Synthesis of Current Data on Helium and Hydrogen Concentrations in Lunar Regolith*

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Abstract

Combined results of (1) analysis and subsequent interpretation of Apollo regolith and regolith breccia samples, (2) mapping of Hydrogen concentrations in the upper regolith by neutron spectroscopy by Lunar Prospector, (3) the LRO LCROSS impact into permanently shadowed regolith at the lunar south pole, and (4) Earth-based spectroscopic and LRO analysis of the lunar transient atmosphere lead to the following tentative conclusions:

1. Exposed to steady state deposition and release, ilmenite-rich regolith preferentially retains solar wind-derived Helium versus ilmenite-poor regolith.
2. Water and other volatile compounds and elements have been trapped in permanently shadowed areas at high latitudes.
3. Exposed to the steady-state deposition and release, plagioclase-rich regolith preferentially retains solar wind-derived Hydrogen versus plagioclase-poor regolith.
4. Sodium in the lunar transient atmosphere suggests that solar wind protons displace mono-valent Sodium (and possibly Potassium) present in solid solution in the crystal lattice of plagioclase. Similar cation replacement takes place during weathering of plagioclase on Earth.
5. Cold trapping of Helium-3 in high latitude regions may occur; however, direct measurement of its degree is not currently feasible.
6. Helium in the lunar transient atmosphere indicates that thermal and/or micro-meteor impact releases solar wind volatiles from the regolith, making those volatiles subject to migration and re-implantation as well as entrainment in the passing solar wind.
7. No data exists on the concentration of solar wind-derived Hydrogen or Helium in permanently shadowed areas. The density of transient Helium in the lunar atmosphere, however, shows little or no latitudinal variation in surface derivation.

Available information points future commercial lunar Helium-3 production toward the “inferred resource” areas in Mare Tranquillitatis. The potential remains great, however, for the existence of commercial quantities of cold-trapped Helium-3 in the regolith of high-latitude plains. This potential is significant enough that any Helium-3 production initiative should seriously evaluate the cost and benefit of a lunar orbiter mission capable of mapping Helium-3 distribution at high latitude as well as globally.

Selected References

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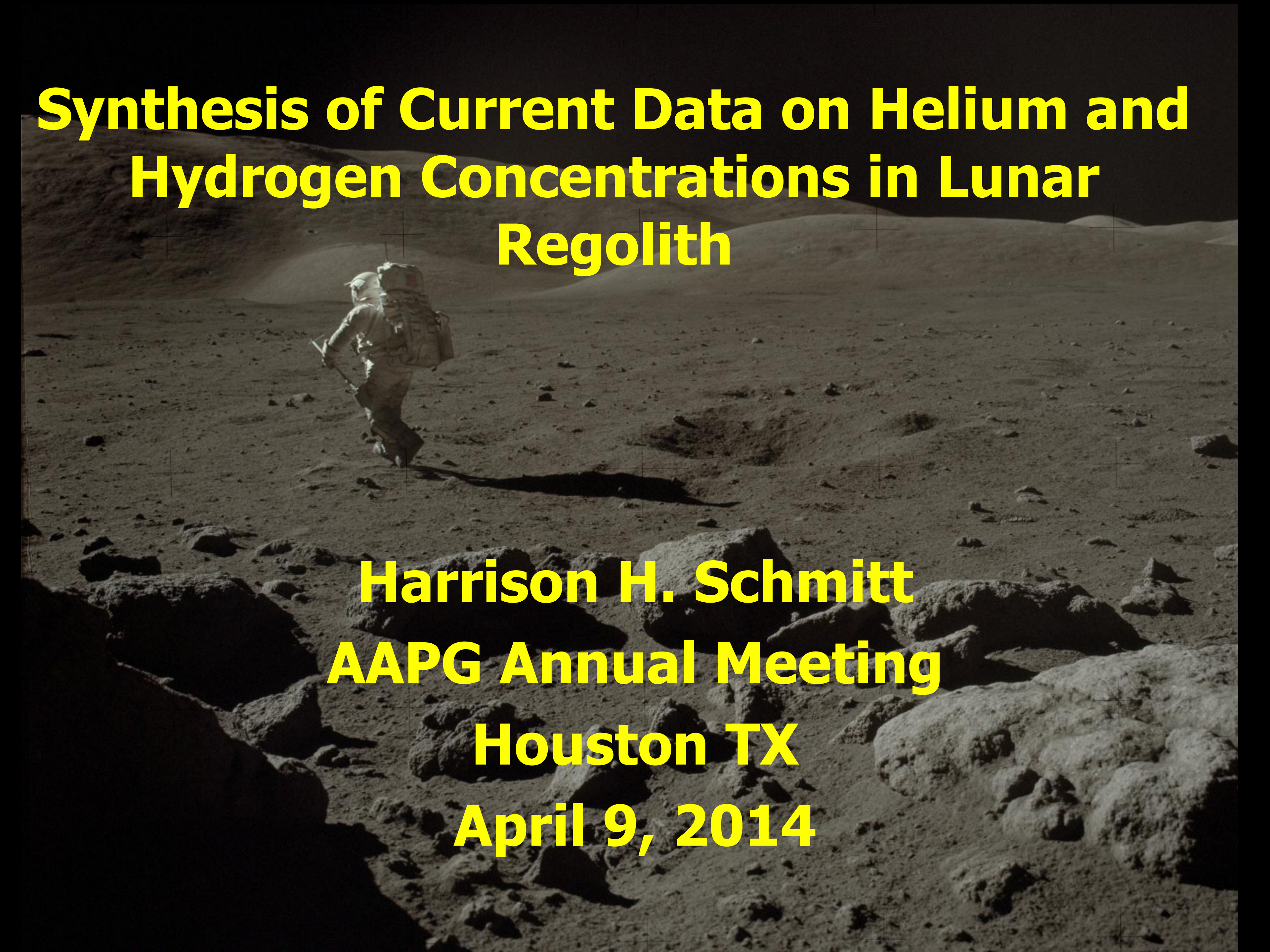
Website

http://www.projectrho.com/public_html/rocket/engines.php; http://www.projectrho.com/rocket/rocket3c2.html (website accessed July 26, 2014)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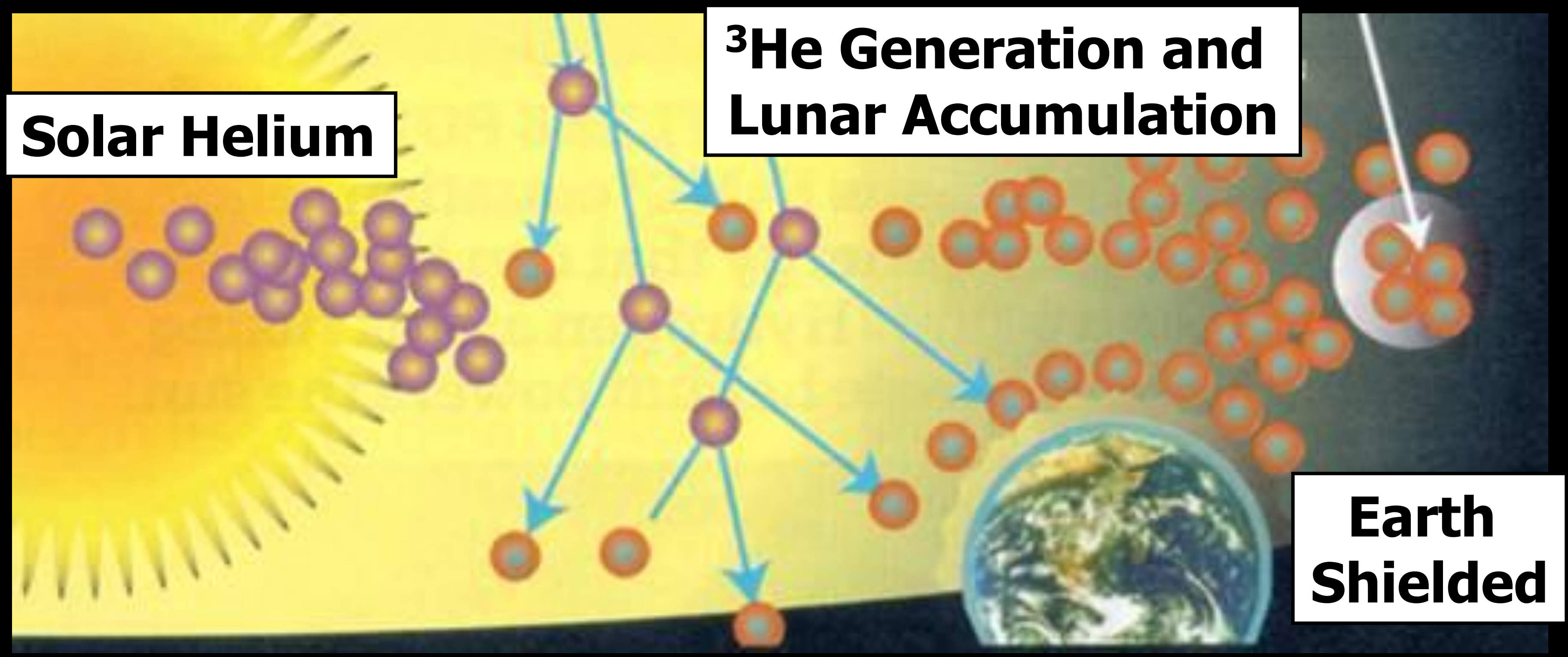
Harrison H. Schmitt
AAPG Annual Meeting
Houston TX
April 9, 2014

