Lunar University Network for Astrophysics Research:
Year 4 Report to
The NASA Lunar Science Institute
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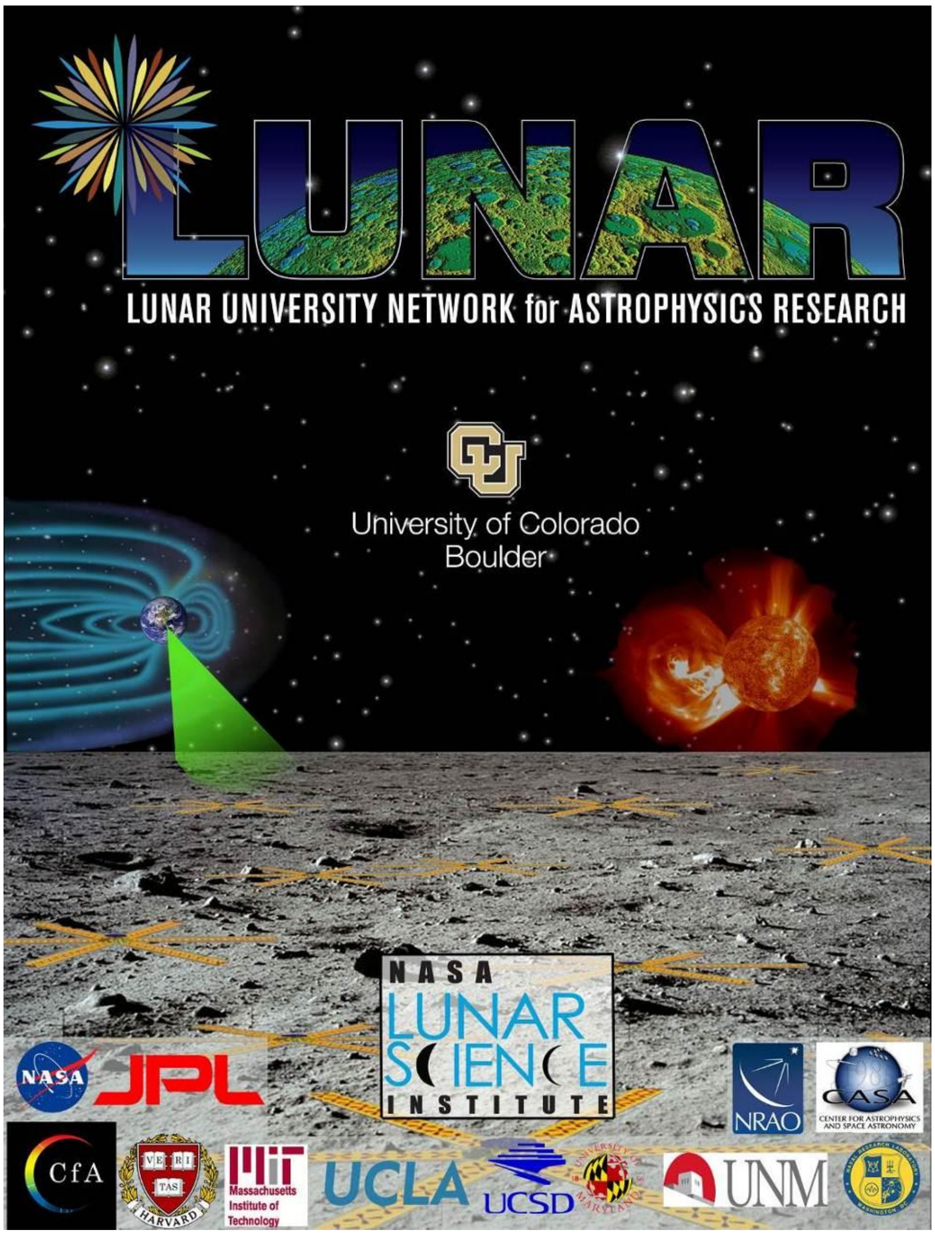
Principal Investigator: Jack Burns, University of Colorado Boulder
Deputy Principal Investigator: Joseph Lazio, JPL



Overview of LUNAR

The Lunar University Network for Astrophysics Research (LUNAR) is a team of researchers and students at leading universities, NASA centers, and federal research laboratories undertaking investigations aimed at using the Moon as a platform for space science. LUNAR research includes Lunar Interior Physics & Gravitation using Lunar Laser Ranging (LLR), Low Frequency Cosmology and Astrophysics (LFCA), and Heliophysics.

