1. Executive Summary

The Network for Exploration and Space Science (NESS) team led by P.I. Jack Burns at the University of Colorado Boulder is an interdisciplinary effort that investigates the deployment of low frequency radio antennas in the lunar/cis-lunar environment using surface telerobotics. The purposes of these radio telescopes are cosmological and astrophysical measurements of neutral hydrogen at the end of the Dark Ages, during Cosmic Dawn, and at the onset of the Epoch of Reionization; radio emission from the Sun; and extrasolar space weather and exoplanets. NESS continues to advance instrumentation and a data analysis pipeline for the study of the first luminous objects (first stars, galaxies and black holes) and departures from the standard model of cosmology in the early Universe, using low frequency radio telescopes shielded by the Moon on its farside. The design of an array of radio antennas at the lunar farside to investigate the Dark Ages, Heliophysics, and Exoplanet Magnetospheres, is a core activity within NESS, as well as the continuous research of theoretical and observational aspects of these subjects. NESS keeps developing designs and operational techniques for teleoperation of rovers on the lunar surface facilitated by the planned Lunar Gateway in cis-lunar orbit. New experiments, using rovers plus robotic arms and Virtual/Augmented Reality simulations, are being performed to guide the development of deployment strategies for low frequency radio antennas via telerobotics.

2. Team Project Report

2.1. Primordial Hydrogen Cosmology

2.1.1. Theoretical predictions of the 21-cm Signal

A key goal of low-frequency radio telescopes on and near the Moon is to observe the Cosmic Dawn, the period (about 100 million years after the Big Bang) when the first stars and black holes formed. While such sources are individually far too faint to be observed directly, the radiation generated by them can be measured through the 21-cm emission line of neutral hydrogen, which pervades the Universe during the Cosmic Dawn. The lunar environment is ideal for observing this signal, because it avoids contamination by terrestrial sources and is free of distortions induced by Earth's ionosphere.

Unfortunately, the signal is still very difficult to detect, and theoretical predictions of the 21-cm signal are essential for optimizing instrument design to measure properties of the Cosmic Dawn. At UCLA, Co-I Furlanetto and his group have studied how "warm" dark matter scenarios will affect the Cosmic Dawn (Mebane & Furlanetto, in prep), offering a range of new template signals for optimizing instrumental analyses. Mebane has also developed a framework to incorporate these first stars and black holes into the popular prediction code 21cmFAST and is studying how they modify fluctuations in the signal (Mebane et al., in prep), which radio arrays on the lunar farside hope to eventually observe. Additionally, a key challenge in studying the Cosmic Dawn is in disentangling the effects of "normal" galaxies from the exotic first stars. Trapp & Furlanetto (2020) showed how future space telescopes will pin down the contributions from the former, while Furlanetto (2021) showed how "normal" galaxies evolve during this era in a new suite of models.

2.1.2. Experimental progress

An early-career researcher (D. Lewis, B.S. 2019) analyzed long integrations acquired by the EDGES ground-based spectrometer to determine the average strength of radio recombination lines (RRLs) away from the plane of the Milky Way galaxy. RRLs are the result of electrons transitioning between very high orbital energy states within atoms in the interstellar medium. They are observed in both emission and absorption and are a potential foreground for 21cm cosmology observations. This work is the first time they have been characterized in the regions of the sky targeted by upcoming 21cm observations of Cosmic Dawn and the Dark Ages. Surprisingly, RRLs were detected when averaged across the cold regions of the sky. Results from the analysis are in preparation for publication and suggest that future 21cm cosmology observations, such as those planned by DAPPER and FARSIDE, will need to excise spectral channels where the lines occur.

2.1.3. Data Analysis Pipeline for Global 21-cm Signal Experiments

For a series of papers describing our data analysis pipeline, the second (Rapetti et al. 2020) and third (Tauscher, Rapetti & Burns 2020b) were published. Paper II presents the final step of the pipeline, in which Bayesian inference is performed to estimate the parameter probability distribution of given non-linear signal models, while analytically marginalizing over linear parameters of the beam-weighted foreground obtained following the technique described in Paper I. As shown for simulated cases, this methodology is able to recover input parameter values properly accounting for statistical and systematic uncertainties. In Paper III, we show the key advantages of employing multiple correlated global 21-cm spectra at different driftcan times and/or Stokes polarization parameters. Our pipeline naturally analyzes data in this manner allowing to leverage the fact that the beam-weighted foreground component of the data changes as a function sky view during drift scan observations and it is polarized, whereas the signal does not change and it is unpolarized.