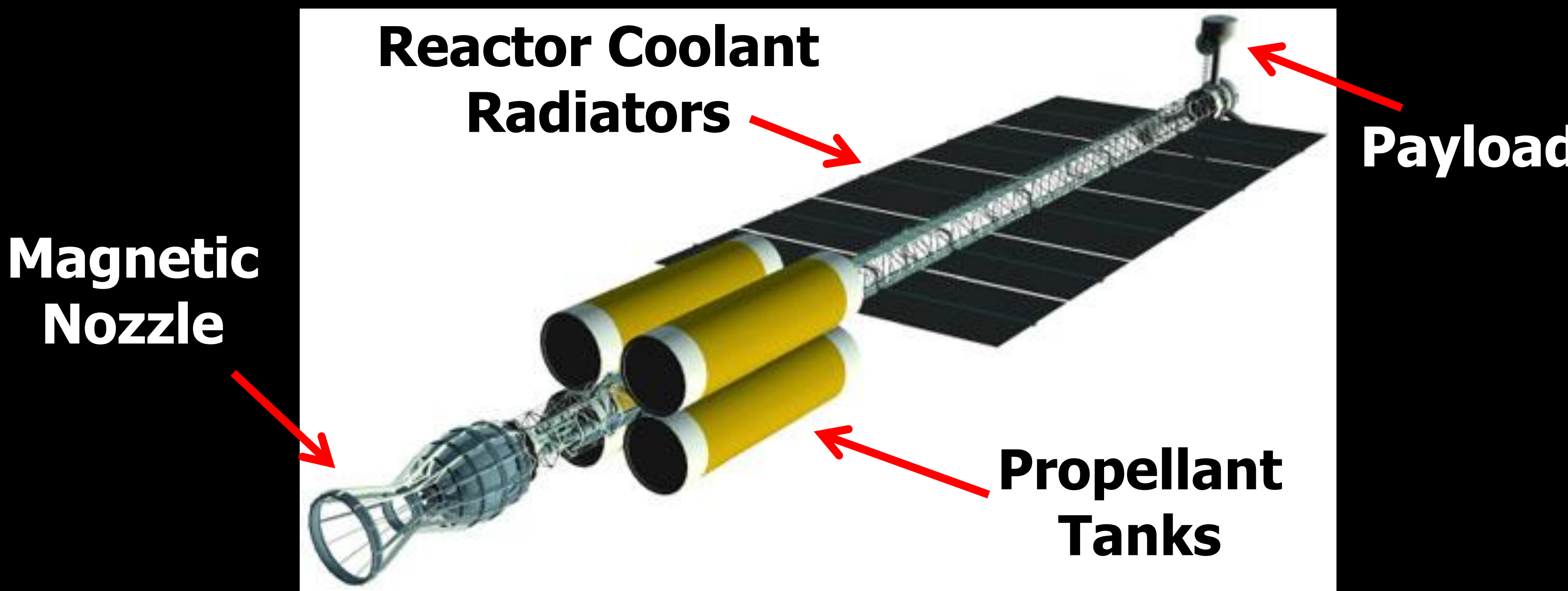
Helium-3 from the Solar Wind



Schmitt (2004)

^{3}He-D Fusion Rocket

Fuel is ^{3}He and deuterium. 1 atom of Deuterium fuses with 1 atom of ^{3}He to produce 18.35 MeV of energy. One GW of power requires burning only 0.00285 grams of ^{3}He -D fuel sec^{-1}.



http://www.projectrho.com/rocket/rocket3c2.html

LUNAR REGOLITH

Undisturbed Grade For Apollo 11 Helium-3 >20 ppb

1000 MWe Fusion Power Plant (D-^3He) Requires ~100kg Helium-3/year

100 Kg Helium-3 Requires Mining 2km^2 to Depth of 3m and Processing the <100 μm Fraction (~50 Wt.%)

100 Kg Helium-3 Has Steam Coal Equivalent Value of $140 Million (Coal @$2.50/million Btu)

Schmitt (2006)

Lunar Helium-3

- Arrives at the Moon With The Solar Wind
  - Hydrogen (protons) = 96%
  - Helium (alpha particles) = 4%
  - Carbon, Nitrogen and Oxygen Ions = <0.1% each

- Embedded In Particles of the Lunar Regolith
  - H/He Mass Ratio = ~1-3
  - $^{4}He/^{3}He$ Mass Ratio = ~3100-3600
  - ^{3}He Concentration (Grade) = ~20 wppb (Apollo 11)

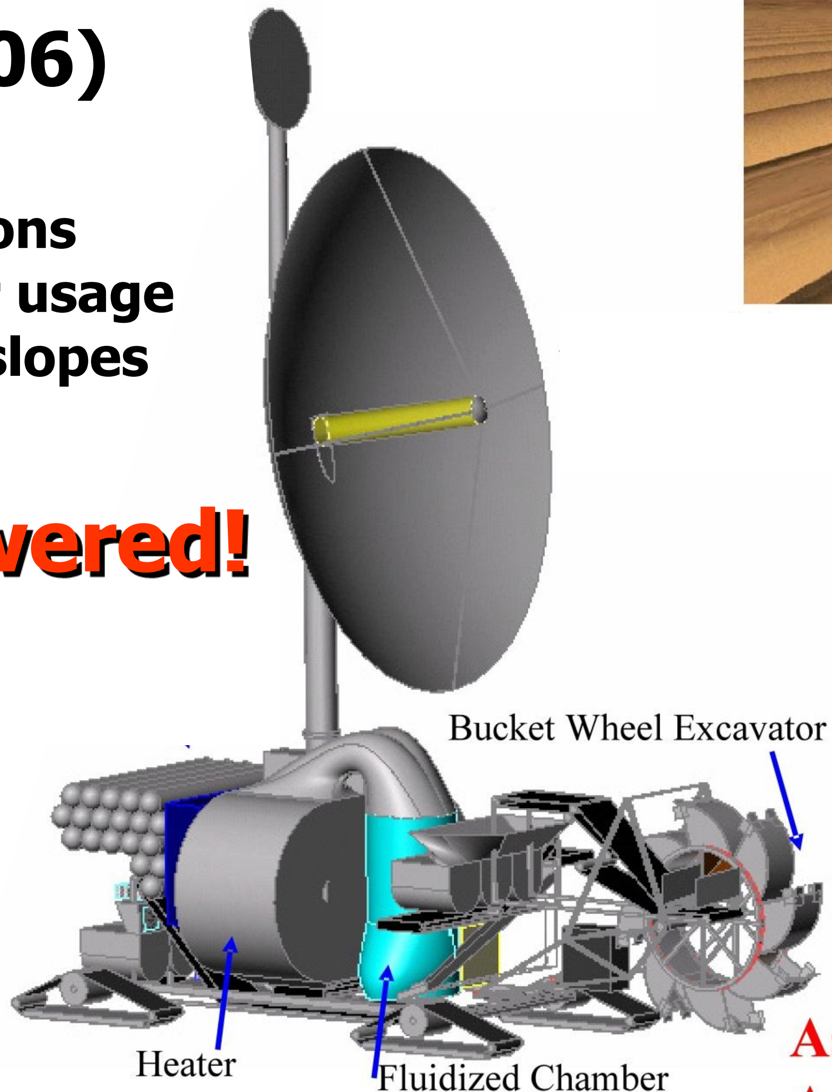
- Solar Wind Volatiles Can Be Released From Regolith
  - Agitation (40-50%)
  - Heat (~80-90% at ~700ºC after Pre-heat to 600ºC)

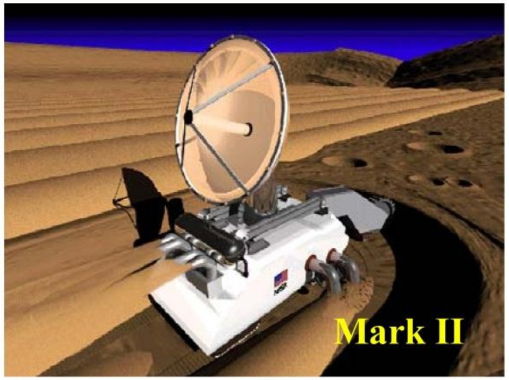
Hydrogen and ^{3}He Mining

Matt Gajda et al. (2006)

Mass 9.7 tons
350 kW power usage
Handles 30° slopes

Solar Powered!





