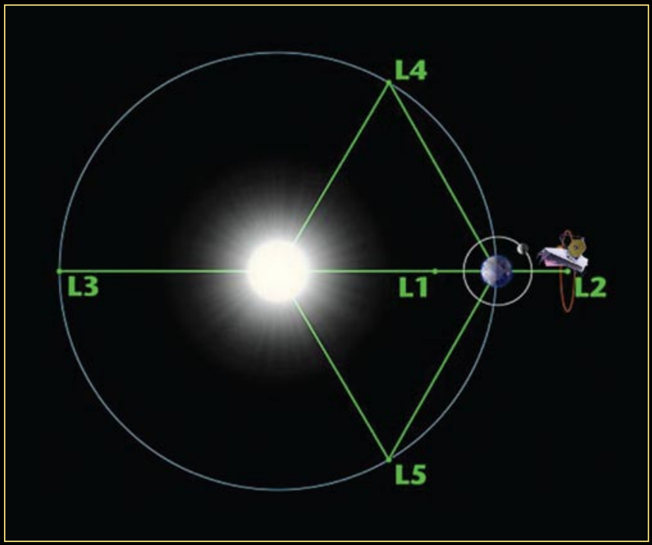


A schematic of a calorimeter for intermediate energy cosmic rays.

A calorimeter on the Moon could measure intermediate energy ($E \sim 10^6$ GeV/particle) cosmic rays. These are thought to be accelerated in supernova shocks. The Moon offers the possibility to detect the primary particles rather than the secondaries produced in showers in the Earth's atmosphere. On the advantages side, the calorimeter could make use of lunar resources (e.g., it could be constructed of layers of regolith), but it would require a significant infrastructure (e.g., to move around some 150 tons of regolith). On the disadvantages side, given that such a calorimeter would not, in fact, address the most pressing questions of cosmic ray physics (e.g., the origin of the ultra-high-energy, $\sim 10^{20}$ eV, cosmic rays), the attractiveness of such an experiment is limited.

3.3 Astrophysics Enabled by VSE Infrastructure

The past few decades have demonstrated repeatedly and unambiguously the excellent capabilities of free-flying observatories. These capabilities exist even in low-Earth orbits (LEO; e.g.,



Sun-Earth Lagrange points (not to scale)

HST) and certainly at Lagrange points (such as the Sun-Earth L2 or L1; e.g., *WMAP*, *SOHO*), or even in Earth-trailing heliocentric orbits (e.g., *SPITZER*). These capabilities include:

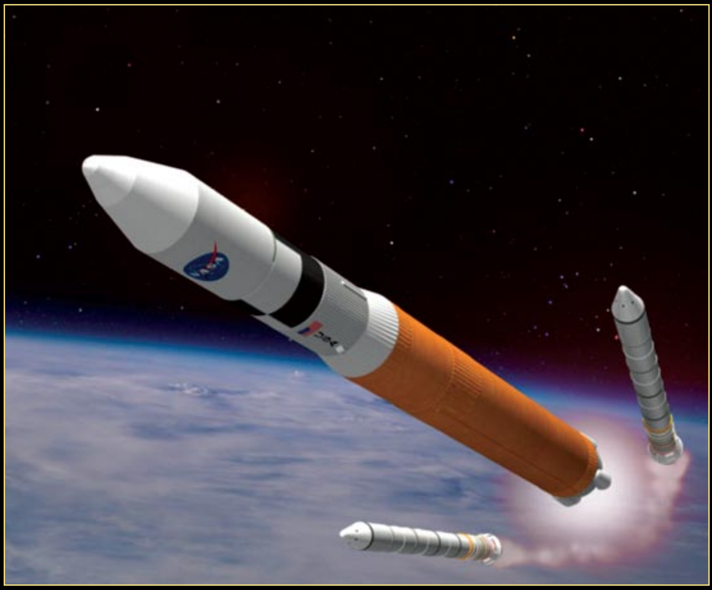
1. All-sky access;
2. Diffraction-limited performance;
3. Very precise pointing and attitude control;
4. Thermal equilibration and temperature stabilization; and
5. Efficient operations.

Many of the existing or planned observatories (such as *CHANDRA*, *LISA*, *SAFIR*, *TPF-C*) were designed for free space and cannot operate from the lunar surface. In general, from a scientific (and even cost) perspective, any research proposed to be performed from the lunar surface should be compared to free space. Fortunately, however, the transportation infrastructure that will be developed for the VSE (in particular the ARES V rocket and the Crew Exploration Vehicle [CEV]) could be used to provide heavy lift (and maybe even servicing) capabilities to the Earth-Sun or Earth-Moon Lagrange points. I note in particular that the ARES V has a fairing almost 10 m in diameter, and a lifting power of a few tens of tons to the Sun-Earth L2. *These capabilities are ideally suited for the transportation of the type of large-aperture telescopes* (*or their components*) *envisioned for a broad range of future astronomical missions*. Furthermore, large fairings may allow for the launch of telescopes with monolithic (rather than deployable) mirrors, reducing perhaps some technical challenges. Another fact worth noting is that the potential energy difference between the Earth-Sun

L2 and the Earth-Moon L1 is such that it requires only a $\Delta v \sim 50$ m sec^{-1} to transfer between them. *The important point is that the VSE should be planned so as not to preclude—and to the extent possible to include—capabilities that will enable astrophysics from free space.*

Capabilities of great interest include:

1. Large fairings to allow for the launch of large telescopes;
2. Advanced telerobotics to allow servicing of telescopes in free space;
3. EVA capabilities for astronauts;
4. High bandwidth communications; and
5. A low-cost transportation system between Lagrange points.



The VSE infrastructure should be planned so as to include capabilities that will enable astrophysics from free space.

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