Moon Express

Advancing Commerce and Science

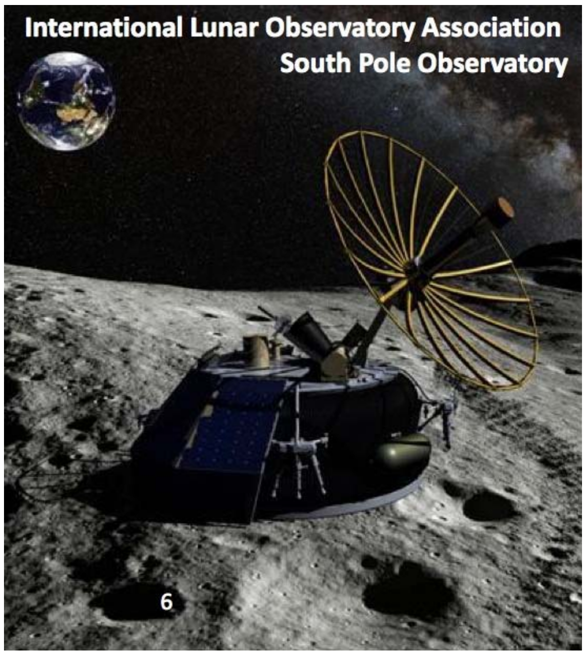
Paul D. Spudis
Bob Richards
Jack Burns

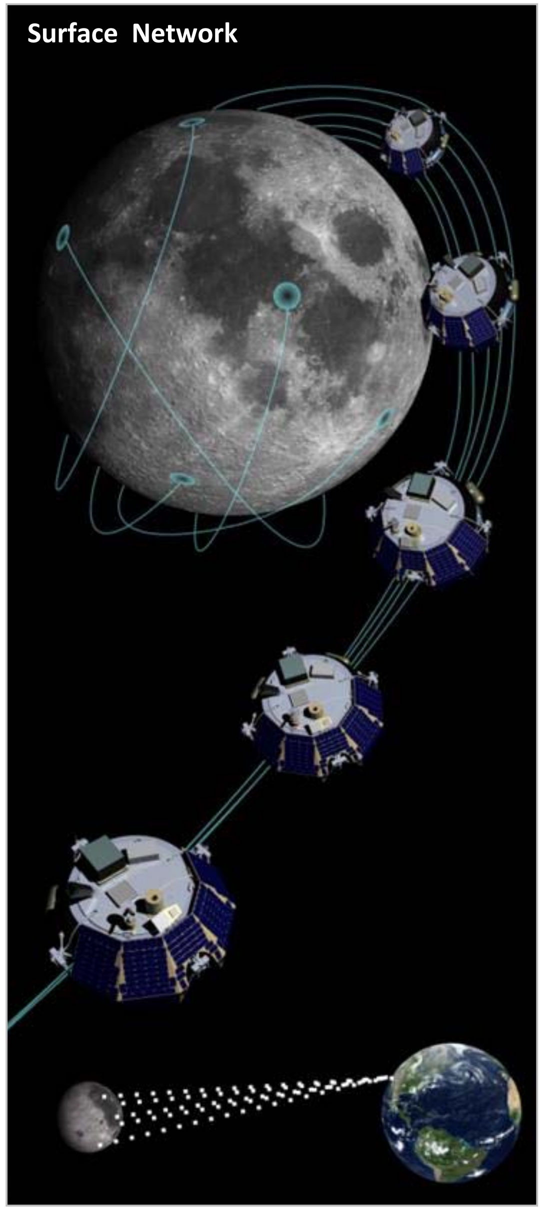
Moon Express Inc.

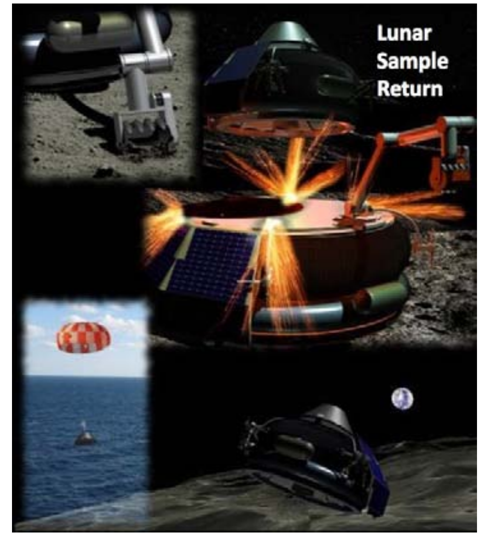
October, 2013

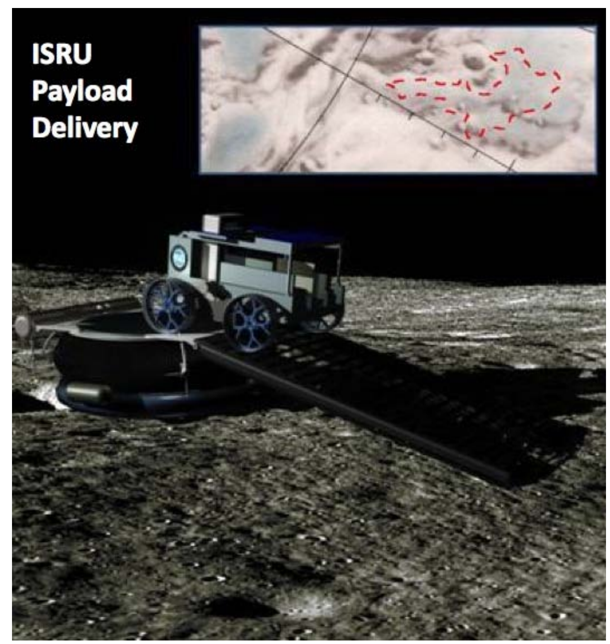
Moon Express Landers

Possible Missions









MoonEx Small Lander

60 Kg Class MX-1 Vehicle

Mission Types:

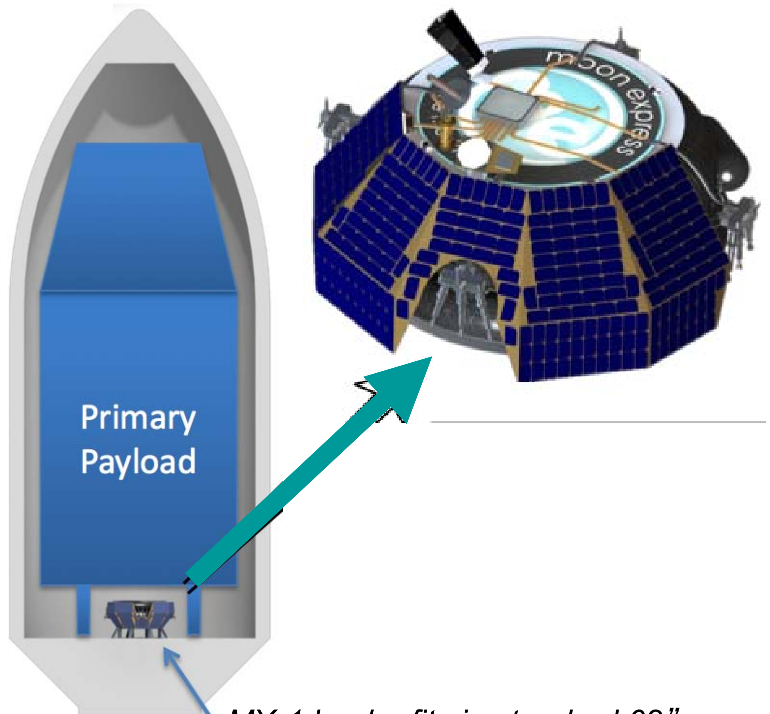
- Small lander
- In-space propulsion module
- Orbit rendezvous and proximity ops
- Ascent vehicle for sample return

Wet Mass: 450 kg

- Secondary/ESPA capable

Single Stage Design

- TLI, cruise, braking, decent and landing
- High thrust/weight bi-prop main engine (1g at start of burn)
- Precision 6 DOF vernier control
- 12 pulse mode maneuvering/descent and thrust vector control engines



MX-1 lander fits in standard 62" ESPA as secondary payload

50 kg Class	GTO to WSB	TLI to WSB	TLI Direct
Price per Mission	$75M	$110M-135M*	$125M-150M*
Payload Price/Kg	$3M	$2M	$2.5M
Payload Mass	26 kg	66 kg	54 kg
Payload Average Power	10W	10W	10W
Payload Volume	>3ft³	>3ft³	>3ft³
Data Rate	100 kbps	100 kbps	100 kbps
Flight Duration	3-6 months	3 Months	4 days
Surface Mission Duration	2 weeks	2 weeks	2 weeks
Example LV	Falcon 9 / Secondary GTO	Shared Falcon 9, *Dedicated Falcon 9	Shared Falcon 9, *Dedicated Falcon 9
Launch Mass	450 kg	450 kg	450 kg

MoonEx Medium Lander

400 Kg Class MX-2 Vehicle

Mission Types:

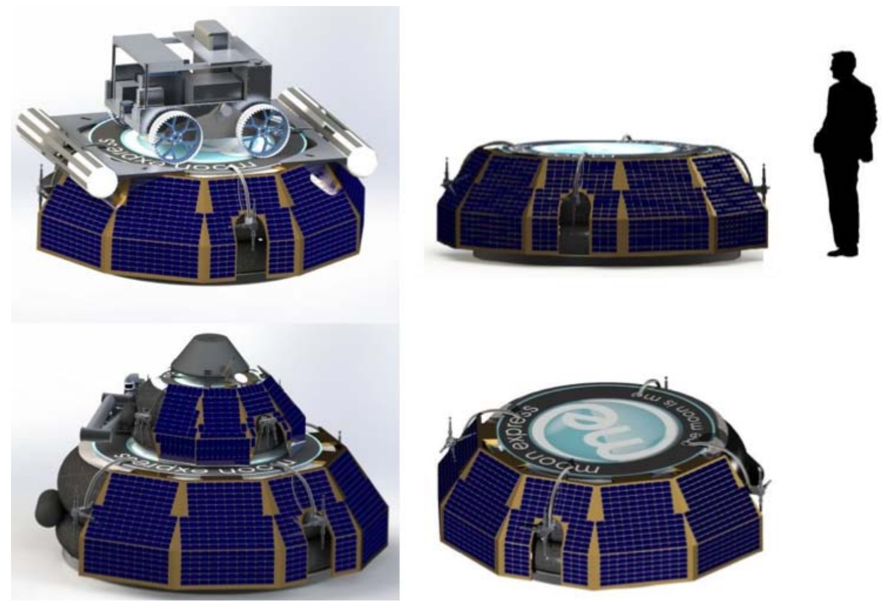
- Medium lander
- Sample return delivery system
- 400 kg landed payloads (e.g. RESOLVE ISRU Rover)
- In Space Propulsion Module
- Orbit rendezvous and proximity ops