Mass of Volatiles Extracted (tonnes/yr @ 10ppb)	
H_2O	108.9
N_2	16.5
CO_2	56.1
H_2	201.3
^{4}He	102.3
CH_4	52.8
CO	62.7
^{3}He	0.033

Assumed 10ppb!
Actual >20ppb

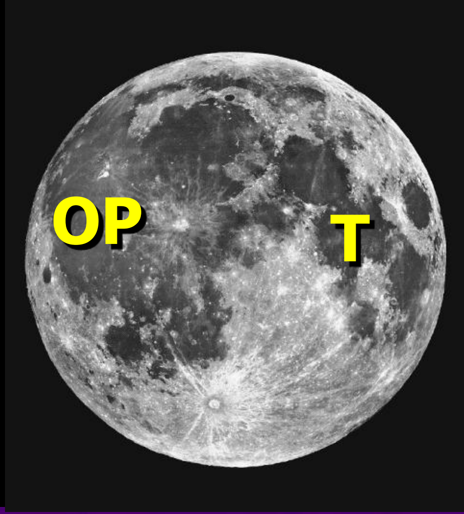
Data Sources for Known Helium-3 Resource Concentrations

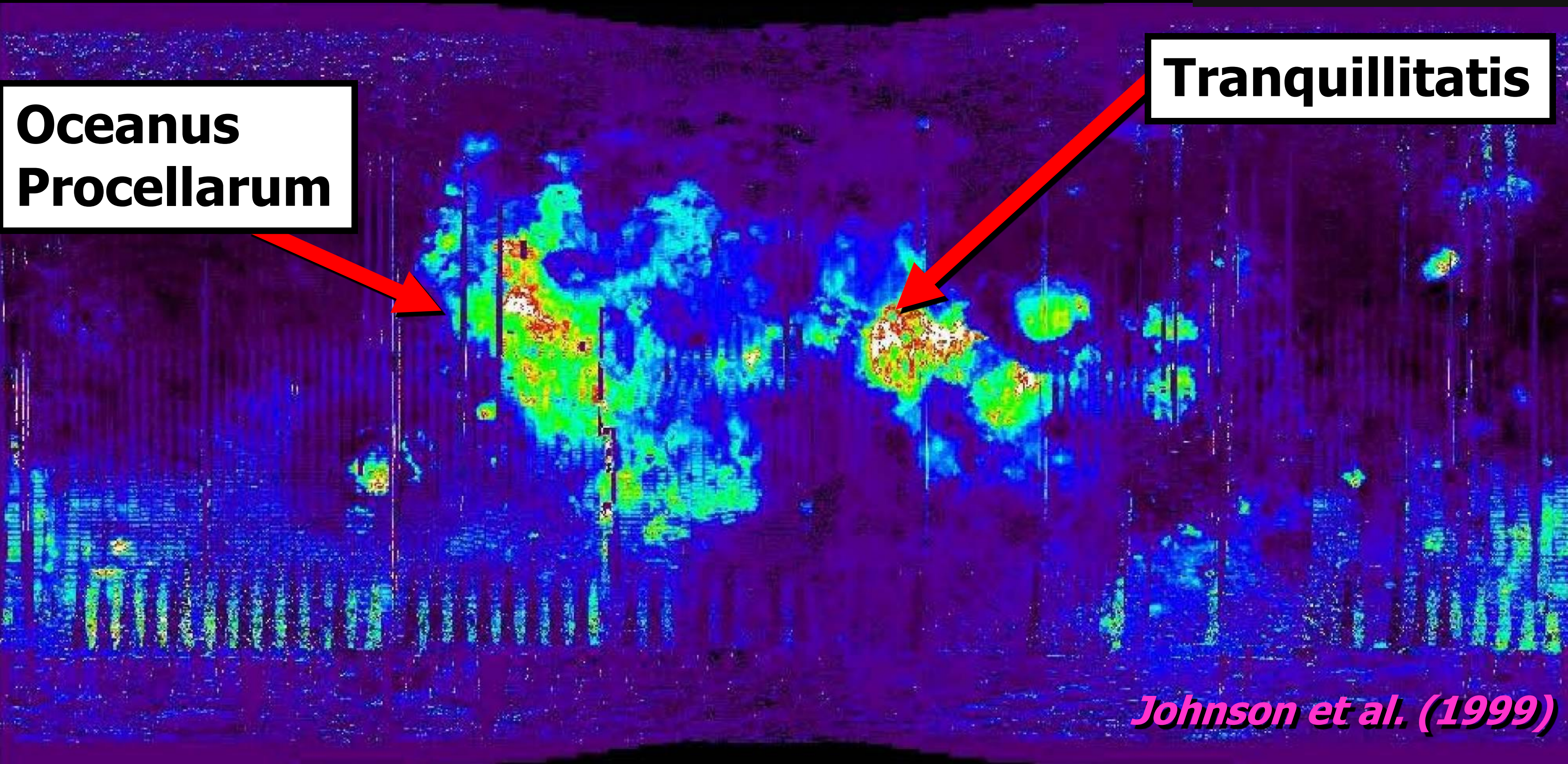
- Apollo Samples, Particularly Apollo 11 (10084)
- Direct Correlation With Mare Basalt Titanium Content
  - Comparison of Apollo 11 and 17 with 12 and 15
- Direct Correlation With Finest Particle Fraction in Regolith (<100 μm ~50% by Volume)
- Future Geological Interpretation of Mining Variables
  - Depth of Regolith (Average ~ 6m for oldest Mare)
    - Robotic Seismic Surveys for Mining Planning
  - Minable Area vs. Craters and Boulder Fields (~50%)
    - Photo-Mapping for Mining Planning
  - Buried Boulder Distributions
    - Real-Time Look-Ahead Radar and Seismic
  - Geotechnical Parameters
    - Robotic Mapping of Cohesion, etc.

Lunar ^3He Distribution

>270,000 km^2 minable
(high- and medium-grade)

Lewis (1996)

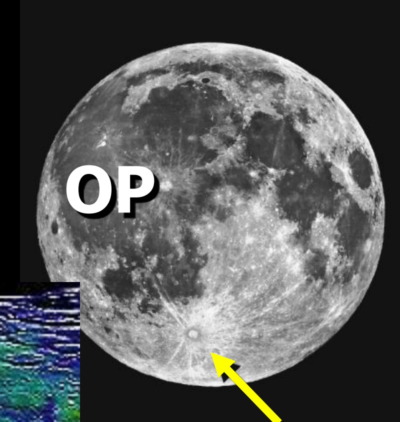


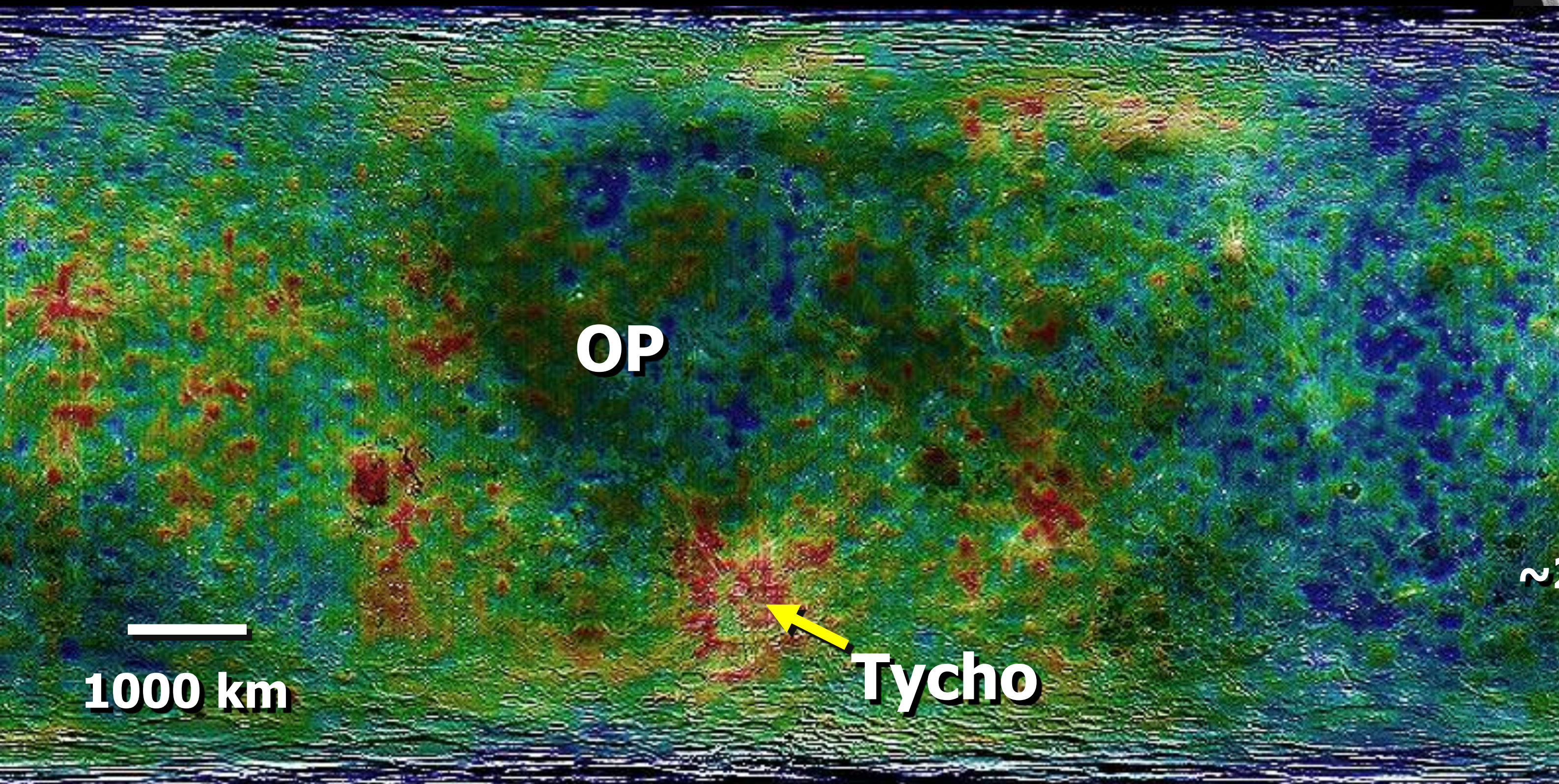


Johnson et al. (1999)

