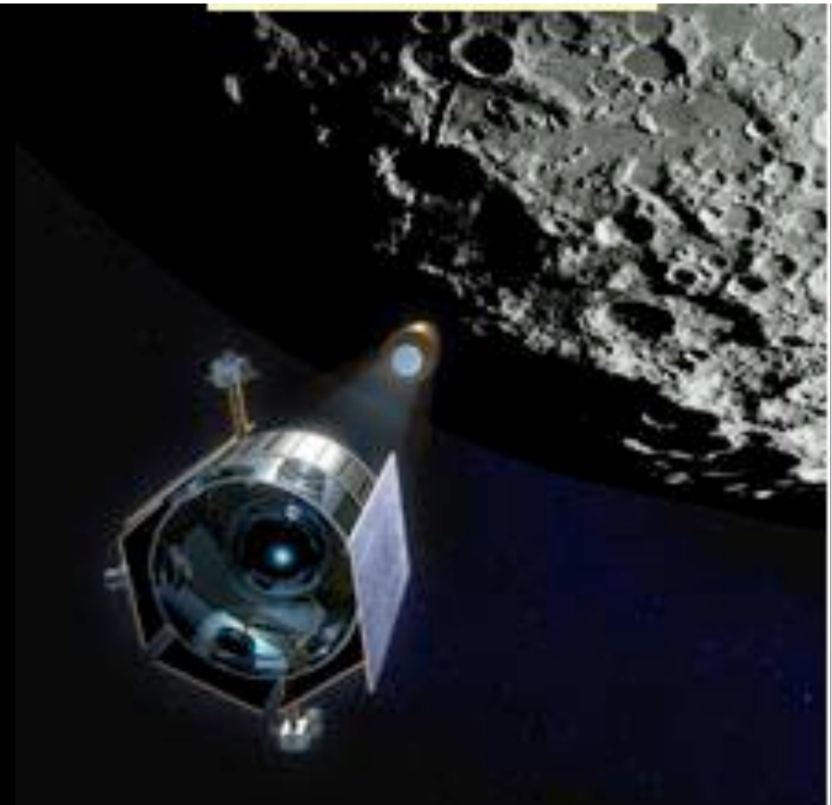
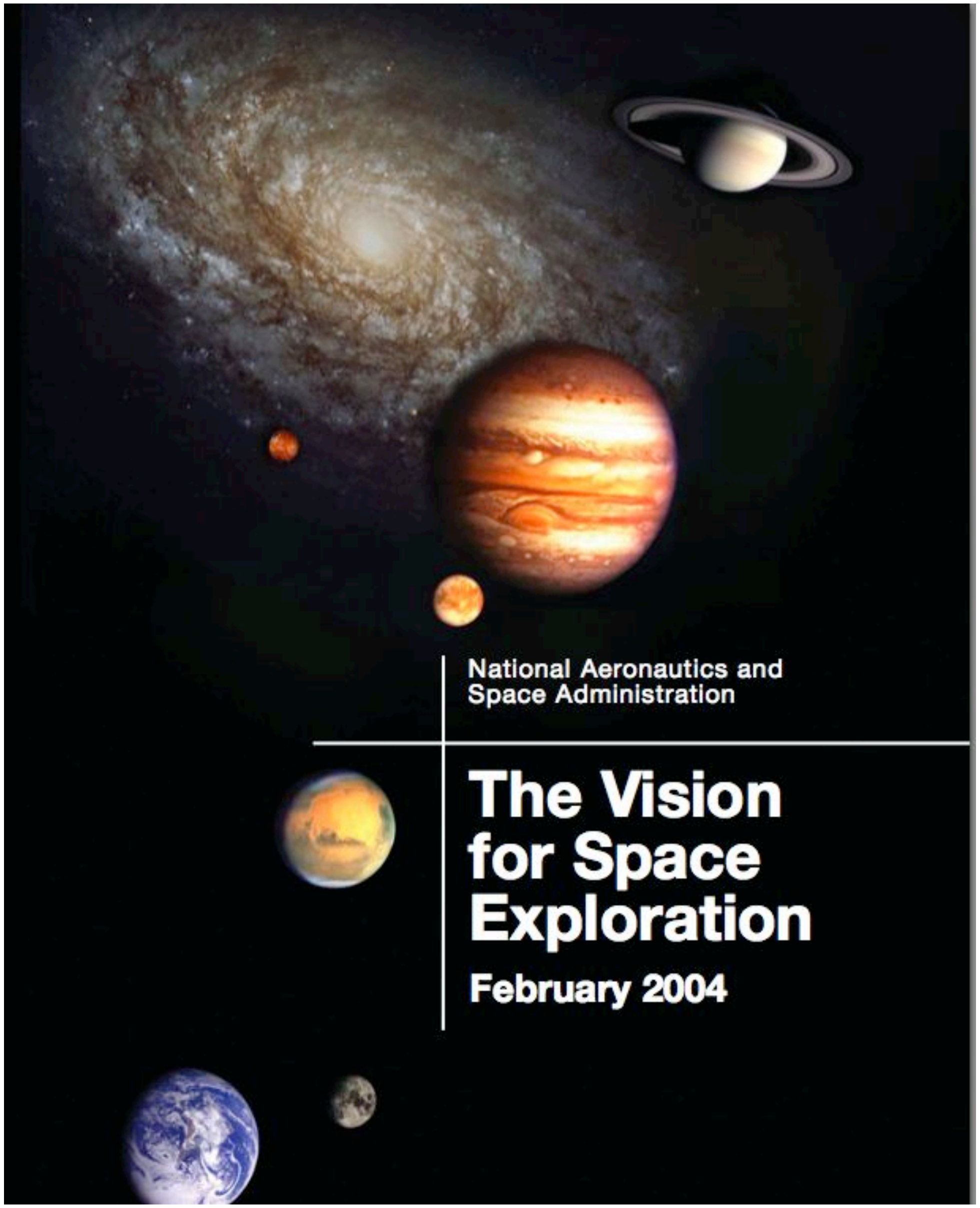
Slamming Rockets into the Moon: An Overview of the LCROSS Mission at NASA Ames!



Dr. Jennifer L. Heldmann
NASA Ames Research Center / SETI Institute
June 27, 2006

LCROSS: Lunar CRater Observation and Sensing Satellite

NASA's Vision for Space Exploration



Goals and Objectives

· Retire the space shuttle by 2010

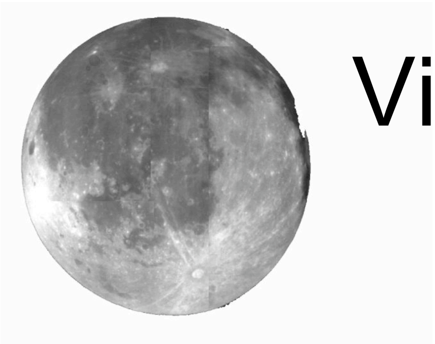
· Honor international commitments re. the International Space Station

· **Conduct a series of robotic missions to the Moon as human precursor missions starting in 2008**

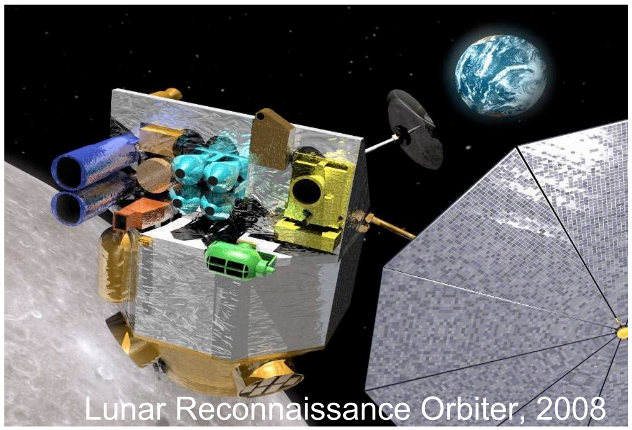
· Develop the Crew Exploration Vehicle (CEV, capable of transporting humans to the Moon and beyond)

· Human missions to the Moon by 2020

· Human missions to Mars …



Vision for Space Exploration: Lunar Missions



Lunar Reconnaissance Orbiter, 2008

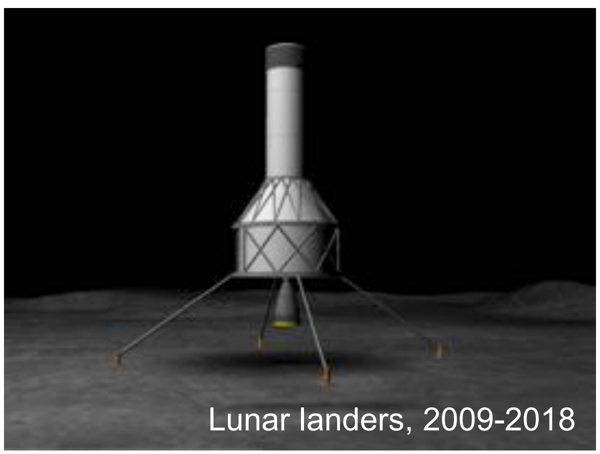
LCROSS, 2008

Major Milestones

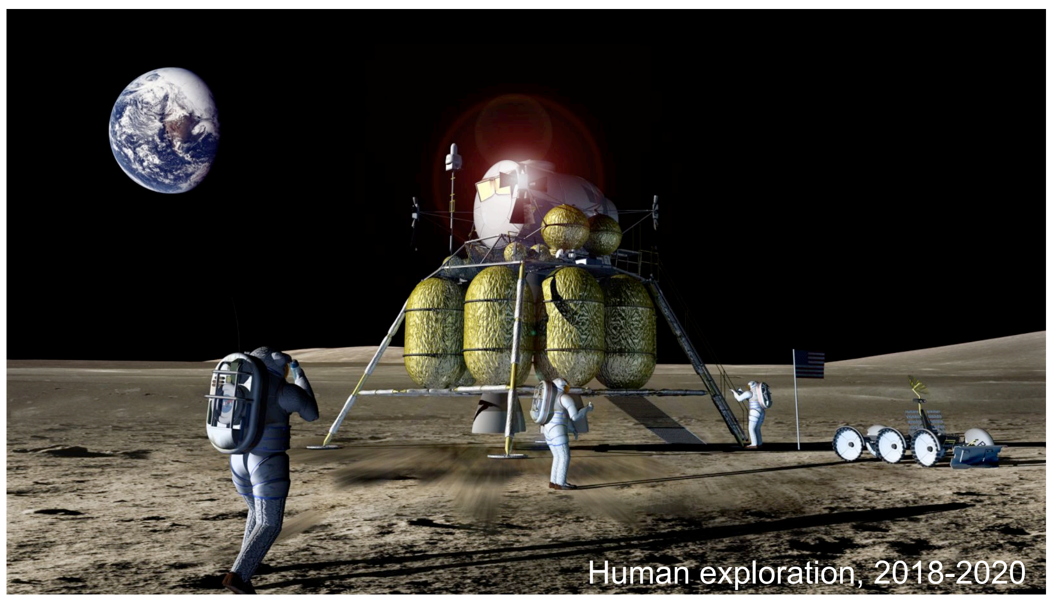
2008: launch of the Lunar Reconnaissance Orbiter and LCROSS

2009-2018: robotic missions to lunar surface

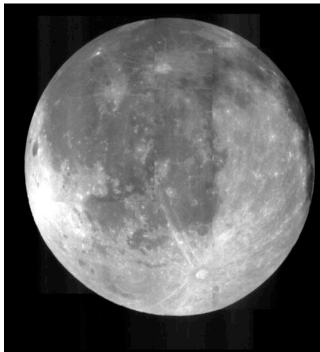
2018-2020: crewed flight to Moon



Lunar landers, 2009-2018



Human exploration, 2018-2020



Site Selection is Keystone to Planning

Site selection process drives lunar program from both ends:

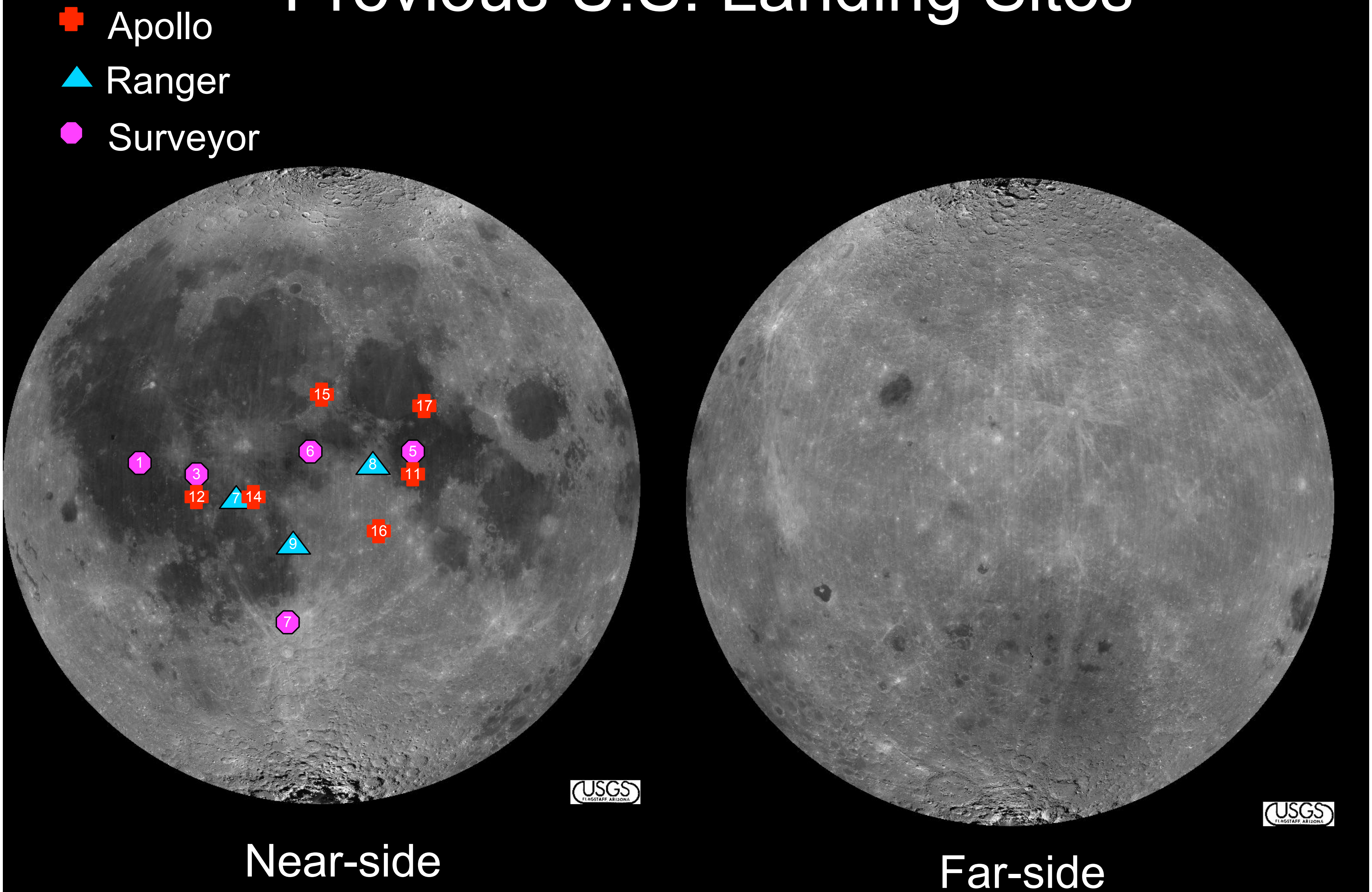
LONG TERM PLANNING

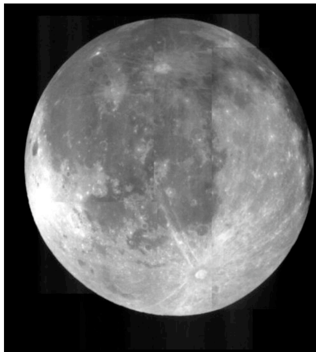
1) Forces definition of activities on Moon (e.g. Mars preparation implies base)
2) Helps resolve architecture