Lunar Laser Ranging

Opto-Thermal Simulation

The purpose of the Opto-Thermal Simulation is to evaluate the heating effects of the solar illumination, and then incorporate these heat loads into the energy exchanges between the Cube Corner Reflector (CCR) and space, between the CCR and the sun shade and the heat inputs from the sun and the thermal radiation from the regolith. This simulation has been developed at U. Maryland in connection with INFN-LNF in Italy. Fig. 1 illustrates a typical temperature distribution in the CCR, and Fig. 2 a computation of the regolith temperature since the radiation from the regolith affects the LLR Retroreflector.

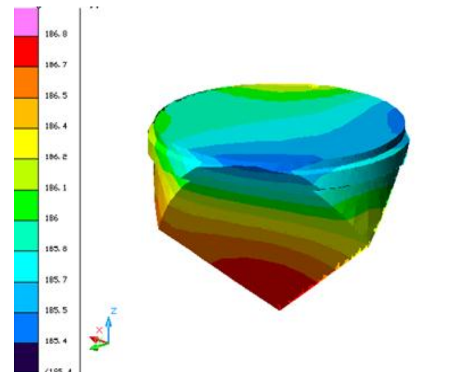


Figure 1 Illustration of the result of the simulation program computing the temperature distribution in the CCR. This temperature distribution is then used to then determine Far field diffraction pattern & the magnitude of the return signal.

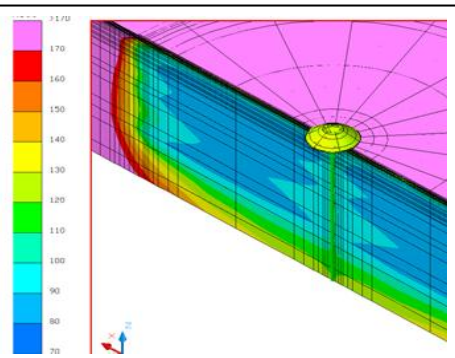


Figure 2 Sample of regolith temperature distribution for a MLI blanket surrounding the retroreflector.

Within the past year, the simulation has been refined to include a number of additional effects and to improve the running speed, since the run for a single set of the twelve relevant parameters requires about two days with detailed operator involvement. In addition, new thermal coatings for the sunshade and for the housing have been incorporated.

Optical Material Effects

The properties of the optical material for the CCR have been studied. Interferograms of the optical behavior of the CCR have been made and the simulation upgraded to incorporate these in evaluating the performance, in the form of the signal received on earth.

Velocity Aberration

Since the retroreflector on the Moon is moving with respect to the observatory on earth, the laser return arrive offset from the observatory. As a result, the angles between the back faces of the CCR must be offset to send some of the energy back to the observatory. This software has been developed and is being refined.

Stepped Sunshade:
Reflections of the incoming sun light can be reflected from the interior of the sunshade. In order to reduce this effect, a "stepped" design has been simulated. It reduces the solar energy striking the CCR by 40%. In order to evaluate the actual effect, such a sunshade has been fabricated (Fig. 3). This will be tested in the Satellite/lunar laser ranging Characterization Facility (SCF) in Frascati, Italy late this spring. These tests will identify any un-modeled effects to allow the simulation to best represent the real world.

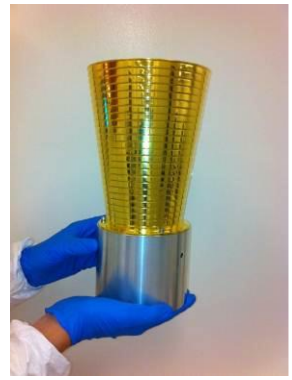


Figure 3 Retroreflector Conceptual Design, especially addressing stepped sunshade, for SCF testing.

Pnuematic Drilling to Thermally-Anchor CCR:
In order to deploy the next-generation CCR in a manner that the thermal changes in the support of the package do not change the position at the tens of microns level, the package must be anchored into the regolith at a depth of nearly a meter. Drilling in this manner has traditionally been very difficult during the Apollo missions. However, HoneyBee Corp. funded by LUNAR has developed the "pneumatic" drilling technology. This has been tested in compacted regolith simulant in vacuum and at 1/6 g.