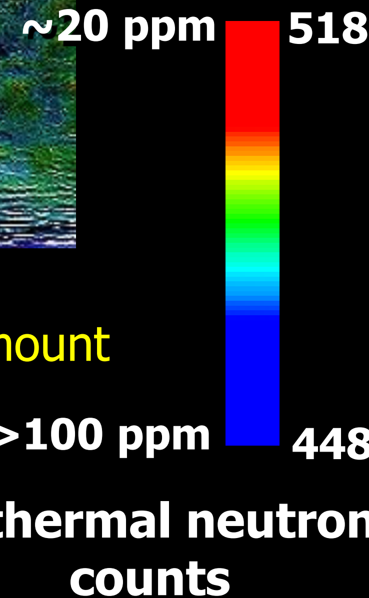
Global hydrogen—Exogenic

Implantation from Solar Wind





A ~0.4-mi^2 (1-km^2) area of mare regolith at 40-ppm hydrogen could be mined to a depth of ~3.3 ft (1 m) to extract an equivalent amount of hydrogen for launching the Space Shuttle (Spudis, 1996).



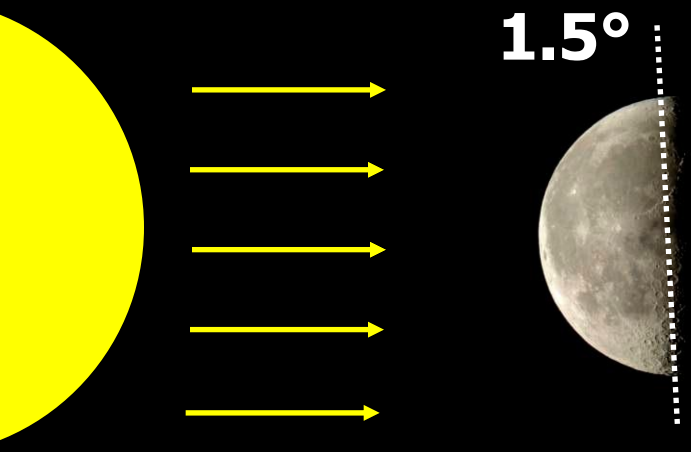
High Latitude ^{3}He Potential

- Regional cold-trapping
- Local concentrations in permanent shadowed craters
- First Question: Is solar-wind hydrogen useful as a surrogate for Helium?
  - Hydrogen concentration in maria does not directly correlate with Titanium concentration
- Second Question: Is high-latitude Hydrogen actually "Solar Wind" Hydrogen?
  - Water from comets, pyroclastic eruptions, etc.

Volatiles at the Poles—Exogenic

Impacts from comets

10^{13} kg water: past 2 Ga (Arnold, 1979)



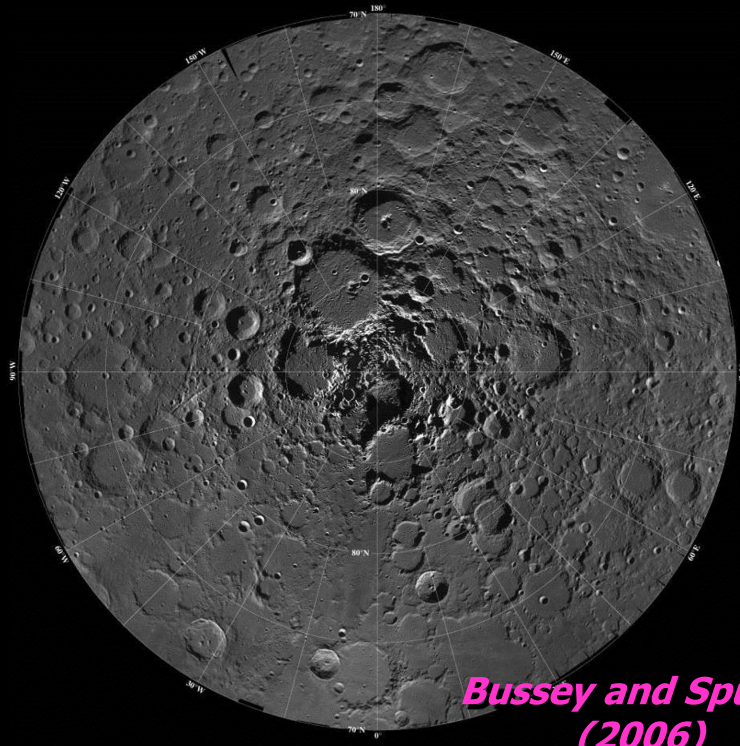
View from the Moon's South Pole

Kaguya Photograph

LRO-Based Photo-Mapping of Permanent Shadow

- **South Polar Region (60-90º S. Lat.)**
  - **91,409 km²**
- **North Polar Region (60-90º N. Lat.)**
  - **169,508 km²**
- **Total: 260,917 km²**
- **Potential Helium-3 resources at 40 ppb**
  - **33,563 tonnes**
- **Note: Areas minable to 3 m depth based on 50% of total area of smooth plains >25 km²**

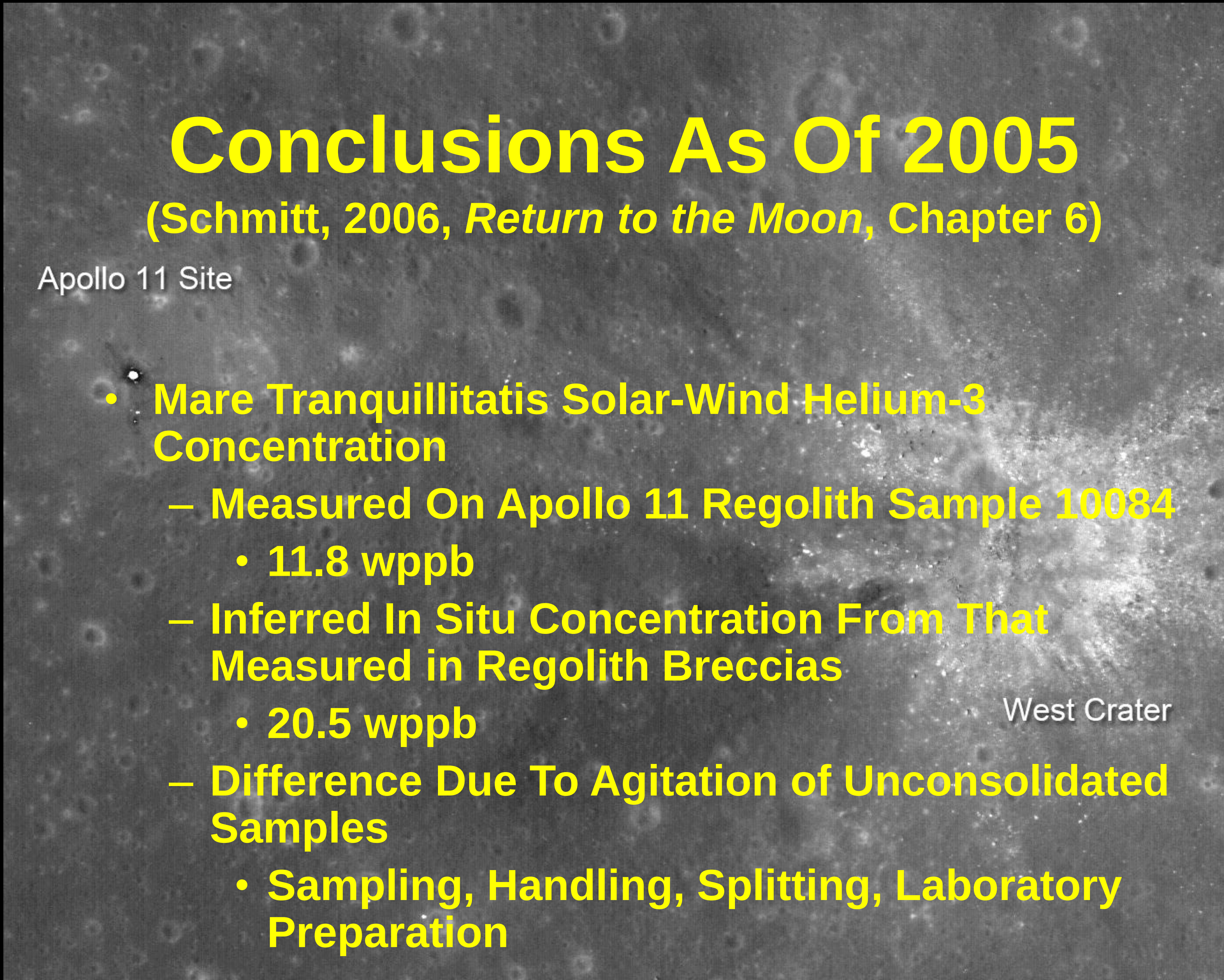
North Polar Region



Bussey and Spudis (2006)

