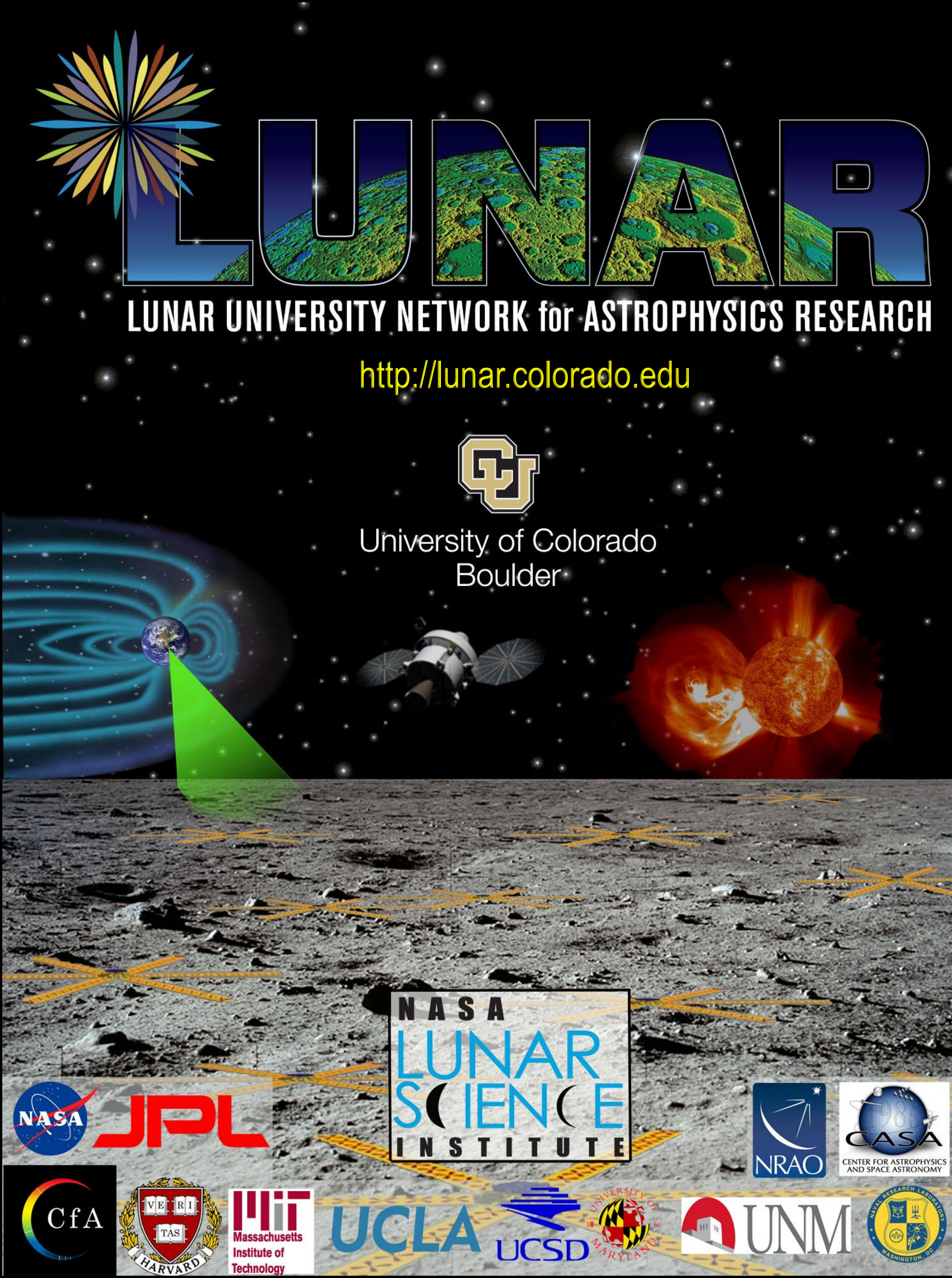
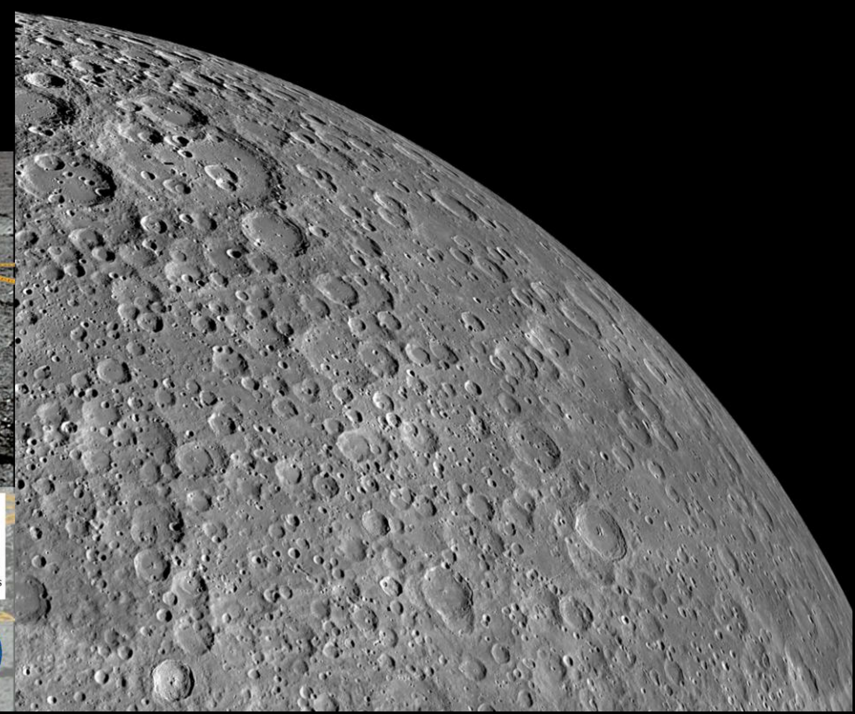


SPACE SCIENCE FROM THE MOON

Jack Burns for the LUNAR Team
University of Colorado Boulder
and
NASA Lunar Science Institute



SUMMARY OF THE FIRST 3 YEARS OF LUNAR

- **Some Statistics**
  - Number of Co-Is and Collaborators involved in LUNAR research: ***Over 50***
  - Number high school, undergraduate & graduate students, postdoctoral students who have been "influenced" by LUNAR research & training: ***45***
  - Number of refereed publications: ***62***
  - Number of conference proceedings, conference presentations, & abstracts: ***220***

- **Awards to LUNAR Team Members**

  - ***Steven Furlanetto (UCLA)*** – Helen B. Warner Prize from the American Astronomical Society given to astronomer who is <36 yrs old for significant work in theoretical astronomy.

  - ***Justin Kasper (Smithsonian CfA) –*** Presidential Early Career Award.

  - ***Judd Bowman (Arizona State) –*** NASA Roman Technology Fellowship.
  - ***Jack Burns (U. Colorado) –*** NASA Medal for Exceptional Public Service; elected Fellow of the American Association for the Advancement of Science.

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Key Projects Overview

	Decadal Survey Science	Strategic Knowledge Gaps
Heliophysics & Space Radiation	• "Solar radio emission provides uniquely powerful sources of diagnostic information with the potential for transformational insights into solar activity and its terrestrial impacts." • "Goal 1. Determine the origins of the Sun's activity and predict the variations in the space environment." • "Shock waves appear throughout the heliosphere where they facilitate the transition from supersonic to subsonic flow, heat the plasma and act as accelerators of energetic particles." *Heliophysics Decadal*	• Radiation: Radiation sensors • Regolith: Space weather modeling • Plasma Environment: Interaction of radiation with planetary surfaces • Plasma Environment: Propagation of radiation thru space • Human Health/ Performance: Space radiation effects
Lunar Laser Ranging	• "critical to understand nature & evolution of lunar interior from crust to core" *Planetary Science Decadal* • "promising and cost-effective way to test General Relativity & other theories of Gravity" *Astrophysics Decadal*	• Regolith: Obscuration by dust • In-situ Resource Utilizations: Pneumatic drilling for retroreflector emplacement • Operations/Operability: Pneumatic drilling; improve geodetic grid on surfaces
Low Frequency Radio Science	• "Cosmic Dawn: What were the first objects to light up the Universe & when did they do it?" *Astrophysics Decadal* • "planetary exospheres … are poorly understood" need "insight into how they form, evolve, & interact with space environment" *Planetary Sciences Decadal*	• Radiation: Advance warning; particle acceleration at shocks • Regolith: Interaction of nanodust with airless body surfaces • Plasma Environment: Understand charge reservoirs in low conductivity environment
Exploration Science & Mission Concept Development	• "A great mystery now confronts us: When and how did the first galaxies form out of cold clumps of hydrogen gas and start to shine—when was our cosmic dawn?... Astronomers must now search the sky for these infant galaxies and find out how they behaved and interacted with their surroundings." *Astrophysics Decadal* • "The exploration and sample return from the Moon's South Pole-Aitken basin is among the highest priority activities for solar system science…A robotic lunar sample return mission has extensive feed forward to future sample return missions from other locations on the Moon as well as Mars and other bodies in the solar system." *Planetary Science Decadal*	• Radiation: Test radiation shielding; long duration radiation exposure • Reliability: Teleoperation from Lagrange Points • Operations/Operability: Mission Ops at Lagrange points

Heliophysics & Space Radiation

Leads: Justin C. Kasper, CfA; Bob MacDowall, GSFC; Joseph Lazio, JPL; Jack Burns, U. Colorado

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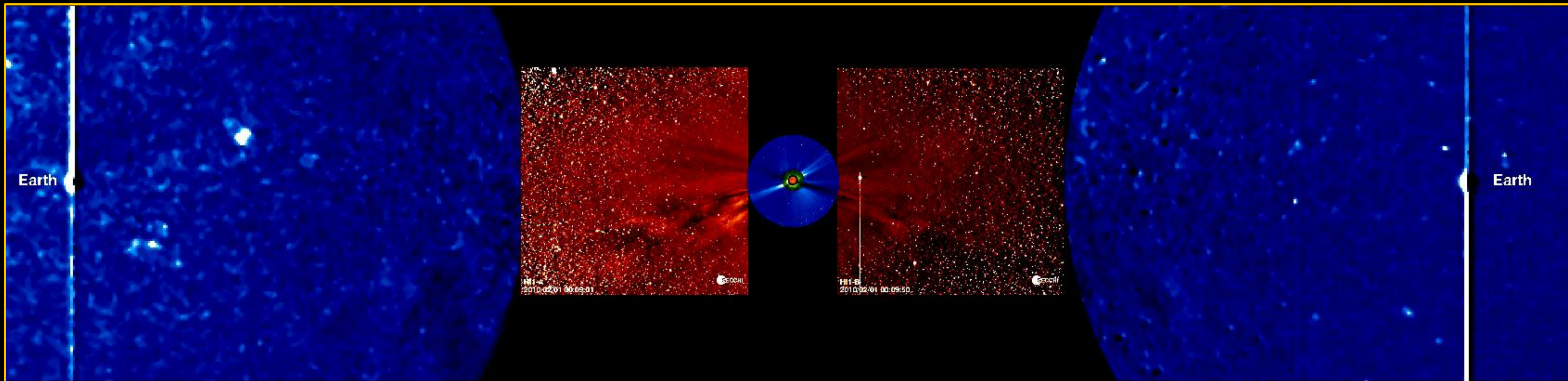
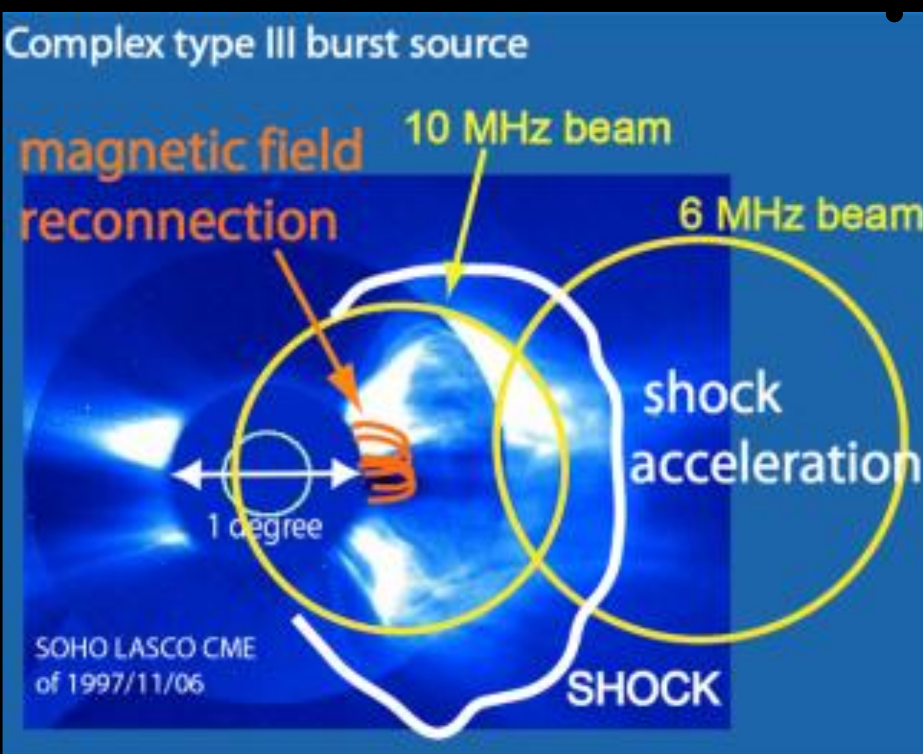
How are high energy particles accelerated in the Heliosphere?