Wet Mass: 2500 kg

- Shared to GTO or dedicated Falcon 9 launch to TLI

Single Stage Design

- TLI, cruise, braking, decent and landing
- High thrust/weight bi-prop main engine (1g at start of burn)
- Precision 6 DOF vernier control
- 12 pulse mode maneuvering/descent and thrust vector control engines

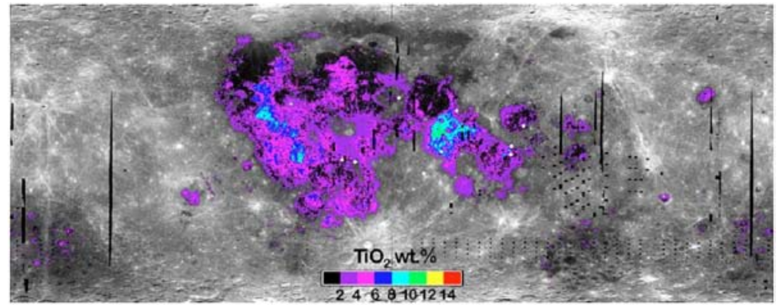


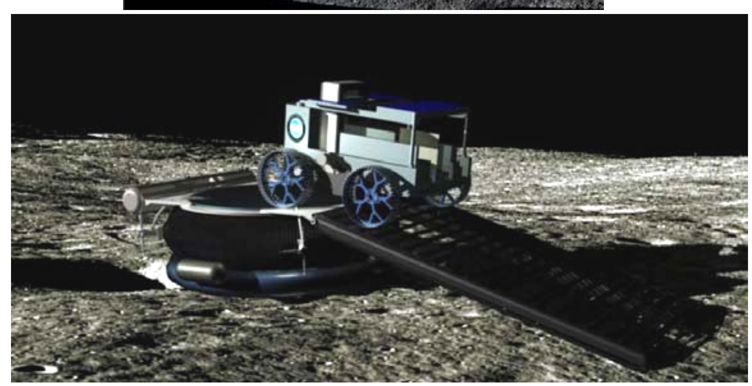
400kg Class Lander	GTO to WSB	TLI to WSB	TLI Direct
Price per Mission	\$150M	\$175M	\$175M
Payload Price/Kg	\$1.2M	\$0.6M	\$0.7M
Payload Mass	162 kg	405 kg	321 kg
Payload Average Power	50W	50W	50W
Payload Volume	>30ft^3	>30ft^3	>30ft^3
Data Rate	100 kbps	100 kbps	100 kbps
Flight Duration	3-6 months	3 Months	4 days
Surface Mission Duration	2 weeks	2 weeks	2 weeks
Example LV	Shared GTO	Falcon 9 / Dedicated	Falcon 9 / Dedicated
Launch Mass	2500 kg	2500 kg	2500 kg

Strawman Lander Mission

Lunar Pyroclastics

- Many accessible targets in central near side, relatively safe (low slopes, low degrees of surface roughness, block-poor)
- Important scientific, resource and operational benefits
- Mission scope can be scaled to early, small lander or later more ambitious delivery of long-lived surface rover

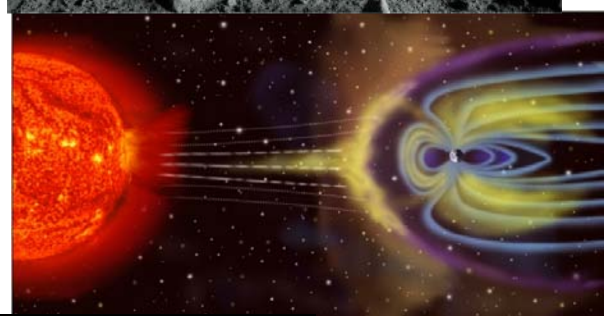


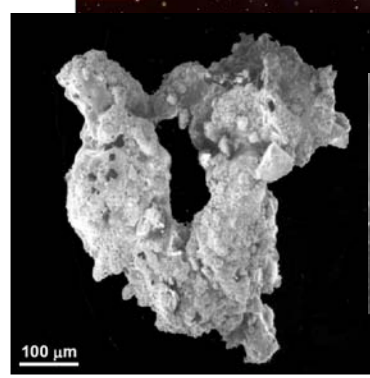


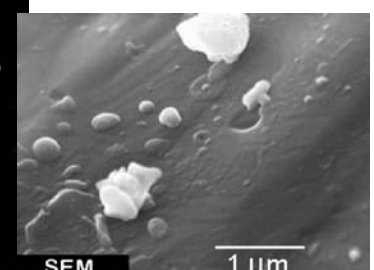
Volatile Resources of the Moon

- Bulk regolith (soil) is exposed to space environment
- Solar wind gases implanted onto dust grains; typical H_2 concentration ~ 50-100 ppm
- Concentrations of solar wind gases increase with decreasing grain size (highest in finest fractions) and increasing Ti content (highest in high-Ti regoliths)
- Lunar high-Ti pyroclastic deposits in theory should have the highest solar wind gas content
  - Uniform, fine-grained (~50 micron) glass spheres
  - Black spheres are devitrified glass; exposed micro-crystals of ilmenite
  - Therefore, high-Ti black glass of pyroclastic origin should be rich in solar wind H_2