Low Frequency Cosmology and Astrophysics (LFCA)

Theoretical Tools and Science Development

Furlanetto has continued to study theoretical models of the first galaxies. As these are the most likely sources for the photons that drive the neutral hydrogen 21 cm signal, understanding their properties is crucial for predicting and interpreting that signal from future lunar observatories. Furlanetto and his group focused on several aspects of these sources, including the relative velocity of dark matter and baryons, the internal structure and star formation laws of the most distant known galaxies (at redshifts ~ 6–8), their contribution to the near-infrared background, and the development of a "standard model" for cosmic reionization based on *Hubble Space Telescope* observations. The latter was done in conjunction with the UDF12 team (PI: R. Ellis). Pritchard and Loeb, in collaboration with A. Liu and M. Tegmark, explored details of foreground removal for global 21 cm experiments from a starting point of building a maximum likelihood estimator for the signal that assumed nothing about the signal itself. This research complements earlier LUNAR work led by Harker, Burns et al. that approached the same problem from a Bayesian perspective that assumed a detailed signal model. This work resulted in a publication that demonstrated a) the feasibility of removing foregrounds in realistic situations, and b) the importance of making use of spatial information for the foreground removal. Loeb and Furlanetto published a new textbook on *The First Galaxies in the Universe* (540 pages) that summarizes the motivation and scientific background for a lunar radio telescope in observing Cosmic Dawn. Using one-dimensional radiative transfer calculations, CU grad student Mirocha, Burns et al. investigated the discrepancies in gas properties surrounding model stars and accreting black holes that arise solely due to spectral discretization. Even in the idealized case of a static and uniform density field, it was found that commonly used discretization schemes induce errors in the neutral fraction and temperature by factors of two to three on average, and by over an order of magnitude in certain column density regimes. A method for optimally constructing discrete spectra was developed, and it was shown that, for two test cases of interest, carefully chosen four-bin spectra can eliminate errors associated with frequency resolution to high precision.

Antenna Technology Development

Stewart and Hartmann deployed a prototype lunar surface antenna at the JVLA site in New Mexico. This test was the first with the lunar surface antenna on a dry desert soil, a far more realistic lunar analog than used for previous testing. They found good agreement between numerical simulations and measurements of the electromagnetic properties (gain, response pattern, and feedpoint impedance). Bradley developed a new approach to receiver calibration for a switching radiometer. It makes use of the fact that the low noise amplifier's scattering and noise parameters are invariant to the network's input impedance. The calibration procedure, which utilizes both high precision *a priori* laboratory measurements of the circuit temperature-dependent parameters together with real-time monitoring of the circuit's physical temperature, was designed from first-principles. A project report was written detailing the calibration procedure. Jones investigated whether a lunar surface radio antenna, useful for studying either the global 21 cm signal or the lunar ionosphere, could be deployed while a lander was in its descent phase, before reaching the surface. The initial assessment was that this approach is promising, but "sand blasting" by the lunar regolith has yet to be considered fully. Taylor and colleagues took advantage of the completion of the first station of the Long Wavelength Array to investigate imaging the sky at low frequencies (10–88 MHz) (Fig. 4). This work resulted in a better characterization of the emission of the galactic background, strong radio sources and sources of transient emission. These observations will inform the design of future instruments.

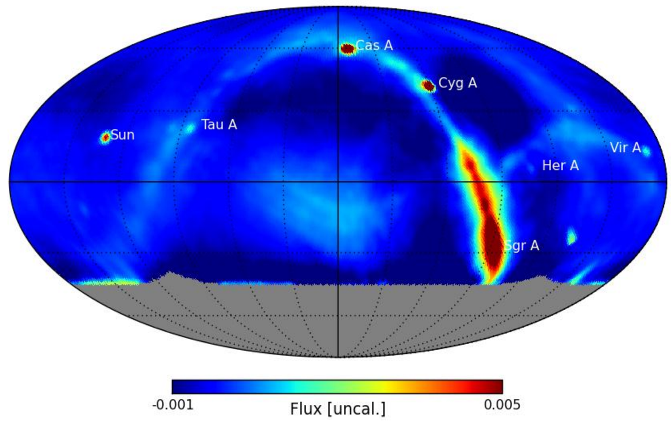


Fig. 4. Image of the sky at 52 MHz, corresponding to a redshift of approximately 25, as acquired by the LWA. The Milky Way Galaxy is apparent as the arc across the image, and various radio sources are indicated. The radio emission shown represent foregrounds for future lunar surface observations of *Cosmic Dawn*.

LUNAR Simulation Laboratory

The LUNAR Simulation Facility at Colorado is used to test the effects of the harsh lunar environment on materials and hardware. LUNAR team members recently finished construction on a second thermal-vacuum chamber that contains a bed of JSC-1 lunar simulant for a more realistic representation of the lunar surface. Copper-coated Kapton was thermally cycled for one month, with each 24 hour cycle representing a lunar day or night. The Kapton showed greater thermal variation than pieces tested in the original vacuum chamber, possibly due to the simulant regolith deforming with the Kapton and maintaining greater thermal contact than the aluminum table.

