Radio Wavelength Observatories within the Exploration Architecture

By J. LAZIO¹, R. J. MACDOWALL², J. BURNS³, L. DEMAIO², D. L. JONES⁴, AND K. W. WEILER¹

¹Naval Research Laboratory, 4555 Overlook Ave. SW, Washington, DC 20375-5351 USA
²NASA, Goddard Space Flight Center, Greenbelt, MD 20771 USA
³Center for Astrophysics & Space Astronomy, University of Colorado, Boulder, CO 80309 USA
⁴Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109

Observations at radio wavelengths address key problems in astrophysics, astrobiology, and lunar structure including the first light in the Universe (the Epoch of Reionization), the presence of magnetic fields around extrasolar planets, particle acceleration mechanisms, and the structure of the lunar ionosphere. Moreover, achieving the performance needed to address these scientific questions demands observations at wavelengths longer than those that penetrate the Earth’s ionosphere. Hence, we describe a series of lunar-based radio wavelength interferometers of increasing capability. The Radio Observatory for Lunar Sortie Science (ROLSS) is an array designed to be deployed during the first lunar sorties (or even before via robotic rovers) and addressing particle acceleration and the lunar ionosphere. Future arrays would be larger, more capable, and deployed as experience is gained in working on the lunar surface.

1. Key Science

A lunar-based radio wavelength observatory would have two key advantages over ground-based observatories. First, if located on the far side of the Moon, the observatory would be shielded from terrestrial transmissions, both natural and human-generated. Only a small fraction of the radio spectrum is allocated for use by astronomy. Ground-based observatories are often located in remote areas, in an effort to allow them access as much of the spectrum as possible. Nonetheless, many observatories are contending with an increasing fraction of the spectrum being inaccessible. Second, the Earth’s ionosphere is opaque at wavelengths longer than about 30 m (frequencies below about 10 MHz). In contrast, without a permanent ionosphere, the surface of the Moon opens a spectral window that is entirely inaccessible from the ground, potentially to wavelengths as much as two orders of magnitude longer than those accessible from the ground. We summarize here key science that would be enabled by a lunar-based radio observatory.

1.1. Cosmology—Epoch of Reionization

In the standard hot Big Bang cosmology, the Universe started in an initially hot, dense ionized state. As it expanded and cooled, it underwent a phase transition to a largely neutral state at the time of recombination. After recombination, baryons began to collapse into overdense regions, eventually leading to the formation of stars and galaxies. Today, the collective action of stars and galaxies maintain the Universe in a largely ionized state. The Epoch of Reionization (EoR) marks this transition from neutral to ionized and is associated with the development of structures in the Universe. As structures began to form and heat their surroundings, it is expected that the excitation state of hydrogen would become decoupled from the temperature of the cosmic microwave background. Thus, the formation of the first structures may be traced by the 21-cm line emission generated as they heat their surroundings.
Observations of high-redshift quasars and the cosmic microwave background indicate that the EoR was well underway by a redshift \( z \sim 10 \) and concluded by \( z \approx 6 \) \cite{becker2001,djorgovski2001,spergel2006}. The growth of structures, particularly during the linear phase preceding the collapse into stars and galaxies, also suggests redshifted hydrogen signals may be produced from structures with redshifts as large as \( z \gtrsim 50 \) \cite{loeb2004,furlanetto2006}.

The expected wavelength range (\( \lambda > 1.5 \text{ m for } z > 6, \text{ or } \nu \leq 200 \text{ MHz} \)) is a heavily used region of the spectrum (e.g., containing the FM radio band), with little regulatory protection for radio astronomy. Ground-based arrays designed to detect the redshifted H\text{I} signal are being deployed, often in the most radio-quiet regions of this planet. However, the absence of local transmitters may not be sufficient as ionized meteor trails and ionospheric layers can reflect power from distant transmitters. In contrast, the far side of the Moon is an internationally recognized “shielded zone” \cite{itu2005}, with emphasis given to protecting it for observations that are “difficult or impossible from the surface of the Earth,” particularly at wavelengths longer than 1 meter (\( < 300 \text{ MHz} \)). The far side is also protected, during a portion of the lunar orbit, from solar radio emissions. Terrestrial and solar interference may ultimately be a limiting factor for ground-based telescopes and a lunar-based telescope will be necessary to exploit fully the hydrogen signal from the EoR.

1.2. Extrasolar Planets

The magnetic polar regions of the Earth and the solar system giant planets host intense electron cyclotron masers generated by solar-wind powered electron currents. Magnetospheric emission can aid the understanding of extrasolar planets by providing information that will be difficult to obtain otherwise: The existence of a magnetic field constrains the interior of a planet while modulation of the emission can yield its rotation rate. For a terrestrial planet, a magnetic field may be important for habitability, shielding the planet from the harmful effects of energetic charged particles (e.g., \cite{wdowczyk1977}).

Empirical relations for solar system planets suggest that radio emission from extrasolar planets may be detectable over interstellar distances \cite{farrell1999,lazio2004,stevens2005}. Magnetospheric emissions from the solar system planets show a rough correspondence between planetary 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 will be needed to detect and study sub-Jovian mass extrasolar planets.