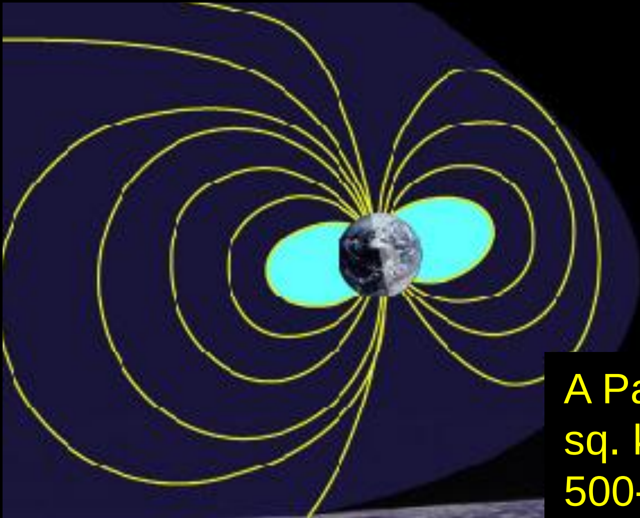




"Solar radio emission provides uniquely powerful sources of diagnostic information with the potential for transformational insights into solar activity and its terrestrial impacts."
NRC Decadal Report *Solar and Space Physics: A Science for a Technological Society*

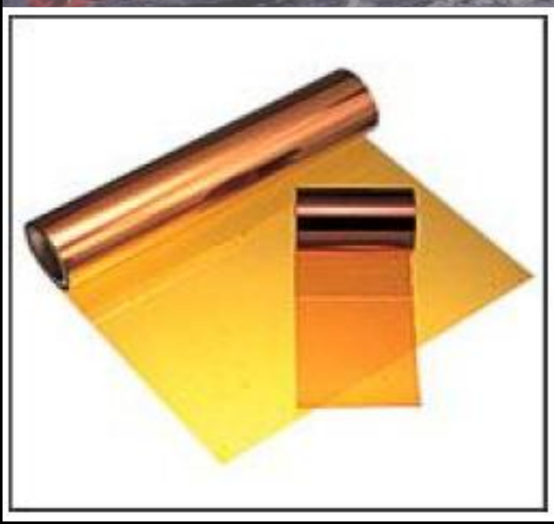
A low frequency radio array will produce the first resolved (≤2° at 10 MHz), high time resolution images of solar radio emissions (outer corona).

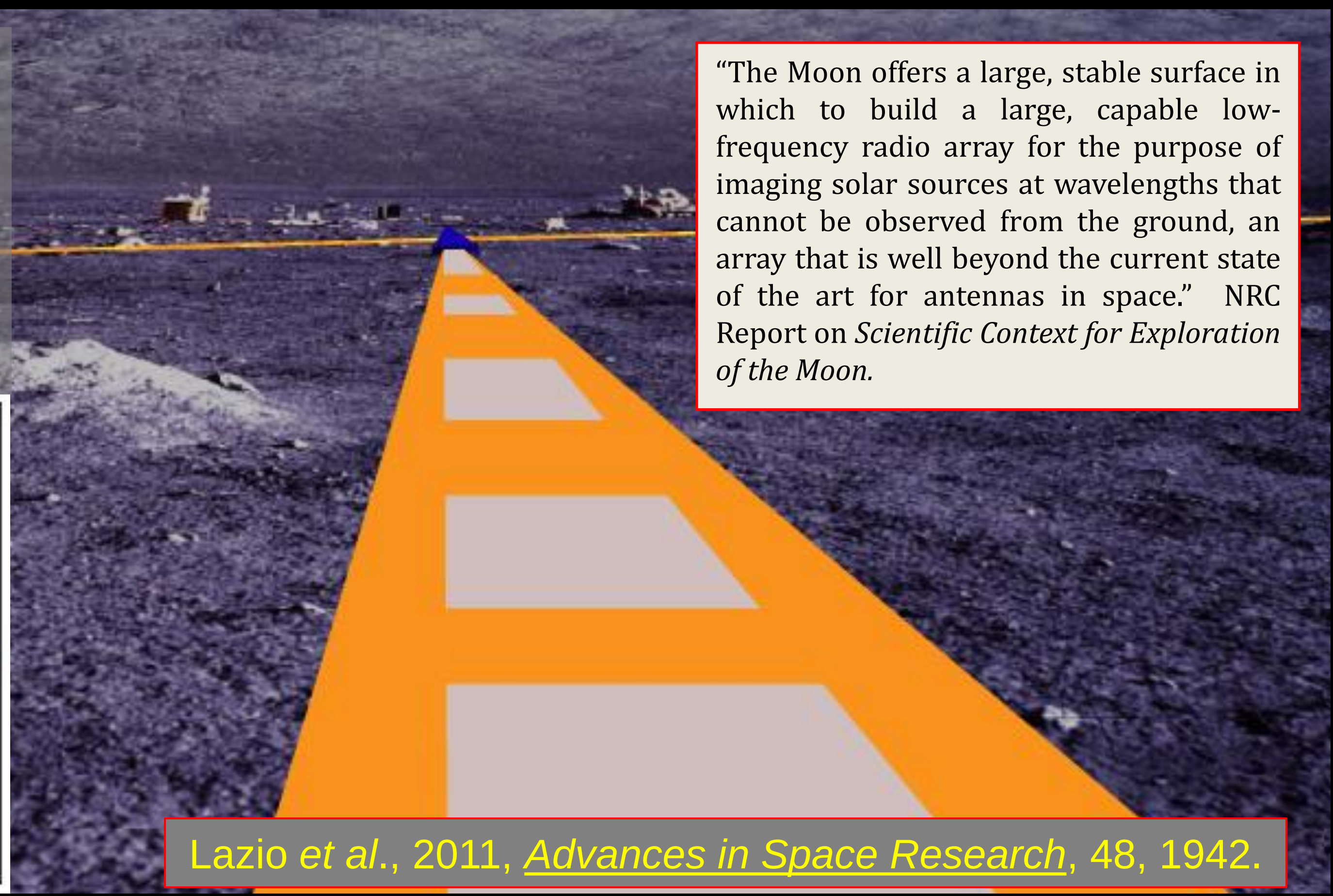
ROLSS: Radio Observatory on the Lunar Surface for Solar Studies



A Pathfinder for a future long-wavelength farside lunar array (10-100 sq. km). Operating at 1-10 MHz (30-300 m). Array consists of three 500-m long arms forming a Y; each arm has 16 antennas.

- Arms are thin polyimide film on which antennas & transmission lines are deposited.
- Arms are stored as 25-cm diameter x 1-m wide rolls (0.025 mm thickness).



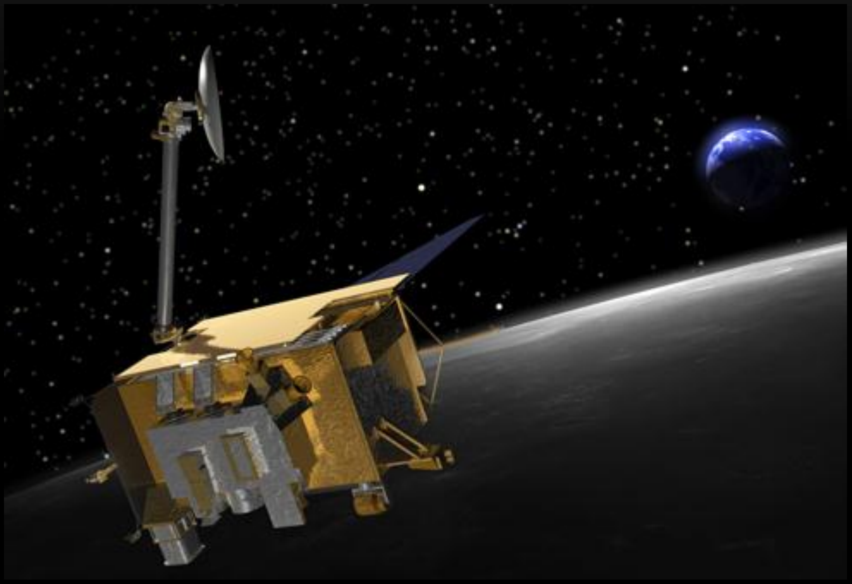


"The Moon offers a large, stable surface in which to build a large, capable low-frequency radio array for the purpose of imaging solar sources at wavelengths that cannot be observed from the ground, an array that is well beyond the current state of the art for antennas in space." NRC Report on *Scientific Context for Exploration of the Moon.*

Lazio *et al*., 2011, Advances in Space Research, 48, 1942.

MEASUREMENT OF RADIATION IN INTERPLANETARY SPACE

Example: CRaTER on LRO



=>Important to place similar instruments to measure radiation at E-M L2 and on lunar surface.

CRaTER investigation goals:

- Measure and characterize the deep space radiation environment in terms of LET spectra of galactic and solar cosmic rays (particularly above 10 MeV).
- Develop a novel instrument, steeped in flight heritage, that is simple, compact, and comparatively low-cost, but with sufficiently large geometric factor to measure LET spectra and its time variation in the lunar orbit.
- Investigate the effects of shielding by measuring LET spectra behind tissue-equivalent plastic.
- Test models of radiation effects and shielding by verifying/validating model predictions of LET spectra with LRO measurements.

Justin Kasper (CfA) is Co-I on CRaTER

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Gravitational Physics & the Lunar Interior via Lunar Laser Ranging

Leads: Douglas Currie, U. Maryland; Stephen Merkowitz, GSFC;

Thomas Murphy, UCSD

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Lunar Interior Science with LLR

- Core data set for lunar interior is the historical record of the librations. Most effectively obtained by obserivng all 5 retroreflectors in short period of time (which APOLLO can do). This cancels a number of systematic errors.

- Liquid Core: Fluid core moment of inertia is latest lunar geophysical parameter to emerge from LLR analysis.
  - For uniform liquid Fe core without an inner core, LLR predicts radius of 390±30 km.
  - For Fe-FeS eutectic, radius would be 415 km.