In another paper (Tauscher, Rapetti & Burns 2020a), assumptions in traditional global 21-cm experiments were critically examined, and problematic aspects of not sufficiently incorporating the chromaticity effects of the antenna beam on the foreground demonstrated. In addition, a new analysis that does not assume any signal model was presented and shown to produce valuable results based solely on beam-weighted foreground modeling. Such constraints can then be utilized to form the likelihood function for a Bayesian inference analysis of a given signal model, without any further foreground marginalization required. In two other papers, Bassett et al. (2021) and Hibbard et al. (2020), further data analysis advances were developed, in the former, to test the goodness-of-fit of our modelling, and in the latter, to extend and compare beam-weighted foreground models.

For the Dark Ages Polarimeter PathfindER (DAPPER) mission concept, funding was pursued, received and employed for instrument and pipeline maturation.

2.1.4. Instrument Development

2.1.4.1. Advanced Receiver Development

Precise measurements in cosmology force stringent requirements on the stability and calibration accuracy of space-borne radiometers such as the type being considered for DAPPER. NESS supported graduate student David Bordenave is advancing the state-of-the-art in correlation receiver technology to meet these goals. The correlation receiver, first introduced to radio astronomy in the 1960s, was known for its sensitivity and stability. David is improving upon these attributes by modernizing the electronics and extending its capabilities through a novel, four-channel configuration for the analysis of the E-field polarization characteristics of the incoming radiation. The initial prototype of this receiver is being developed to measure

Figure 1: Photo of the initial DAPPER/CTP prototype receiver module. Full dual polarization version with noise calibration was assembled and is ready for correlation tests.

the absolute sky brightness at 310 MHz using the clear-aperture radio telescope in Green Bank, WV, but it will eventually be used with this telescope to produce a high-accuracy, polarization sky map at this frequency, a critical input to the DAPPER data analysis pipeline. The second version, operating from 60-110 MHz, is currently under development at NRAO for DAPPER.

2.1.4.2. FARSIDE Concept Instrumentation

As part of the FARSIDE concept development, a graduate student at ASU (N. Mahesh) has begun investigating the polarization properties of the array. Conventional antennas used in radio astronomy have the phase centers of each of the two polarization elements co-aligned. FARSIDE, however, will have offset phase centers for its two polarization elements due to including both of its polarization dipoles sequential on a single tether deployed by a rover. This creates a unique response pattern for the FARSIDE antennas that must be accounted for during image processing. Initial results suggest that the FARSIDE polarization properties introduce manageable effects into the instrument response. Over the next year, we plan to expand the investigation to fully simulate FARSIDE observations, including realistic sky and antenna models.

2.2. Surface Telerobotics

Immersion provided by virtual and mixed reality (VMR) head-mounted display (HMD) robotic interfaces improves efficiency and situation awareness without increasing the workload of operators. To fully examine the capabilities that HMD technologies afford in the construction of radio telescopes on the Moon, CU graduate student M. Walker, supervised by D. Szafir, and J. Burns, is examining multi-perspective VMR HMD interface designs. Egocentric (1st person) and exocentric (3rd person) designs are being explored to examine overall effectiveness as well as optimal use cases for either design paradigm. By combining the design concepts seen in 1st person virtual control room interfaces (Figure 2) and 3rd person cyber-physical interfaces, we hypothesize interfaces will offer significant operational advantages when a robot operator on the Moon can simultaneously access both egocentric and exocentric perspectives. We are investigating how this type of combined interface can facilitate group collaboration during mobile robot teleoperation/supervision planning and live missions by rendering virtual telepresence user avatars that share the virtual space within the interface.

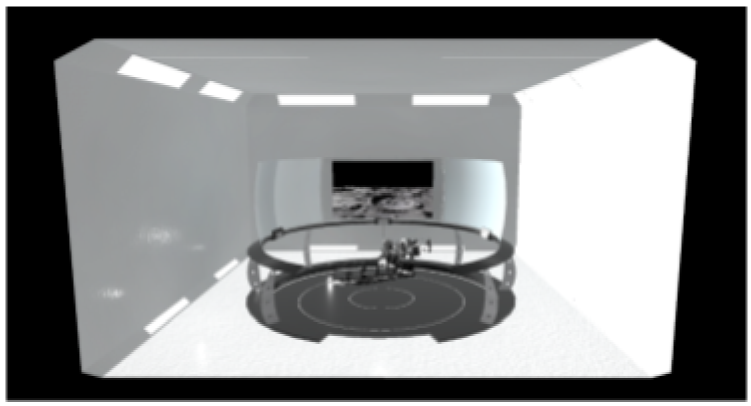

Figure 2. The CU prototype mixed reality robot teleoperation interface that presents both an egocentric 3D video stream and an exocentric 3D reconstruction to operators.