1.3. Particle Acceleration

Acceleration of particles to super-thermal and relativistic velocities occurs in a variety of astrophysical environments, from the Sun and other dwarf stars to neutron stars and black holes to quasars. A fundamental astrophysical problem is understanding the mechanisms and sites of particle acceleration. A key aspect of particle acceleration mechanisms is the low energy population which provides the “seeds” from which the highest energy particles result. These low energy particles emit, and are best studied at, the longest wavelengths.

Within the inner heliosphere (2–10 solar radii, \( R_\odot \)) measured from the Sun’s center) intense electron beams are produced, at times with particles having energies rivaling “the energies of some accelerated particles in the distant [quasars]” \cite{chupp1993}, and a significant fraction of solar wind heating occurs. Radio wave observations and spacecraft coronagraphs, notably those on the Solar Heliospheric Observatory (SOHO), have provided dramatic indications of the violent, magnetically-driven activity of the Sun.
and its connection to particle acceleration. Because of its proximity and brightness, the inner heliosphere is one of the best places to study the fundamental physics of particle acceleration.

Solar radio bursts are one of the primary manifestations of particle acceleration in the inner heliosphere. Previous space-based radio observations have been from single dipole instruments with no imaging capabilities. Thus, fundamental questions remain about particle acceleration sites. For example, at 1 AU, electron acceleration generally occurs where the shock normal is perpendicular to the magnetic field (quasi-perpendicular, Bale et al. 1999), similar to acceleration at planetary bow shocks and other astrophysical sites. In the corona, the magnetic field is largely radial, yet the existing radio observations suggest that the acceleration site is in front of a CME, a quasi-parallel geometry. An imaging instrument, one with even modest angular resolution, is required to locate the sites of radio emission, and therefore the electron acceleration.

2. Lunar Radio Observatories

Interest in placing a radio telescope on or around the Moon pre-dates the Apollo missions (North American Aviation 1966; Greiner 1967). A series of workshops and conferences describe scientific goals and preliminary concepts (Weiler 1986a; Burns et al. 1989; Mumma & Smith 1990; Kassim & Weiler 1990; Stone et al. 2000). We begin by discussing technical aspects of the surface of the Moon as an observatory site; the scientific aspects are discussed above. We then turn to how radio observatories might be deployed, with the capability of lunar radio observatories growing with the human presence.

2.1. The Moon as an Astronomical Site

Some of the value of the Moon as an astronomical site (at long wavelengths) is also true for a space-based array, and there have been proposals for such arrays (Weiler 1986b; Jones et al. 2000; MacDowall et al. 2006). In contrast to free-flying telescopes at shorter wavelengths (Lester et al. 2004), the lunar surface offers two significant benefits to a radio array.

(1) A dipole in space responds to the full 4π sr, so a free-flying array must image the full sky all of the time, with all of the sources present (Sun, Jupiter, . . . ). Limited mass budgets have restricted proposed arrays to a small number of elements. The resultant challenge is to image the entire sky with an extremely sparse aperture. In contrast, on the Moon, the lunar surface shields 2π sr, making the imaging problem less challenging, and imaging algorithms developed for terrestrial interferometers can be utilized, whereas a space array requires the development of new algorithms. Also, it is practical to deploy a much larger number of dipoles. (2) In order to form an interferometer, antenna separations must be known and maintained to a fraction of a wavelength during the observations. While the relevant wavelengths are large (~ 100 m), station keeping does necessitate use of on-board resources. In contrast, the lunar surface is stable with an extremely low level of seismic activity, so antenna positions can be determined once and then assumed constant.

2.2. Radio Observatory for Lunar Sortie Science (ROLSS)

The ROLSS array is a concept designed for deployment during the first lunar sorties (Figure 1). It is intended to conduct astronomical observations of the Sun, primarily for the purpose of probing particle acceleration mechanisms, as well as to serve as a pathfinder for future, larger arrays.

The baseline ROLSS array consists of 3 arms arranged in a Y configuration with an
The operational wavelength range of 30–300 m (1–10 MHz), i.e., at wavelengths longer than can be accessed from the ground. Each arm hosts 16 antennas and is 500 m long, providing approximately $2^\circ$ angular resolution at 30-m wavelength (10 MHz).

The arms themselves consist of a polyimide film (PF) on which electrically-short dipole antennas are deposited, and they hold the transmission system for sending the electrical signals back to the central processing facility, located at the intersection of the arms. The central processing facility would select a 100 kHz sub-band within the operational wavelength range, filter and digitize the signals, then downlink them to the ground for final imaging and scientific analysis.

2.3. **Future Observatories**

Observations at long wavelengths can address a number of important science priorities, as discussed above, however, the arrays required to conduct the requisite observations are much larger than the ROLSS array. A value of interferometers is that they can “grow,” with scientific capability increasing as the number of antennas is increased. Indeed, many of the ground-based radio interferometers have been preceded by prototypes having a much smaller number of antennas, but which were scientifically productive themselves, and scientific observations began with many of the ground-based radio interferometers well before they reached their final complement of antennas.

