ASTROPHYSICS FROM THE MOON

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JILA Astrophysics Lunch Seminar
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National Space Exploration Policy, Authorized by Congress

- Complete the International Space Station
- Safely fly the Space Shuttle until 2010
- Develop and fly the Crew Exploration Vehicle (Orion) no later than 2014
- Return to the Moon no later than 2020
- Extend human presence across the solar system and beyond
- Implement a sustained and affordable human and robotic program
- Develop supporting innovative technologies, knowledge, and infrastructures
- Promote international and commercial participation in exploration

NASA Authorization Act of 2005

The Administrator shall establish a program to develop a sustained human presence on the Moon, including a robust precursor program to promote exploration, science, commerce and U.S. preeminence in space, and as a stepping stone to future exploration of Mars and other destinations.
Components of the Constellation Program

- **Ares V** - Heavy Lift Launch Vehicle
- **Ares I** - Crew Launch Vehicle
- **Orion** - Crew Exploration Vehicle
- **Earth Departure Stage**
- **Lunar Lander**
Exploring the Cosmos From the Moon
• “Extraordinary radio-quiet of lunar farside” would be a “powerful tool to investigate the *Dark Ages* of the Universe … in highly redshifted signals from neutral hydrogen”.

• Imperative to subject Einstein’s model of gravity to the utmost scrutiny. Lunar laser ranging is on the frontline of such tests.
The Universe In Transition

From the CMB

WMAP

400,000 yrs after Big Bang

The Dark Ages

Today

Recombination (400,000 yrs)

Reionization & 1st stars (~10^9 yrs)

To

Clusters Of Galaxies

HST
Light From a Dark Age

How the universe grew from dark soup to twinkling galaxies

Looking for the beginning of time...

About 13.7 billion years ago, the universe burst into existence, creating both space and time.

Gravitational lens

Inflation era

Billions of years since the start of the universe

Half a billion years after the Big Bang, temperatures had fallen so low that the cosmos went dark. Half a billion years later, baby galaxies had begun to shine. What happened in between laid the foundations for the modern universe.

Inside the Dark Era

The Dark Ages Begin

When the cosmos is about 400,000 years old, it has cooled to about the temperature of the surface of the Sun, allowing subatomic particles to combine for the first time into elements. The first burst of light from this Big Bang shines forth at this time. It is still detectable today in the form of a faint whisper of microwaves streaming in from all directions in space. The discovery of these microwaves in 1964 confirmed the existence of the Big Bang.

The earliest stars were extremely large and dense, weighing at 50 to 100 times the mass of the Sun, and more. The crushing pressures at their cores made them burn through their nuclear fuel in only a million years or so, and caused them to spew out such intense radiation that it kept other stars from forming. The first "galaxies" may have consisted of clouds of hydrogen and helium surrounding just one "star.

The death of the first stars triggered the formation of fewer stars, creating the first normal-looking dwarf galaxies. Their radiation in turn burned through the remaining clouds of hydrogen, bringing the dark ages to an end.

What they’re really seeing

Richard Ellis of CalTech has found distant galaxies warped into odd, elongated shapes, as though they were being glimpsed through a cosmic farhouse mirror. The light from these galaxies could ordinarily never be glimpsed through existing telescopes.
Reionization and the Dark Ages

Time since the Big Bang (years)

- ~400,000
- ~500 million
- ~1 billion
- ~9 billion
- ~13.7 billion

Fluctuations are at about 10 mK
Hydrogen

Excitation rate = (atomic collisions) + (radiative coupling to CMB)

Couple $T_s$ to $T_k$

Couples $T_s$ to $T_{\text{CMB}}$

Predicted by Van de Hulst in 1944; Observed by Ewen & Purcell in 1951 at Harvard

$n_1/n_0 = g_1/g_0 \exp(-T_*/T_s)$ where $g_1/g_0=3$, $T_* = 0.068$ K

21 (1+z) cm = 1420/(1+z) MHz

At z=10, $\lambda = 2.3$ m (130 MHz)
At z=50, $\lambda = 10.7$ m (30 MHz)
21cm Tomography of Ionized Bubbles During Reionization is like **Slicing Swiss Cheese**

*Observed wavelength ↔ distance*

21cm (1+z)

(Loeb, 2006, astro-ph/063360)
Primary Challenge for Earth Arrays: Foregrounds

- Terrestrial: radio broadcasting & digital TV
- Ionospheric distortions
- Galactic synchrotron emission
- Extragalactic: radio sources
  \((\text{Di-Matteo et al. 2004})\)
Lunar Advantage: No Interference