Earth-Moon L-2 Mission Concept

Burns, Kring (LPI), Lazio, & Kasper developed a concept for a crewed mission to the Earth-Moon L-2 point in which the astronauts would tele-operate a lunar surface rover or rovers. These lunar surface assets could be used to collect lunar samples for a sample-return mission, and deploy lunar surface antennas to study the global 21 cm signal.

Radio Heliophysics

Heliophysics Key Project Year Four Goals were divided between (1) Studies of fundamental low frequency radio science, (2) Development of new techniques to measure interplanetary dust using the frequency spectrum of fluctuations induced by dust impacts, and (3) general support of the NLSI and LUNAR projects.

Nanodust Impacts

Recent work has highlighted the ability of electric field antennas on spacecraft to indirectly characterize dust by detecting the expanding plasma produced when a high-speed dust grain impacts the spacecraft. LUNAR post-doc Zaslavsky derived analytic expressions for the time-dependent voltage waveform measured by an electric field antenna embedded in the expanding plasma plume produced by a hyper-kinetic dust impact. These predictions were compared with observations of the waveforms produced by dust impacts detected with the WAVES/TDS experiment on the STEREO spacecraft. Zaslavsky found that the analytic predictions successfully matched the relative strength of the signals seen by the three different antennas on each spacecraft, and the total strength proportional to the product of dust grain mass and impact velocity.

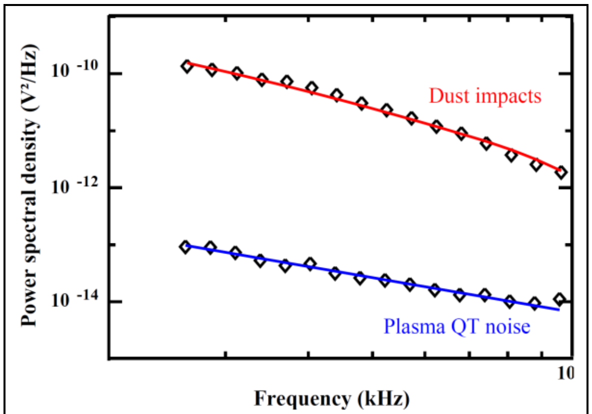


Fig. 5: Power spectrum measured by *STEREO A*. The upper spectrum is typical of dust measurement, whereas the lower one corresponds to the plasma quasi-thermal noise measurement. The lines correspond to the best fit, in case of dust (red) and plasma thermal noise (blue).

LUNAR postdoc Le Chat used the analytic equations for the time-dependent voltage waveform in Zaslavsky et al. (2012), and derived expressions for the frequency dependent signature of a dust impact. Fig. 5 compares the typical spectrum of low frequency fluctuations in the solar wind (blue) with the spectrum recorded as a dust particle struck the spacecraft. Overall, the functional form of the predicted signal matched the observations from the spacecraft very well. Le Chat's results are significant because they allow us to use the STEREO spacecraft observations to derive continuous and unbiased measurements of the variability of nanodust flux in interplanetary space. These measurements were then used produce a more accurate estimate of the mass distribution of interplanetary dust than has been published previously, using a model that required fewer assumptions than previous works.

The Radio Heliophysics project focuses on various aspects of radio observations of particle acceleration, in particular, low-frequency (<10 MHz) radio emissions produced in the outer corona and heliosphere by flare- and shock- accelerated electrons. Such radio bursts have never been imaged, because their frequencies are blocked by Earth's ionosphere, and because no adequate radio interferometric array has been assembled in space to make such imaging observations. Thus a key goal has been to study implementation an aperture synthesis array on the lunar surface to observe the low-frequency radio bursts. This observatory, which we call the Radio Observatory on the Lunar Surface for Solar Studies (ROLSS), has been studied extensively. With ~50 monopole antennas covering a total diameter of order 1 km, it is a project that can be implemented with a lunar lander of moderate capabilities.


Fig. 6. (Left) GSFC summer interns with cross bow-launched anchor deployer. (Right) Inflatable tube with dipole antennas; the tube has been deflated after a successful deploy.

The ROLSS antennas are planned to be deposited on polyimide film that would be unrolled on the lunar surface. To facilitate that effort, LUNAR team members at GSFC focused on various aspects of a pathfinder mission for ROLSS, that would test antenna design and other aspects of ROLSS. The ROLSS pathfinder (ROLSS-P) would be a small package (volume of order 0.01 m^3) that could be the science payload on a small lander or carried as a secondary payload. Deploying the 1-3 antennas comprising the sensing elements of ROLSS-P could be done with a variety of techniques. LUNAR has tested hardware for launched anchor deployment and inflated tube deployment. Fig. 6 shows examples of the hardware being tested. Elements of deployment and inflation testing were performed by interns as their summer 2012 project at GSFC. From these tests, we have derived a much better understanding of the primary risks for each type of deployment and the terrains for which they work the best.