A sustainable lunar presence permits low-latency robotics. This enables missions such as the FARSIDE array. The mission design requires a teleoperated rover to deploy antenna nodes from its lander onto the lunar surface. These types of lunar missions leveraging human-robot interactions will require new methods of robotic failure recovery. Using stereo imaging capabilities, CU students M. Bell and P. Curlin, under the supervision of Burns, have begun to create virtual/augmented reality interfaces for both teleoperation and simulated failure recovery. By developing our virtual recovery sandbox (Figure 3), we can create a virtual space representative of the rover's current state and environment. This provides the ability to

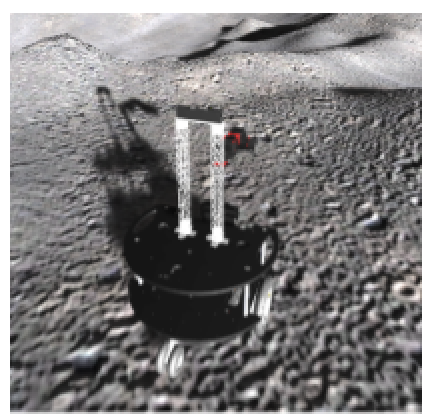

Figure 3. The Armstrong rover viewed from the exocentric standpoint, within the virtual recovery sandbox; A risk-free virtual solution development environment.

troubleshoot problems as if the operator were next to the rover itself, in an exocentric perspective. If proven to support teleoperated failure recovery, this sandbox may be leveraged in a variety of robotic applications. We plan to compare our model with traditional control and failure recovery methods, with the focal point on construction of lunar telescopes.

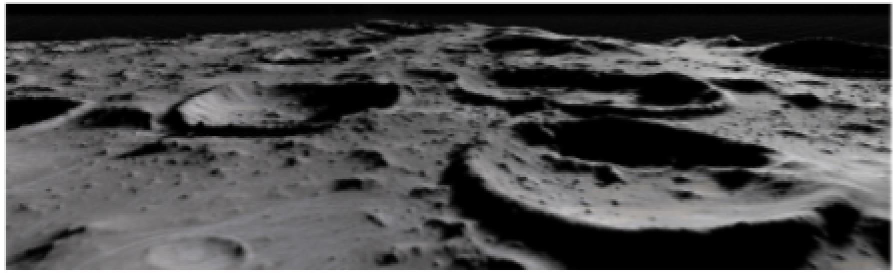

Figure 4. Synthetic lunar terrain developed using LROC- NAC images.

Virtual planetary environment simulators provide a fast, flexible, and cost-effective alternative to field analogs for generating datasets for algorithm design/testing, operations planning, operator training, and mission mock-ups. At CU, postdoc M. Menon along with Walker, Szafir, and Burns have developed a scalable and modular simulation framework that generates photometrically accurate lunar virtual environments. The framework renders the environment using the Unity game engine and integrates with the Robotic Operating System (ROS) to simulate the robots interacting with the environment. The lunar topography with high-resolution terrain is modeled by overlaying Digital Terrain Models generated from Lunar Reconnaissance Orbiter-Narrow Angle Camera (see Figure 4). We modelled the robotic systems as ROS nodes, which accept inputs from simulated sensors like stereo cameras, LIDAR, and an Inertial Measurement Unit (IMU). We incorporated dynamic tessellation to the terrain, making the simulator memory-efficient yet capable of adding details like wheel tracks. FARSIDE is used as our case study. We are working on a navigation algorithm called Simultaneous Localization And Mapping (SLAM). We will carry out a comprehensive comparative study and will use the results to design navigation and teleoperation algorithms specific to Moon.