100 MHz
z=13

200 MHz
z=6

Destination: Moon!
Remaining challenge: Low Frequency Foreground

- Coldest regions: $T = 100 \left(\nu/200 \text{ MHz}\right)^{-2.7} \text{ K}$
- Highly ‘confused’: 3 sources/arcmin$^2$ with $S_{0.2} > 0.1$ mJy

Solution: fitting in the spectral domain
The Global (sky-averaged) HI Signal

\[ \Delta T_{\text{min}} = \frac{T_{\text{sys}}}{(\Delta \nu \cdot t)^{1/2}} \]

where \( T_{\text{sys}} \) = sky temperature \( \sim 17,000 \text{ K} \) at 30 MHz

Gas heated above CMB by x-rays

Cosmic Twilight Ly\( \alpha \) flood from Pop III stars (Wouthuysen-Field Effect)

collisions, gas cools faster than CMB

Global signal can be detected by single dipole in orbit above lunar farside!

LADEE = Lunar Atmosphere & Dust Environmental Explorer

Jester & Falcke, 2008, *New Astronomy Reviews*

1 yr integration with Sky-noise limited dipole

\( (T_{\text{obs}} - T_{\text{for}})/T_{\text{for}} \times 10^{-6} \)
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).
Laboratory Testing of Polyimide Film as Low Frequency Antenna Backbone

Experimental Set-up

- 12 24-hr duty cycles with $T = -150 \, ^\circ C$ to $100 \, ^\circ C$.
- Exposed to UV with deuterium lamp during “day cycle”.

Results

- No significant change in material or electrical characteristics during thermal cycling.

In collaboration with Ted Schultz and Bobby Kane, CU CASA
• ROLSS will produce the first high angular resolution (<1° at 10 MHz), high time resolution images of solar radio emissions (outer corona).
• ROLSS will study how high energy particles are generated on the Sun. This radiation is a danger to future astronauts.
Dark Ages Lunar Interferometer (DALI)

**DALI concept.** *(Left, upper right)*: Possible location in the Tsiolkovsky crater. *(Upper right insert)*: Artist’s concept of lander; DALI would have pallets of rovers instead of an astronaut habitat module. *(Lower right)*: Individual station contains ~100 electrically-short dipoles. ~1000 stations are planned.
Big Questions in Cosmology that DALI may help to answer

- What is the correct theory of inflation (deviations from Gaussianity in 21-cm power spectrum)?
- What is Dark Energy and how does it evolve in time?
- Were there “exotic” heating mechanisms, such as Dark Matter decay, that occurred before the first stars formed?
- How did matter assemble into the first galaxies, stars, and black holes?
Constraints on Gravitational Physics: Lunar Laser Ranging

Current Capabilities

- Accuracy ≈ 1 mm.
- Strong Equivalence principle $\eta < 4.5 \times 10^{-4}$.
- $\dot{G}/G < 10^{-12}$ per year.
- Deviation from inverse-square law is $< 10^{-10}$ times strength of gravity at $10^8$ m scales.

Lead Scientists: T. Murphy, D. Currie, S. Merkowitz
Dark Energy or Alternative Gravity

- Currently envisioned to be addressed by wide-field observations from free space (JDEM).

\[ H^2 - \frac{H}{r_c} = \frac{8\pi}{3} G_N (\rho + \rho_{DE}) \]

- Can be tested by experiments on the lunar surface; laboratory and accelerator experiments.
Next-Generation Laser Retroreflector Array for the Moon

Capabilities

- Reduce temporal spread by a sparse arrangement of corner cubes.
- Accuracy goal = 10 μm which improves limits on gravity by factor of 1000.
- Goal is to constrain covariant version of MOND (TeVeS), new non-metric forms of gravity, & Moon’s liquid core.
Ares V enables a fully deployed 8-m or folded, segmented 15 - 20m telescope to be deployed in a single launch.

Without Ares V, multiple launches, complex folded optics, and/or on-orbit assembly would be the only alternatives for deploying space telescopes larger than ~7-m.
• DALI & ROLSS will observe the low frequency Universe from the Moon: the Dark Ages and solar coronal mass ejections.

• Gravity models will be tested with new fidelity using a next-generation lunar laser retroreflector array.

• Ares V presents opportunity to launch large aperture telescopes to L2 and the lunar surface.