Inter-Team Collaborations

The LUNAR team worked with ***Kring*** (CLSE) to develop the concept of an Earth-Moon L2 mission in which astronauts would control lunar surface assets to pursue simultaneously high priority science goals from both the Planetary Sciences and Astronomy Decadal Surveys.

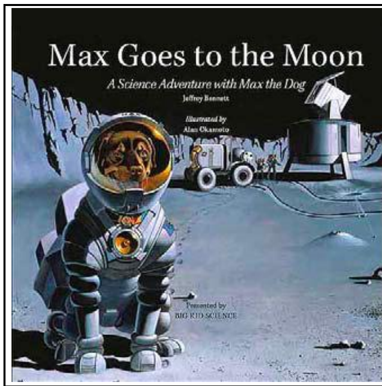
The LUNAR team worked with ***Farrell*** (DREAM) to refine the science case for a lunar surface radio antenna to study the ionized lunar atmosphere.

The LUNAR team worked with ***Farrell*** (DREAM) in searching for radio emissions from extrasolar planets, which would be an important secondary scientific goal for a future lunar radio telescope.

Education & Public Outreach (EPO)

The LUNAR team has a diverse and aggressive EPO effort aimed at enhancing the awareness and knowledge about the Earth-Moon system. In Year 4, we completed our signature EPO effort with the premier and national distribution of our children's planetarium show. LUNAR also used the Solar Eclipse of the Sun in May of 2012 to increase public awareness of science and NASA's role.

Our children's planetarium program is based on the award-winning book, "Max Goes to the Moon" by local Boulder author Dr. Jeffrey Bennett. NASA astronaut Alvin Drew played a role in the development of this show. On Drew's mission to the International Space Station he had the opportunity to read the story "Max Goes to the Moon" to the children of Earth. Using our well-developed process of "formative evaluation", we showed the program to test audiences of school children of the target age and also to hundreds of lunar scientists at the 2011 Lunar Science Forum. The feedback we gathered resulted in significant improvements to the show. In March of 2012 Astronaut Alvin Drew came to Fiske Planetarium to help launch this program at our national premier. "Max" is now playing at 6 planetariums across the country and more are in the process of acquiring it. It has been promoted by the International Astronomical Union.



In May 2012 an annular solar eclipse was visible in the western half of the US. LUNAR partnered with the CCLDAS team led by M. Horanyi to take over the university football stadium (Folsom Field). We also distributed roughly 40,000 eclipse glasses to K-12 students. Our event became the largest crowd on record in one place to watch a solar eclipse. Roughly 10,000 people attended this event. It was broadcast extensively on TV including ABC World News Tonight. We had NASA and Fiske videos and animations playing on the stadium's "Big Screen Video" that explained eclipses and also highlighted NASA missions that have enhanced our knowledge of the Earth-Moon system.

Peer-Reviewed Publications

Total Refereed Publications = ***88***

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Bowman, J. 2012 July 28, Spirit of the Senses Science Salon (informal question and answer session, 25 participants), Tempe, AZ

Bowman, J. DARE deployment blog: http://asuexplorers.wordpress.com/tag/dare/

Bowman, J. "EDGES," Conference on Foregrounds for CMB and 21 cm, Zadar, Croatia, May 23-27, 2011 (invited, session chair)

Bowman, J. "Experiment to Detect the Global EoR Signature: Overview and Early Science," Hydrogen Cosmology Workshop, Harvard, May 18-19, 2011 (invited, session chair)

Bowman, J. "Hydrogen Epoch of Reionization Array (HERA)," URSI-USNC, Special Session on Large-N Radio Arrays: Issues and Algorithms, Boulder, CO, January 5-8, 2011 (invited)

Bowman, J. "MWA Status and New Science," The Path to SKA-low Workshop, Perth, Australia, Sept. 6-9, 2011 (invited, session chair)

Bowman, J. "Overview of 21m Observables," Conference on Novel Telescopes for 21 cm Cosmology, Penticton, Canada, June 14, 2011 (invited review)

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Czekala, I., & Bradley, R. 2010, “Calibrating Astronomical Antenna Arrays with Man Made Satellites," American Institute of Aeronautics & Astronautics (AIAA), Region I-MA Student Conference, Blacksburg, VA

Czekala, I., & Bradley, R. 2010, “Calibrating Astronomical Antenna Arrays with Orbiting Data Satellites, Atlantic Coast Conference (ACC) "Meeting of the Minds" Conference, Atlanta, GA