2.3. Heliophysics

Co-I Kasper and Collaborator Hegedus have progressed on the Sun Radio Interferometer Experiment (SunRISE) mission formulation. SunRISE is a Heliophysics Mission of Opportunity that is currently in Phase B. SunRISE will consist of 6 CubeSats with radio receivers that together form an interferometer. SunRISE will circle the Earth in a GEO graveyard orbit and sample the low radio frequency range 0.1-20 MHZ and make rudimentary images below the ionospheric cutoff for the first time. Data will be recombined on the ground, forming a synthetic aperture. SunRISE's primary science is to localize type II radio bursts within coronal mass ejections (CMEs) to identify the site of particle acceleration of solar energetic particles (SEPs), as well as to map the trajectories of energetic electron packets associated with type III bursts. Hegedus has also shown through robust modeling of the data processing and science analysis pipelines that SunRISE will be able to discern between different possible acceleration regions, even those that result in similar Type II burst structure in frequency and time from

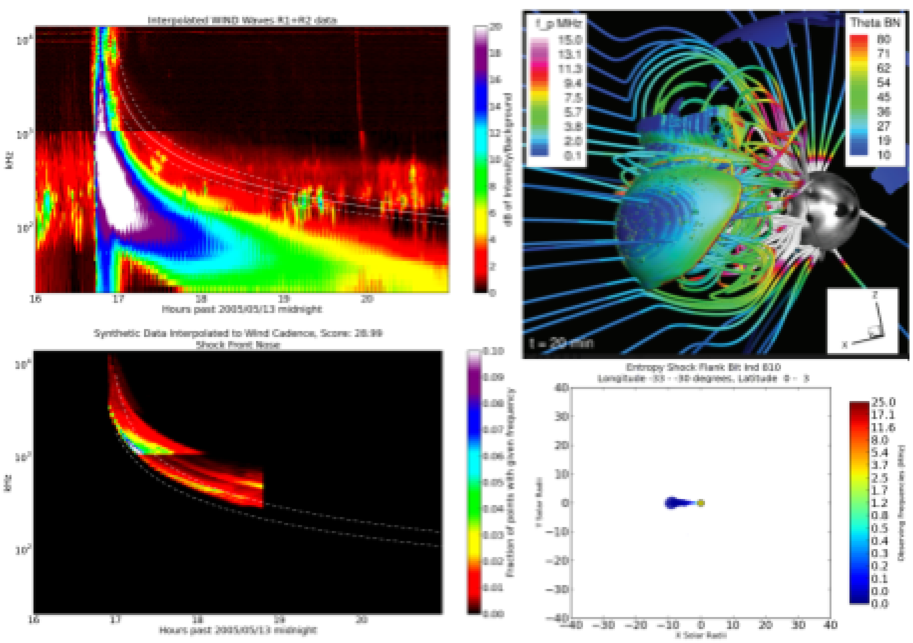

Figure 5. See detailed description in the text.

individual antenna measurements. Figure 5 displays a summary of these results, showcasing a SunRISE case study using a 05/13/2005 CME. In the upper left is real radio data from the Wind/WAVES antenna showing the powerful type II radio burst from the 2005 CME. The type II burst can be seen as the red, less intense descending emission starting around 1 MHz, after the white, more intense type III burst that descends far more quickly. In the upper right is a snapshot from an Alfven-Wave driven Solar wind Model (AWSOM) MHD simulation of the 2005 event with the shock identified from the entropy ratio. The lower left is a synthetic spectra made from the identified shock in the MHD data with the dashed white line identifier from the real spectra above. Note that this is a column normalized histogram of points with upstream plasma frequency in the specified radio range, not a true brightness spectra. In the lower right are SunRISE reconstructions of the progression of the type II radio burst, with a hypothesized truth image coming from the identified shock in the MHD simulation, using a subselection of the entropy derived shock front on the eastern edge of the shock on the left. Each colored ellipse corresponds to a SunRISE reconstruction of the simulation derived input for each frequency channel over time, tracing out the path of the emission.

2.3.1. Instrument Development

1) ROLSES (Radio wave Observations at the Lunar Surface of the photoElectron Sheath) is a NASA-Provided Lunar Payload to place a radio frequency spectrometer on the lunar nearside. NESS member Bob MacDowall is the PI, and Jack Burns and Michael Reiner were other NESS team members on the proposal. ROLSES will provide information about the electron density from 1 to 3 m above the surface, which is relevant information for other lunar surface radio observatories. It will also work to get radio data that will relate to several science and technical goals. ROLSES will go to the lunar surface on the Nova-C lander of Intuitive Machines. Flat-sat testing will take place in January 2021, and the figure shows the ROLSES boards stack that was ready in the end of December 2020 for the flat-sat testing. The intuitive Machines new plan will now have the Nova-C lander go to Oceanus Procellarum in November 2021.