Librations of the Moon

"Deploying a global, long-lived network of geophysical instruments on the surface of the Moon to understand the nature and evolution of the lunar interior from the crust to the core…to determining the initial composition of the Moon and the Earth-Moon system, understanding early differentiation processes that occurred in the planets of the inner solar system". *Vision and Voyages for Planetary Science in the Decade 2013-2022*

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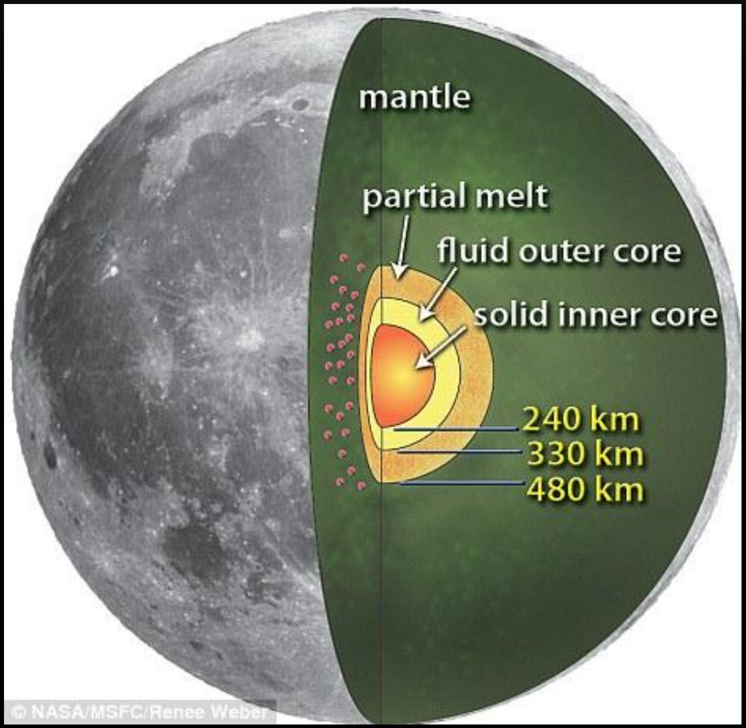
Lunar Interior Science with LLR

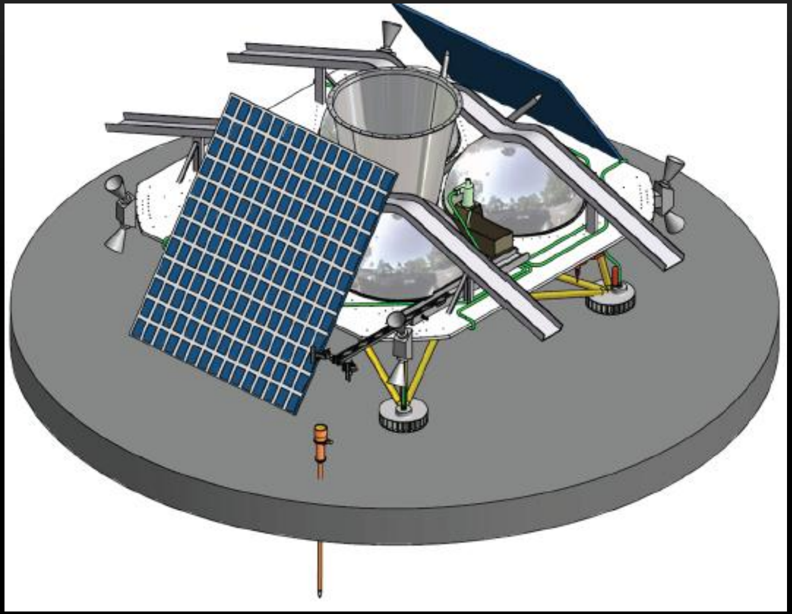
- Oblateness of the lunar core: detection of oblateness is independent evidence of fluid core. For 390 km core, difference between major & minor axes is ≈80 km.
- Search for a solid inner core: We expect the Moon has solid core interior to the fluid core, but it remains undetected. Using librations, this is a goal for next generation LLR with factor of 100 improvement in accuracy (~10 μm).
- GRAIL (in collaboration with Zuber & Smith) + LLR = map the Moon from the crust to the core. Constrain core boundary conditions & global crustal deformations.



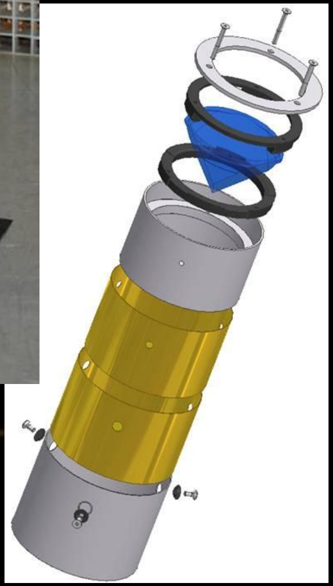
GRAVITATIONAL PHYSICS WITH LLR

"A new Lunar Laser Ranging (LLR) program, if conducted as a low cost robotic mission or an add-on to a manned mission to the Moon, offers a promising and cost-effective way to test general relativity and other theories of gravity." "These are tests of the core foundational principles of general relativity. Any detected violation would require a major revision of current theoretical understanding... The installation of new LLR retroreflectors to replace the 40 year old ones might provide such an opportunity."

NRC Decadal Report: *New Worlds, New Horizons in Astronomy & Astrophysics, Panel on Particle Astrophysics & Gravitation*



- For example, LLR places best limits on the fractional rate of change of Newton's Gravitational constant G (10^{-12}/yr).



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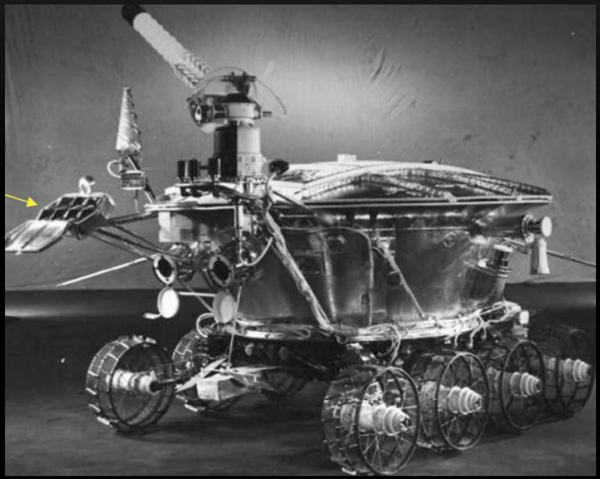
RECOVERY OF LUNOKHOD 1 RETROFLECTOR WITH APOLLO

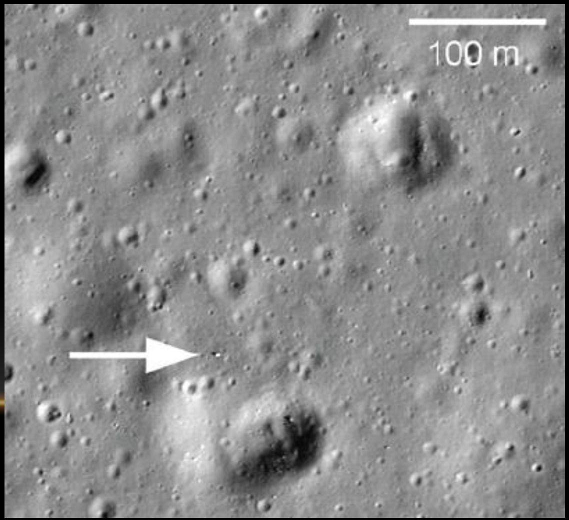
THOMAS MURPHY, UNIVERSITY OF CALIFORNIA, SAN DIEGO

Apache Point Observatory Lunar Laser-ranging Operation (APOLLO)



Lunokhod 1 Lander

- Offset was 40 m (270 ns) in projected range (100 m lateral), putting signal at edge of gate.
- Exploration: Selenographic coordinate system for Moon.
- Potential Science: Offers best leverage on libration determination => key for Center of Mass determination & lunar interior study.



LROC image of Lunokhod 1 site

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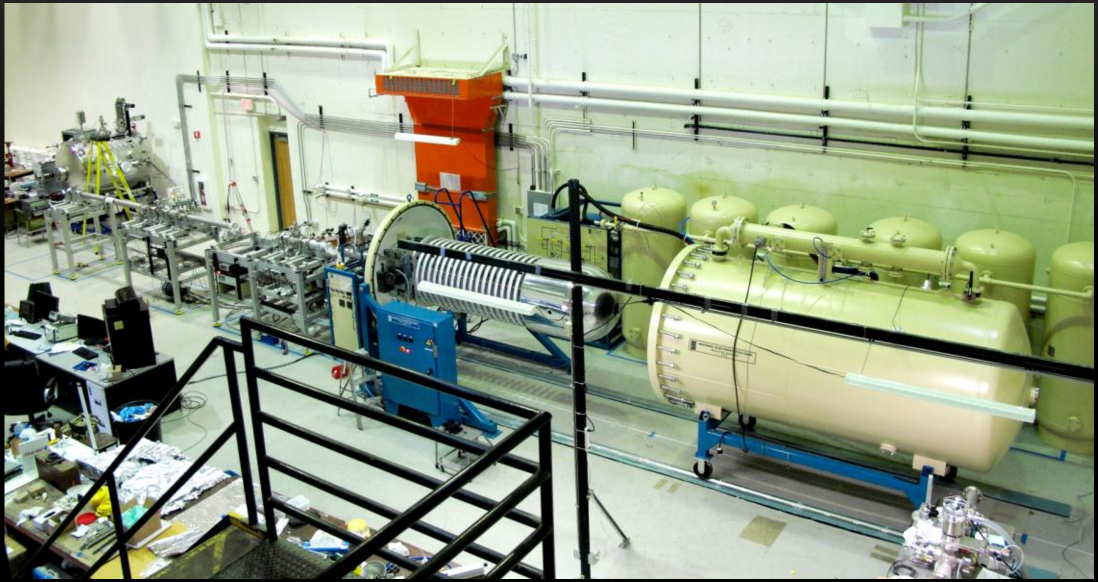
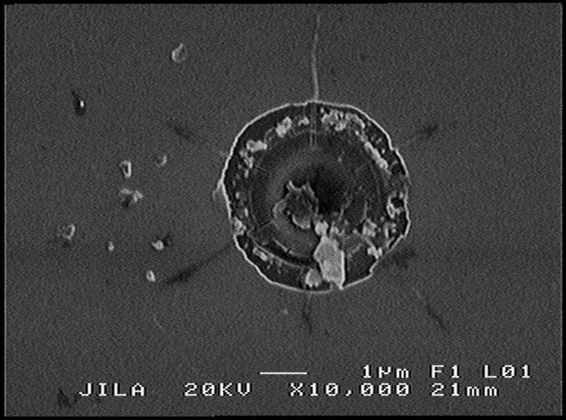
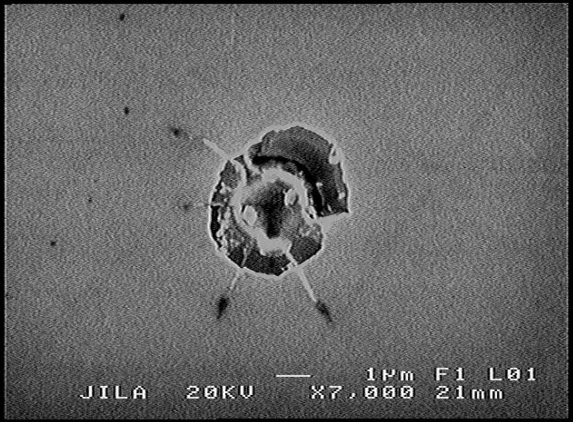
CCLDAS DUST ACCELERATOR AT U. COLORADO => DUST IMPACT EFFECTS ON RETROREFLECTOR OPTICS







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COLLABORATIONS WITH *MOON EXPRESS*