Darling, J. 2011 October, “Mining the Sky with WISE: Extreme Starbursts Spoofing H I and Other Oddities,” Contributed talk for “Through the Infrared Looking Glass: A Dusty View of Galaxy and AGN Evolution” meeting, Pasadena, CA

Darling, J. “Hydrogen 21 cm Absorption Line Searches and Studies with SKAMP,” Science with SKAMP: Widefield Spectroscopy of the Southern Sky, Sydney, Australia

Darling, J. “Redshifted OH Lines with SKAMP: Detection and Science,” Science with SKAMP: Widefield Spectroscopy of the Southern Sky, Sydney, Australia

Datta, A. 2012, “Dark Ages Radio Explorer – Field Tests of a Prototype Instrument,” NASA Lunar Science Forum, NASA/Ames Research Center.

Datta, A., Bowman, J., Carilli, C.L., 2011, "Bright Foreground Subtraction Requirements for Redshifted 21 cm Measurements", Understanding Galactic and Extragalactic Foregrounds, Zadar, Croatia

Datta, A., Burns, J. , Bowman, J. , 2012, "Exploring the Dark Ages and Epoch of Reionization with the HI signal", International Conference on Modern Perspectives of Cosmology and Gravitation, Indian Statistical Institute, Kolkata

Davis, K., Kruger, L., Fast, H., Burns, J., 2011, “Radio Cosmology from the Moon: Determining Kapton’s reliability as a radio telescope material”, NLSI Lunar Science Forum.

Dell’Agnello, S.; Currie, D. G.; Delle Monache, G. O.; Lops, C.; M. Martini 2010 “LLRRA21/MoonLIGHT: a 2nd Generation Lunar Laser Ranging Array for Precision Gravity Tests and Lunar Science Measurements” at the Conference Global Lunar Conference – Beijing, China.

Delle Monache, G. O.; Dell'Agnello, S. Currie, D.; Martini, M. Vittori, R.; Cantone, C.; Boni, A. Berardi, S. Patrizi, G. Maiello, M. Tibuzzi, M. Garattini, M. Lops, C. Ciocci, E. Graziosi, C. Bianco, G. Intaglietta, N. *MoonLIGHT, a Lunar Laser Ranging Retroreflector Array for the 21st Century, and the ASI-INFN Etrusco-2 project* American Astronomical Society, AAS Meeting #220, #117.06 05/2012

Duncan, D., 2010, "Progress in LUNAR EPO", Robotic Science From the Moon Workshop. Boulder, CO.

Duncan, D. 2012, "'Max Goes to the Moon' Planetarium program for grades 1-5," NASA Lunar Science Forum, NASA/Ames Research Center.

Duncan, D., Benjamin, M., 2011, "EPO for the LUNAR Team", NLSI Lunar Science Forum.

Fast, H., Kruger, L., Davis, K., Burns, J., 2011, "Testing the Deployment of Lunar Radio Antenna Material with a Microrover under Simulated Lunar Conditions", NLSI Lunar Science Forum.

Furlanetto, S. 2009 September, "The Dark Ages of the Universe," Packard Fellows Meeting

Furlanetto, S. 2010, "Cosmic Dawn: The Birth of the First Galaxies," Los Angeles Astronomical Society, Los Angeles, CA

Furlanetto, S. 2010, "Cosmic Dawn: The Birth of the First Galaxies," Friends of the Mt. Wilson Observatory, Altadena, CA

Furlanetto, S. 2010, "The Redshifted 21 cm Signal," The First Billion Years (Keck Institute of Space Studies, California Institute of Technology), Pasadena, CA

Furlanetto, S. 2010, "Cosmology at Low Radio Frequencies," scientific colloquium, Aspen Center for Physics, Aspen, CO

Furlanetto, S. 2010, "Cosmology at Low Radio Frequencies," cosmology & astrophysics seminar, University of Pennsylvania, Philadelphia, PA

Furlanetto, S. 2011, "Cosmic Dawn: The Birth of the First Galaxies," Santa Monica Amateur Astronomy Club, Santa Monica, CA

Furlanetto, S. 2011, New Frontiers at High Redshifts Conference, Cambridge, UK, July 2011, "Lessons from Helium Reionization"

Furlanetto, S. 2012 May, Stanford University, Cosmology Seminar, Palo Alto, CA

Furlanetto, S. 2012 May, University of California, Berkeley, Cosmology Seminar, Berkeley, CA

Furlanetto, S. 2012, "Toward a Physical Understanding of the First Galaxies," NASA Lunar Science Forum, NASA/Ames Research Center.

