

**RADIO WAVELENGTH OBSERVATORIES AND THE EXPLORATION ARCHITECTURE.** J. Lazio<sup>1</sup>, R. MacDowall<sup>2</sup>, J. Burns<sup>2</sup>, L. Demaio<sup>3</sup>, D. Jones<sup>4</sup>, and K. Weiler<sup>1</sup> <sup>1</sup>Naval Research Laboratory, 4555 Overlook Ave. SW, Washington, DC 20375, [Lazio@nrl.navy.mil](mailto:Lazio@nrl.navy.mil), <sup>2</sup>Goddard Space Flight Center, Greenbelt, MD 20771, <sup>3</sup>Center for Astrophysics & Space Astronomy, University of Colorado, Boulder, CO 80309, <sup>4</sup>Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109

**Introduction:** Observations at radio wavelengths address key problems in astrophysics and astrobiology including the first light in the Universe (Epoch of Reionization), extrasolar planets, and particle acceleration. The requisite observations require access to wavelengths longer than those that penetrate the Earth's ionosphere, extremely “radio quiet” locations such as the Moon's far side, or both. The Radio Observatory for Lunar Sortie Science (ROLSS) is designed to be deployed during the first lunar sorties and addressing particle acceleration. Future arrays would be larger, more capable, and deployed as experience is gained on the lunar surface.

**Key Science:** A lunar radio observatory has key advantages over ground-based observatories: (1) The Earth's ionosphere is opaque longward of about 30 m (frequencies below 10 MHz). Without a permanent ionosphere, the surface of the Moon opens a spectral window that is inaccessible from the ground. (2) A far-side observatory would be shielded from natural- and human-generated terrestrial transmissions.

**Cosmology.** In the hot Big Bang cosmology, the Universe started in a dense, ionized state. As it expanded and cooled, it underwent a transition to a neutral state (recombination). After recombination, baryons began to collapse into overdense regions, leading to the formation of stars and galaxies. Today, their radiation maintains the Universe in an ionized state. The *Epoch of Reionization* (EoR) is thus associated with the development of the first structures. As structures began to heat their surroundings, the excitation state of hydrogen decoupled from the temperature of the cosmic microwave background (CMB). Thus, the formation of the first structures may be traced by their 21-cm line emission.

Observations of quasars and the CMB indicate that the EoR was underway by a redshift  $z \sim 10$  and concluded by  $z \approx 6$  [1,2,3]. The growth of structures, particularly during the linear phase preceding the collapse into stars and galaxies, suggests that H I signals also may be produced at  $z > 50$  [4,5].

The implied wavelength range ( $\lambda > 1.5$  m for  $z > 6$ , or  $\nu < 200$  MHz) is a heavily used spectral region (e.g., FM radio). Ground-based EoR arrays designed to detect the H I signals are being deployed, some in the most radio-quiet regions of this planet, but the absence of local transmitters may not be sufficient as ionized

meteor trails and ionospheric layers can reflect power from distant transmitters. The far side of the Moon is an international *shielded zone* [6], with an emphasis on wavelengths  $\lambda > 1$  m ( $\nu < 300$  MHz). The far side is also protected, during a portion of the lunar orbit, from solar emissions. Interference will likely be a limiting factor for ground-based telescopes, and a lunar telescope will be necessary to exploit the EoR H I signal.

**Extrasolar Planets.** The magnetic polar regions of the Earth and the solar system giant planets host electron cyclotron masers generated by solar-wind powered electron currents. Magnetospheric emission provides information about extrasolar planets that will be difficult to obtain otherwise: The existence of a magnetic field constrains planetary interior modeling while modulation of the emission can yield its rotation rate. For a terrestrial planet, a magnetic field may affect habitability, shielding the planet from the harmful effects of energetic particles.

Empirical relations for solar system planets suggest that radio emission from extrasolar planets may be detectable [7,8,9]. The solar system planets show a rough correspondance between mass and emission wavelength, and *only Jovian radio emissions are at a short enough wavelength that they can be detected from the ground*. Observations above the Earth's ionosphere are needed to study sub-Jovian mass planets.

**Particle Acceleration.** Acceleration of particles to super-thermal and relativistic energies occurs at the Sun and dwarf stars, neutron stars and black holes, and quasars. Fundamental problems include understanding the mechanisms and sites of particle acceleration and the low energy population that provides the “seeds” for the highest energy particles. Low energy particles emit, and are best studied at, long wavelengths.