J. Lazio (JPL), J. Burns (Colorado), D. Currie (Maryland), Bob Richards (Moon Express), Alan Stern (Moon Express)

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Low Frequency Radio Science

Leads: Joseph Lazio, JPL; Jack Burns, U. Colorado; Judd Bowman, ASU; Richard Bradley, NRAO; S. Furlanetto, UCLA

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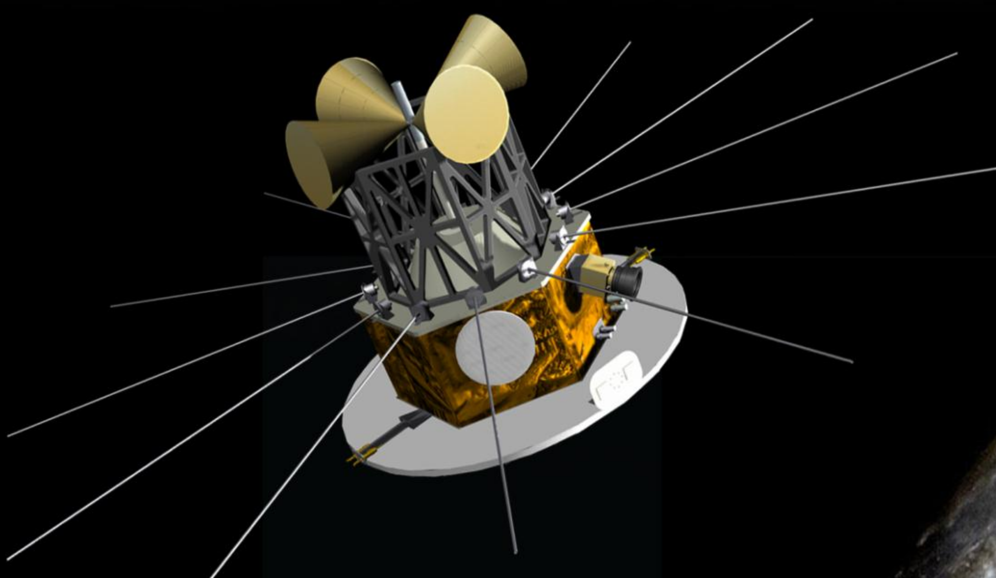
DARE

DARK AGES RADIO EXPLORER

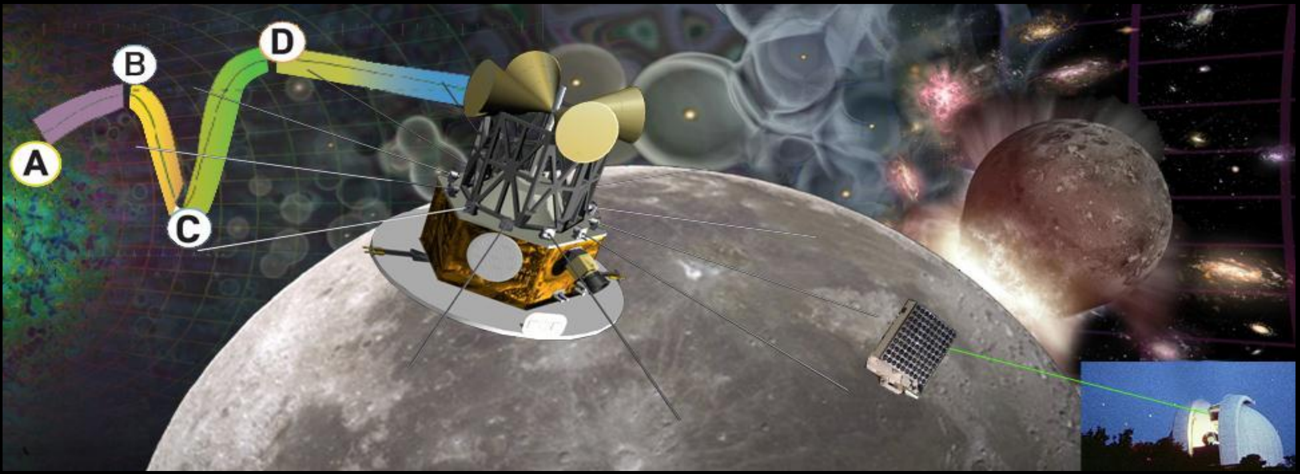


Burns *et al.*, 2012, Advances in Space Research, 49, 433.
http://lunar.colorado.edu/dare/

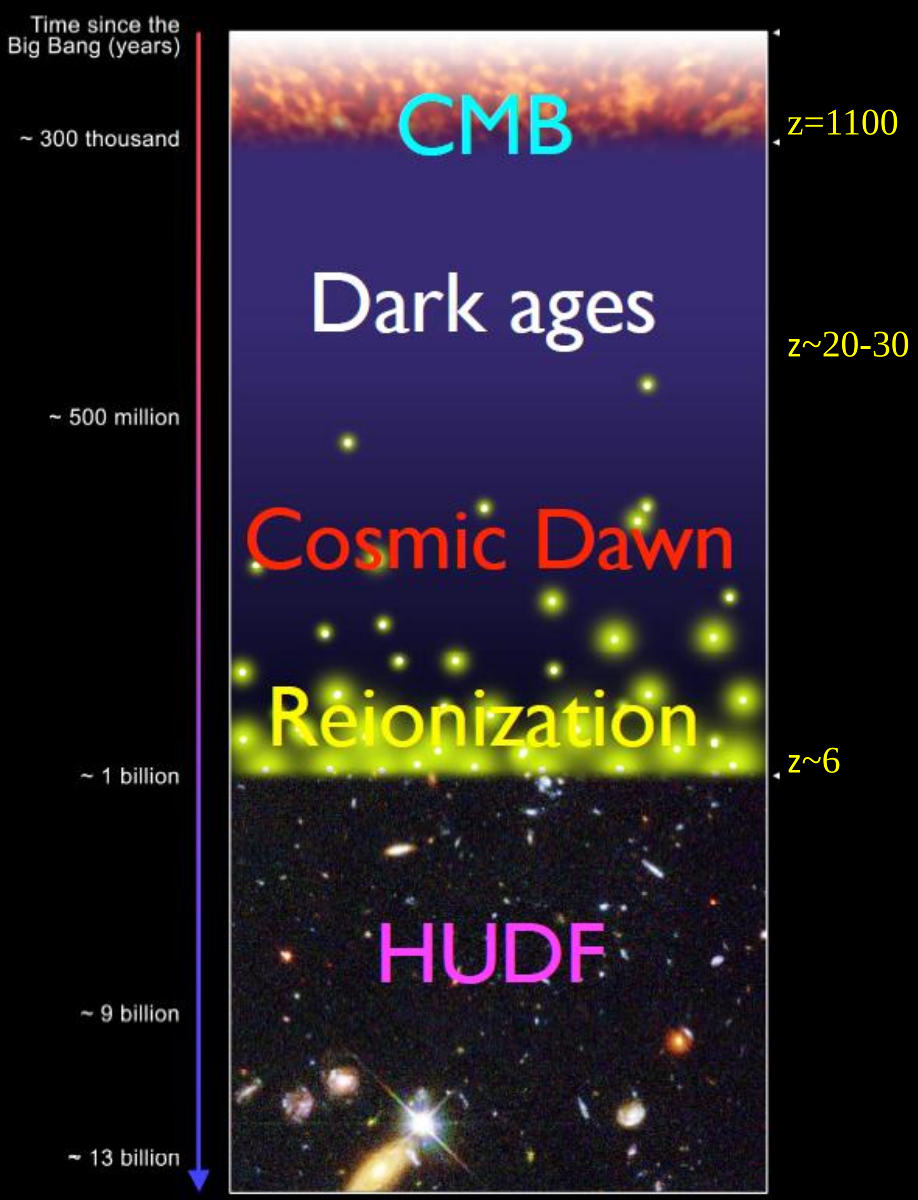
Astro 2010 identifies Cosmic Dawn as a top science objective: Searching for the First Stars, Galaxies & Black Holes

"A great mystery now confronts us: When and how did the first galaxies form out of cold clumps of hydrogen gas and start to shine—when was our cosmic dawn? Observations and calculations suggest that this phenomenon occurred when the universe was roughly half a billion years old, when light from the first stars was able to ionize the hydrogen gas in the universe from atoms into electrons and protons—a period known as the epoch of reionization… Astronomers must now search the sky for these infant galaxies and find out how they behaved and interacted with their surroundings." ***=> This is DARE's science!***

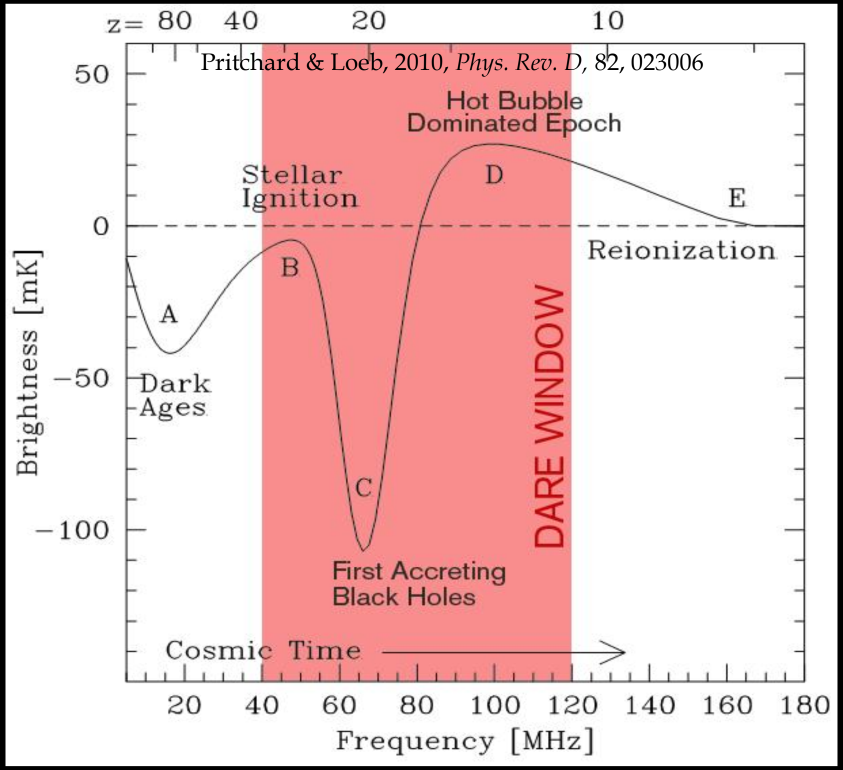
"What were the first objects to light up the Universe and when did they do?" We can uniquely address this mystery with DARE in lunar orbit (sky-averaged 21-cm spectrum) .