Conclusions As Of 2005

(Schmitt, 2006, *Return to the Moon*, Chapter 6)

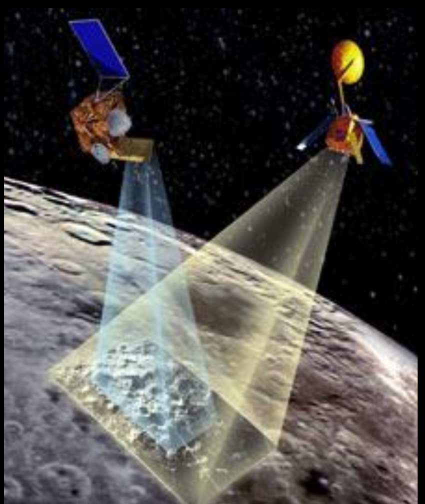


- **Mare Tranquillitatis Solar-Wind Helium-3 Concentration**
  - **Measured On Apollo 11 Regolith Sample 10084**
    - **11.8 wppb**
  - **Inferred In Situ Concentration From That Measured in Regolith Breccias**
    - **20.5 wppb**
  - **Difference Due To Agitation of Unconsolidated Samples**
    - **Sampling, Handling, Splitting, Laboratory Preparation**

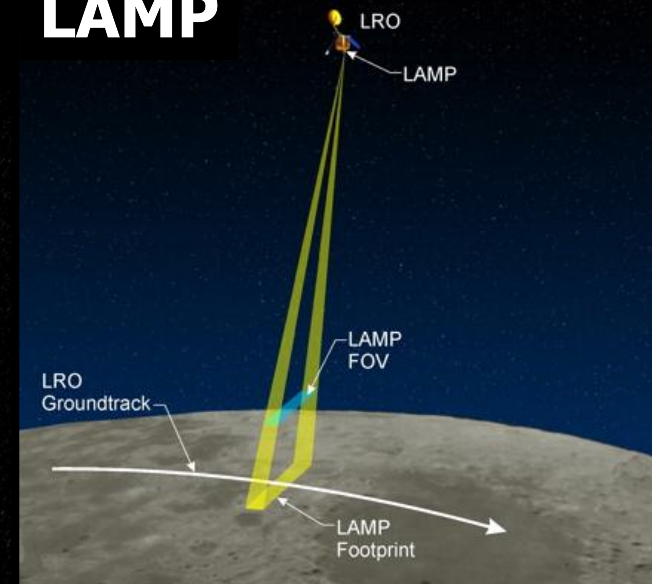
Lunar Reconnaissance Orbiter

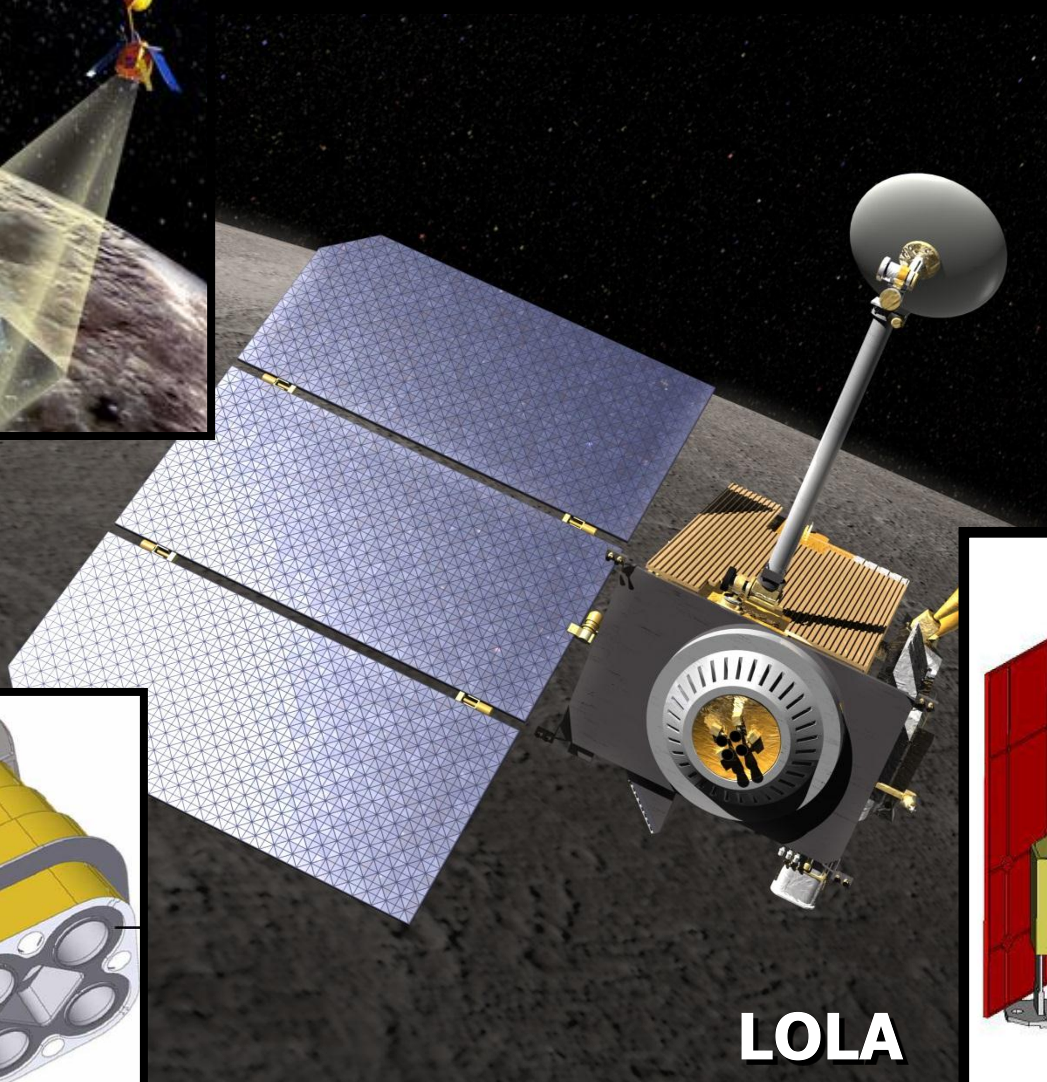
Launched in June 2009

Mini-SAR