A strawman illustration of the staged deployment of lunar radio interferometers is the following.

**Stage I (ROLSS)** A small interferometer located on the near side.

**Stage II** A modest-sized interferometer (e.g., 256 dipoles spread over a few to several kilometers), possibly though not necessarily located on the far side of the Moon. Such an interferometer might be capable of detecting the brightest extrasolar planets, and verifying ground-based observations of the EoR.

**Stage III** A fully capable interferometer located on the far side.

Part of this work was carried out at the Jet Propulsion Laboratory, California Institute
of Technology, under contract with the National Aeronautics and Space Administration. Basic research in radio astronomy at NRL is supported by 6.1 Base funding.

REFERENCES

Bale, S. D., Reiner, M. J., Bougeret, J.-L., et al. 1999 The Source Region Of An Interplanetary Type II Radio Burst. Geophys. Res. Lett., 26, 1573–1576.

Becker, R. H., Fan, X., White, R. L., et al. 2001 Evidence for Reionization at z ~ 6: Detection of a Gunn-Peterson Trough in a z = 6.28 Quasar. Astron. J., 122, 2850–2857.

Burns, Jack. O., Duric, N., Johnson, S., & Taylor, G. J. 1989 A Lunar Far-Side Very Low Frequency Array NASA.

Chupp, E. L., & Benz, O. A. 1993 Particle Acceleration Phenomena in Astrophysical Plasmas: International Astronomical Union Colloquium 142. Astrophys. J. Suppl., 90

Djorgovski, S. G., Castro, S. M., Stern, D., & Mahabal, A. 2001 On the Threshold of the Reionization Epoch. Astrophys. J., 560, L5–L8.

Farrell, W. M., Desch, M. D., & Zarka, P. 1999 On the Possibility of Coherent Cyclotron Emission from Extrasolar Planets. J. Geophys. Res., 104, 14025–14032.

Furlanetto, S. R. 2006 Bubble, Bubble, Toil, and Trouble: 21 cm Measurements of the High-Redshift Universe. New Astron. Rev., 50, 157–161.

Greiner, J. M. 1967 Utilization of Crater Reflectors for Lunar Radio Astronomy. Working Group on Extraterrestrial Resources, Fifth Annual Meeting

International Telecommunications Union (ITU) 2005 Article 22 and supporting Recommendation 479, version 2005-03

Jones, D., Allen, R., Basart, J., et al. 2000 The Astronomical Low-Frequency Array: A Proposed Explorer Mission for Radio Astronomy. In Radio Astronomy at Long Wavelengths (ed. R. G. Stone, K. W. Weiler, M. L. Goldstein & J.-L. Bougeret) vol. 119, p. 339–349. Amer. Geophys. Union.

Kassim, N. E., & Weiler, K. W. 1990 Low Frequency Astrophysics from Space: Proceedings of an International Workshop Springer-Verlag.

Lazio, T. J. W., Farrell, W. M., Dietrick, J., Greenlees, E., Hogan, E., Jones, C., & Hennig, L. A. 2004 The Radiometric Bode’s Law and Extrasolar Planets. Astrophys. J., 612, 511–518.

Lester, D. F., Yorke, H. W., & Mather, J. C. 2004 Does the Lunar Surface Still Offer Value as a Site for Astronomical Observatories? Space Policy, 20, 99–107.

Loeb, A., & Zaldarriaga, M. 2004, Measuring the Small-Scale Power Spectrum of Cosmic Density Fluctuations through 21 cm Tomography Prior to the Epoch of Structure Formation. Physical Rev. Lett., 92, id. 211301.

MacDowall, R. J., Gopalaswamy, N., Kaiser, M. L., et al. 2006 Microsat and Lunar-Based Imaging of Radio Bursts. In Planetary Radio Emissions VI. (ed. H. O. Rucker, W. S. Kurth, & G. Mann) p. 491–504. Austrian Academy Press.

Mumma, M. J., & Smith, H. J. 1990 Astrophysics from the Moon: Proceedings of the Workshop Amer. Institute of Physics.

North American Aviation Inc., Space Information Division 1966 Research Program on Radio Astronomy and Plasma for Apollo Applications Program Lunar Surface Missions: Final Report (NASA-20198)

Spergel, D. N., Bean, R., Doré, O., et al. 2006 Wilkinson Microwave Anisotropy Probe (WMAP) Three Year Results: Implications for Cosmology. Astrophys. J., submitted

Stevens, I. R. 2005 Magnetospheric Radio Emissions from Extrasolar Giant Planets: The Role of the Host Star. Mon. Not. R. Astron. Soc., 356, 1053–1063.

Stone, R. G., Weiler, K. W., Goldstein, M. L., & Bougeret, J.-L. 2000 Radio Astronomy at Long Wavelengths Amer. Geophys. Union.

Wdowczyk, J. & Wolfendale, A. W. 1978, Cosmic Rays and Ancient Catastrophes. Nature, 288, 510–512.

Weiler, K. W. 1986a Radio Astronomy from Space National Radio Astronomy Observatory. Weiler, K. W. (PI) 1986b The Low Frequency Space Array, NASA proposal.