Cosmic Dawn: The First Stars & Galaxies



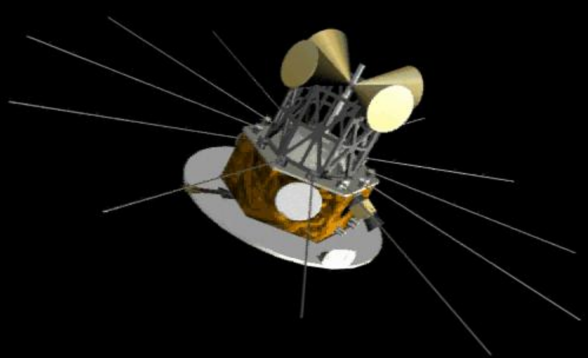
S.G. Djorgovski et al. & Digital Media Center, Caltech

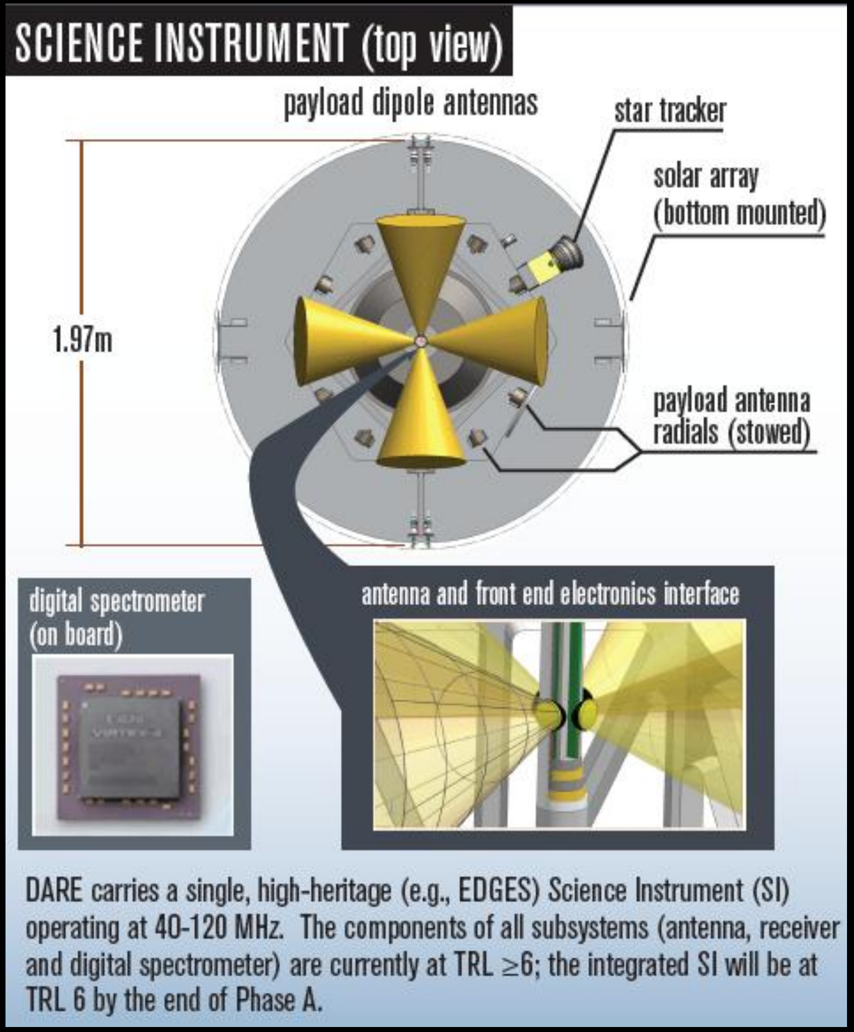


- Hyperfine transition of redshifted neutral hydrogen is only probe of this early epoch.
- Frequencies 40-120 MHz => need lunar farside to be free of RFI and ionospheric effects.
- “Turning Points” in above spectrum measure (1) ignition of first stars, (2) emission from first black holes, (3) beginning of reionization.

DARE Instrument

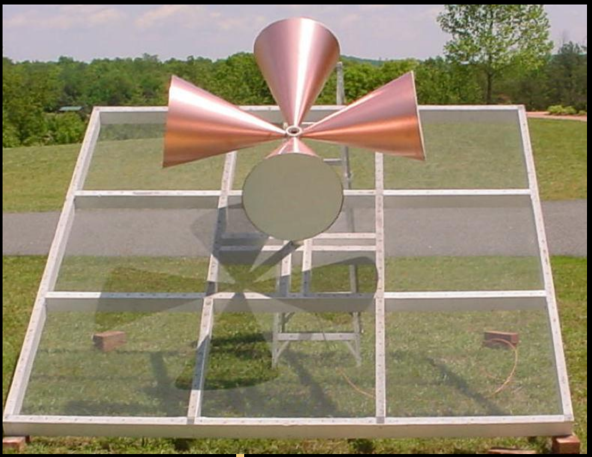
- DARE carries a single, high-heritage instrument operating at 40-120 MHz.
- Components of all three subsystems (antenna, receiver and spectrometer) are at TRL ≥ 6.
- Engineering prototypes have been constructed which will take the integrated instrument to TRL 6 by end of 2013.



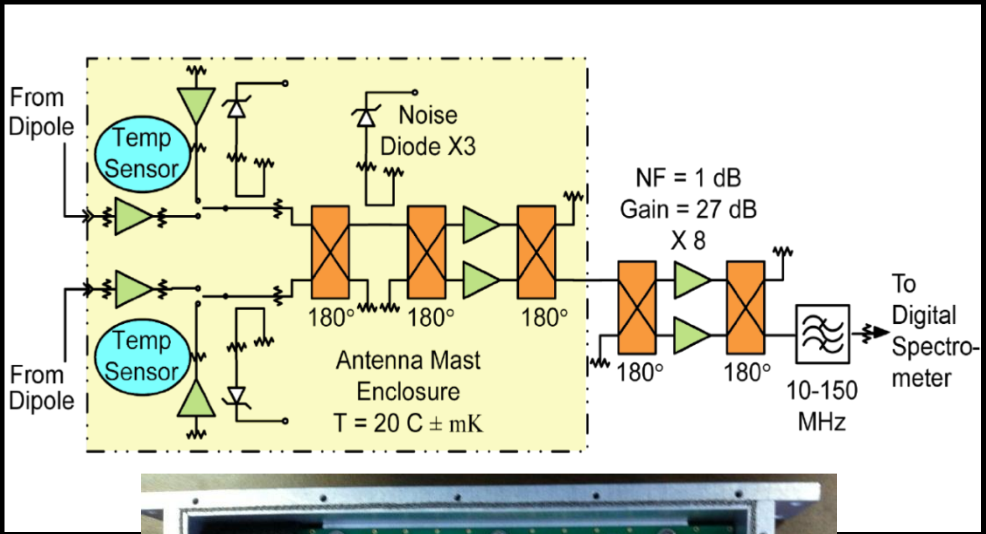


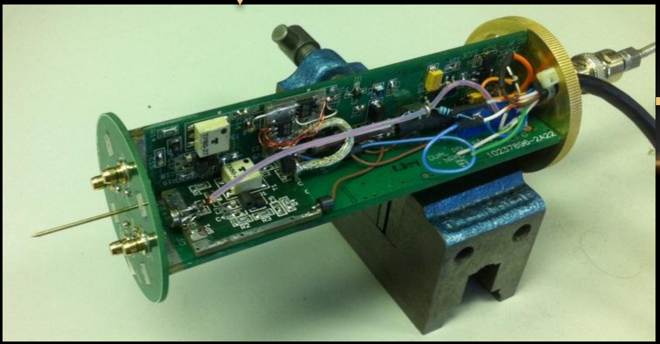
DARE ENGINEERING PROTOTYPE: COMPONENTS

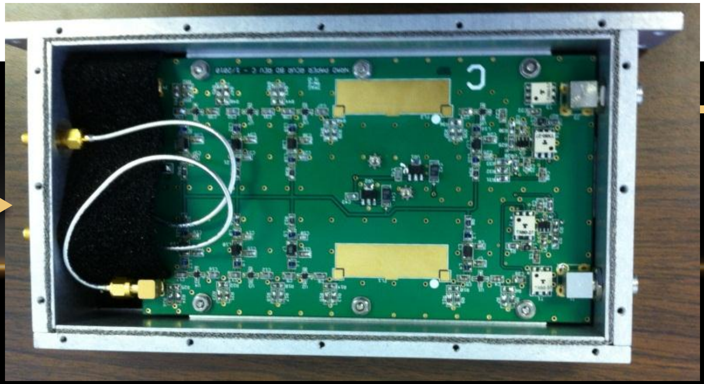
- DARE will operate at low radio frequencies between 40-120 MHz
- Components of all three subsystems (antenna, receiver and spectrometer) are at TRL ≥ 6
- Instrument Verification Program underway to have the integrated instrument at TRL 6

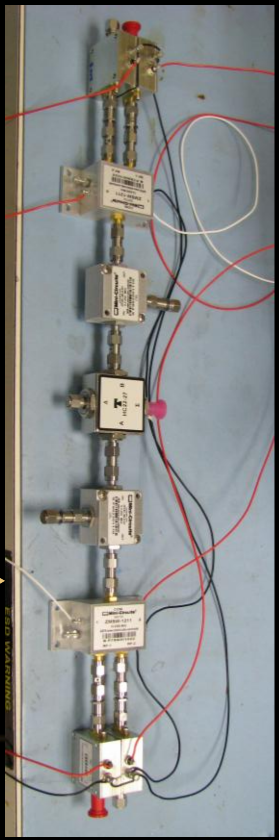


Antenna + BALUN (NRAO)