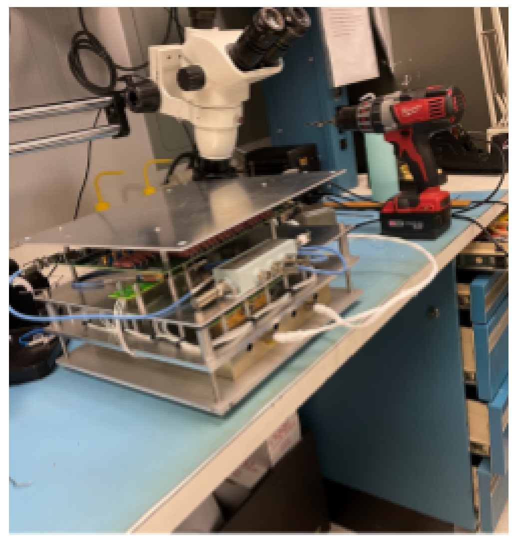

Figure 5. The ROLSES payload must undergo flat-sat testing at Intuitive Machines in January 2021, and since the payload is not completed, the relevant data and power boards and a data simulator will go to Intuitive Machines in the stack shown in the figure.

2) LuSEE (Lunar Surface Electromagnetic Experiment) is a NASA LISTP lunar payload set of instruments, proposed by Stuart Bale, U.C. Berkeley, with several NESS team members included on the proposal. It is a unique LISTP payload, because it is almost a duplicate of the Parker Solar Probe FIELDS instrument suite, which measures magnetic, DC electric, radio, and other data. Therefore, LuSEE's goals are to: (i) measure the DC electric and magnetic fields, including plasma waves; (ii) measure electrostatic signatures of dust impacts; (iii) measure radio emissions from the Sun, Earth and outer planets; (iv) address the formation and structure of the lunar photoelectron sheath and the interaction of the lunar surface with plasma from the solar wind and terrestrial magnetotail; (v) probe the structure and dynamics of the tenuous lunar exosphere. Although it still doesn't have a lander assigned yet, the plan is to go to the Schrödinger crater near the lunar south pole on the farside. A key NESS team member involvement is that GSFC MAG team will provide the fluxgate magnetometer for LuSEE, led by Bob MacDowall.

2.4. Extrasolar Space Weather

The detection of exoplanetary radio emission, as well as the detection of stellar radio bursts indicative of coronal mass ejections (CMEs) and stellar energetic particle events (SEPs), is critical for diagnosing planetary habitability and understanding the role that planetary magnetospheres play in shielding their atmospheres from the space weather environments of their host stars. **Lunar-based low-frequency radio telescopes are vital for expanding our reach beyond the Jovian-like magnetospheres that are accessible from the ground to the terrestrial-like magnetospheres that can only be detected from space.**

Figure 6. Looking east from the center of OVRO-LWA, a dipole array in California operating at sub-100 MHz frequencies that images the entire viewable hemisphere to simultaneously monitor thousands of stellar systems in search of stellar and planetary radio emission.

The Owens Valley Radio Observatory Long Wavelength Array (OVRO-LWA, led by NESS Co-I Hallinan) is a ground-based array that serves as a pathfinder to future lunar-based low-frequency radio arrays (e.g. FARSIDE), providing a framework for the operation and design of a survey targeting extrasolar space weather science from the lunar surface. OVRO-LWA targets nearby stellar systems to monitor for stellar CMEs and SEPs, as well as radio signatures of planetary magnetospheres — specifically, the Jovian-like magnetospheres that are detectable from within Earth's ionosphere. The OVRO-LWA is a 288-element dipole array in California (see Figure 6), operating at sub-100 MHz frequencies and imaging the entire viewable hemisphere at 10-second cadence. This allows for the simultaneous monitoring of thousands of stellar sources for radio emission indicative of space weather events. The Caltech team led by Hallinan, which also includes JPL postdoc and NESS team member Marin Anderson, is analyzing the 1000 hours of OVRO-LWA data that was collected prior to the decommissioning of the Phase II array in February 2020. The data span 33–48 MHz, ideal for targeting a sample of hot Jupiters for auroral radio emission. The OVRO-LWA data also overlap with observations from NASA's Transiting Exoplanet Survey Satellite (TESS), providing unprecedented simultaneous optical and low radio-frequency coverage of a sample of nearby (< 25 pc) stars in order to search for evidence of CMEs associated with large flares detected in the optical band. Results from this 1000-hour dataset with OVRO-LWA will be published in 2021.