Radio wave observations and spacecraft coronagraphs, notably those on the Solar Heliospheric Observatory (SOHO), have provided dramatic indications of the Sun's violent, magnetically-driven activity and its connection to particle acceleration. Because of its proximity, the heliosphere is one of the best places to study the fundamental physics of particle acceleration.

Heliospheric particle acceleration is manifested in solar radio bursts. Previous space-based radio observations, using single dipoles with *no imaging capabilities*, have left fundamental questions. At 1 AU, e.g., acceleration occurs where the shock normal is quasi-perpendicular to the magnetic field [10], similar to

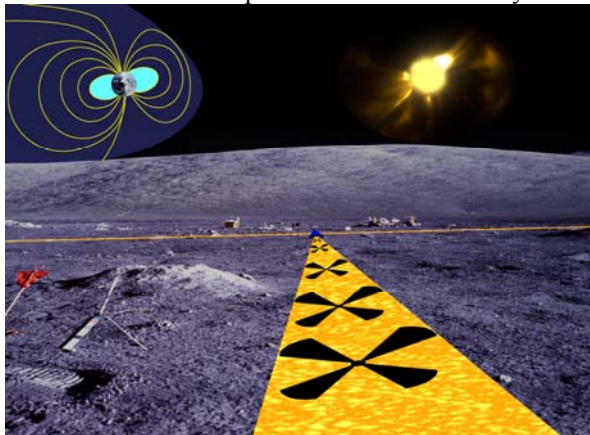
acceleration at planetary bow shocks and other astrophysical sites. In the corona, the magnetic field is largely radial, yet observations suggest *quasi-parallel* acceleration. An imaging telescope, even one with modest resolution, could locate the sites of radio emission and electron acceleration.

**Lunar Radio Observatories:** Interest in a lunar radio telescope predates the Apollo missions [11,12]. A series of workshops describe scientific goals and preliminary concepts [13,14,15,16,17].

*The Moon as an Astronomical Site.* While there have been proposals for a space-based radio array [18,19,20], in contrast to free-flying telescopes at shorter wavelengths [21], the lunar surface offers significant benefits to a radio array.

(1) A dipole in space responds to  $4\pi$  sr, so a free-flying array must image the full sky all of the time, with all of the sources present (Sun, Jupiter, ...). Mass budgets have restricted proposed arrays to a small number of elements, presenting the challenge that entirely new imaging algorithms need to be developed. On the Moon, it is practical to deploy a larger number of dipoles and only  $2\pi$  sr is visible so that algorithms developed for terrestrial arrays can be utilized. (2) In order to form an interferometer, antenna separations must be known and maintained to a fraction of a wavelength. While the relevant wavelengths are large (~100 m), station keeping does necessitate use of on-board resources. With the Moon's low level of seismic activity, antenna positions can be determined once and then assumed constant.

*Radio Observatory for Lunar Sortie Science (ROLSS).* The ROLSS array is a concept designed for deployment during the first lunar sorties. It is intended to probe particle acceleration in the inner heliosphere as well as to serve as a pathfinder for future arrays.



**Figure 1.** An artist's impression of the ROLSS array on the lunar surface.

The baseline ROLSS array consists of 3 arms arranged in a Y configuration and operates over the wavelength range of 30–300 m (1–10 MHz), wave-

lengths largely inaccessible from the ground. Each arm hosts 16 antennas and is 500 m long, providing  $2^\circ$  resolution at  $\lambda 30$ m (10 MHz). The arms themselves consist of a polyimide film on which dipole antennas are deposited, and they hold the transmission lines for sending the signals back to an array processing package, located at the intersection of the arms. The array processing package would digitize the signals and downlink them to the ground for imaging and analysis.

*Future Observatories.* The arrays required to conduct many of the observations described above are larger than the ROLSS array. Arrays can “grow,” with scientific capability increasing as the number of antennas increases. Many ground-based arrays were preceded by scientifically productive prototypes, and scientific observations began with many ground-based arrays well before they reached their final complement of antennas.

A strawman deployment plan for lunar radio arrays is the following: **Stage I (ROLSS)** A small array on the near side. **Stage II** A modest-sized interferometer (e.g., 256 dipoles over a few to several kilometers), possibly though not necessarily located on the far side. Such a telescope might detect the brightest extrasolar planets and verify ground-based EoR observations. **Stage III** A fully capable telescope on the far side.

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