NEAR TERM PLANNING

1) Targets list for LRO imaging
2) Forces rationalization of approach to polar ice (Clarify how site selection depends on H content)
3) Defines RLEP2 science objectives

Previous U.S. Landing Sites





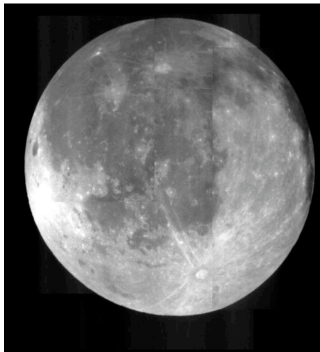
Landing Site Selection

Site Considerations:

1) General accessibility of landing site (orbital mechanics)
2) Landing site safety
3) Mobility
4) Mars analog
5) Power
6) Communications
7) **ISRU considerations**
8) Geologic diversity

Approach:

Consider each of the criteria separately as per below to determine optimal landing sites, then integrate the requirements & suggested sites to recommend optimal candidate landing sites considering all categories of site selection criteria.



Lunar Ice Summary

ICE

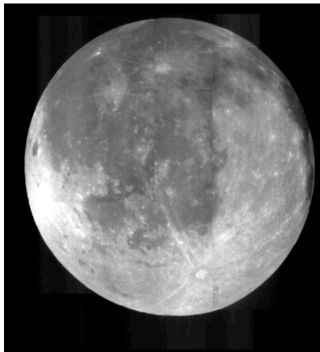
Nozette, Spudis et al.:

- Clementine bistatic radar = ice.
- Arecibo = ice.
- LP = ice.

* H measurements not definitive. Below 1-1.5% H, form of H unknown.

Not ICE

- Clementine bistatic radar = irreproducible results for ice, same signals seen in sunlit areas.
- Arecibo = not ice, same signals seen in sunlit regions, not anomalous in Shackleton.
- LP = why more Hydrogen detected in the north when more permanent shadow in the south?
- Theory = H_2O evolution in lunar cold trap reaches equilibrium over time (diffuse deposits, 0.41% by mass).



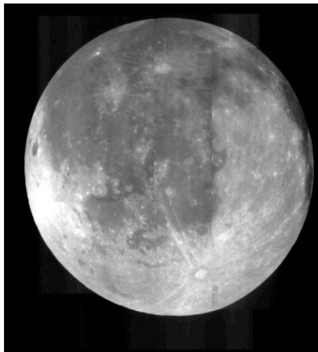
So the obvious questions are ….

Is there water ice in the permanently shadowed regions(s) at the lunar pole(s)?

If so, how much?

If not, what is the source of the H?

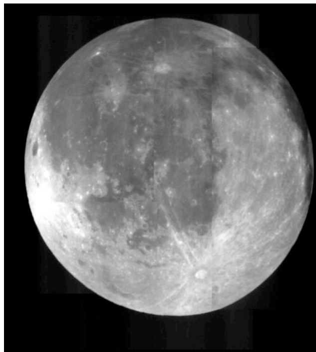
*note this is more of a science talk than an engineering talk so does not address issues such as the feasability of extracting ice (if it exists) from a permanently shadowed region or other engineering-type issues.



Mission Opportunity

Enter LCROSS

LCROSS is a comanifested payload (same launch vehicle as NASA’s Lunar Reconnaissance Orbiter (LRO) slated for launch October 31, 2008).



Mission Opportunity

LCROSS is a comanifested payload (same launch vehicle as NASA's Lunar Reconnaissance Orbiter (LRO) slated for launch October 31, 2008).

The schedule is fast …

January 10, 2006: NASA RFI call to industry.

January 25, 2006: RFIs due from industry to NASA.

February 14, 2006: Secondary payload proposals due

February 22, 2006: Secondary payload downselect by HQ

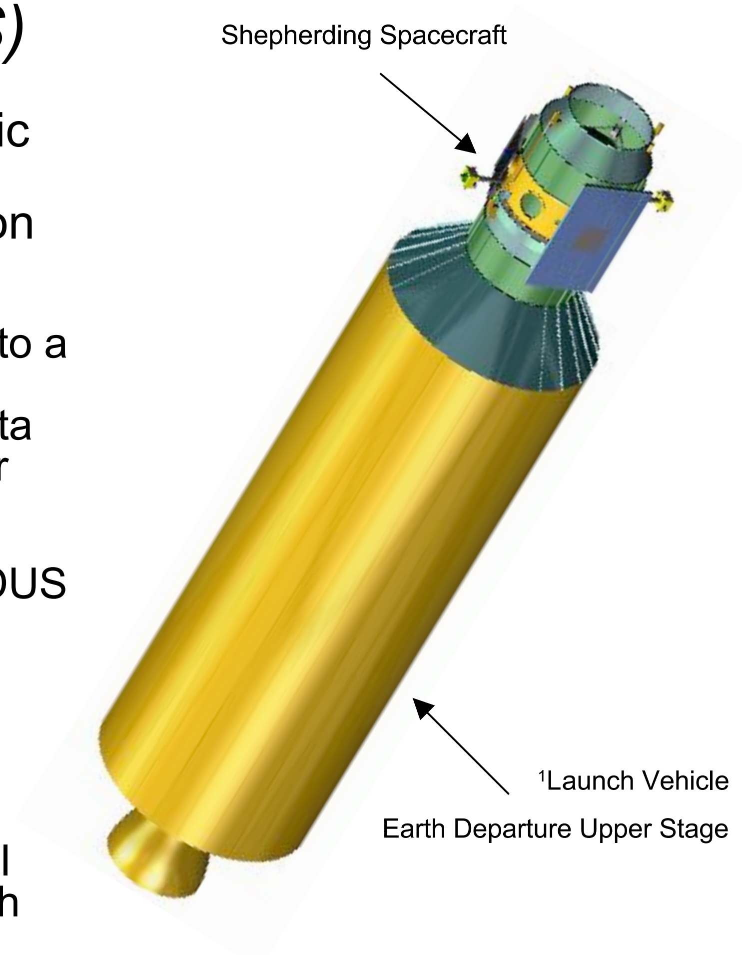
March 29, 2006: Briefings to HQ (4 downselects)

April 10, 2006: LCROSS selected for flight

Mission Description

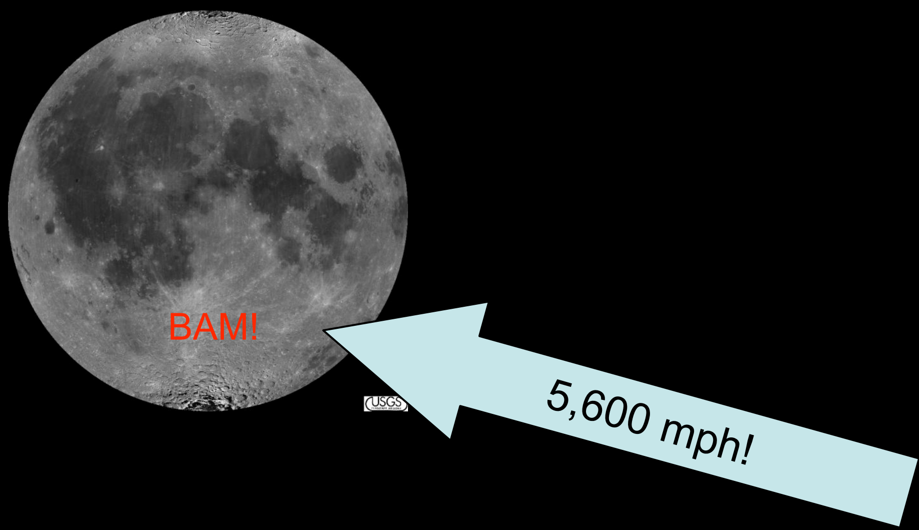
Lunar CRater Observing and Sensing Satellite (LCROSS)

- The LCROSS Mission is a Lunar Kinetic Impactor employed to reveal the presence & nature of water on the Moon
  - LCROSS Shepherding S/C (S-S/C) accurately directs the 2000 kg EDUS[1] into a permanently shadowed region at a lunar pole, creating a substantial cloud of ejecta (~60 km high, >200x the energy of Lunar Prospector)
  - The S-S/C decelerates, observes the EDUS plume, and then enters the plume using several instruments to look for water
  - The S-S/C itself then becomes a 700 kg secondary impactor
  - Lunar-orbital and Earth-based assets will also be able to study both plumes, (which may include LRO, Chandrayaan-1, HST, etc)



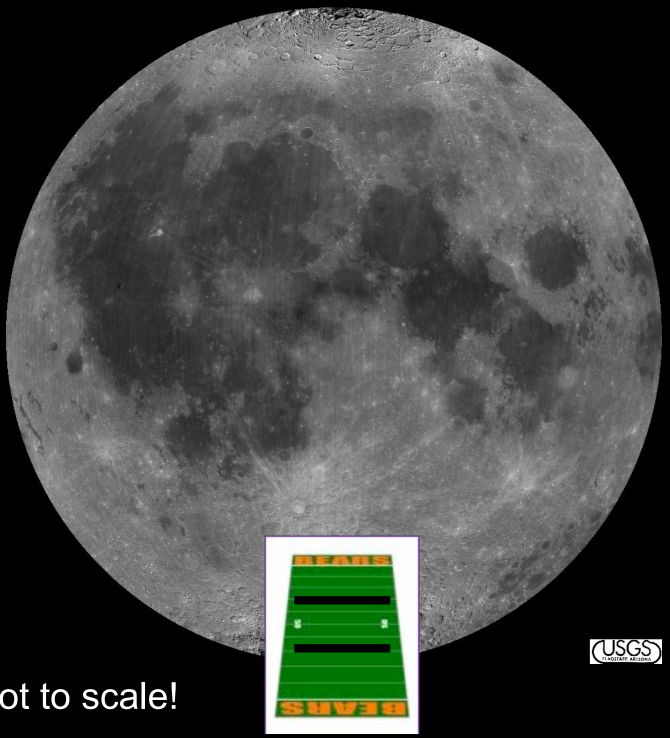
This is an exciting mission!

We're taking the LV's upper stage (~ the weight of a big SUV) and impacting it into the north or south pole of the Moon at 5,600 mph.



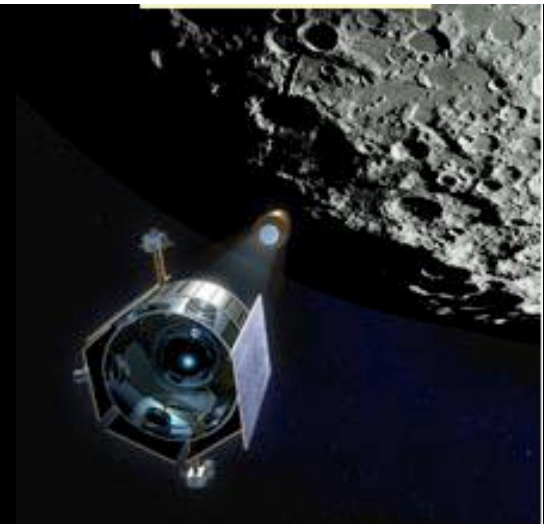
This is an exciting mission!