Problem: we have never sampled a mature lunar dark mantling deposit

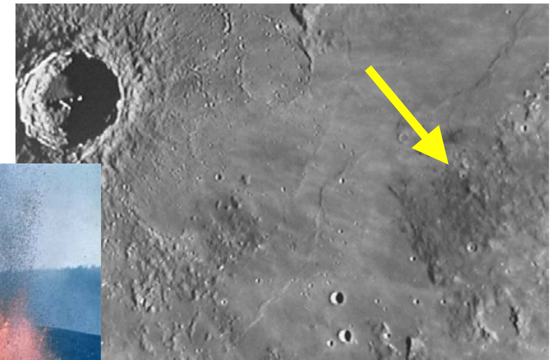


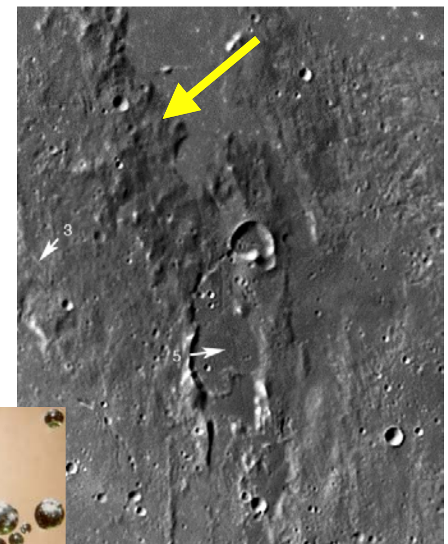


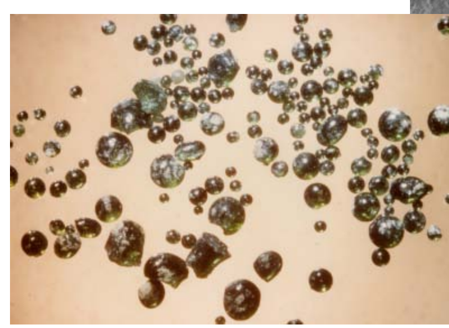


Lunar Pyroclastic Deposits

- Volcanic ash deposits cover maria and highlands
- Caused by fire-fountain eruptions, similar to those in Hawaii
- Very fine-grained, low viscosity magmas, explosively shot into space
- Come from very deep within the Moon (~400 km); driven by interior volatiles (types unknown)
- How do these ash deposits evolve and mature on the lunar surface over time?







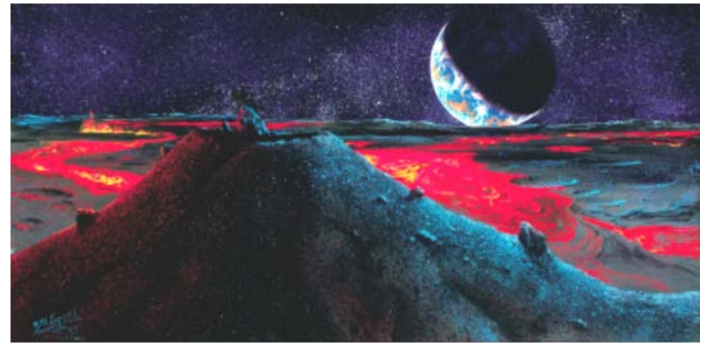
Value of Lunar Pyroclastics

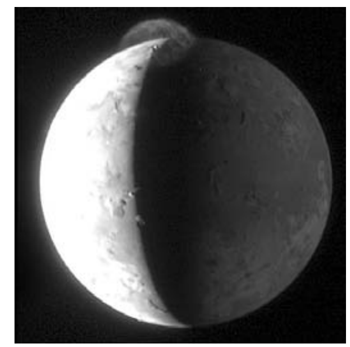
Scientific value

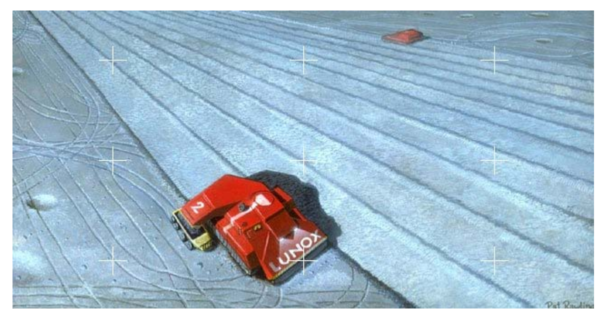
- Primitive, unmodified magmas from the deep mantle
- Source regions contain volatiles
- Eruption mechanisms, dynamics - source of deep-seated rock fragments?

Resource value

- Uniform, fine-grained deposits - easy feedstock for resource processing
- Solar wind gas content may be enhanced in pyroclastics; if so, a potential “ore” deposit for H_2 recovery