Work has also begun on Phase III of the OVRO-LWA, which will expand the existing array to its final configuration of 352 dipoles spanning a 2.6 km diameter area, providing 5 arcminute spatial resolution at the top of the band. Work on the Phase III array also includes a full redesign of the analog and digital signal processing systems, as well as efforts to measure the individual beam patterns of all 352 dipole antennas via multiple methods (including via drone). The latter of these will be a relevant step in demonstrating the capability of mapping FARSIDE dipole antennas via orbiting calibration beacon. Precise knowledge of the antenna gain pattern is essential for achieving the sensitivity necessary for detecting extrasolar space weather events.

3. Inter-team/International Collaborations

Collaborator Hegedus was a Co-Investigator on two proposals in the European Space Agency's Call For Ideas, "Exploring the Moon with a large European lander". One was inspired by his recent paper in Radio Science, "Measuring the Earth's Synchrotron Emission From Radiation Belts With a Lunar Near Side Radio Array" with European co-author Baptiste Cecconi from Observatoire de Paris submitting the step 1 proposal titled "Van-Allen Belts Imaging from the Moon (VABIM)". The other proposal was titled "Sunbeam (Sun Bursts

Explorer by Radio Array on the Moon)", with the lead being Antonio Vecchio from Radboud University in the Netherlands.

Burns was a collaborator on a successful ESA concept study proposal called LunarLOFAR. This is a low frequency radio array from the lunar farside with elements in common to the NESS FARSIDE concept. Over this next year, we will be investigating a potential ESA/NASA collaborative study of a lunar low frequency radio array including the science cases for the instrument.

Co-I Fong participated in the "International Space Station as a Mars Mission Analog: A Virtual International Workshop on Innovative Research and Operations Approaches". The purpose of this workshop was to bring together international strategic leaders in human spaceflight (NASA, CSA, ESA, JAXA, etc.) to develop creative approaches to using the International Space Station as an analog for preparation for Mars mission and to be implemented in its 3rd decade of operations. Fong provided recommendations for the use of robots in transit, particularly for performing in-flight maintenance and augmenting crew situation awareness.

4. Public Engagement

4.1. From Cosmic Dark to Cosmic Dawn: An Outreach Website

Lunar radio arrays promise transformational science in our understanding of cosmology. They will provide the most sensitive probe available of exotic physics in the early Universe, and they will provide the most sensitive studies of the formation of the first stars and black holes during the Cosmic Dawn. This science is so new that very little of this promise has filtered out to the public. As part of NESS's outreach effort, the UCLA group is leading the development of an outreach website to help fill this gap. Co-I Furlanetto and undergraduate student Erika Hoffman have made significant progress on developing the first phase of the website this year.

The website, titled From Cosmic Dark to Cosmic Dawn, will provide a comprehensive overview of the science we can learn from these studies as well as the technology behind the many telescopes that will study this era. The first phase (which we hope to make public in spring 2021) is aimed at the "educated lay person" enthusiastic about popular science. We are leveraging the nonlinearity of websites to allow viewers to engage in multiple ways: following the technology or the science, diving deep into particular topics, or following the timeline for a quick overview. The site will have pages on major science topics (such as The First Stars; see draft version in Figure 7, which shows the introductory section of this page), telescopes, and key concepts. We will take full advantage of hyperlinks to cross-reference related topics and provide background whenever possible.