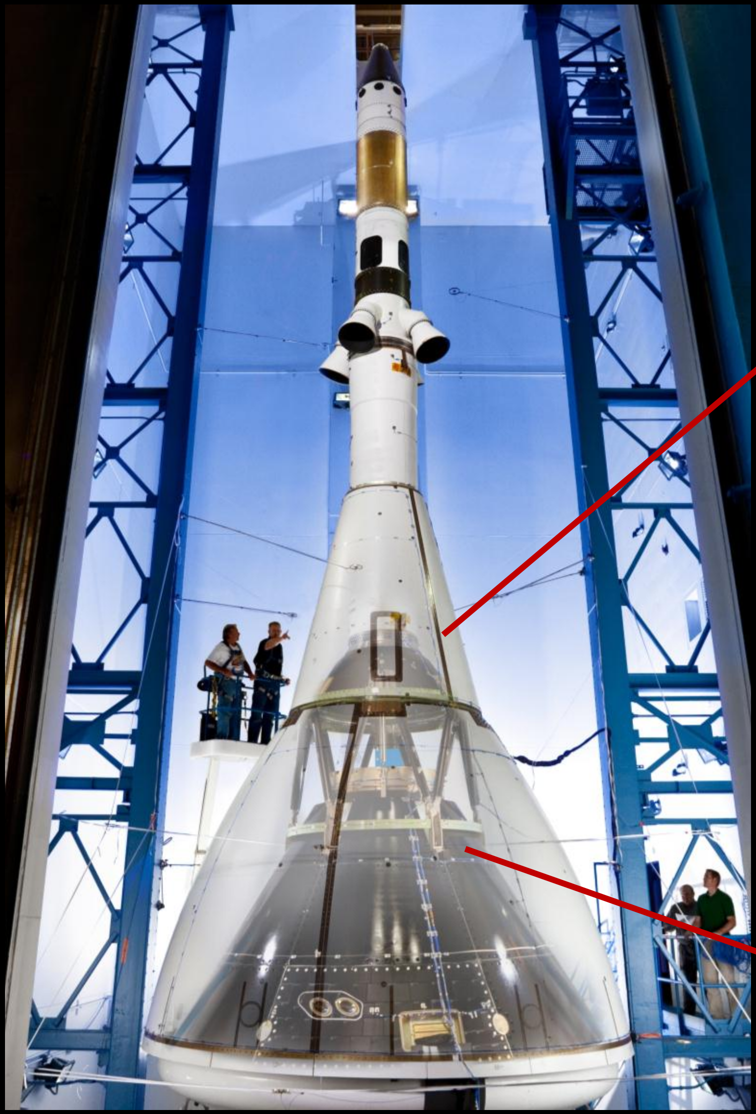


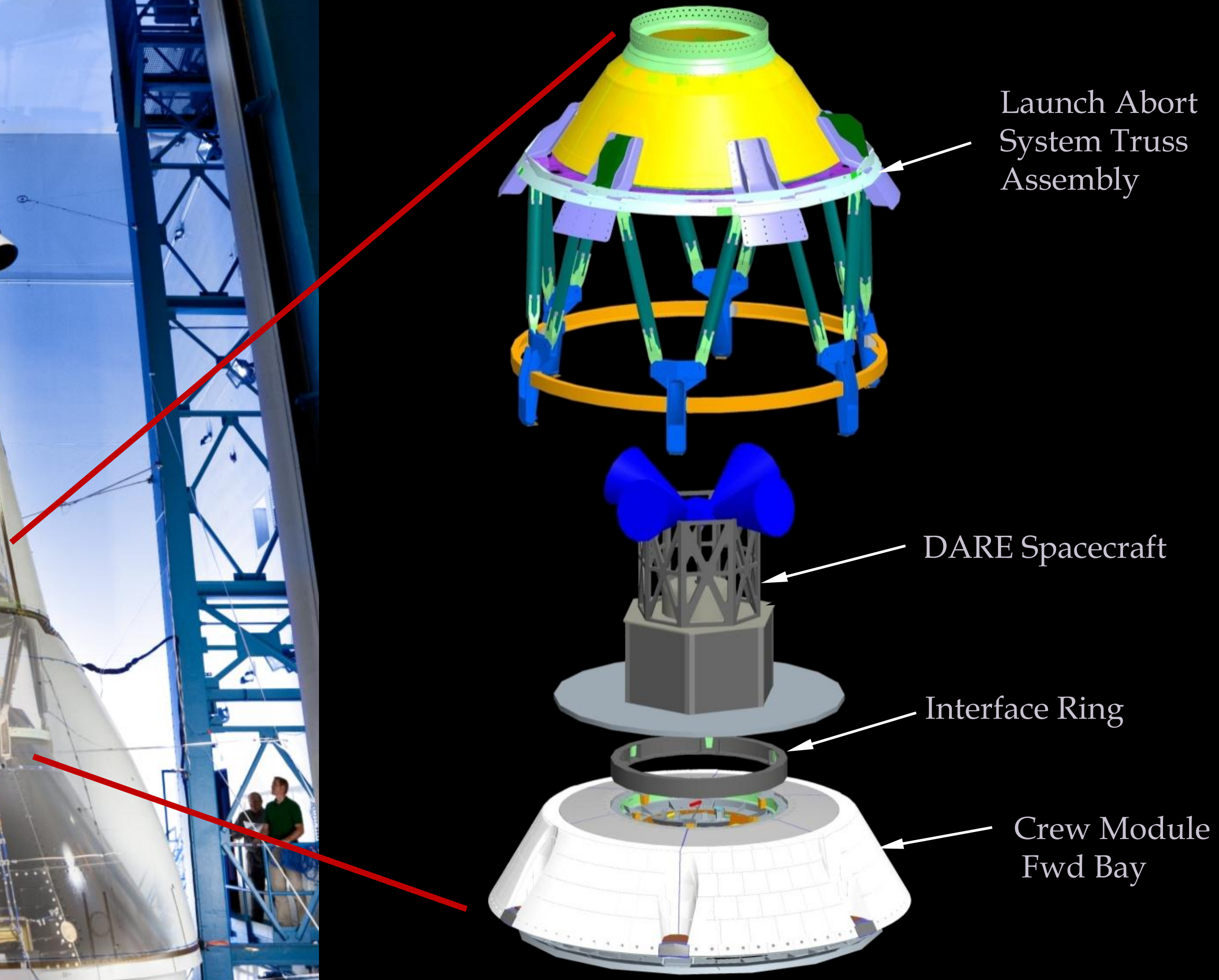


Front End Receiver (NRAO)

Digital Spectrometer (JPL)

Launch Option: Secondary Payload on 2017 Orion Test Flight





LUNAR Exploration Science

Leads: Jack Burns, U. Colorado; Joe Lazio, JPL/Caltech, Justin Kasper, CfA

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E-M L2-FARSIDE EXPLORATION AND SCIENCE MISSION CONCEPT

Jack Burns, U. Colorado Boulder & NLSI

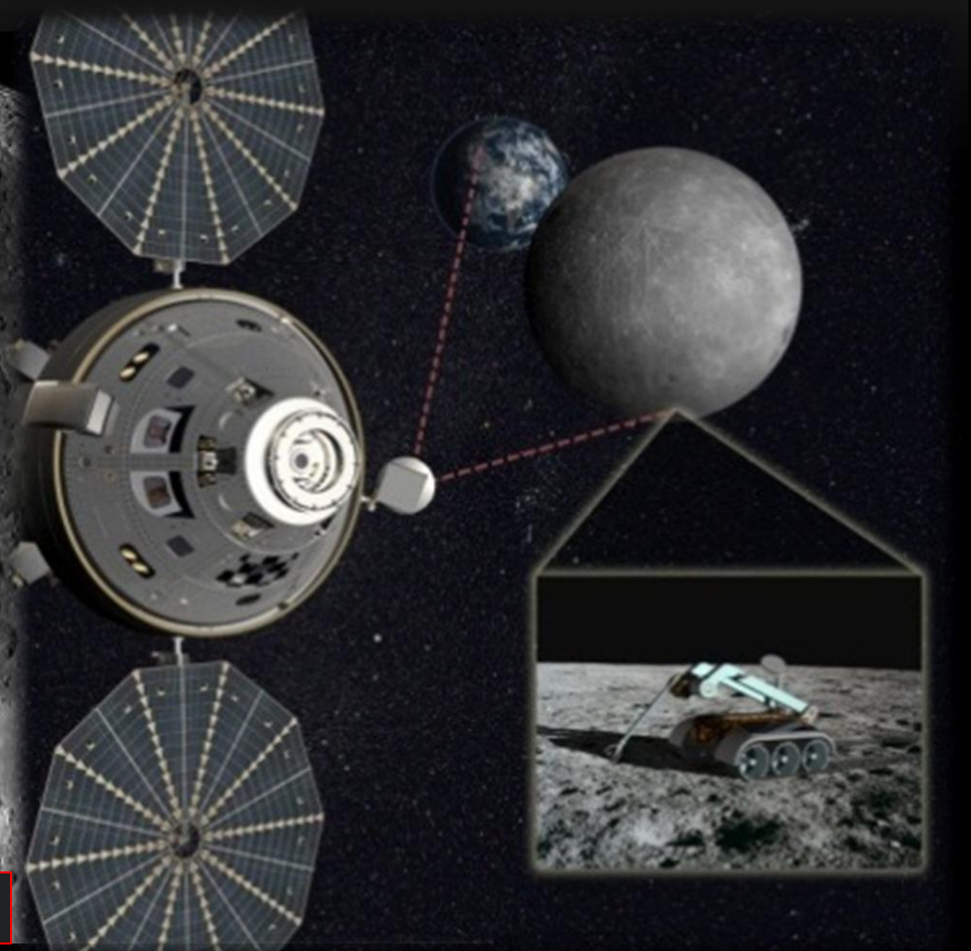
David Kring, Lunar & Planetary Institute & NLSI

Scott Norris, Lockheed Martin Space Systems

Josh Hopkins, Lockheed Martin Space Systems

Joseph Lazio, JPL/Caltech & NLSI

Justin Kasper, Harvard-Smithsonian Center for Astrophysics & NLSI



Burns *et al*., 2013, Advances in Space Research, in press.

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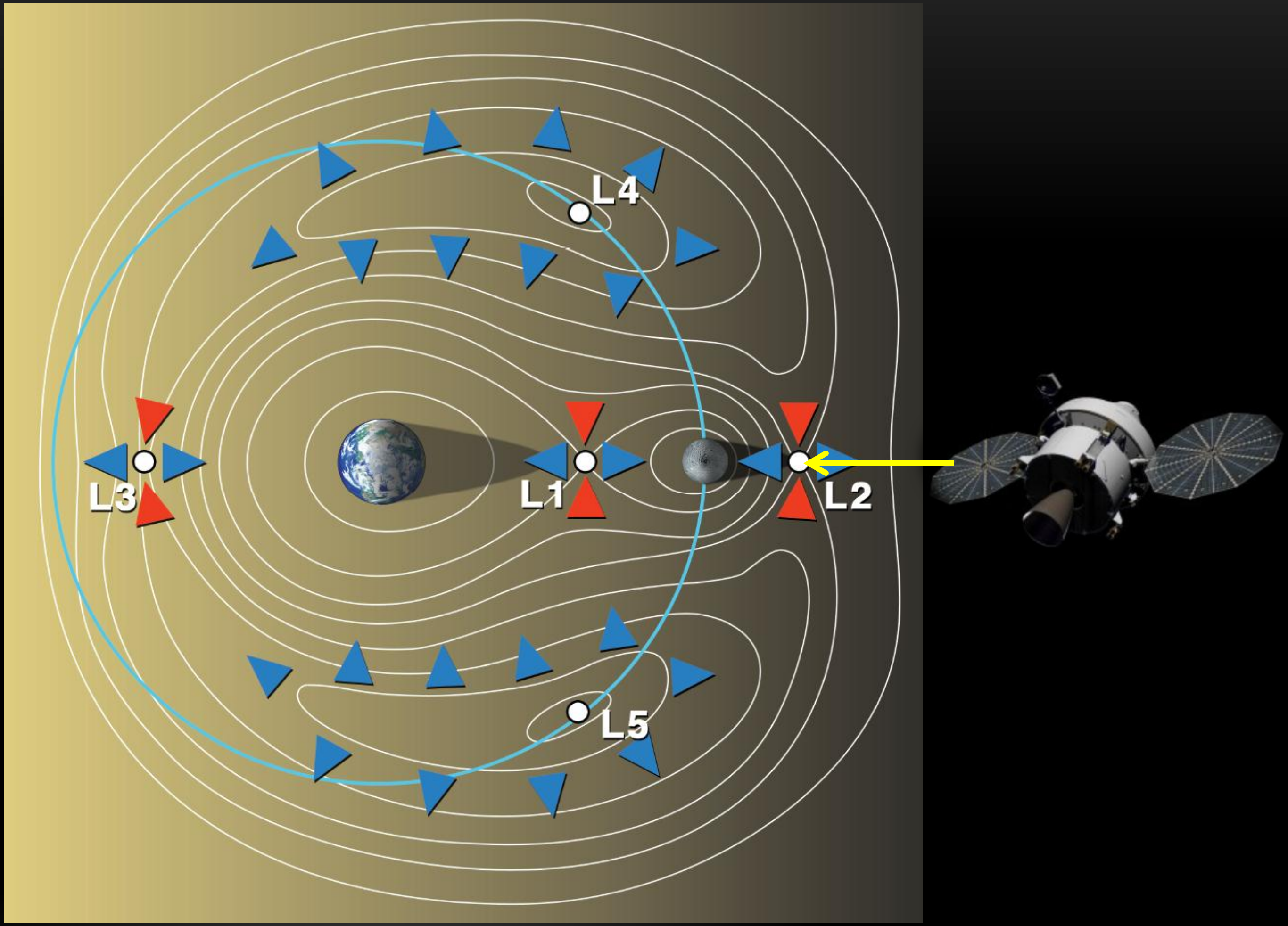
ORION CREW VEHICLE AT L2 WILL TELEOPERATE ROVER ON FARSIDE

- This mission is much less expensive than Apollo-style missions since no humans are on the lunar surface.
- Mission is affordable with NASA's current & notional outyear budgets.
- Timetable for first mission(s) is late in this decade.