The impact will excavate a crater on the south or north pole the size of <u>1/3 of a football field</u>, <u>16 feet deep.</u>

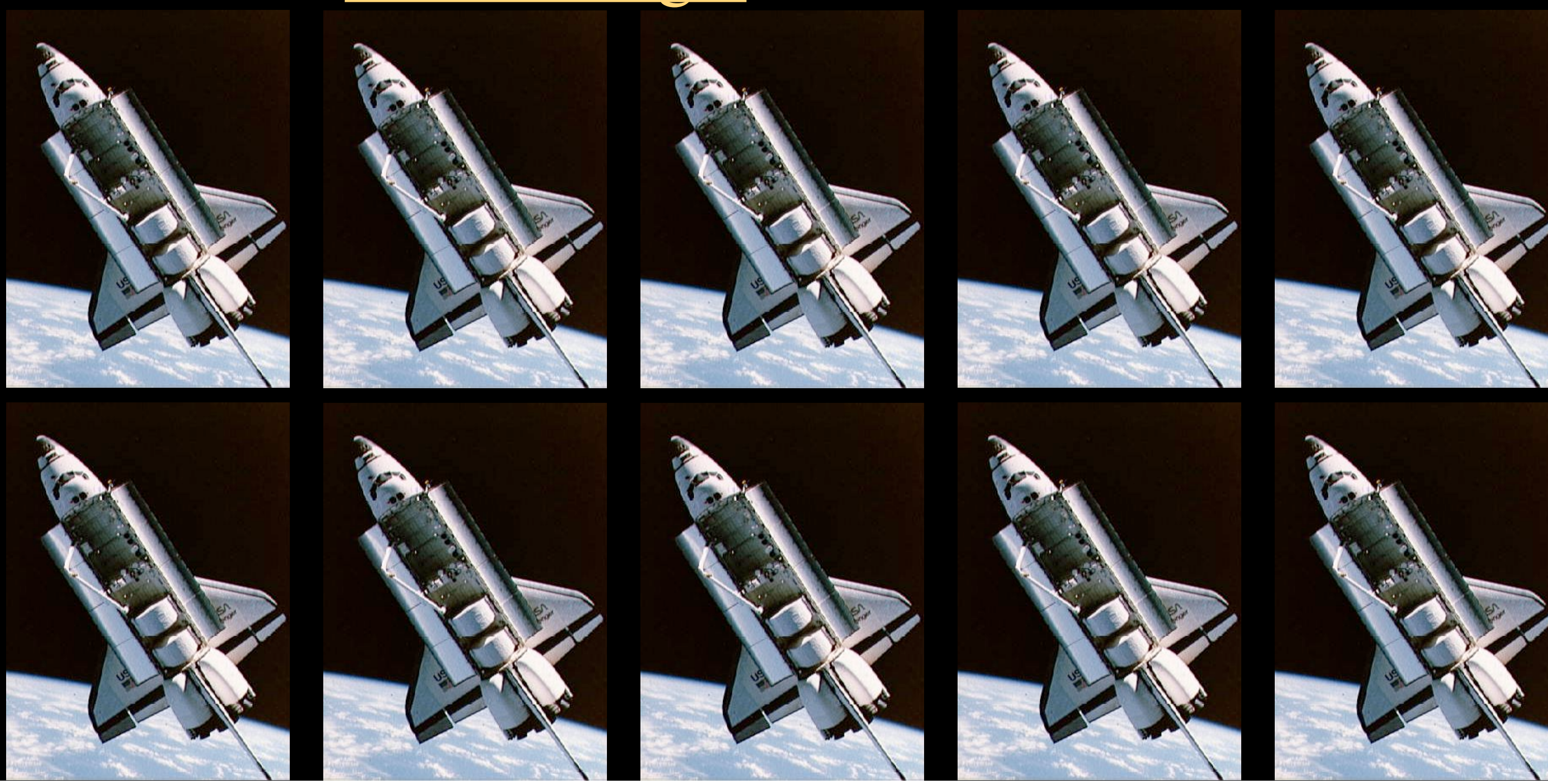


*note image not to scale!

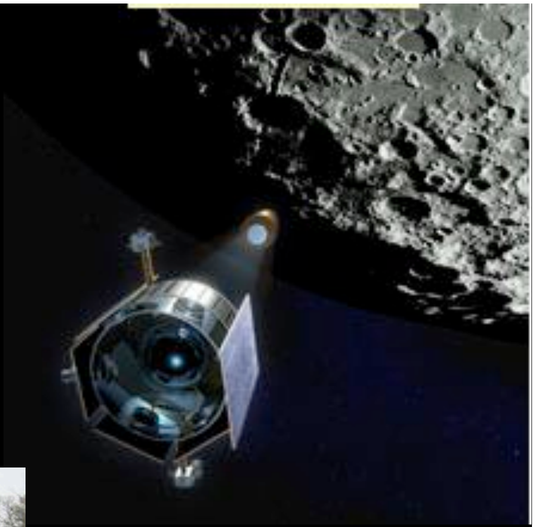
This is an exciting mission!



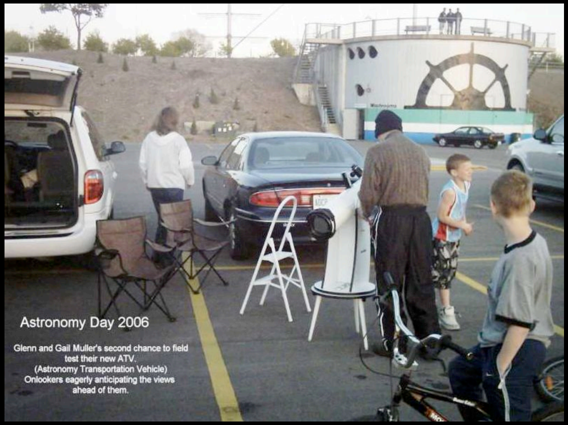
The amount of material (dust and possibly ice) could fill 10 Shuttle cargo bays and with the bulk of the plume reaching altitudes over 30 miles high.

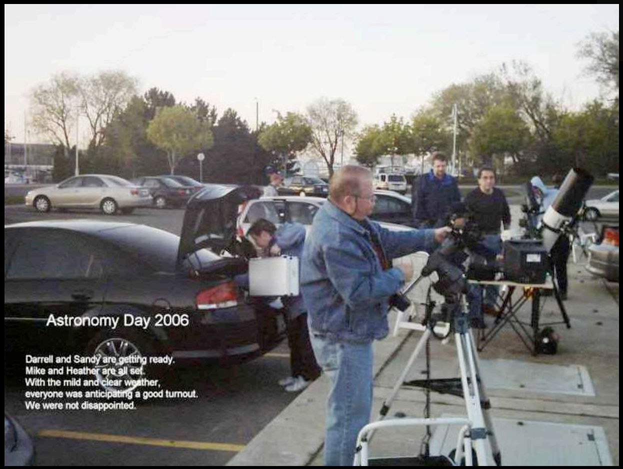


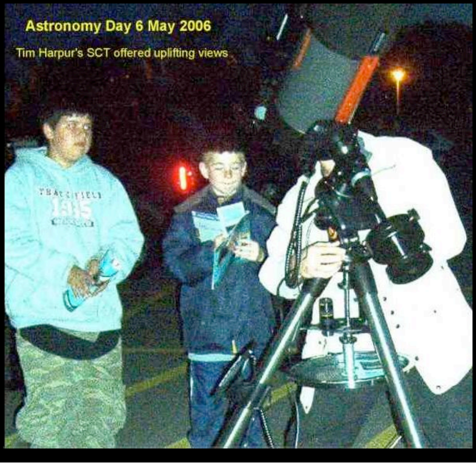
This is an exciting mission!

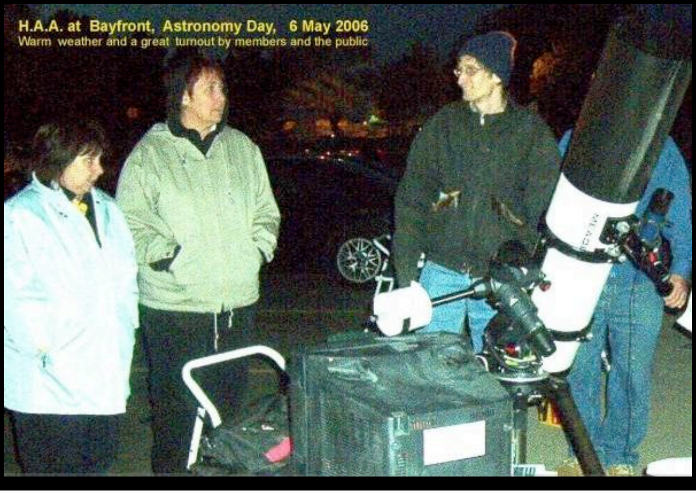


We believe reasonable grade amateur telescopes may be able to witness the impact plume.









www.amateurastronomy.org

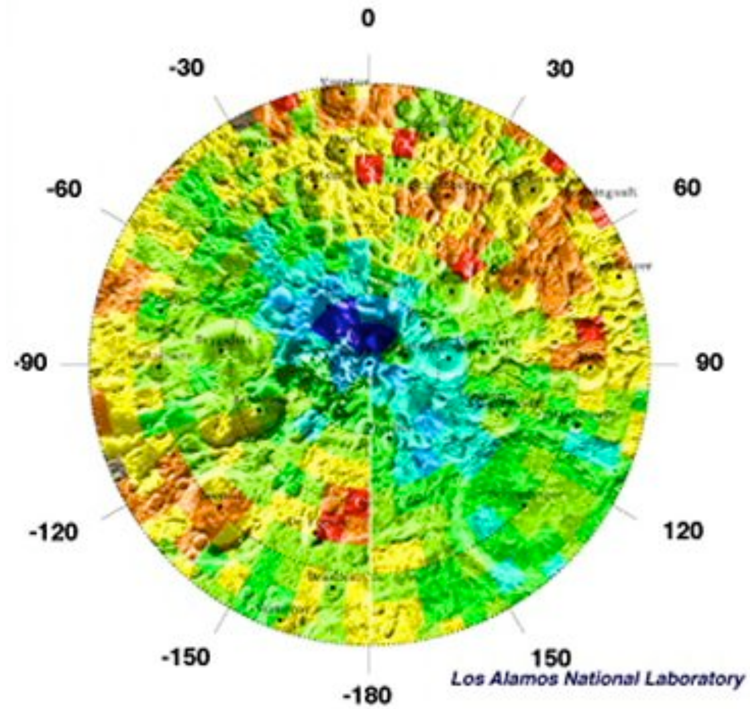
Mission Objectives & Goals

The nature of lunar polar hydrogen is the single most important driver to the long term Exploration architecture

• Need to understand Quantity, Form, and Distribution of the hydrogen

• The lunar water resource can be estimated from a minimal number of "ground-truths"

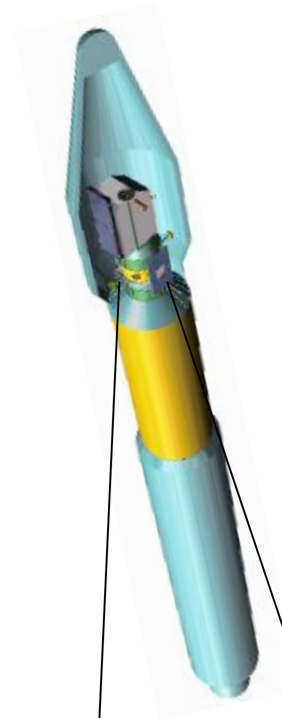
• Early and decisive information will focus and simplify future RLEP missions



SP Hydrogen Abundance
(LP data)

LCROSS provides ground-truth for LP and LRO neutron data sets

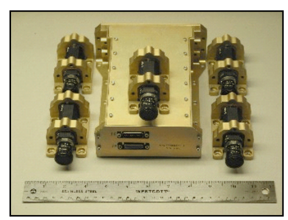
Mission Hardware



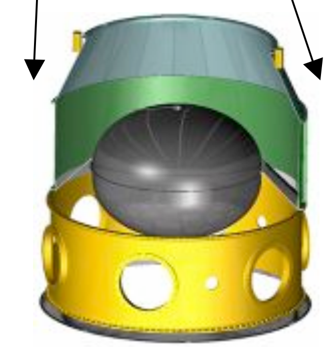
- **EDUS of the LRO EELV:**
  - Either an Atlas V or a Delta IV
  - ~2000kg (after boil-off)
  - Low risk to LRO due to use of the same adapter (straight load path), interface and separation systems

- **Shepherding Spacecraft & Instruments:**
  - ESPA ring spacecraft structure
  - Visual cameras
  - Infrared cameras
  - Near infrared spectrometers
  - Heritage command & data handling avionics
  - Other components common with LRO or already flt qual'd
  - 70 to 80% of software is "reused"

Near IR Spectrometer



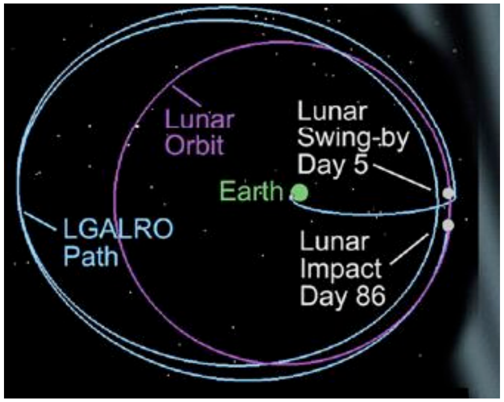
Visual & IR Cameras



ESPA Ring
Spacecraft Structure

Mission Timeline

– **Lunar Gravity Assist, Lunar Return Orbit (LGALRO):** Following the release of LRO, the S-S/C & EDUS will enter a ~86 day orbit (5 day lunar swing-by, 81 day earth orbit):
  1. Allows for LRO to become operational
  2. Allows for EDUS propellant boil-off
  3. Allows for impact targeting



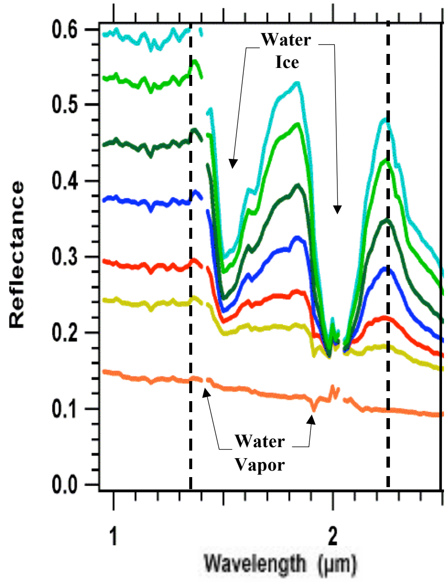
– **Upon separation from EDUS, about 7 hours before impact,** the S-S/C will decelerate to trail the EDUS by 15 minutes and position itself to capture EDUS impact images and impact plume data

– **During the 15 minutes after EDUS impact,** the S-S/C will be collecting and transmitting data, then slightly divert its trajectory to impact the same general area at T+15 minutes, but offset by several hundred meters.