Furlanetto, S. 2013 February, Harvard-Smithsonian Center for Astrophysics Colloquium, Cambridge, MA

Harker, G., 2010, "Update on power spectra", LOFAR EoR plenary meeting, Groningen, the Netherlands

Harker, G. 2012, "A flexible, Monte Carlo approach to modeling data from DARE and its ground-based prototype," NASA Lunar Science Forum, NASA/Ames Research Center.

Jones, D. 2012, "Inflate-While-Falling Concept for Lunar Low Frequency Antennas," NASA Lunar Science Forum, NASA/Ames Research Center.

Kruger, L., Burns, J., Alfaro, R., & Lettang, F. 2010, "Exploration of the Dark Ages: An Investigation into Kapton's Suitability as a Radio Telescope Material," NASA Lunar Science Forum, NASA/Ames Research Center.

Kruger, L., Tuan, K., Yarrish, C., Davis, K., Burns, J. 2012, "Materials Testing for a Lunar Radio Telescope with the LUNAR Simulant Thermal-Vacuum Chamber," NASA Lunar Science Forum, NASA/Ames Research Center.

Lazio, J. 2009 June, "The Lunar Radio Array," National Capital Astronomers, College Park, MD

Lazio, J. 2009 July, "The Lunar Radio Array," NLSI Lunar Science Forum 2009, NLSI Executive Committee meeting, NASA/Ames Research Center

Lazio, J. 2009 September, "The Lunar Radio Array," Virginia Amateur Astronomy Society, Charlottesville, VA

Lazio, J. 2009 October, "The Lunar Radio Array," Ottumwa High School, Ottumwa, IA

Lazio, J. 2010, "Magnetospheric Emissions from Extrasolar Planets," Aperture Array Verification Programme, Cambridge, United Kingdom

Lazio, J. 2010, "Magnetospheric Emissions from Extrasolar Planets," scientific colloquium, National Radio Astronomy Observatory, Green Bank, WV

Lazio, J. 2012, "Astrophysics and heliophysics: science from the Moon", NLSI Lunar Science Forum.

Lazio, J. 2012 November, "The Dark Ages Radio Explorer," University of Texas at Brownsville colloquium, Brownsville, TX

Lazio, J. 2012 December 11, "The Dark Ages Radio Explorer," Carnegie Observatories

colloquium, Pasadena, CA

Loeb, A. 2010, “The First Stars,” conference banquet lecture, Pennsylvania State University, State College, PA

Loeb, A. 2010, “The First Light,” Galaxy Evolution, Potsdam, Germany

Loeb, A. 2010, “The First Light,” Texas Symposium 2010, Heidelberg, Germany

Loeb, A. 2010, “The First Stars,” conference opening lecture, Austin, TX

Loeb, A. 2010, “How Did the First Stars and Galaxies Form?” Harvard Physics Department, Cambridge, MA

Loeb, A. 2010, “How Did the First Stars and Galaxies Form?” Munich Cosmology Colloquium, Munich, Germany

Loeb, A. 2010, “How Did the First Stars and Galaxies Form?” scientific colloquium, Hebrew University, Jerusalem, Israel

Loeb, A. 2010, “How Did the First Stars and Galaxies Form?” scientific colloquium, Tel Aviv University, Tel Aviv, Israel

MacDowall, R. 2012 February, "Solar Radio Burst Imaging from the Lunar Surface - ROLSS and ROLSS Pathfinder", NLSI Director's Seminar,

MacDowall, R. 2012, “Polyimide film antenna deployment for a pathfinder lunar radio observatory”, NLSI Lunar Science Forum.

Mani, H. 2012, “Deployment of DARE Prototype Instrument to Western Australia,” NASA Lunar Science Forum, NASA/Ames Research Center.

Mirocha, J. 2012, “Disentangling the assembly history of galaxies and super-massive black holes with 21-cm observations from the lunar farside” NLSI Lunar Science Forum.

Pritchard, J. 2010, scientific colloquium, Cambridge University, Cambridge, United Kingdom

Pritchard, J. 2010, scientific colloquium, Carnegie Mellon, Pittsburgh, PA

Pritchard, J. 2010, scientific colloquium, Oxford University, Oxford, United Kingdom

Pritchard, J. 2010, scientific colloquium, Perimeter Institute for Theoretical Physics, Waterloo, Ontario, Canada

Pritchard, J. 2010, scientific colloquium, University of California, Berkeley, Berkeley, CA

Pritchard, J. 2010, scientific colloquium, University of Chicago, Chicago, IL

Pritchard, J. 2010, scientific colloquium, University of Waterloo, Waterloo, Ontario, Canada

Pritchard, J. 2010, scientific colloquium, Yale University, New Haven, CT

Rogers, A. E. E., & Bowman, J. D. 2012, "Recent Advances with EDGES and the Status of Global 21 cm Experiments," International Union of Radio Science-U.S. National Committee (Boulder, CO)

Stewart, K. 2012, "Field Tests and Numerical Simulations of Lunar Polyimide Film Antennas," NASA Lunar Science Forum, NASA/Ames Research Center.