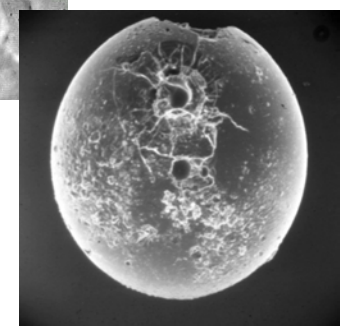


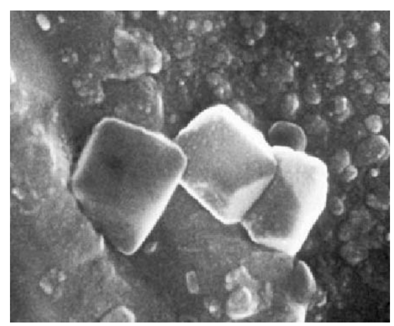




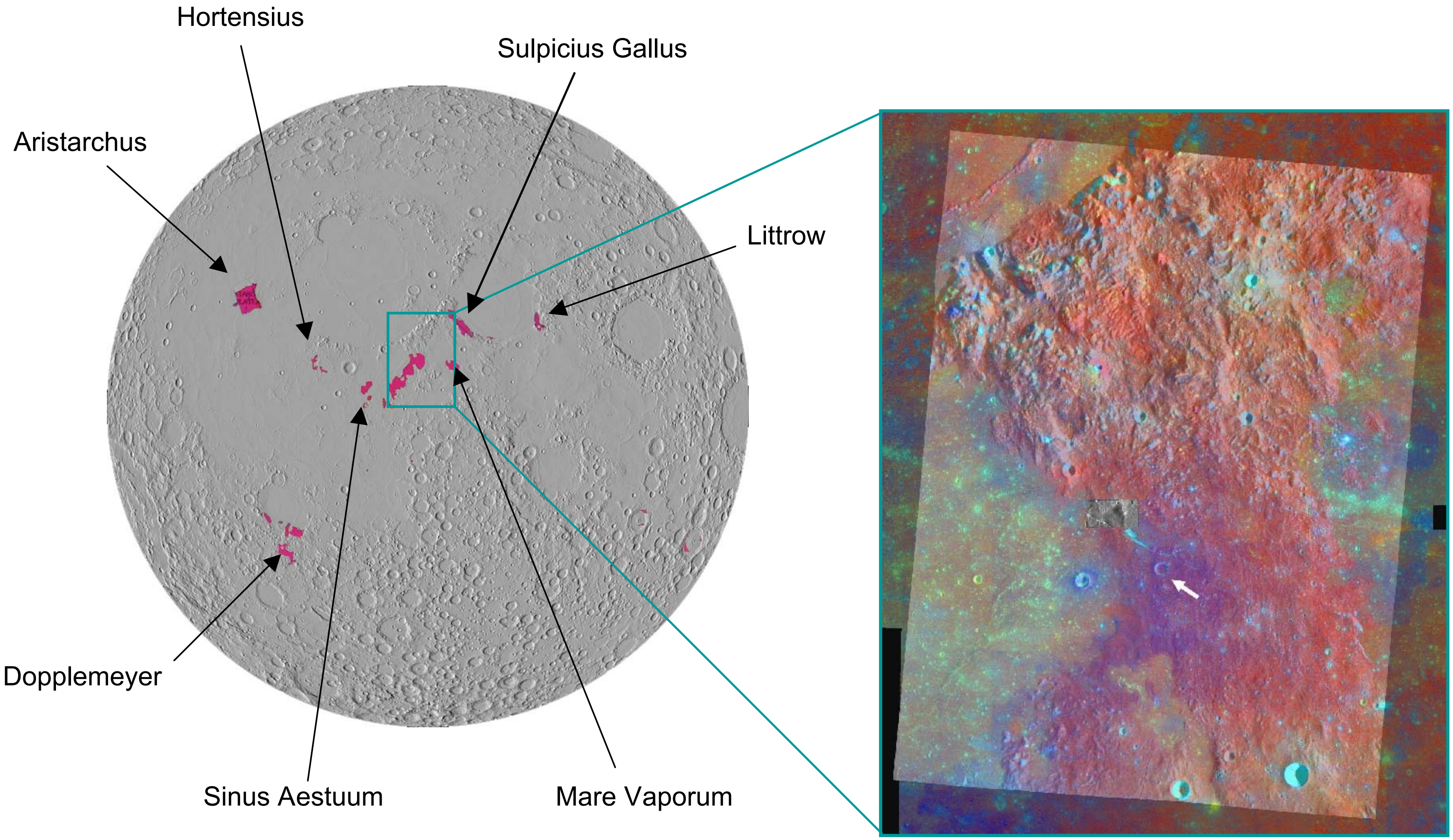
What don’t we know?

- Composition and ages of regional deposits
- Eruption properties - rates, dynamics
- Maturity of dark mantle deposits
- Solar wind gas content and variability
- Presence of xenoliths and deep-seated rocks
- Surface conditions and physical properties; welded zones v. unconsolidated debris
- Vent structure, volcanic bombs?