Event/Maneuver	Event Time	Delta-V m/sec	Propellant Mass (kg)	Impactor Wet Mass (kg)
Trans Lunar Injection *	L+~1hr	3140	--	2920
Lunar Swingby Targeting*	L+~1.5 hrs	66	--	2920
TCMs**	(L+1,4 days)	(50)	67	2853
Swingby of Moon	L+5 days	--	--	2853
Lunar Targeting Maneuver	L+67 days	41	53	2800
TCMs**		(50)	64	2736
S-S/C Separation	T-7hrs	--	--	650
S-S/C Braking Man. (15 minutes)	T-6.5 hrs	53	16	634
EDUS Impact	T=0	--	--	2736
S-S/C Impact	T+15 min	--	--	634
Total		**194**	**200**	
Propellant Reserve			**100**	
Total Mass of Propellant			**300**	
Propellant Margin			**50%**	

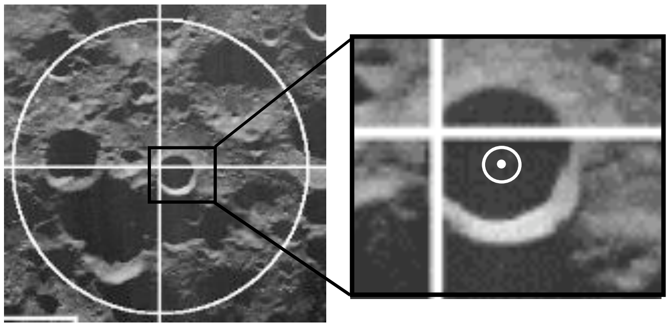
Mission Operations

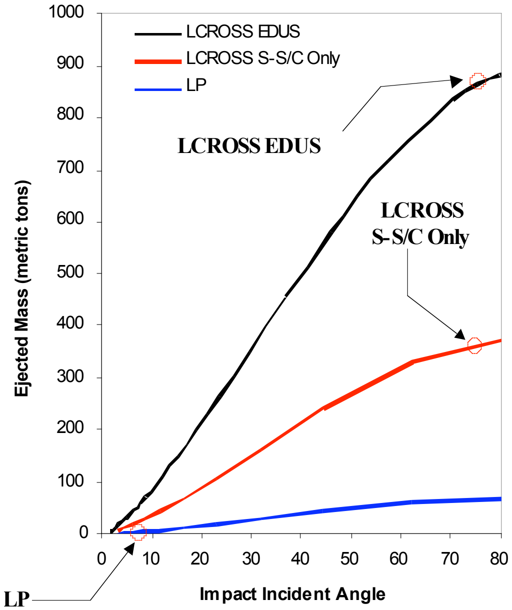
– **S-S/C and Instruments**:
1. Approx 14 minutes after separation from EDUS, the S-S/C will enter the ejecta cloud created by EDUS impact
2. S-S/C instruments will monitor & measure the ejecta.
3. The S-S/C can be directed to impact within 100m of the EDUS.

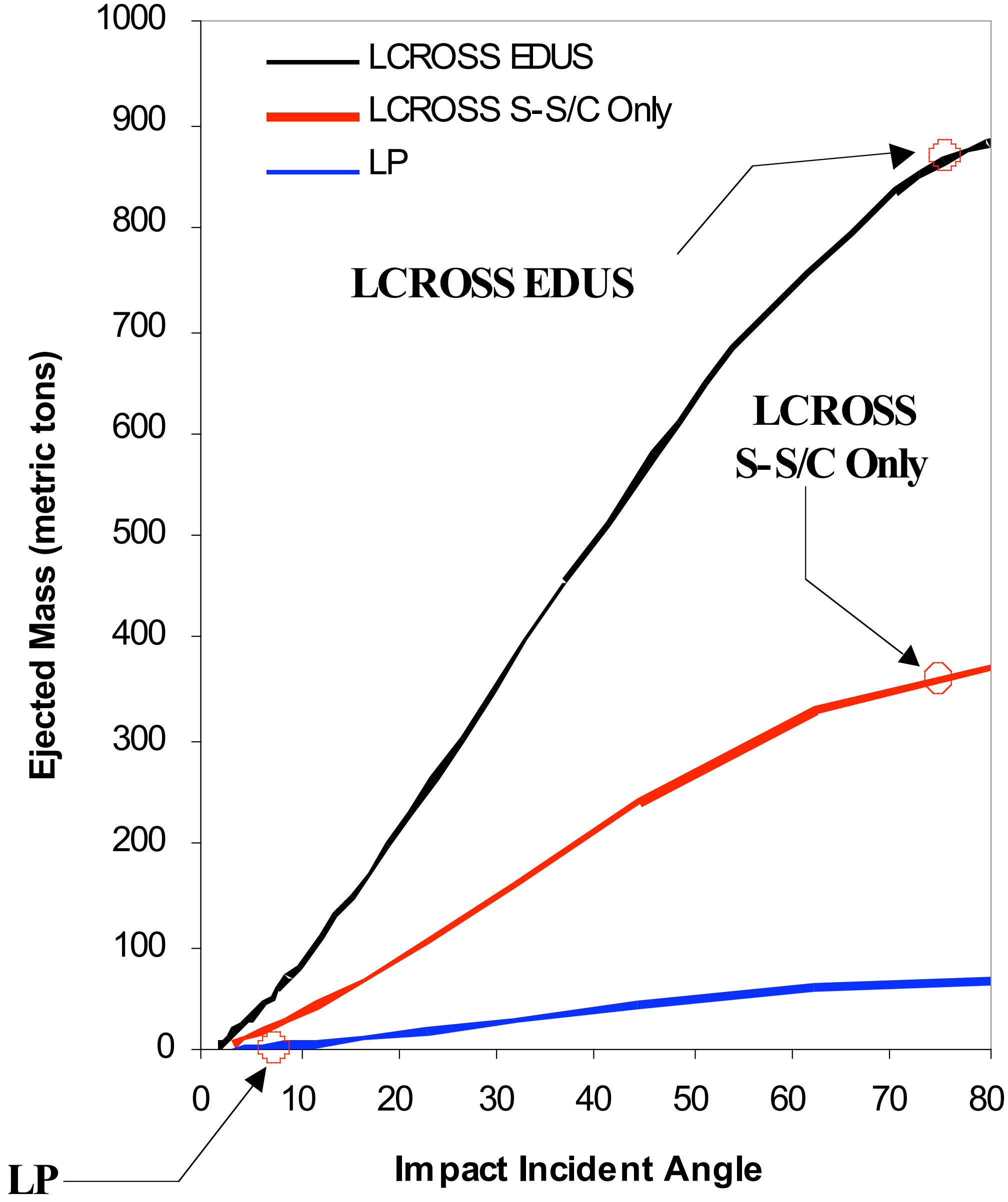


– **Additional investigation opportunities:**
1. Earth-based: Hawaii, Continental US, Chile, Spain, Canary Islands, Australia
2. Orbit-based: SWAS, HST, Spitzer, LRO, Chandrayaan, Selene, etc.

– **Expected EDUS impact accuracy** of 3km.
Anticipated impact velocity > 2km/s at an angle > 70 degrees to the plane of the surface.





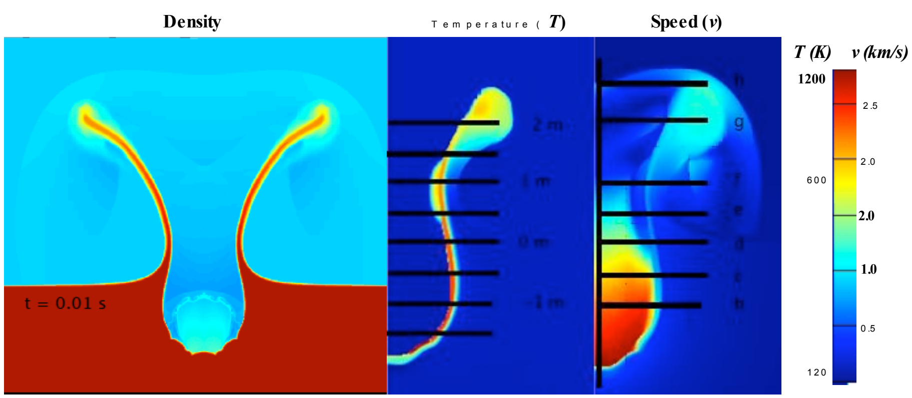


Comparison of LCROSS & Lunar Prospector impacts

Impact Model Validation

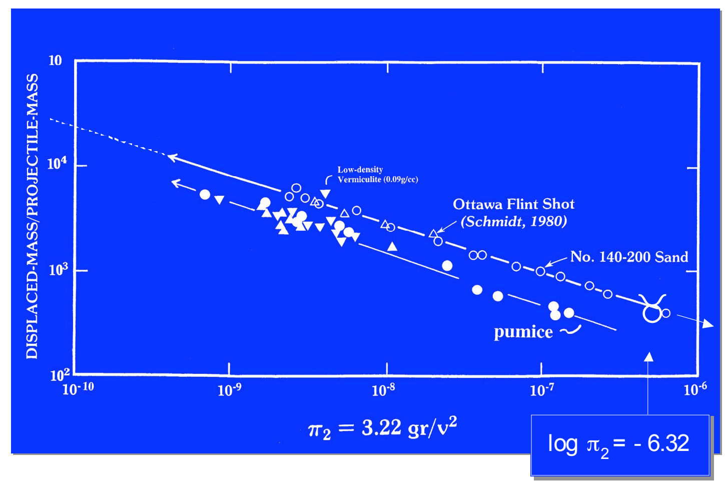
- The impact model used to estimated ejecta mass is based on widely used semi-empirical relations (Jay Melosh)
- Predicted crater size, depth, ejecta mass and velocity were calibrated against highly sophisticated impact models (Eric Asphaug) and experimental data (Peter Schultz)

Simulations, like the one below for a 2000 kg lunar impact, were used to estimate the impact plume dynamics and characteristics. The figures show the plume 0.01 sec after impact.



Asphaug (2006)

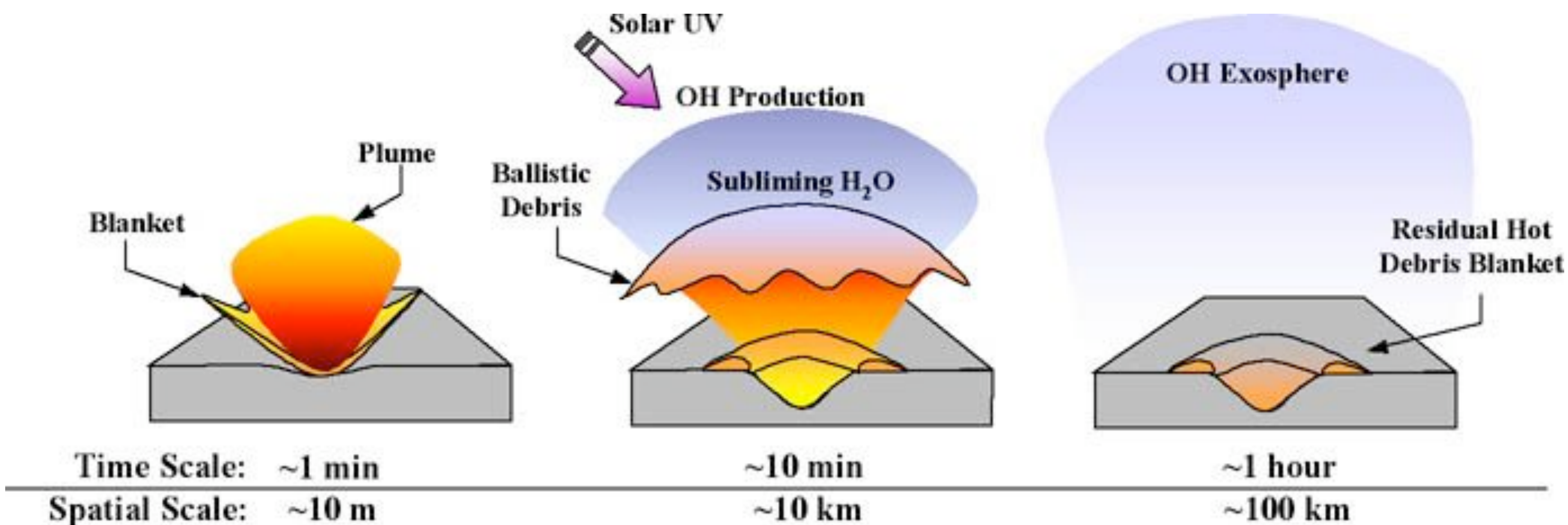
Cratering Efficiency from Experiments



Schultz and Gault (1985)

World Class Impact Science

Impact Observation Strategy



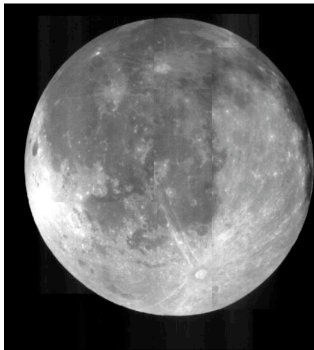
- Bright Impact Flash
- Thermal OH Production
- Rapid Thermal Evolution

- Expansion of Plume
- Thermal Evolution
- H_2O ice sublimation
- Photo-production of OH

- Residual Thermal Blanket
- Expanding OH Exosphere

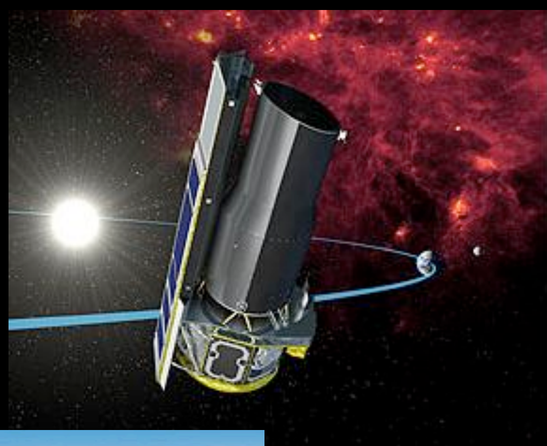
The combination of ground-based, orbital and in-situ platforms span the necessary temporal and spatial scales: from sec/meters to hours/km

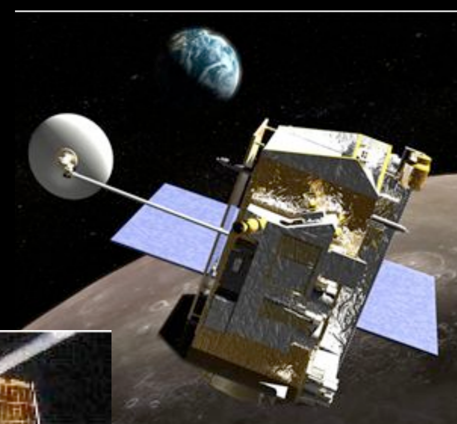
The LCROSS mission has multiple layers of observing