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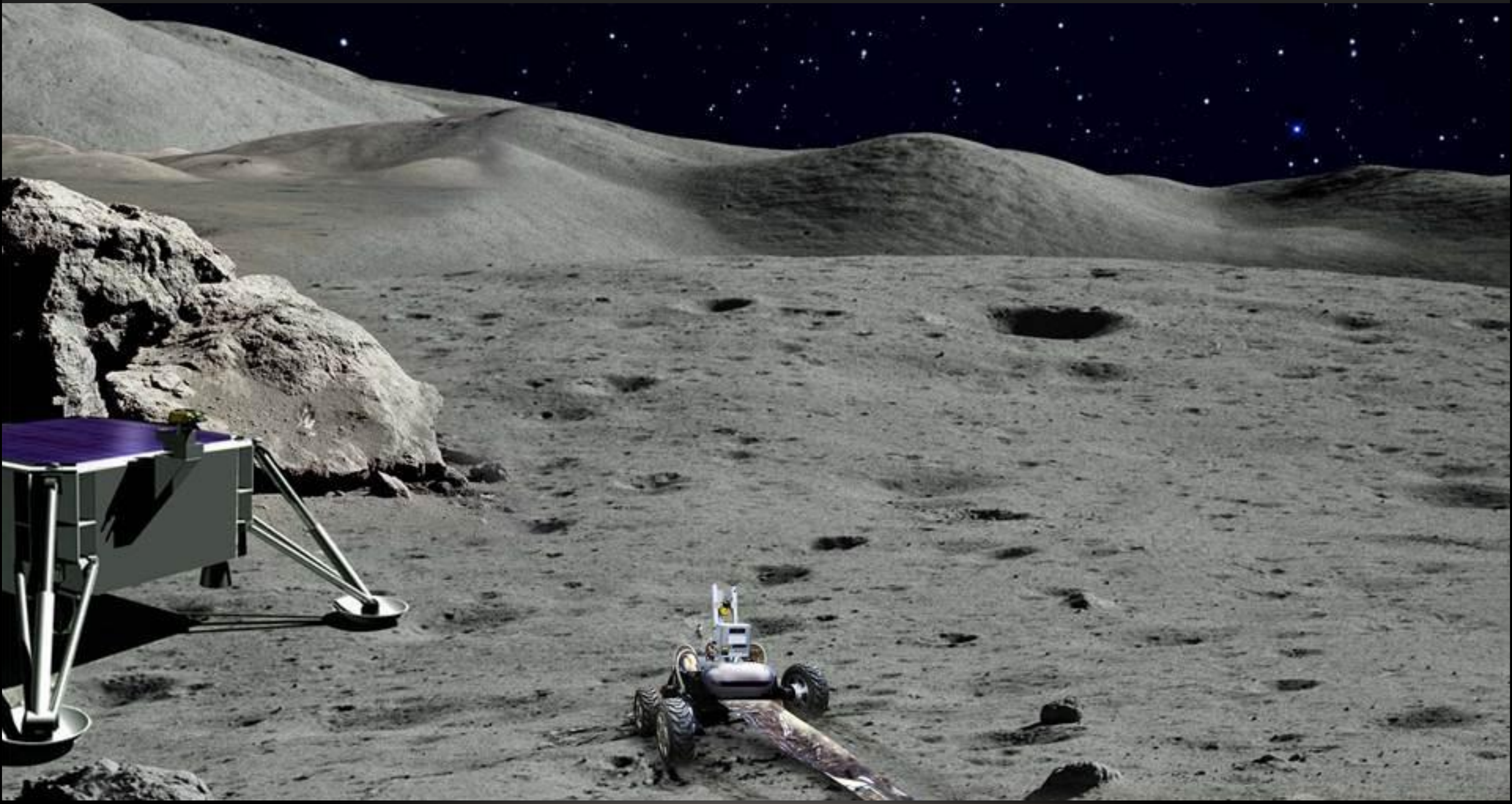
MISSION CONCEPT: ORION PRECEDED BY UNMANNED LANDER + ROVER TO FARSIDE SURFACE



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TELEROBOTIC GEOLOGICAL INVESTIGATION OF THE LUNAR FARSIDE

Science Goals

- *Highest priority*: test the lunar cataclysm hypothesis. Earth & Moon severely modified by swarm of asteroids 3.9-4.0 billion yrs ago.
- Determine age of oldest impact basin-forming event on Moon to anchor beginning of basin-forming epoch.
- Provide data on flux of impactors which may have been caused by major rearrangements of giant planets.
- Constraints on delivery of biogenic materials & environmental consequences of bombardment which may be linked to origin & evolution of life on Earth.

"The exploration and sample return from the Moon's South Pole-Aitken basin is among the highest priority activities for solar system science…A robotic lunar sample return mission has extensive feed forward to future sample return missions from other locations on the Moon as well as Mars and other bodies in the solar system."

NRC Decadal Report: *Vision and Voyages for Planetary Science in the Decade 2013-2022*

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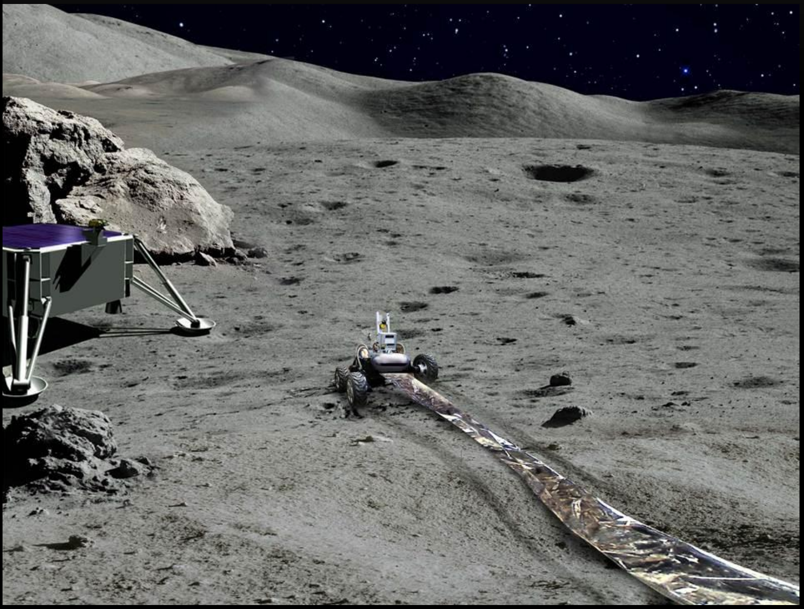
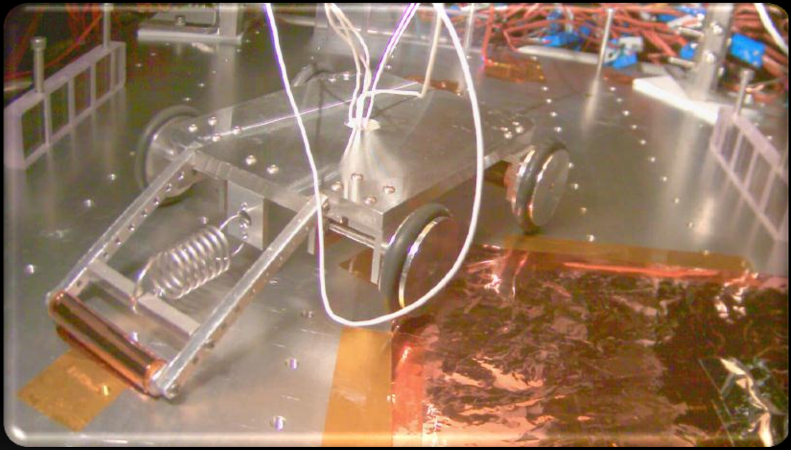
DEPLOYMENT OF KAPTON FILM ANTENNAS

- Metallic conductor deposited on surface of Kapton film.
- Unrolled, deployed by rover remotely operated from Orion on radio-quiet farside.
- Operate at $\nu < 100$ MHz.
- Film tested in vacuum chamber, with thermal cycling & UV exposure similar to lunar surface conditions, & in the field.



Artist's conception of roll-out Kapton film antenna on the Moon

Kapton antenna test in New Mexico



Rolling out Kapton film inside vacuum chamber with teleoperated mini-rover

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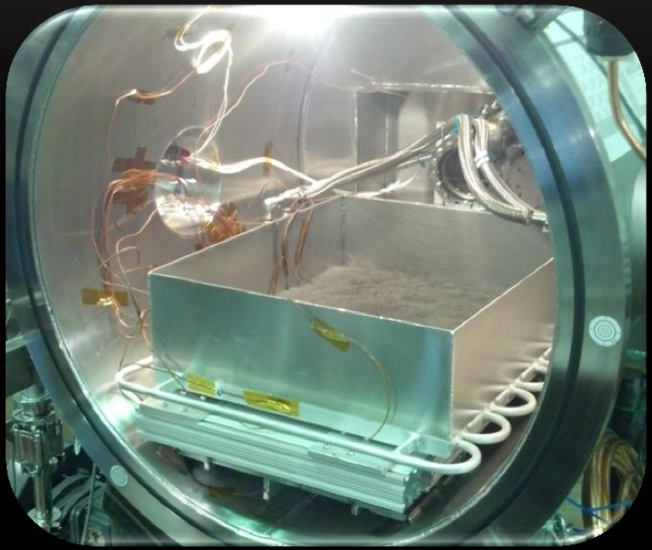
LUNAR & AIRLESS BODIES SIMULATION LABORATORY

UNIVERSITY OF COLORADO BOULDER



Simulation Capabilities

- Two vacuum chambers (10^{-7} Torr operating pressure)
- Thermal cycling between lunar night and day (-150°C to 100°C)
- UV deuterium lamp to mimic potentially damaging solar wavelengths (Lyα)
- Lunar simulant regolith bed of JSC-1
- Real time video feed and recording

Student-Lead Experiments

- Materials testing of Kapton
- Electronics survivability through the lunar night
- Thermal/survivability testing of a joint actuator from JPL's ATHLETE rover
- Student designed mini-rover and deployer

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TELEROBOTICS TESTS FROM THE ISS

Collaborators: T. Fong & M. Bualat, NASA Ames; J. Lazio, JPL
Student: L. Kruger, University of Colorado

- Demonstration of telerobotic deployment of Kapton film is scheduled using Ames K-10 rover and astronauts aboard International Space Station (ISS) in summer 2013.

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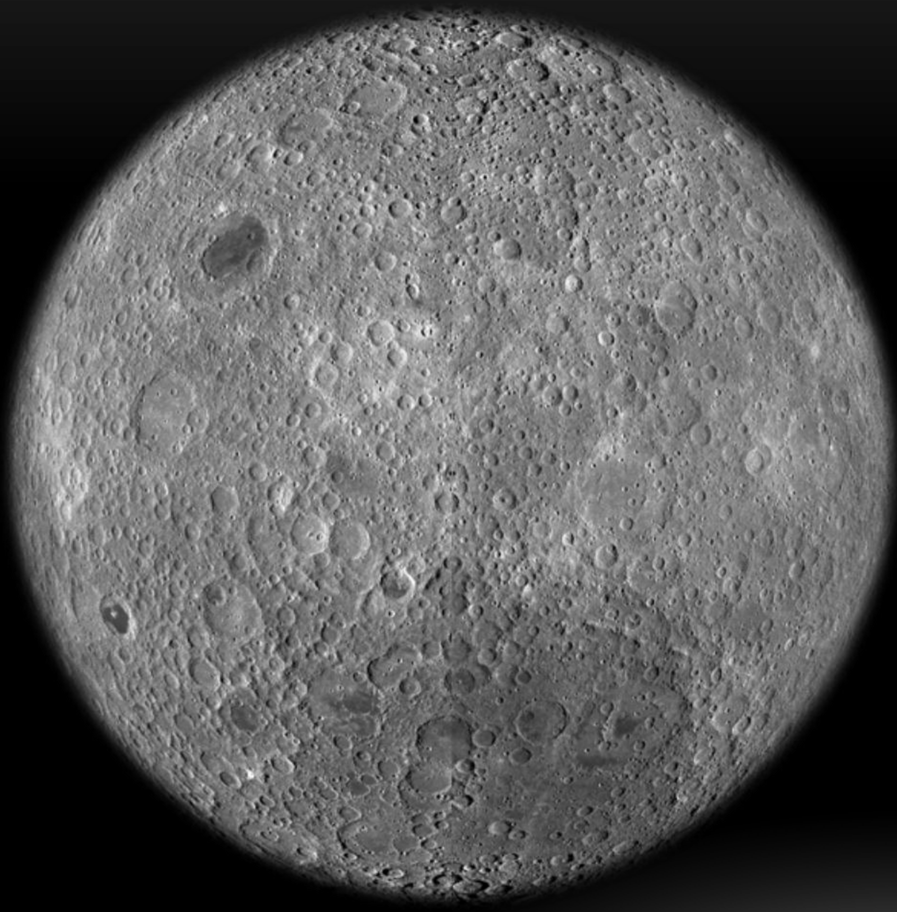
WHY EXPLORE THE LUNAR FARSIDE?