Yarrish, C., Kruger, L., Tuan, K., Davis, K., Burns, J., McQuinn, C. 2013. 2012, "Thermal Testing of ATHLETE Lunar Rover Components to Determine Survivability on the Moon," NASA Lunar Science Forum, NASA/Ames Research Center.

Zacny, K. 2012, "Development and Testing of the Pneumatic Lunar Drill for the Emplacement of the Corner Cube Reflector on the Moon," NASA Lunar Science Forum, NASA/Ames Research Center.

Zacny, K. 2012, "Percussive Excavation for Lunar Mining and ISRU," NASA Lunar Science Forum, NASA/Ames Research Center.

Zuber, M. 2012, "Overview and first science results from the GRAIL mission", NLSI Lunar Science Forum.

List of Undergraduate Students, Graduate Students, Postdoctoral Fellows, and New Faculty involved in the LUNAR Team

Numbers next to students indicate publications and presentations.

University of Colorado Boulder

- Undergraduate Students
    - Riccardo Alfaro-Contreras 1
    - Miles Crist
    - Kristina Davis 4
    - Kelsey Degeorge
    - Katherine Grasha
    - Michael Leitshuh
    - Erin Macdonald 1
    - Karynna Tuan 2
    - Christopher Womack
    - Christopher Yarrish 2

- Graduate Students
    - Adrienne Dove (crossed-trained with Mihaly Horanyi's team)
    - Harrison Fast 2
    - Laura Kruger 5
    - Francesca Lettang 1
    - Jordan Mirocha 7
    - David Schenck
    - Samuel Skillman 7
    - Kyle Willett
    - Ting Yan 1
    - Benjamin Zeiger 3
- Postdoctoral Fellows
    - Abhirup Datta (NASA NLSI Postdoctoral Fellow)
    - Geraint Harker
    - Stephen Skory (25% NLSI funding)

Arizona State University

- Undergraduate students
    - Maggie Blumm
    - Jose Chavez-Garcia
    - Sarah Easterbrook
    - Jared Korinko
    - Connor Schmidt
- Graduate students
    - Jacqueline Monkiewicz
    - Thomas Mozdzen
    - Hamdi Mani 3
    - Kittiwist Piyanat
- Postdoctoral Scholars
    - Danny Jacobs
    - Joseph Munoz
- New faculty
    - Judd Bowman (previously postdoctoral scholar)

Harvard University

- Graduate Students
    - Jonathan Bittner 2
    - Bennett Maruca
    - Eli Visbal 4
    - Peter Adshead 1
- Postdoctoral Fellow
    - Jonathan Pritchard (Hubble Fellow)

Massachusetts Institute of Technology

- Undergraduate Students
    - Rurik Primiani
- Graduate Students
    - Sam Simmons 3

NASA-JPL

- Postdoctoral Fellows
    - Jacob Hartmann

NRC-NRL

- Posdoctoral Research Associates
    - Theodore Jaeger
    - Katie Chynoweth Keating

University of California at Los Angeles (UCLA)

- Undergraduate Students during summer internship at UCLA
    - Sarah Benjamin (Carnegie Mellon)
    - Samuel Johnson Stoever (Cornell) 1
- Graduate Students
    - Lauren Holzbauer 1
- Postdoctoral Fellows
    - Joseph Munoz

Princeton University

- Postdoctoral Fellow
    - Andrei Mesinger

University of Maryland

- Undergraduate Students
    - Philip Massy
- Graduate Students
    - Arunima Jain

University of New Mexico

- Graduate Students
    - Cristina Rodriguez
- Postdoctoral Scholars
    - Jayce Dowell

University of Virginia

- Undergraduate students
    - Ian Czekala 2

Smithsonian Astrophysical Observatory

- Postdoctoral Fellows
    - Gaetan Le Chat
    - Amaud Zaslavsky (now Professor at Universite Paris Diderot)

Thomas Jefferson High School for Science & Technology (Virginia)

• S. Carmichael	2
• J. Clark	2
• E. Elkins	2
• Peter Gudmundsen	2
• Zachery Mott	2
• Melanie Szwajkowski	2
• Nathaniel Shkolnik	1