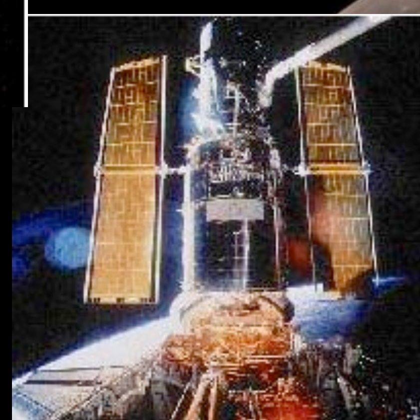


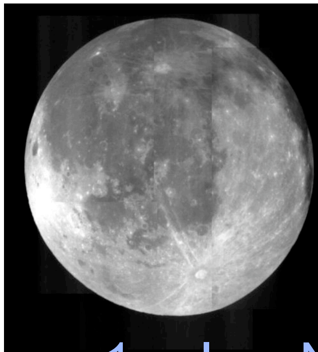
LCROSS Observational Campaign

Lunar, Earth-orbiting , and Ground-based Assets





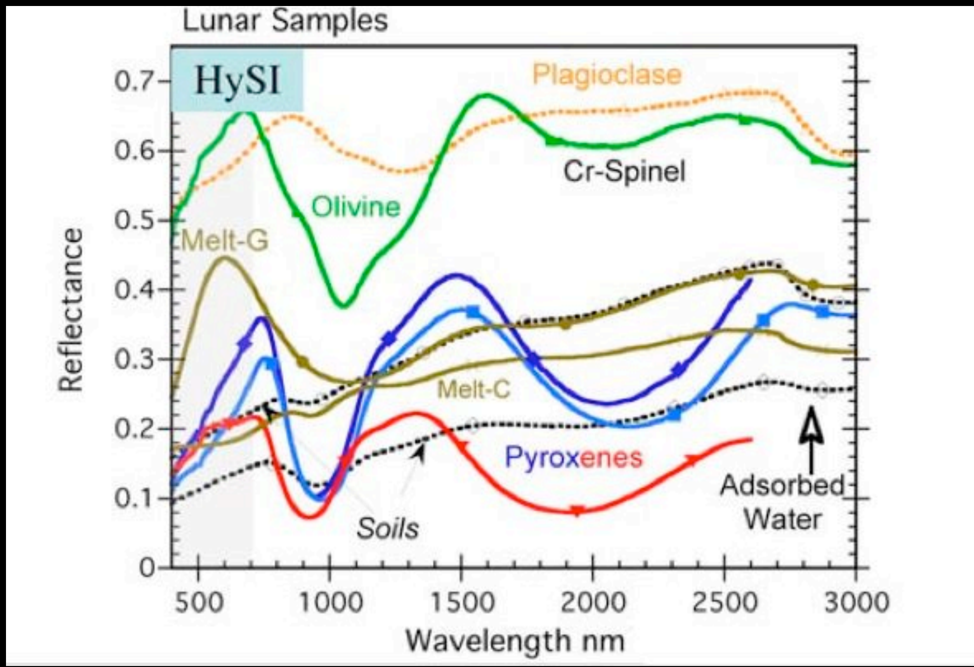




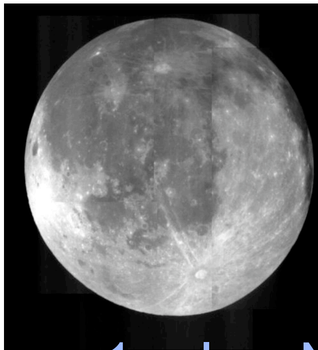
Measurements

1. Ice: Near-IR spectroscopy of the scattered sunlight absorption (fundamental and overtone) features of water ice in situ
2. Vapor: Near-IR spectra of H_2O vapor (sublimed ice) emission bands (overtone vibration bands at 1.4 and 1.9 microns) in situ, and of fundamental bands near 3 microns from ground-based 10 m class telescopes

* Note no sharp water bands at 1.4 and 1.9 microns (overtone). Small feature at 2.9 microns (fundamental) is due to terrestrial water contamination.



Pieters et al., LPSC 2006



Measurements

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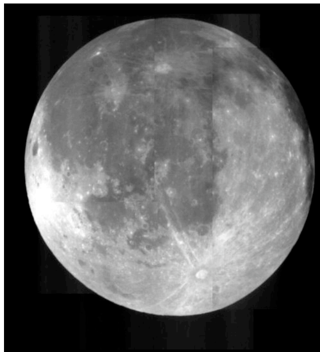
3. Measurement of an extended OH^- atmosphere via spectroscopy at the 308 nm OH^- band at UV-visible wavelengths along with nearby scattering continuum
4. Spectroscopy covering the 619 nm H_2O^+ band and adjacent scattering continuum
5. Narrow band imaging at mid-IR wavelengths to follow thermal evolution of plume and newly deposited regolith, which will be affected by water vapor in the ejecta.



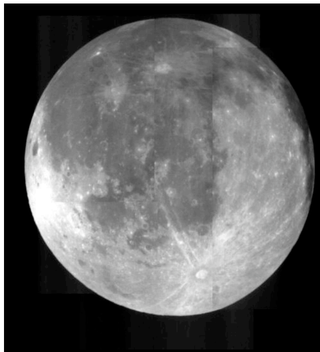
Observational Timescales and Platforms

Product	Measurement	Time Scale	Spatial Scale	Observation “Platform”
Water ice in plume	1	sec-hrs	0.1–10 km	S-/SC
Water vapor in plume	2,3,4,5	sec-days	1-100 km	S-S/C, Ground Based, LRO
Water ice in fresh ejecta	6	min-days	1-100 m	S-S/C, LRO, Chandra
Plume properties	1,2	min-days	0.1-10 km	S-S/C, Ground Based
Regolith properties	6	days	1-100 m	S-S/C, LRO, Chandra

Multiple independent measurement methods are used to

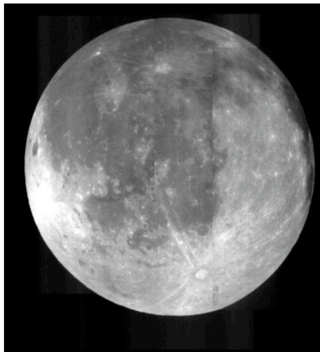
1) characterize the impact event

2) provide a definitive understanding of the amount of water contained in the regolith.

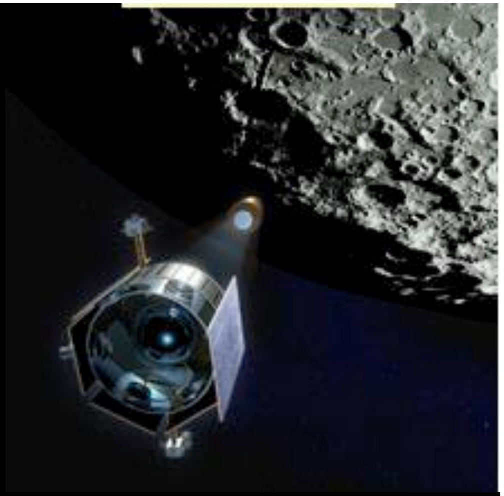


Observational Platforms

1. LCROSS Shepherding Spacecraft
2. Lunar Reconnaissance Orbiter
3. International lunar missions
4. Earth-orbital assets
5. Ground-based telescopes



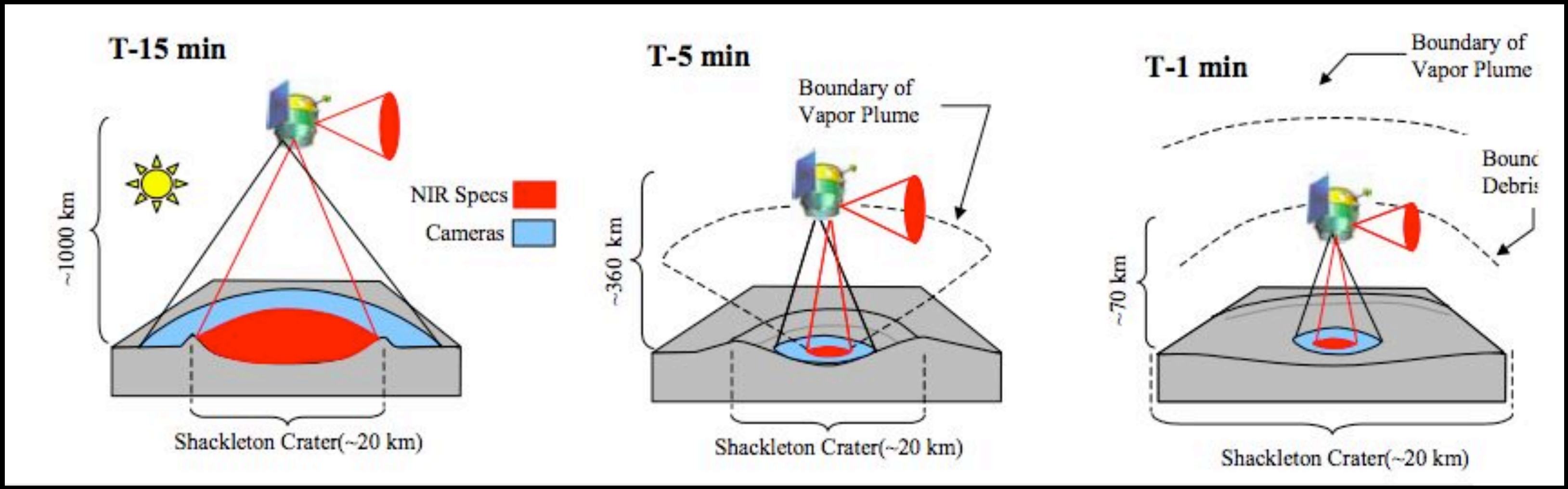
LCROSS S/S-C

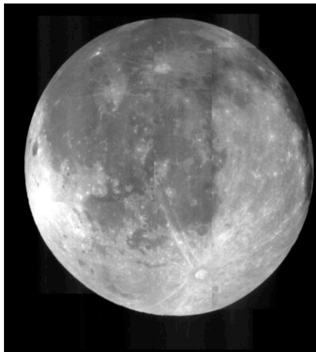


INSTRUMENTS

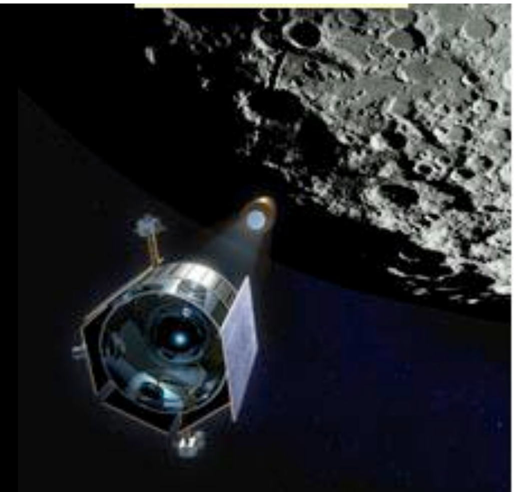
- 2 NIR spectrometers
- 1 Visible context imager
- 1 Visible total luminance diode
- 2 Mid-IR imagers

- 2 NIR imagers
- 1 Visible spectrometer





LCROSS S/S-C

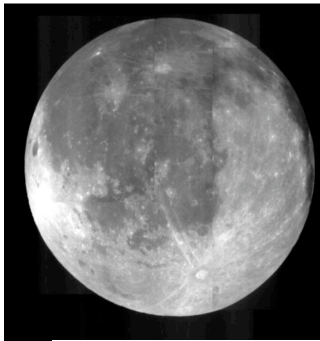


Two near-IR spectrometers

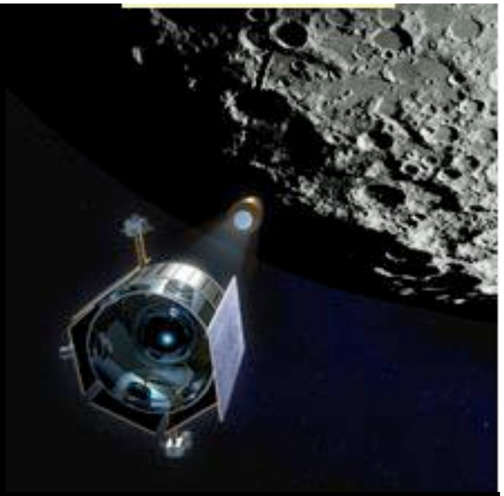
Monitor spectral bands (every second) associated with water vapor, ice, and hydrated minerals in NIR (1.35-2.25 microns) covering the first overtones of H_2O ice (band is free of interference, more brightly illuminated by sunlight than fundamentals near 3 microns).

Regions near 1.4 and 1.9 microns (usually obscured by Earth's atm) also provides sensitive indication of water vapor from ice, shape of band may provide info regarding nature of ice crystals and mineral hydrate.