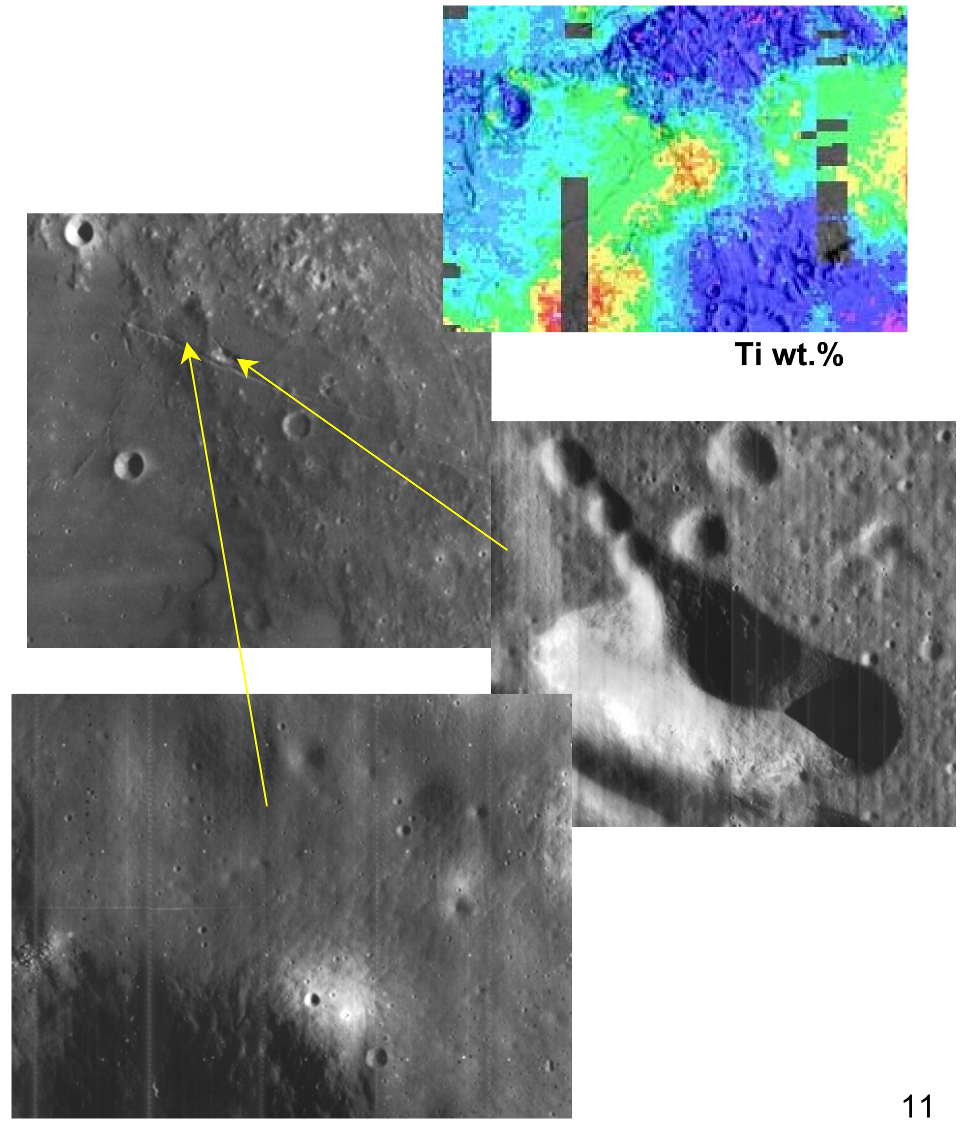
Distribution of Pyroclastics



Rima Bode

Rima Bode Pyroclastic Deposits

- Vast, regional dark mantling deposit (~7000 km^2)
- High-Ti content (black glass?)
- Embayed by (older than) maria 3.5 billion years old
- Complex vent and rille system associated with eruption
- Near center of near side (12º N, 3º W); smoothed terrain of lunar ash beds
- Xenoliths from deep in the Moon may be found near vent



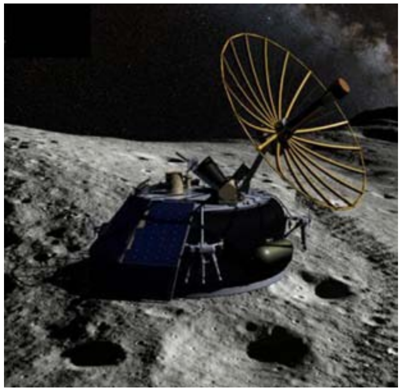
Concept of Operations

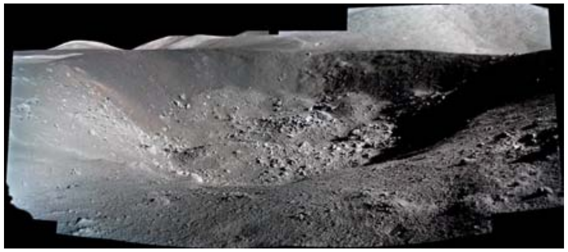
MX-1 mission profile

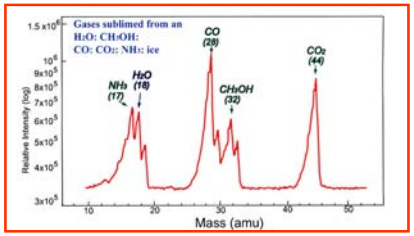
- Soft land within 2 km of chosen target
- Image and map terrain
- Analyze soil for major elements
- Analyze solar wind H_2 content
- Move to new site and repeat; continue until end of mission

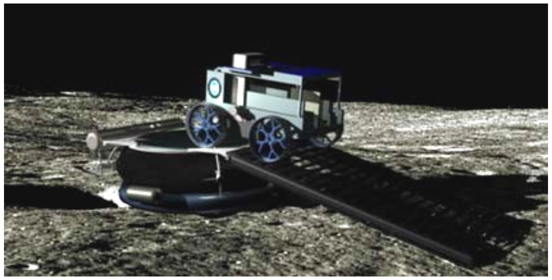
MX-2 profile (with rover)

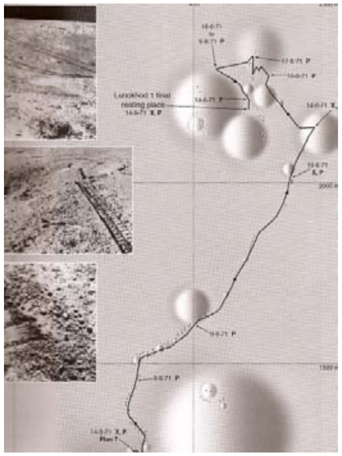
- Deploy and rove extended traverse
- Map and analyze soil compositions and H_2 concentrations at each station
- Post-roving observations