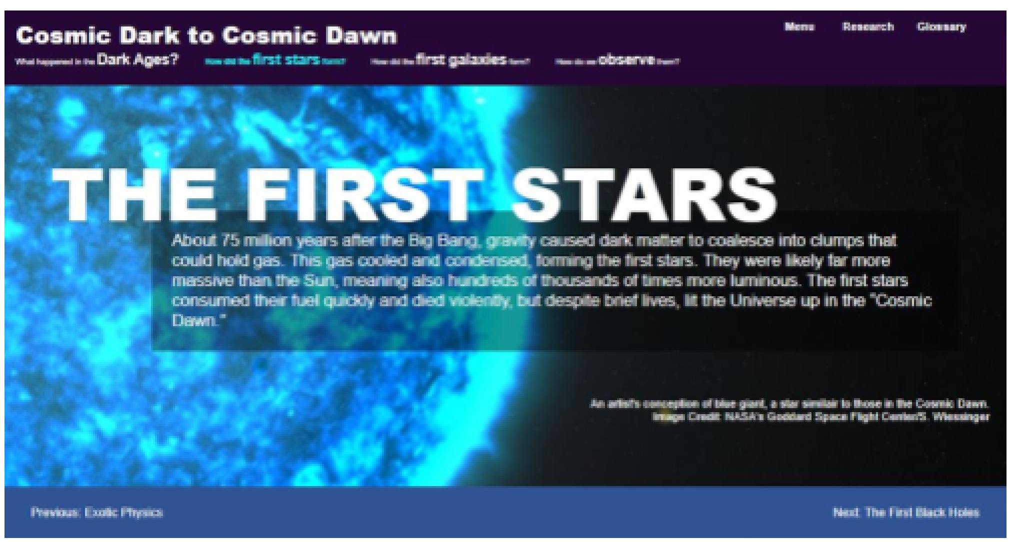

Figure 7. Excerpt of a draft science overview page for the *From Cosmic Dark to Cosmic Dawn* outreach website. The menu at the top identifies key questions to engage readers. Each science page includes a short overview for readers; further down on each page, the key questions will be addressed in more detail.

4.2. Planetarium Show: Forward! To the Moon

In coordination with NESS and Lockheed Martin, Fiske Planetarium at the University of Colorado Boulder has produced a 6-minute prologue to a 25-minute fulldome film that will be released in Summer 2021 entitled *Forward! To the Moon*. The full length film features the NASA Artemis Mission, with emphasis on the Space Launch System, the Orion Crew Vehicle, the Gateway, and telerobotic lunar research that will be enabled by these efforts. The film also includes interviews with NASA astronauts from the The Artemis Team as well as testimonials from engineers associated with robotic lunar science efforts. *Forward!* concludes by highlighting the import role that lunar research will play in future plans for human exploration of Mars.

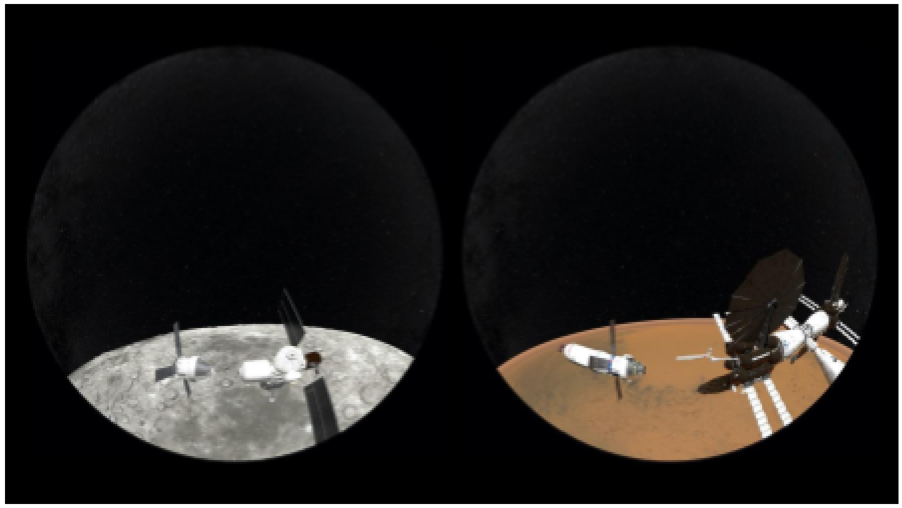

Figure 8. Fisheye projections of two scenes from the fulldome film *Forward! To the Moon*. Image to the left shows the Orion spacecraft docking with the Lunar Gateway. Image to right shows Orion docking with the Mars Basecamp.

Fiske Planetarium hosts a network of over 300 planetarium facilities that regularly download free fulldome content such as *Forward!* Promoted through this network along with the NASA Museum Alliance, Fiske hosted a virtual preview of the film prologue for planetarium and museum directors and staff in October 2020. This event, which included presentations by NASA Chief Scientist Jim Green, SSERVI Director Greg Schmidt, NESS Director Jack Burns, Fiske Director John Keller, and film narrator Kari Byron (from Mythbusters and Crash Test World), was attended by over 60 planetarium and museum representatives. The full length film will premiere at Fiske Planetarium in late summer 2020, along with a film tour at several large planetariums across the US, and will be available free of charge to facilities of all sizes across the globe.