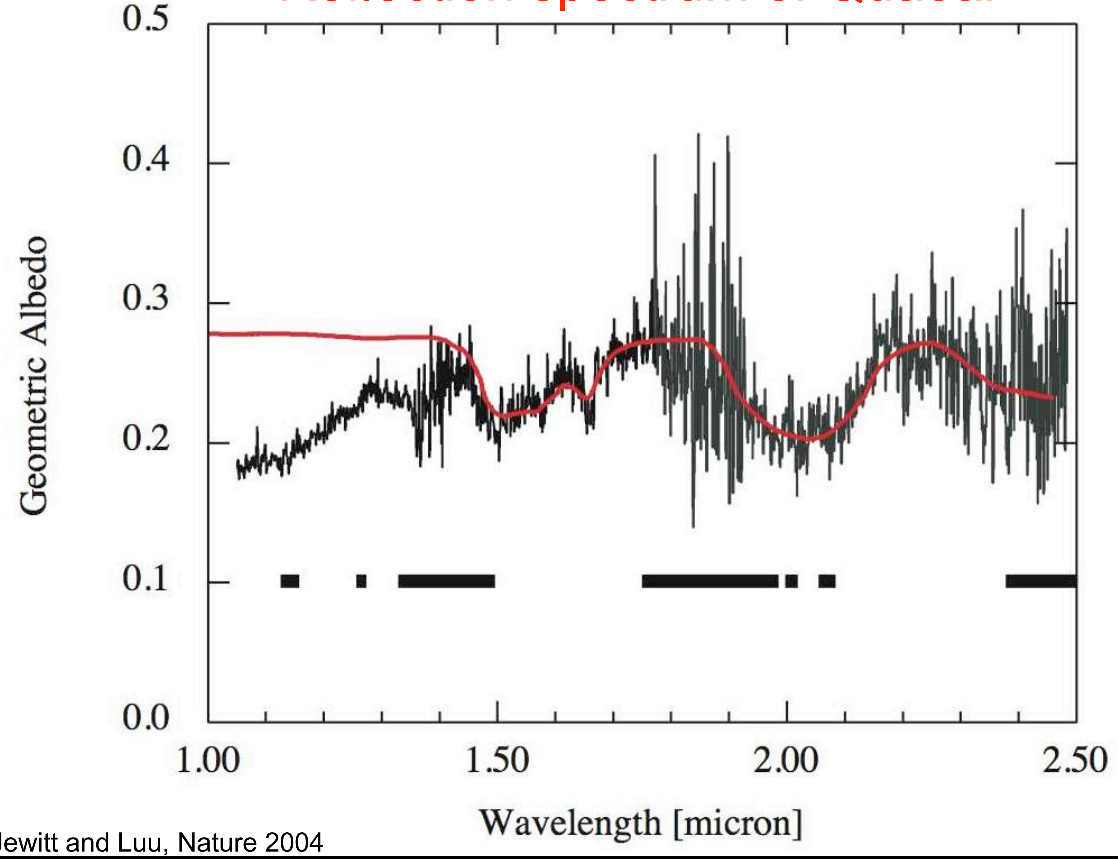
Broad minima at 1.5 and 2.0 microns indicative of water ice



LCROSS S/S-C



Reflection spectrum of Quaoar

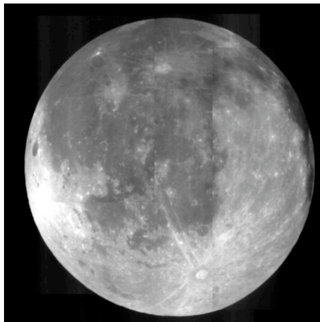


Jewitt and Luu, Nature 2004

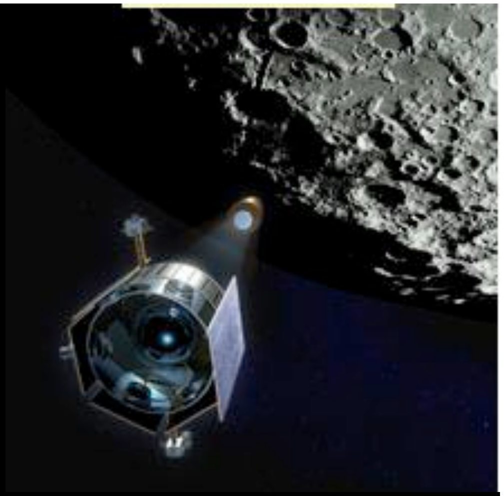
Red line is reference spectrum for water ice.

A sharper minimum at 1.65 microns shows that the ice is crystalline in structure, rather than amorphous.

Broad minima at 1.5 and 2.0 microns indicative of water ice



LCROSS S/S-C



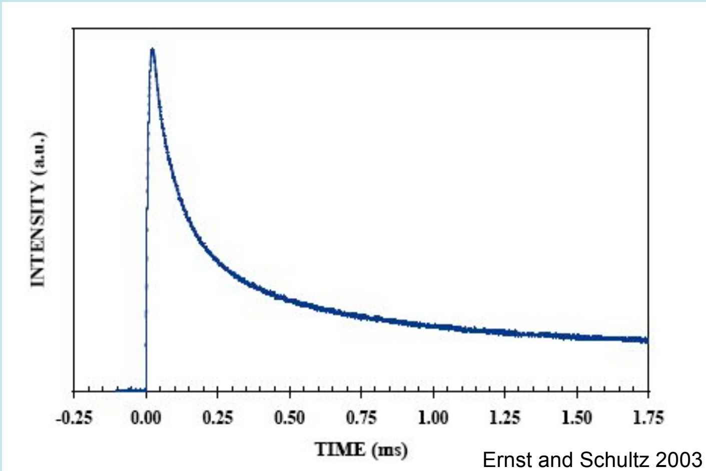
Camera

VIS: context camera to 1) observe EDUS impact, 2) observe ejecta cloud morphology and evolution.

Luminance Diode

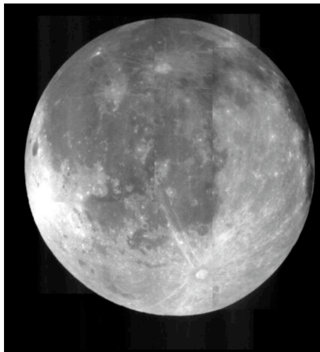
VIS: observe impact flash

- light flash due to thermal heating & vaporization
- shape of the flash's light curve can be used to determine certain initial conditions of the impact
- flash peak intensity depends on impact velocity angle, target & projectile types

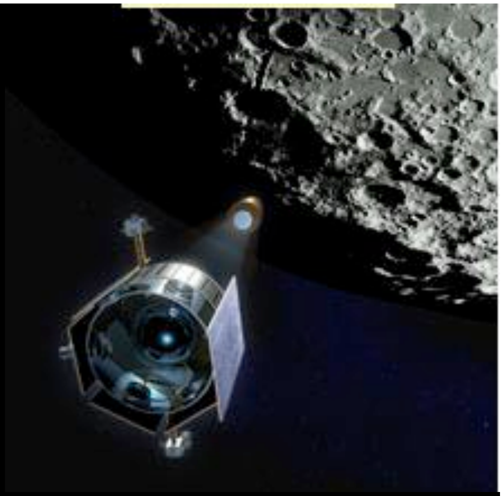


Ernst and Schultz 2003

Light curve as recorded from a photodiode of a typical Pyrex impact into pumice dust at the NASA Ames Vertical Gun Range. Two components can be seen: as intensity peak lasting 50-100 μs that depends on projectile parameters, and a long-lasting decaying blackbody signal dependant on target parameters.

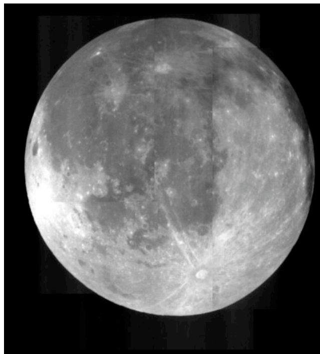


LCROSS S/S-C

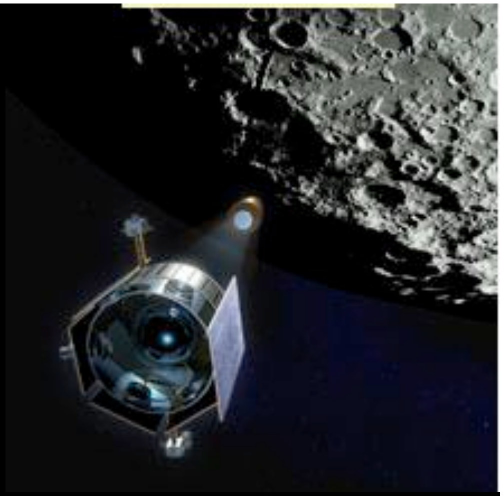


Two cameras

MID-IR (2 wavelengths): look down on permanently shadowed lunar surface to map pre-impact terrain (warmer vs cooler = rocks vs regolith), thermal evolution of plume (dependent upon H_2O vapor concentration in plume), ejecta blanket, and freshly exposed regolith.



LCROSS S/S-C



Two cameras

NIR: 2 wavelengths– obtain spatial distribution data regarding the H_2O (vapor and ice) content.

One spectrometer

VIS: look for H_2O^+ (619 nm) and OH^- (308 nm) radicals from sunlight-ionized and sunlight-dissociated H_2O vapor molecules; look for evidence of organics (e.g. CN = 380 nm).

Lunar CROSS Science Traceability

Orbital platforms

Moon orbiting

LRO (U.S.) 2008
- Diviner
- LAMP
- LEND
- LOLA
- LROC

Selene (JAXA) 2007
- Terrain Camera
- Lunar Radar Sounder
- Laser Altimeter
- Spectral Profiler

Chandrayaan (ISRO) 2007-08
- Terrain Mapping Camera
- Lunar Laser Ranging Instrument
- Moon Mineralogy Mapper
- SIR-2 (NIR spectrom.)

Chang-E (CNSA) 2007
- Instruments not specified

Earth orbiting

Hubble Space Telescope
- NICMOS (Near IR Camera & Multi-object Spectrometer)
- WFPC2 (Wide Field Planetary Camera 2)
- ACS (Advanced Camera for Surveys)

Spitzer Space Telescope
- IRAC (IR Array Camera)
- IRS (IR Spectrograph)
- MIPS (Multiband Imaging Photometer for Spitzer)

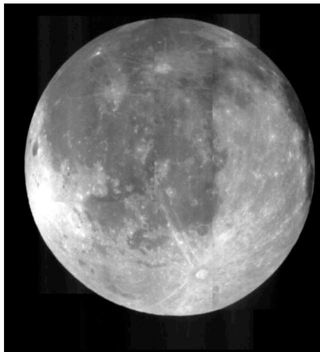
Galaxy Evolution Explorer
- Near-UV at 175-280 nm