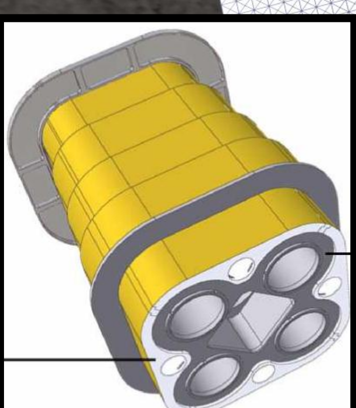


LAMP

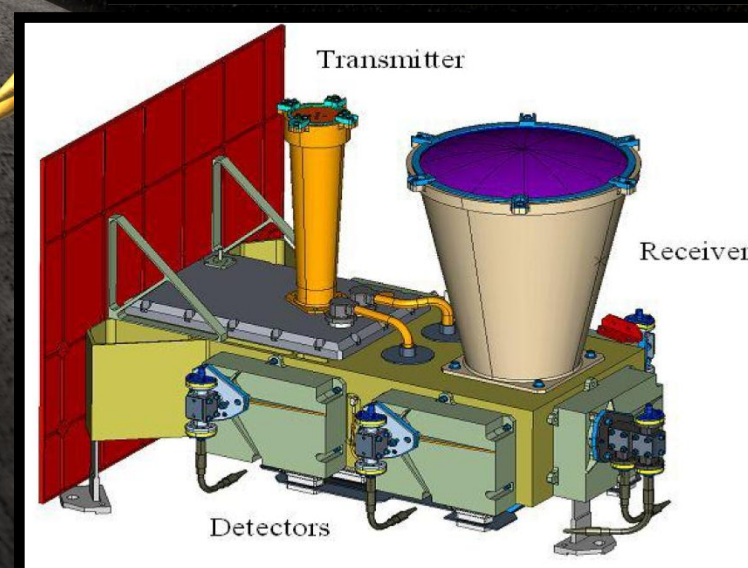




LEND

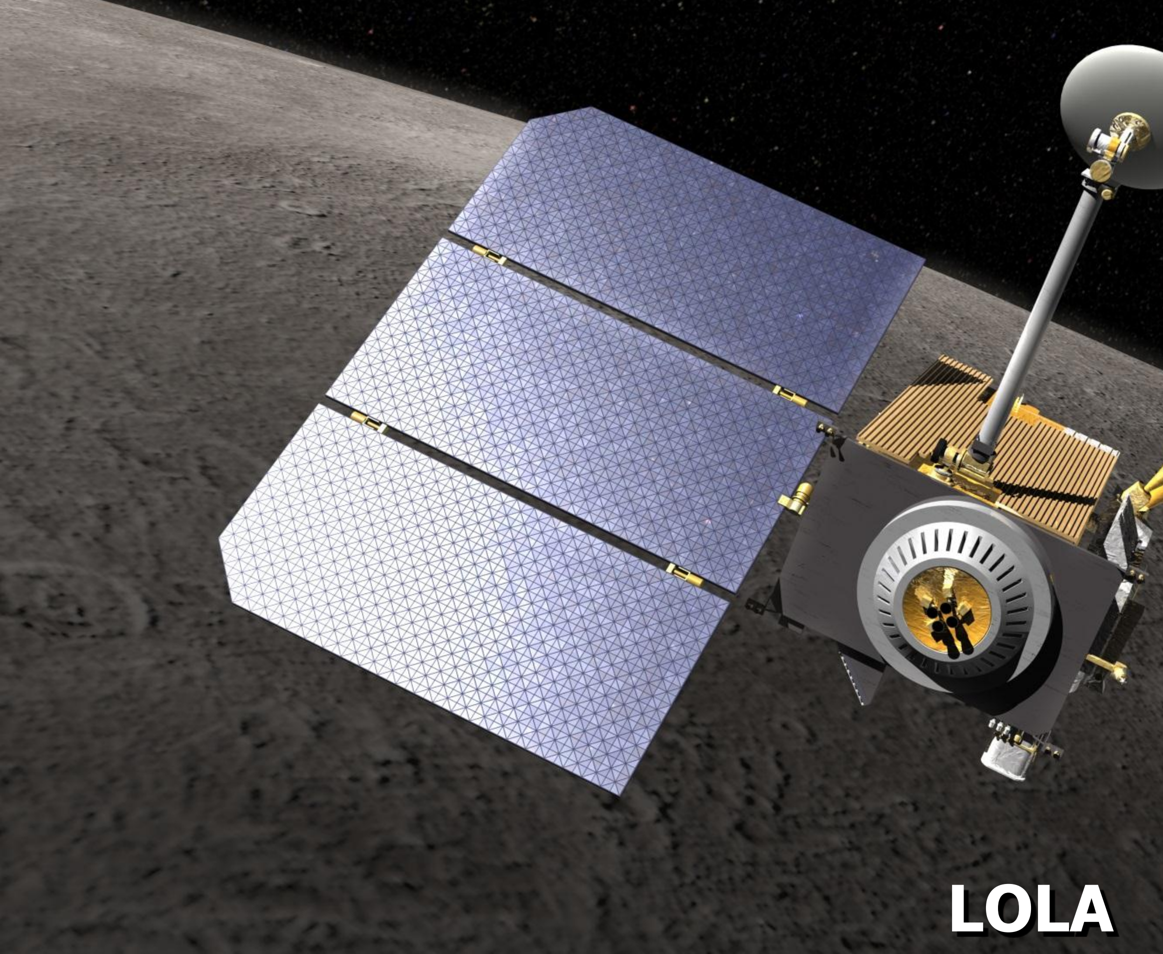


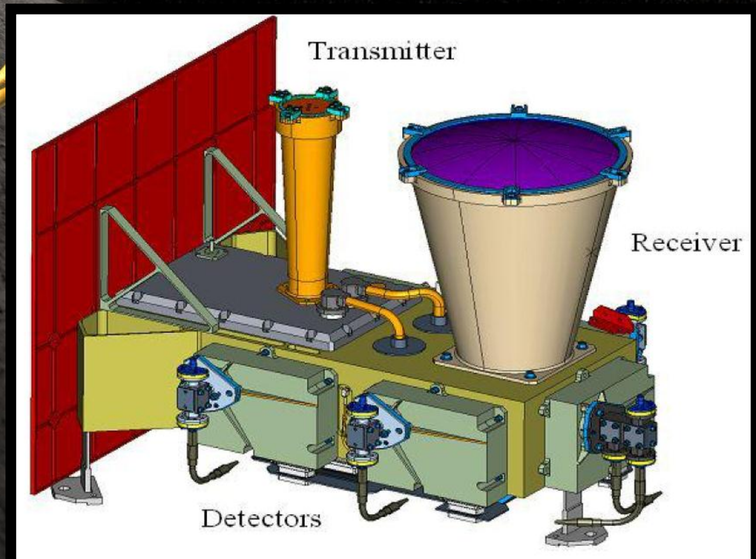
LOLA



LOLA (Lunar Orbiter Laser Altimeter)

- Provide lunar topographic maps from 50-km orbit
- Image PSRs
- Can detect change in reflectivity of regolith with 4 wt % water ice

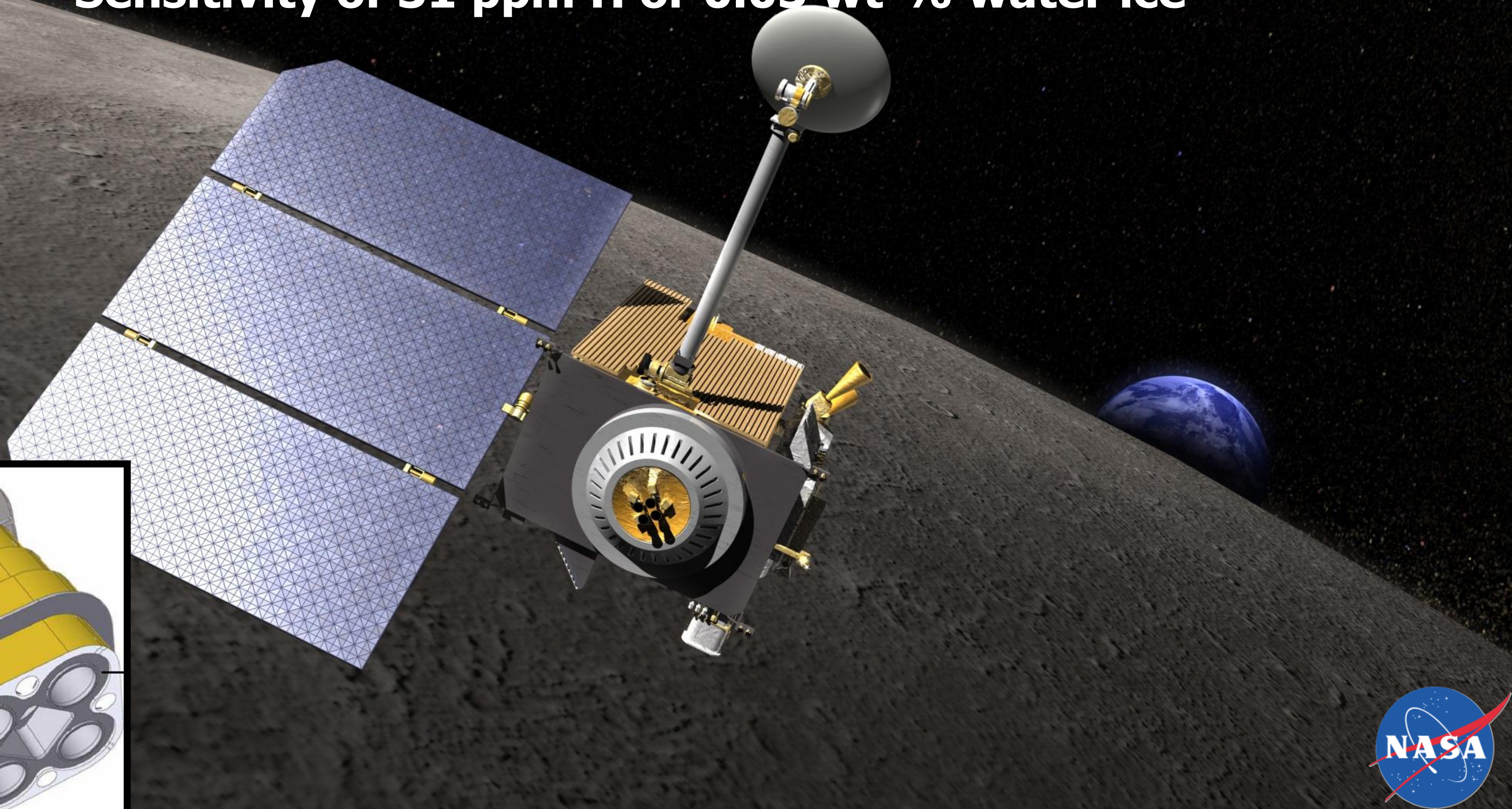




LEND (Lunar Exploration Neutron Detector)

- Measure neutron emission from the lunar surface and local neutron background
- Collimated neutron detector with 1-km field of view
- Map global distribution of hydrogen in regolith:

  Sensitivity of 31 ppm H or 0.03 wt % water ice



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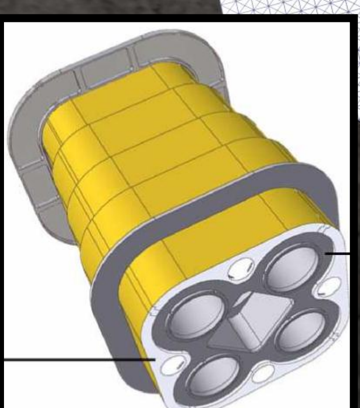
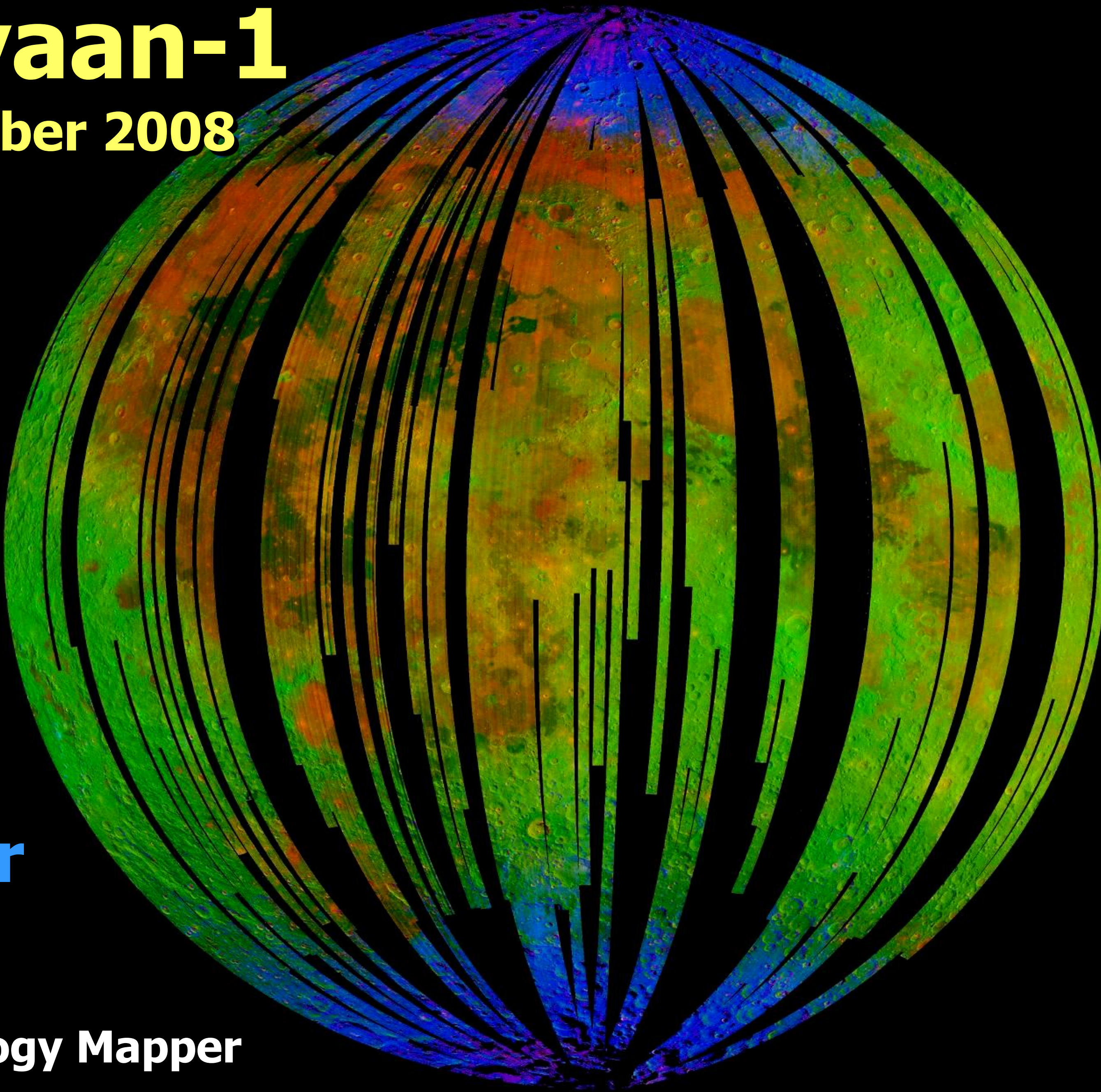


Neutron Spectroscopy Data

- Hydrogen enriched at high latitudes
  - Cold-trapping (up to 1,700±900 ppm)
    - Solar wind hydrogen
    - Water (where T always below 110ºK: No sublimation)
    - Exotic volatiles (Hg, CO_2, HCl, SO_2, NH_3, Na)
- Hydrogen generally enriched at latitudes higher than 60º even without significant permanent shadow
  - Suggests Helium also would be enriched at intermediate and high latitudes

Chandrayaan-1

Launched October 2008



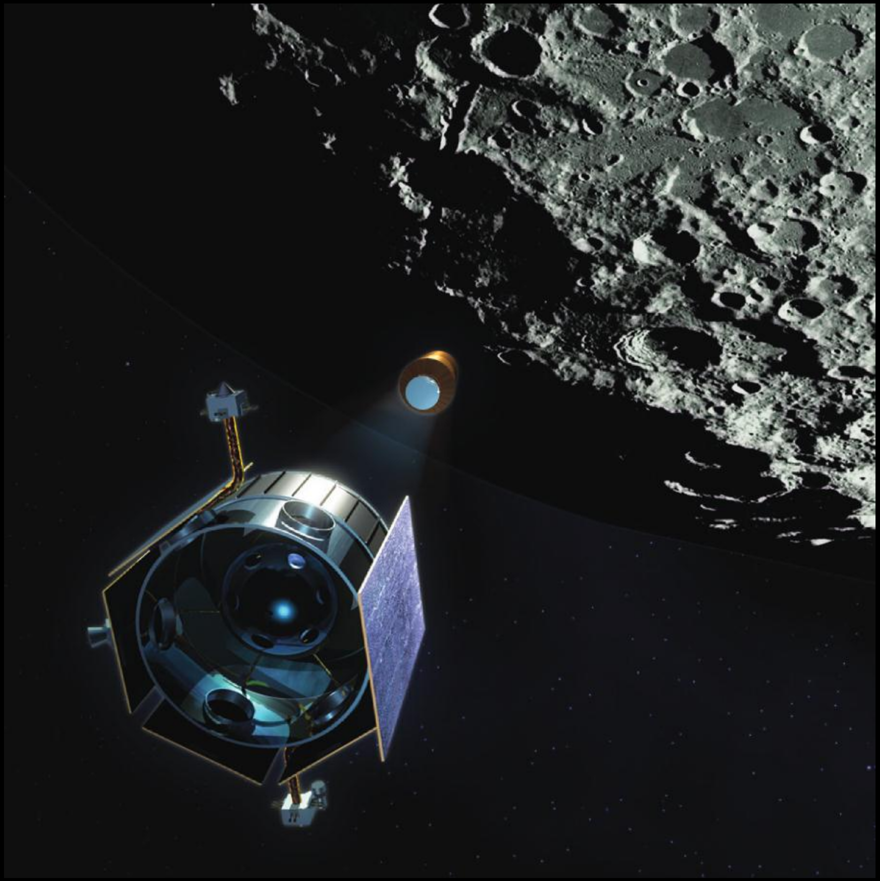
Polar Water Signature

NASA Moon Mineralogy Mapper
September 2009

LCROSS

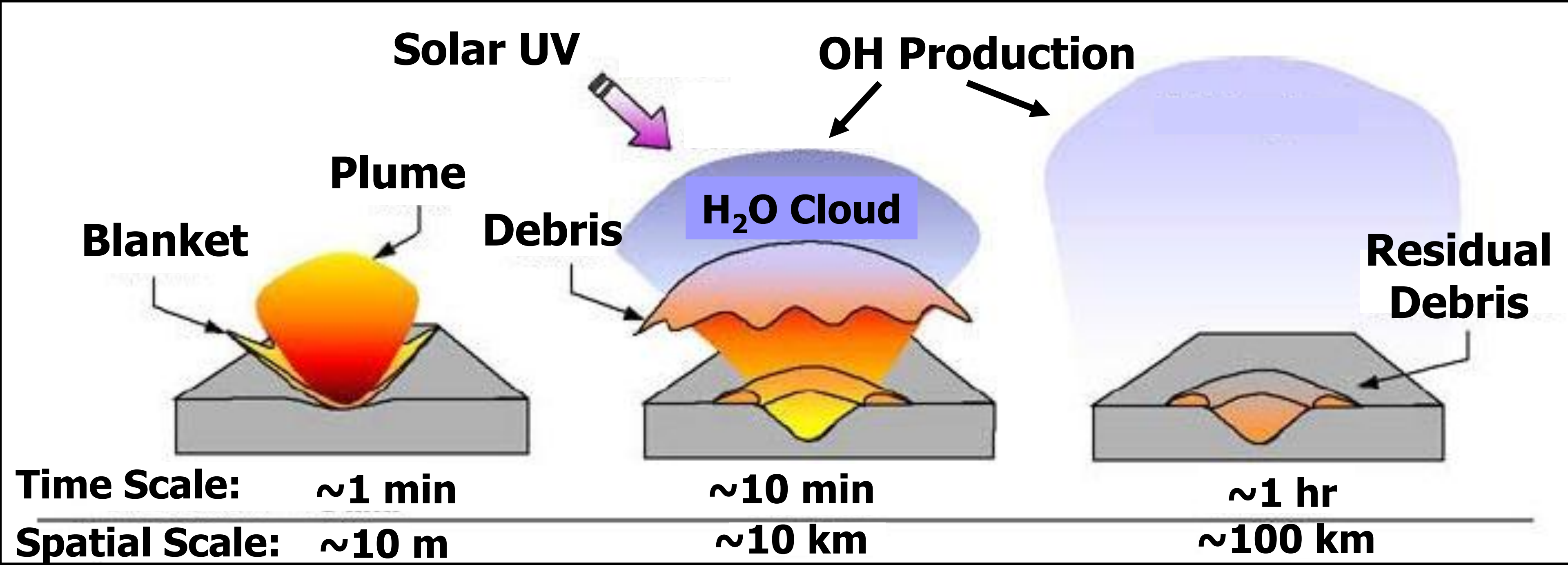
(Lunar CRater Observation and Sensing Satellite)