- A whole new, *unexplored* world in Earth's backyard!
- Opportunity to demonstrate human-robotic exploration strategies needed to explore surfaces of the Moon, asteroids, & Mars.
- Farside includes the South Pole-Aitken basin – possibly the largest, deepest, & oldest impact basin in the inner solar system.
- Farside always faces away from Earth and is, therefore, the only pristine radio-quiet site to pursue observations of the early Universe's *Cosmic Dawn*.

LUNAR COLLABORATIONS WITH NLSI TEAMS

- David Kring from *Center for Lunar Science and Exploration* Team, LPI – L2-Farside mission concept development.
- Maria Zuber from *The Moon as Cornerstone to the Terrestrial Planets: The Formative Years* Team, MIT – GRAIL + Lunar Laser Ranging: from crust to core.
- Bill Farrell from *Dynamic Response of the Environment at the Moon* Team, GSFC – Effects of Solar Wind on polyimide antennas (DC electric field).
- Mihaly Horanyi from *Colorado Center for Lunar Dust and Atmospheric Studies* Team, U. Colorado – Dust impacts on laser retroreflectors.

THE LUNAR TEAM

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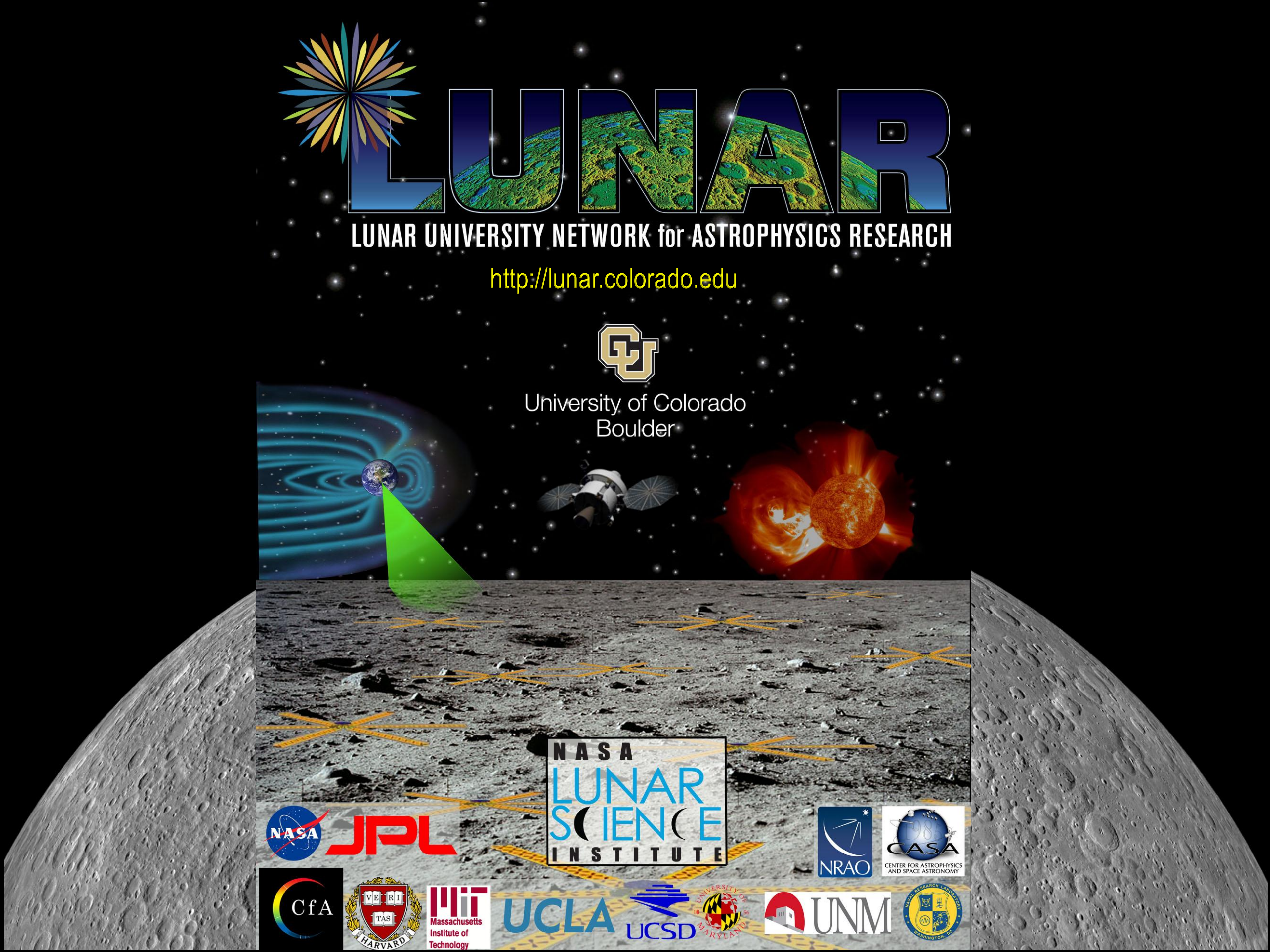
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UNM

ADDITIONAL SLIDES

Measuring the Lunar Ionosphere

"Planetary exospheres [on] the Moon, Mercury, asteroids, and some of the satellites of the giant planets, are poorly understood …. Insight into how they form, evolve, and interact with the space environment would greatly benefit from comparisons … on a diversity of bodies."

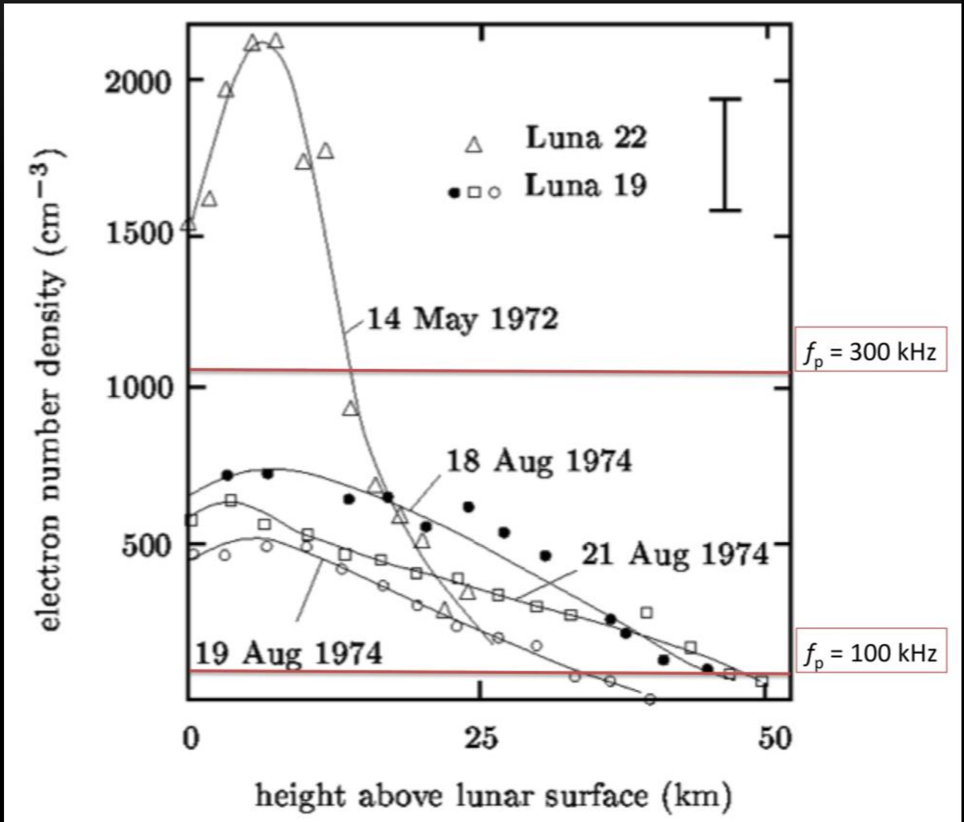
Visions and Voyages for Planetary Science

Provide lunar surface based method for tracking density of lunar exosphere.

- Electromagnetic waves below plasma frequency cannot propagate:

$$f_p = 9 \text{ kHz} \sqrt{n_e}$$

- Existing measurements suggest highly variable exosphere, both in density and altitude
  - 10^3 to 10^4 cm^{-3}
  - Up 10 km
- Spacecraft based measurements subject to (well-known) systematic errors



Lunar exosphere densities derived from radio occultation measurements with the Luna 19 and Luna 22 spacecraft (Vyshlov 1976; Vyshlov & Savich 1978). Horizontal lines show implied plasma frequencies.

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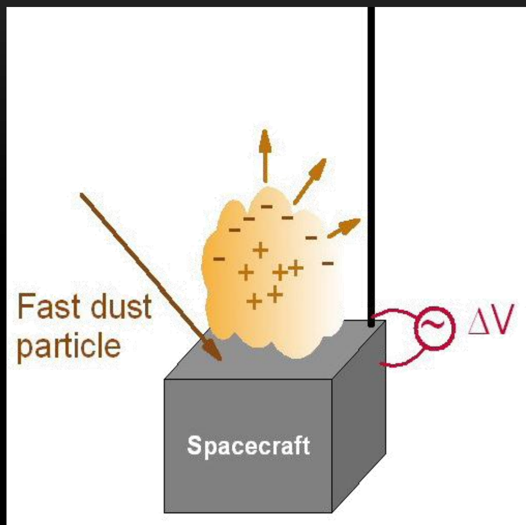
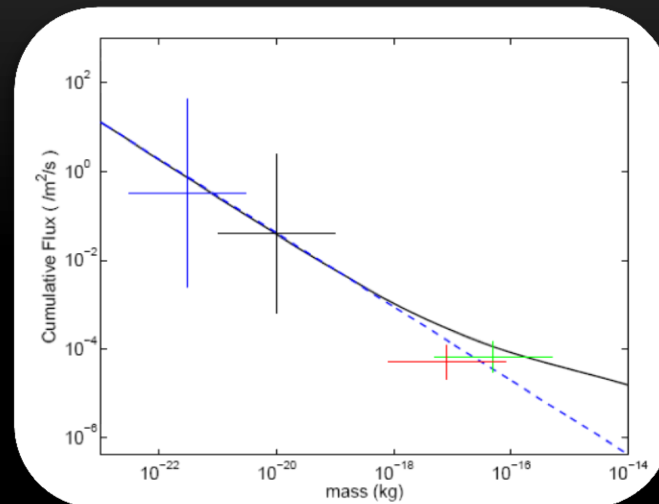
MEASUREMENT OF INTERPLANETARY NANODUST

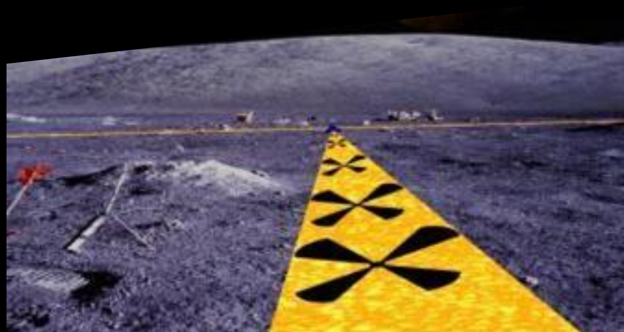
- Nanodust, moving at 100's km/s, may be key source of weathering on airless bodies.



Impact of nanodust grain triggers plasma cloud of electrons that register on radio antenna/receiver.



Flux measured by radio antenna is directly related to mass of dust grains (Zaslavsky et al. 2012, Planetary & Space Science, in press).



=> For a lunar radio array with three arms of 500 m length, width on the arms of 1 m, total surface area is 1500 m^2 which would yield ~1500 impacts/s for nanodust.

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