Far Ultraviolet Spectroscopic Explorer
- UV at 90-120 nm

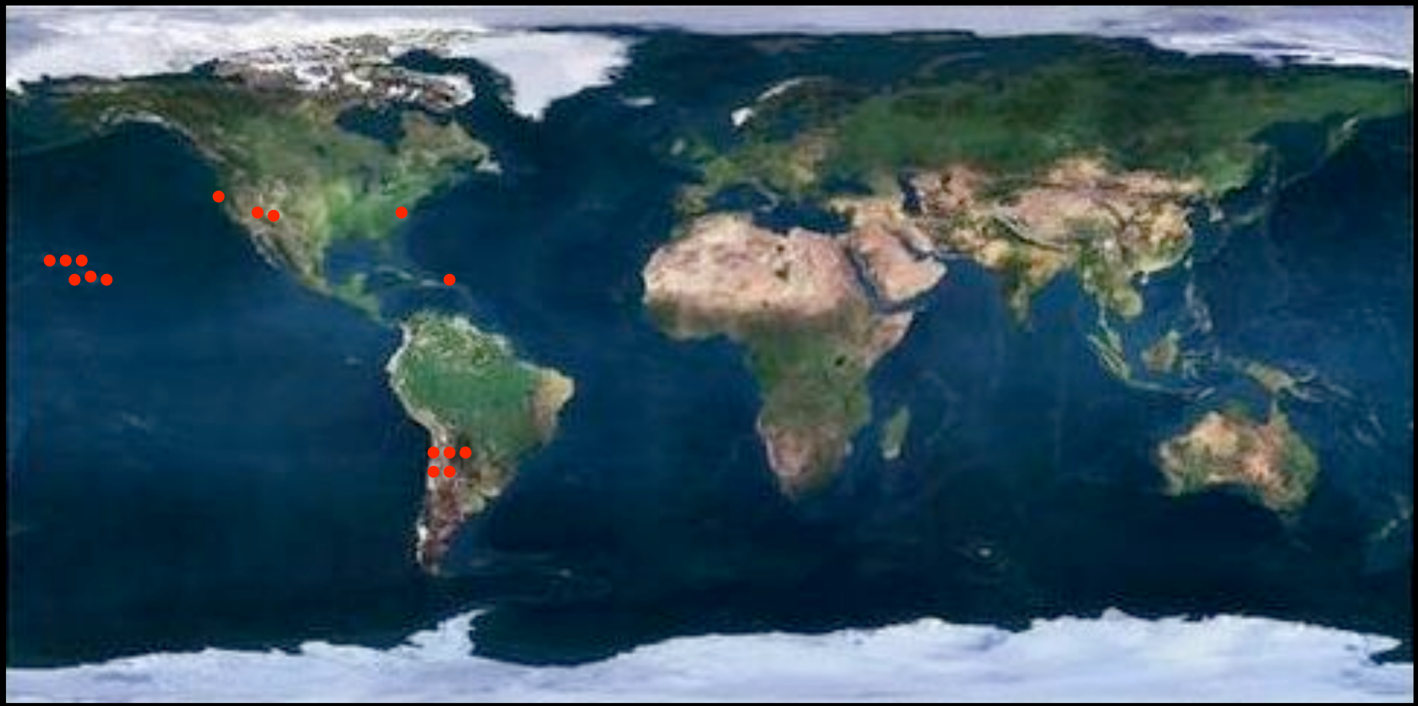
Lunar CROSS Science Traceability

Ground-based observations

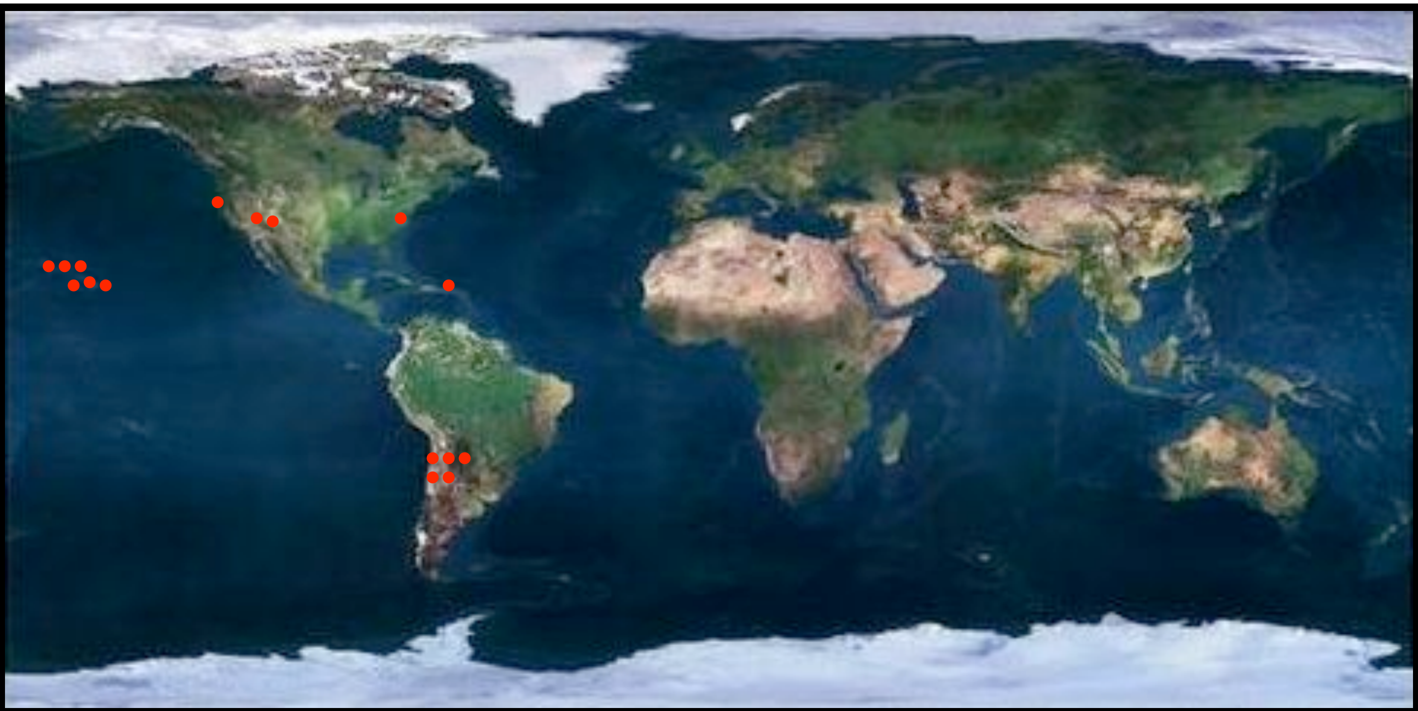
Measurement	Technique	Facilities
Photometric plume brightening	Visible Spectroscopy	ESO at Cerro Paranal, ESO at La Silla, Keck Observatory, Lowell Observatory, Canada-France-Hawaii Telescope, Gemini Observatory, National Optical Astronomy Observatory, La Campanas Observatory,University of Hawaii
	Visible Imaging	ESO at Cerro Paranal, ESO at La Silla Lowell Observatory, Canada-France-Hawaii Telescope, National Optical Astronomy Observatory, La Campanas Observatory, University of Hawaii
IR water vapor & ice	Infrared Imaging	ESO at Cerro Paranal, ESO at La Silla, Keck Observatory, Lowell Observatory, Gemini Observatory North, Gemini Observatory, Subaru Observatory, National Optical Astronomy Observatory, La Campanas Observatory, Infrared Telescope Facility, University of Hawaii, United Kingdom Infrared Telescope
	Infrared Spectroscopy	ESO at Cerro Paranal, ESO at La Silla, Keck Observatory, Gemini Observatory North, Gemini Observatory, Subaru Observatory, National Optical Astronomy Observatory, Infrared Telescope Facility, United Kingdom Infrared Telescope
UV OH in plume & exosphere	UV Spectroscopy	European Southern Observatory at Cerro Paranal



Ground-based Telescopes



Timing of impacts to allow simultaneous observations from Hawaii, Continental U.S., and South America.



12
4
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17
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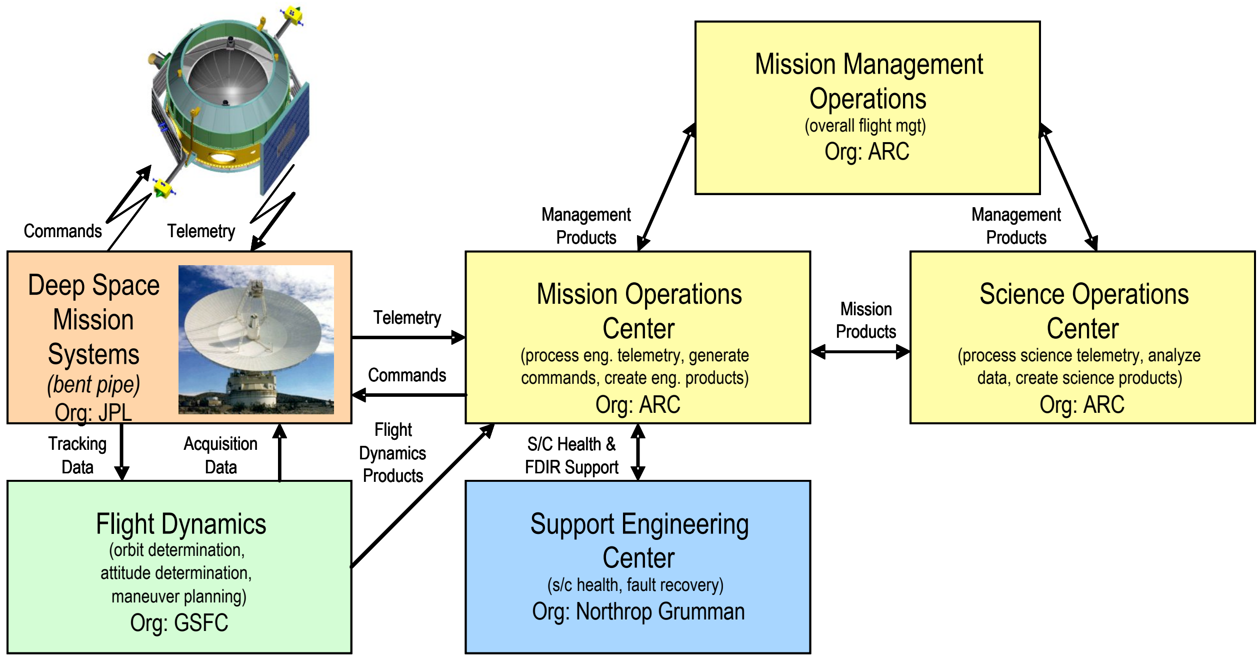
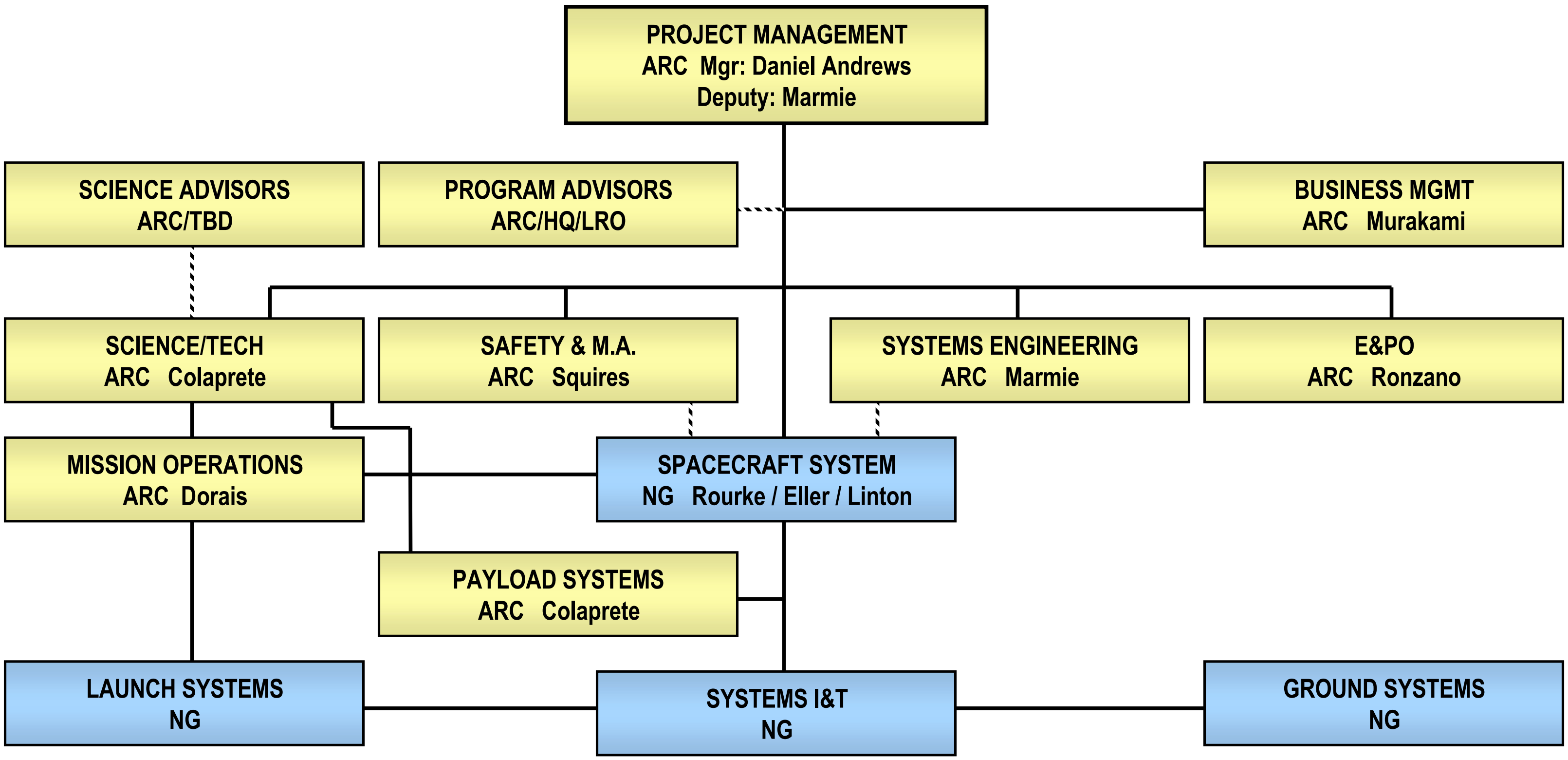
1
2
1. European Southern Observatory, Cerro Paranal
2. European Southern Observatory, La Silla
3. Keck Observatory
4. Lowell Observatory
5. Canada-France-Hawaii Telescope
6. Gemini Observatory North
7. Gemini Observatory
8. Subaru Telescope
9. Arecibo Observatory
10. National Optical Astronomy Observatory
11. La Campanas Observatory
12. Lick Observatory
13. Cerro Tololo
14. InfraRed Telescope Facility (IRTF)
15. University of Hawaii (UH)
16. United Kingdom Infrared Telescope (UKIRT)
17. Greenbank Observatory

Mission Operations



- High Heritage Operations Elements:
  - DSN for tracking
  - GSFC/FDF for Navigation/Trajectory Design
  - ARC Spacecraft and Science Operations
  - Northrop Grumman Subsystems Engineering

Mission Management



LCROSS management duties are split between NASA Ames Research Center (ARC-yellow) and Northrop Grumman (NG-blue).

Project Status

- Near-term milestones (next 6 months)
  - SRR: 7/11/06
  - PDR: 8/28/06
  - Confirmation Review: 9/28/06

Continued work to ensure the success of LCROSS …

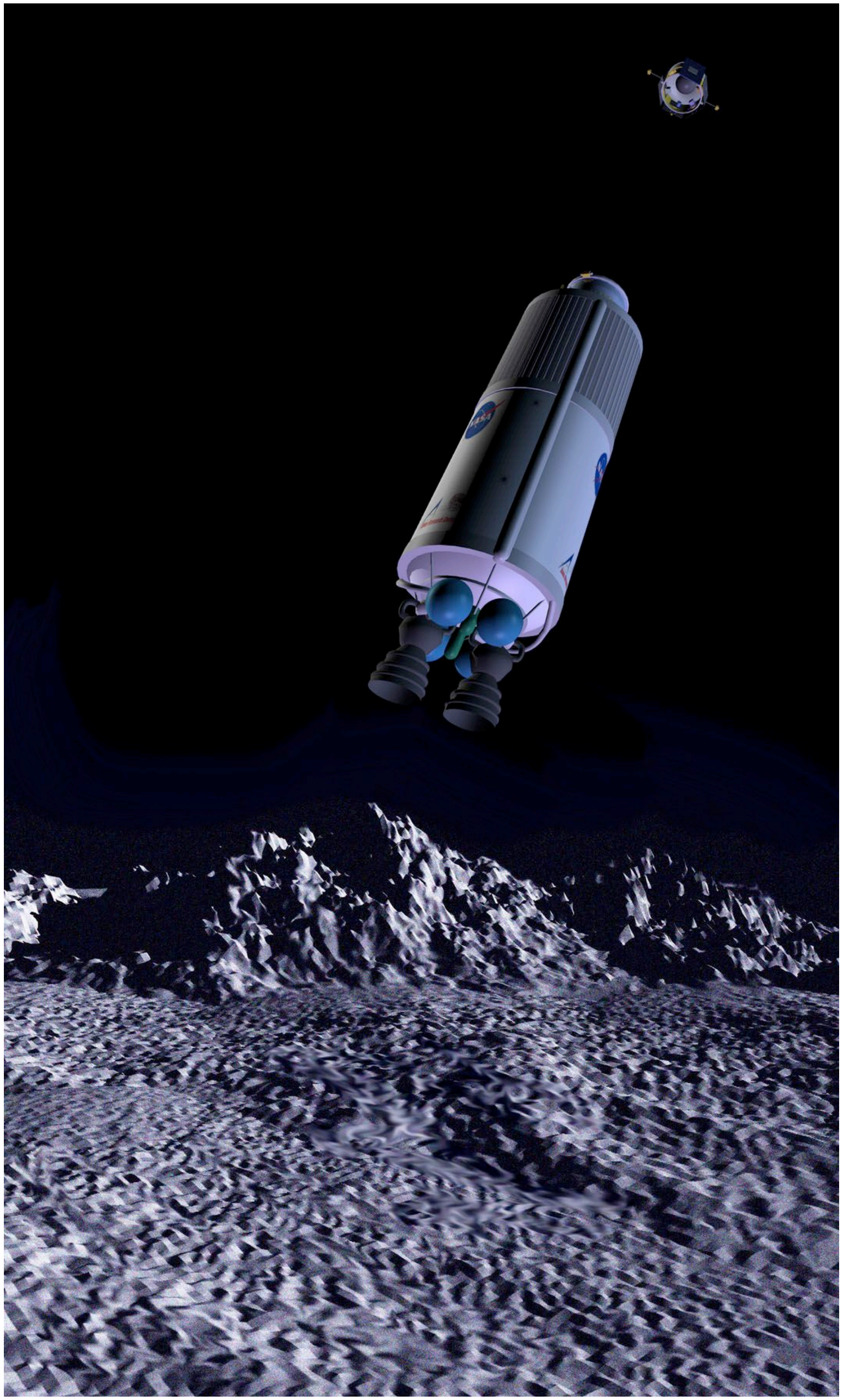
Led by

• Dan Andrews (Project Manager)

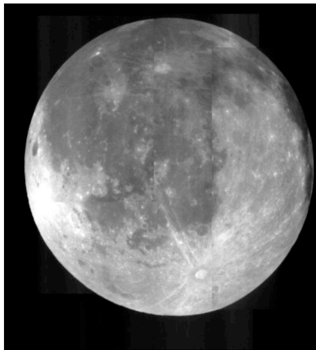
• John Marmie (Deputy Project Manager)

• Tony Colaprete (Science Lead / PI)

• and many others …



Backup slides



Brief Tutorial: Using Neutron Data to Detect Hydrogen

-The moon itself emits neutrons (galactic cosmic rays from space hit the Moon and knock neutrons out of regolith).