- measure the concentration of water ice (ice to dust ratio) in PSRs
- Oct. 8, 2009: Upper stage impact >9,000 km hr^{-1}



LCROSS

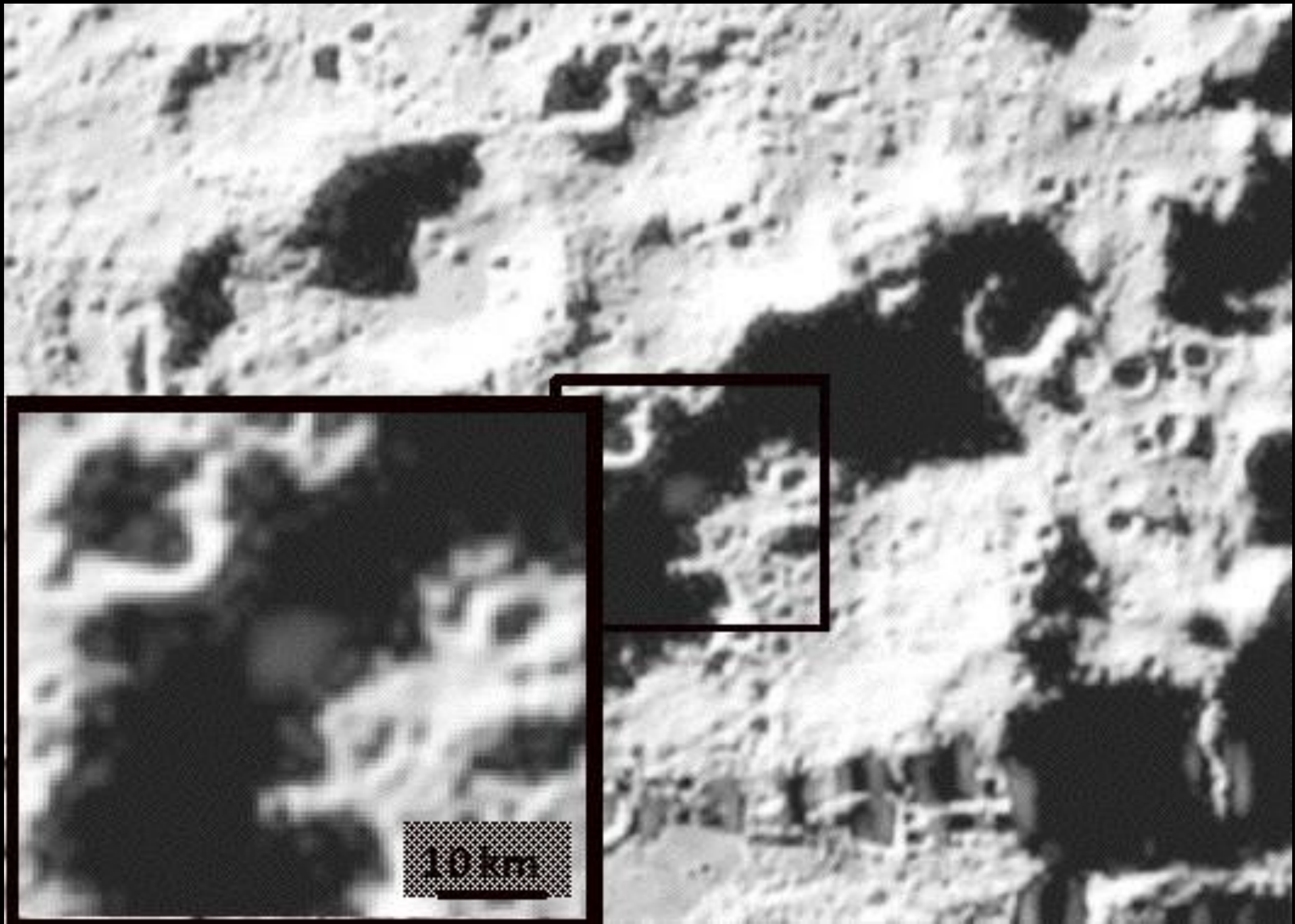
(Lunar CRater Observation and Sensing Satellite)



Impact Plume Model

LCROSS

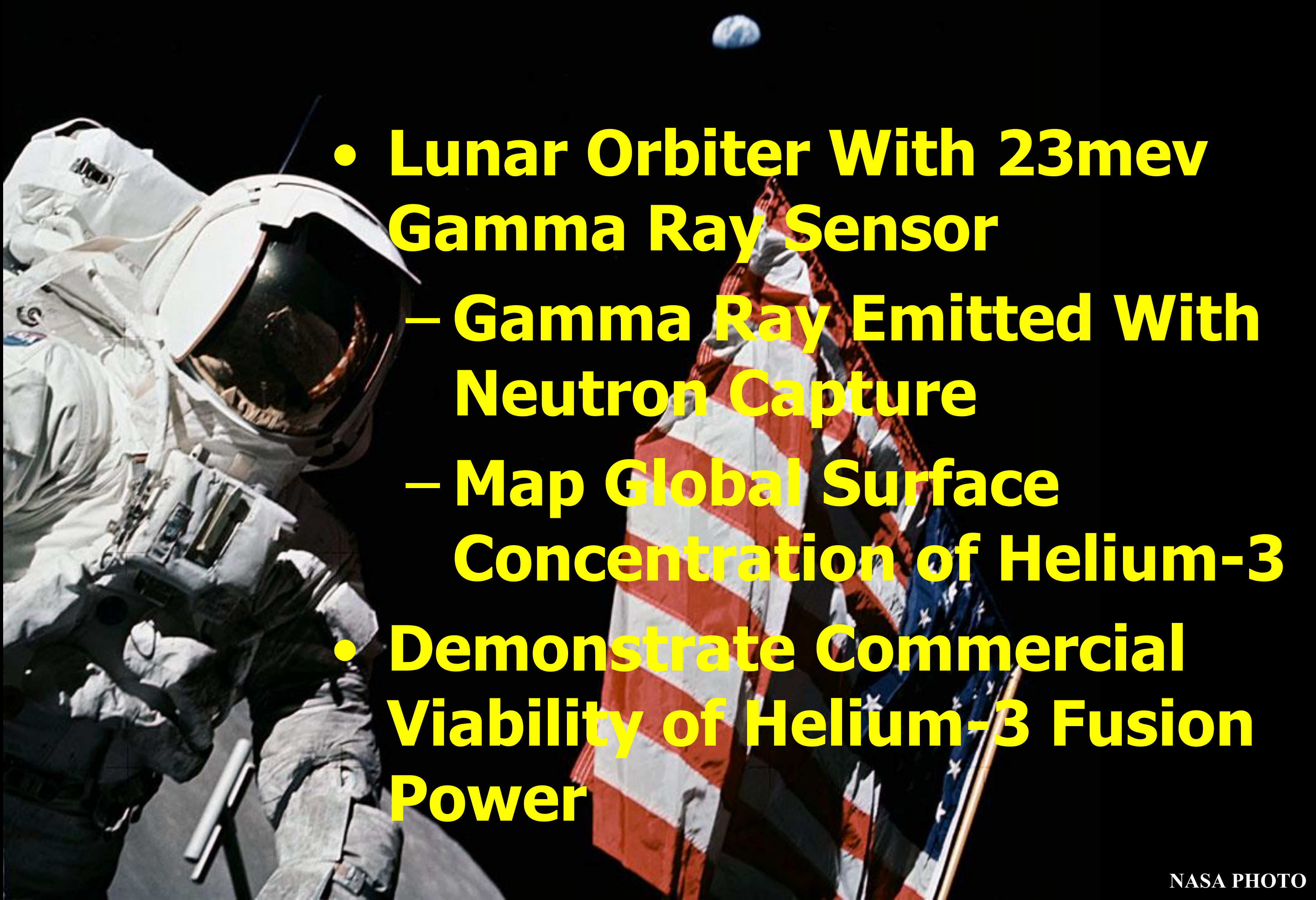
Impact Plume: Cabeus A



Conclusions

- Since 2005, investigators have new information on global hydrogen distribution.
- Suggestion that solar wind hydrogen, and thus helium, have enhanced concentrations above 60º latitude.
- However, distribution of <u>Solar Wind</u> hydrogen cannot be determined separately from new data.
  - Thus, no correlation with Helium-3 is yet possible.
- Helium-3 concentrations, other than for Tranquillitatis regolith, remain uncertain.

Next Steps



- Lunar Orbiter With 23mev Gamma Ray Sensor
  - Gamma Ray Emitted With Neutron Capture
  - Map Global Surface Concentration of Helium-3
- Demonstrate Commercial Viability of Helium-3 Fusion Power

NASA PHOTO