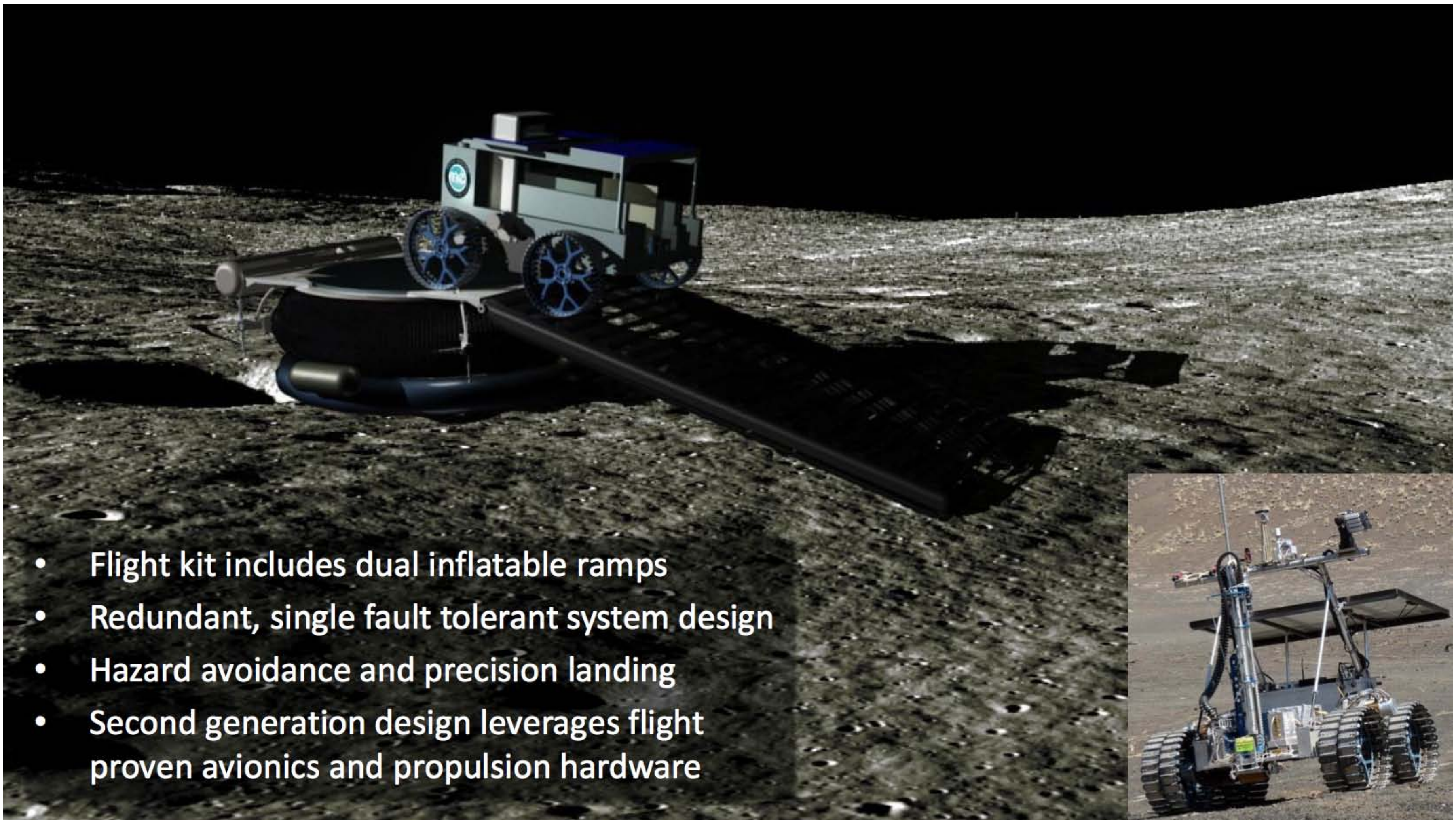






MoonEx Large Lander

ISRU rover delivery

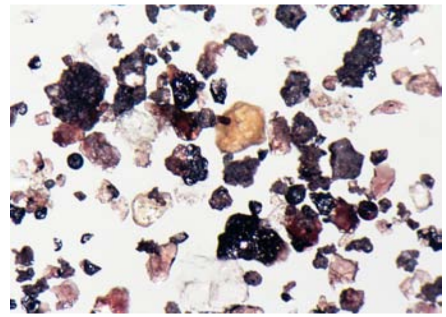


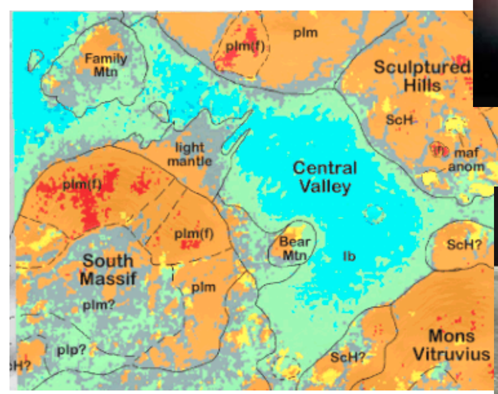
Strawman Instrument Payload

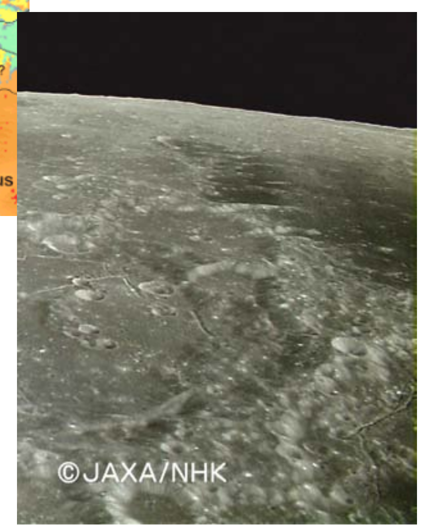
Instrument	Information	Mass (kg)	Power (W)	Dimensions (cm)	Comments/Heritage
APX	Major and minor elements	0.5	3	5 x 5 x 5	Low data rate, analysis time; MER
MS imager	Mineralogy	2	2	7 x 7 x 2	5 bands @ 410, 750, 900, 950, 1000 nm, high rate; Clementine, LROC
EGA	Solar wind gas content	4	8	10 x 10 x 8	Need soil sampler (surface only), low rate; Mars Phoenix lander
Neutron spectrometer	Total hydrogen	0.5	2	20 x 5 x 5	Passive; ~10 min. integration time, low rate; Lunar Prospector, Mars Odyssey
Imaging lidar	Topography	4	10	50 x 30 x 30	Navigate and topographic mapping, high data rate; terrestrial models
Magnets	Magnetic properties	< 0.5	--	5 x 5 x 2	Study magnetic properties of dust, resource and utilization properties; Viking, MER
Laser reflector	Earth-Moon ranging	< 5	--	20 x 20 x 30	New station far from Apollo and Luna sites to serve geophysical and astrophysical studies; Apollo LRRR