-These neutrons move fast at first, then lose energy as they collide with nearby atoms until they finally reach the same temperature as the surrounding material. Midway between this change (fast to slow), the neutrons are “warm” or “epithermal”.

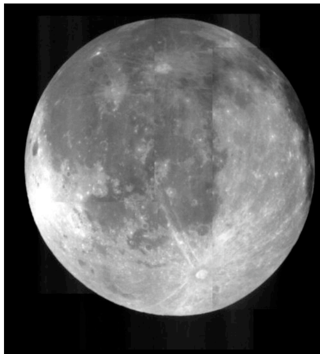
-If you observe a lot of epithermal neutrons --> the initial fast neutrons must be taking awhile to lose energy and become thermal neutrons.

-If you observe few epithermal neutrons --> change from fast to thermal energy levels happens fast.

-The role of hydrogen: An atom of hydrogen has similar mass as a neutron, so when a neutron collides with a hydrogen atom, the neutron loses most of its kinetic energy instantly.

-Therefore by measuring the fluxes of neutrons at several energies we can estimate the amount of hydrogen in the regolith.

“Ice at the Lunar Poles”, Vondrak and Crider, *New Scientist* **91** 2003.



Potential sources and sinks of lunar water ice

SOURCES

-Comet and asteroid impacts

-Reduction of FeO in lunar materials by solar wind hydrogen

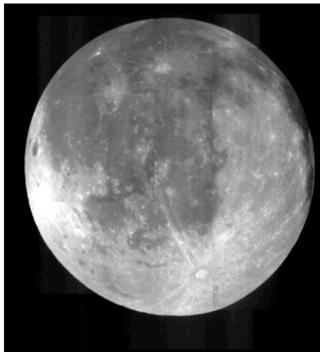
-Juvenile water released from lunar interior over billions of years

SINKS

-Meteoritic bombardment

-Erosion due to particle sputtering

-Photodissociation from interstellar hydrogen Lyman-alpha

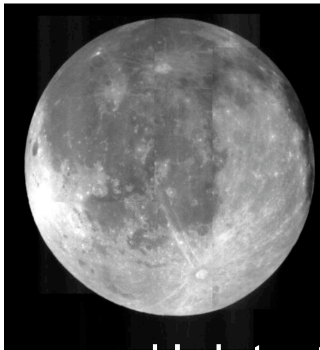


“Integration of lunar polar remote-sensing data sets: Evidence for ice at the lunar south pole”
Nozette, Spudis, et al., *JGR* **106**, 2001.

- LP: hydrogen detected within permanent shadow at south pole, especially at Shackleton crater.
- Clementine: Same areas correlate with Clementine bistatic radar data indicating ice.
- Arecibo: Same areas correlate with “anomalous” high values observed by Arecibo on the lower, sun-shadowed wall of Shackleton crater.

-Estimates from Arecibo and Clementine suggest ~10 km^2 of ice may be present on the Earth-facing wall of Shackleton crater.
-None of the data is definitive but taken together it is plausible that ice occurs in the cold traps on the Moon (notably in Shackleton crater).

LP neutron data, Arecibo, and Clementine data --> Ice in Shackleton.



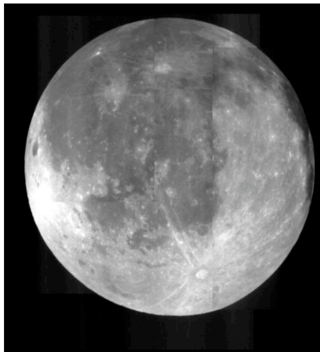
“Fluxes of Fast and Epithermal Neutrons from Lunar Prospector: Evidence for Water Ice at the Lunar Poles”

Feldman et al., *Science* **281**, 1998.

- H detected at both poles.
- Observations are consistent with water ice covered by as much as 40 cm of desiccated regolith within permanently shadowed craters near both poles.
-However, this model is not unique. Could get similar results from
    -Lower water ice abundances in buried deposit
    -Different surface area and surface distribution of the deposit
    -Multilayered geometry (alternating layers of ice and dry regolith)

-Discrepancy: The neutron data suggests more H in the north yet Clementine data suggests there is more area of permanent shadow in the south.
    - All excess H is not in the form of water ice?
    - Clementine data is incomplete? (south pole was observed by Clementine in winter, so some regions may get sunlight in summer)

LP neutron data --> Could be ice at poles.



"Fluxes of Fast and Epithermal Neutrons from Lunar Prospector: Evidence for Water Ice at the Lunar Poles"

Feldman et al., *Science* **281**, 1998.

Hydrogen abundances

NORTH

-North facing rim of Peary Crater

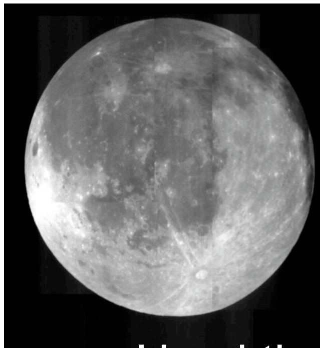
-Linear trend parallel to 130º meridian extending to 77ºN

-Rims of Hermite, Rozhdestvenskiy, and Plaskett craters

SOUTH

-Rim of the South Pole-Aitken basin

-Patches along rim of Shrodinger crater

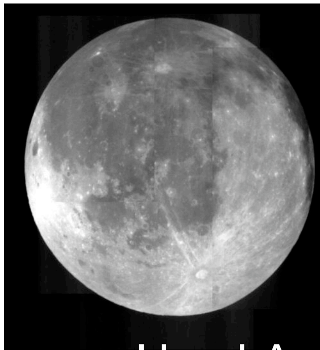


"Arecibo Radar Mapping of the Lunar Poles"
Stacy, Campbell, Ford, *Science* **276**, 1997.

-Used the Arecibo 12.6-cm radar system with resolution of 125 m.
-No areas greater than 1 km^2 found with properties suggestive of the presence of ice.
-Several areas smaller than 1 km^2 were found with these properties, but some of these areas are in sunlight (Clementine, Lunar Orbiter data).
-Features with similar properties were also observed at 47°N (Sinus Iridum).
-Highest backscatter comes from steep crater walls, not crater floor in several cases.
-These observations suggest these are regions of rough surfaces and/or blocky areas rather than icy deposits.

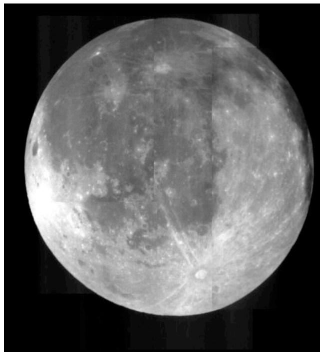
-Clementine radar data is consistent with but not unique to ice deposits.
    -Rock surfaces rough on the scale of the radar wavelength and observed at high incidence angles can result in similar signals.

Arecibo data --> Not necessarily ice.



"Radar Imaging of the lunar poles"
Campbell, *Nature* **426**, 2003.

-Used Arecibo telescope at 70cm for 300 m resolution (can penetrate several meters of lunar dust)
-Areas of crater floors near poles in permanent shadow do not yield strong radar echoes (like Mercury)
-Therefore any lunar ice (if present) must be in the form of distributed grains or thin layers (centimeters or less in thickness).
-This scenario could satisfy the LP results without strong radar backscatter enhancement.



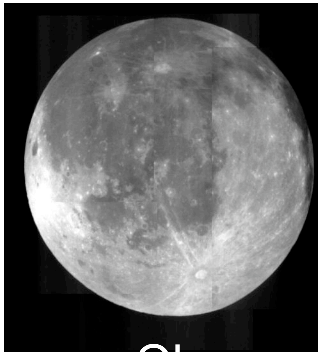
“Radar Imaging of the lunar poles”
Campbell, *Nature* **426**, 2003.

NORTH
Areas of permanent shadow near 85ºN, 63ºE, floor of Hermite crater, several small craters within large polar crater Peary --> radar backscatter is no different than typical lunar highland terrain

SOUTH

Floors of Shoemaker and Faustini craters (permanent shadow) have no strong radar echoes. Interior wall of Shackleton crater has a brighter radar signal - could be ice but is also consistent with radar returns from crater walls not in permanent shadow (therefore attributed to rougher terrain). Floor of Shackleton is not visible to the radar.

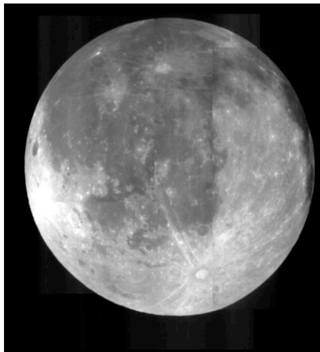
Arecibo data --> Not necessarily ice.



"The Clementine Bistatic Radar Experiment"
Nozette et al., *Science* **274**, 1996.

-Observed enhancement is localized to the permanently shadowed regions of the south. No enhancement is seen in permanently shadowed regions of the north pole or in sunlight areas.
-These observations can be explained by the presence of ice in the permanently shadowed regions of the south pole.

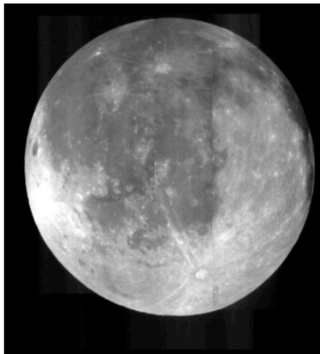
Clementine data --> Ice in Shackleton.



“Regolith properties in the south polar region of the Moon from 70-cm radar polarimetry”
Campbell and Campbell, *in press,* 2005.

-Used Arecibo and Greenbank telescopes at 70 cm, 450 m resolution for latitudes 60º-90ºS, can probe up to 10s of meters below the surface.
-Radar variations attributed to variations in surface and subsurface rock populations.
-Small areas of high enhancement are on shadowed and sunlit terrain, associated with small craters.

Arecibo & Greenbank data --> Not ice in Shackleton.

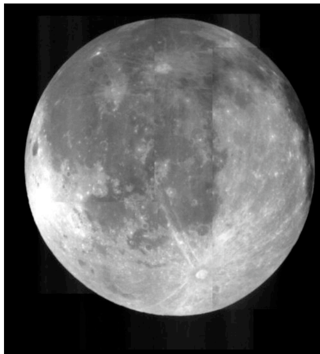


“Regolith properties in the south polar region of the Moon from 70-cm radar polarimetry”
Campbell and Campbell, *in press,* 2005.

-CPR values: larger, old craters w/terraces = moderate CPR; young craters = higher CPR due to more near-surface rugged blocks; smaller craters with sharp rims (e.g. Shackleton) = high CPR. Since CPR values can be high for both shadowed and sunlight regions, likely is not due to ice but rather surface morphology.

-High CPR values are observed in patchy clusters on the floors of both shadowed and sunit craters. Based on Lunar Orbiter photos, high resolution radar data, and the radar scattering properties of terrestrial rugged terrain, the lunar patterns are likely due to proximal ejecta blankets of abundant small craters.

Arecibo and Greenbank data --> Not ice in Shackleton.

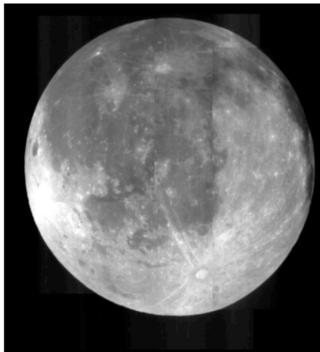


"Regolith properties in the south polar region of the Moon from 70-cm radar polarimetry"

Campbell and Campbell, *in press,* 2005.

-Shackleton crater: -Lower portion of the interior wall is not significantly different in 70 cm scattering properties than sunlit areas of craters with similar morphology.

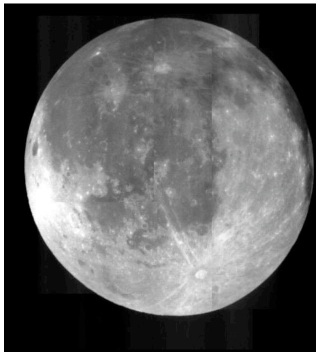
Arecibo and Greenbank data --> Not ice in Shackleton.



“Reanalysis of Clementine bistatic radar data from the lunar south pole”
Simpson and Tyler, *JGR* **104**, 3845-3862, 1999.

-Reanalysis of Clementine bistatic radar data reported by Nozette et al. (1996).
-Unable to reproduce the results of Nozette et al. (1996)
-Any observed backscatter enhancements are not unique to the south pole.
-Observations “easily attributable” to local terrain variations, topography, surface roughness, etc.

Clementine data --> Not ice in Shackleton.



"Space weathering effects on lunar cold trap deposits"
Crider and Vondrak, *JGR* **108**, 3845-3862, 2003.

- A detailed study by Crider & Vondrak simulate the evolution of a H_2O column in a lunar cold trap over time as a function of depth with H_2O arriving from both the solar wind and from comets.
- They conclude that the regolith would reach an equilibrium concentration of H_2O at 4100 ppm (0.41% per unit mass). This equilibrium value would be reach from solar sources alone and comets essentially are superfluous. Time merely increases the thickness of the layer in which ice will be harbored. In 1 billion years the layer would be 1.6 m thick. The ice would be diffuse.
- Their results are consistent with Arecibo observations and within a factor-of-2 *LP* neutron spectrometer values.

Theory --> Not much ice (if present) in Shackleton.