5. Student/Early Career Participation

Undergraduate Students

1. Erika Hoffman (UCLA, beginning June 2020): outreach website designer
2. Phaedra Curlin (University of Colorado Boulder): surface telerobotics
3. Mason Bell (University of Colorado Boulder): surface telerobotics

Graduate Students

4. Richard Mebane (UCLA, until October 2020): theoretical 21-cm studies
5. Adam Trapp (UCLA): theoretical 21-cm studies
6. David Bordenave (Department of Astronomy, University of Virginia): experimental 21-cm studies
7. Neil Bassett (University of Colorado Boulder): 21-cm data analysis studies
8. Joshua Hibbard (University of Colorado Boulder): 21-cm data analysis studies
9. Keith Tauscher (University of Colorado Boulder, until August 2020): 21-cm data analysis studies
10. Michael Walker (University of Colorado Boulder): 21-cm data analysis studies
11. Nivedita Mahesh (Arizona State University): experimental 21-cm studies

Lab Technicians

12. David Lewis (graduated and currently working as a lab technician at Arizona State University before potentially starting graduated studies): experimental 21-cm studies

Postdoctoral Fellows

13. Alexander Hegedus (University of Michigan): simulating space based radio arrays
14. Marin Anderson (California Institute of Technology, Jet Propulsion Laboratory): extrasolar space weather
15. Steve Murray (Arizona State University): 21-cm data analysis studies
16. Midhun Menon (University of Colorado Boulder, until Fall 2020): surface telerobotics
17. Jordan Mirocha (McGill University): theoretical 21-cm studies
18. Bang Nhan (National Radio Astronomy Observatory): experimental 21-cm studies
19. Keith Tauscher (University of Colorado Boulder, from August 2020): 21-cm data analysis studies

New Faculty/Staff Members

20. David Rapetti (in September 2020, transition from Visiting Scientist to Scientist at NASA Ames Research Center/Universities Space Research Association; also affiliated with the University of Colorado Boulder): 21-cm data analysis studies

6. Mission Involvement

1. **SunRISE:** Kasper and Hegedus have progressed on the Sun Radio Interferometer Experiment (SunRISE) mission, a Heliophysics Mission of Opportunity that is currently in Phase B. SunRISE will consist of 6 CubeSats with radio receivers that together form an interferometer. SunRISE will act as a pathfinder for future space based radio arrays like FARSIDE, producing the first basic maps of the low frequency sky and localizing bright transient emission from solar eruptions.

2. **FARSIDE:** Burns and Hallinan are PI and Deputy PI, respectively, of the Farside Array for Radio Science Investigations of the Dark ages and Exoplanets (FARSIDE), which is a Probe-class concept to place a low radio frequency interferometric array on the farside of the Moon. The final Probe-class concept study, completed in partnership with JPL, was submitted to NASA at the end of 2019. Since that study, the FARSIDE design has continued to advance, with the selection of the Blue Moon Lander via the partnership with Blue Origin. The initial design proposed in the study was a single rover for deployment of antennas along a four-petal configuration. This design has evolved into four JPL axel rovers for deployment of antenna-embedded tethers in a four-spiral arms configuration. This redesign significantly reduces the risk posed by the failure of the single deployment rover, as well as mitigates the impact on imaging performance in the event of a single spiral arm failure.

3. **DAPPER:** Burns is PI of the Dark Ages Polarimeter PathfindER (DAPPER) mission concept. The early Universe's Dark Ages, probed by the highly redshifted 21-cm neutral hydrogen signature averaged over the entire sky, is an ideal epoch for a new rigorous test of the standard LCDM cosmological model. DAPPER, operating in the radio-quiet farside, shall search for divergences from the standard model that will indicate new physics such as heating or cooling produced by dark matter, as well as investigate the astrophysics of the first stars, galaxies and black holes in the Cosmic Dawn. A lunar surface version of DAPPER is being proposed to PRISM for deployment in the Schrödinger basin on a lander that will also carry the LuSEE radio science experiment.

4. **VIPER**: Fong is the Deputy Rover Lead for the "Volatiles Investigating Polar Exploration Rover" (VIPER) mission. VIPER is planned to launch in late 2023 and will spend 100 days mapping and surveying four different ice stability regions in a high-latitude area of the Moon. The primary mission objective is to understand the nature and distribution of water and volatiles already confirmed to be there, including measuring mineralogical content such as silicon and light metals from lunar regolith.

7. Awards

NESS Co-I Dr. Richard Bradley received the 2020 NRAO Director’s Distinguished Performance Award: “Rich has made exceptional, unique, and lasting contributions to NRAO’s mission for over 30 years. His body of work covers a broad area of activities, including applied research and engineering, service to the greater scientific community, and teaching and mentoring students.”