Knowledge Gained

- Compositional and physical characterization of a mature, regional pyroclastic deposit
- Direct measurement of implanted solar wind gas
- Surface topographic and geological mapping
- Observations of putative dust levitation
- Resource mapping and prospecting







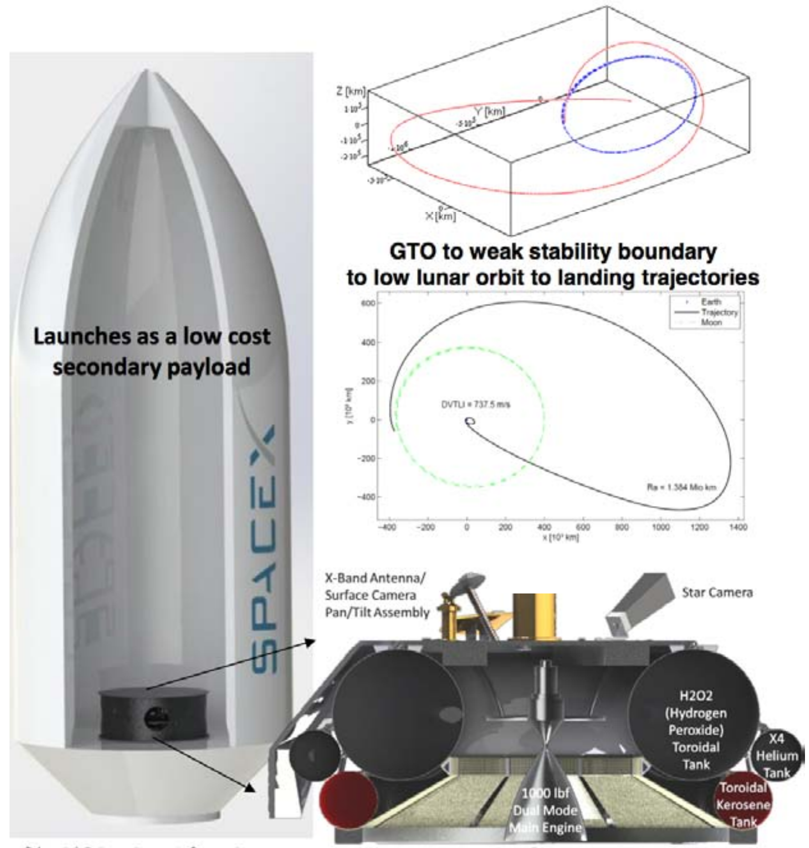
Maiden mission on track for 2015 launch

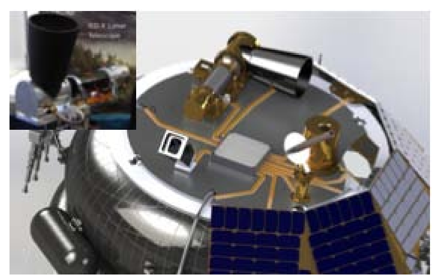
Launch mass: 450 kg

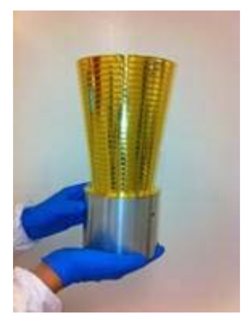
- Secondary payload placed into GTO
- $3M/kg surface delivery
- 26 kg from GTO to lunar surface
  - *Candidate payloads:*
  - International Lunar Observatory
  - Plant growth experiment
  - Google Lunar X-Prize payloads
  - Payloads of opportunity (NASA, international, commercial)

Full scale development underway

- Propulsion, avionics, GN&C systems testing underway
  - Vehicle hover flight testing beginning Dec 2013
  - Launch in fall 2015







MoonEx Large Lander

Lunar Sample Return

Our first lunar sample return by 2020

MX-2 lander delivers to Moon:

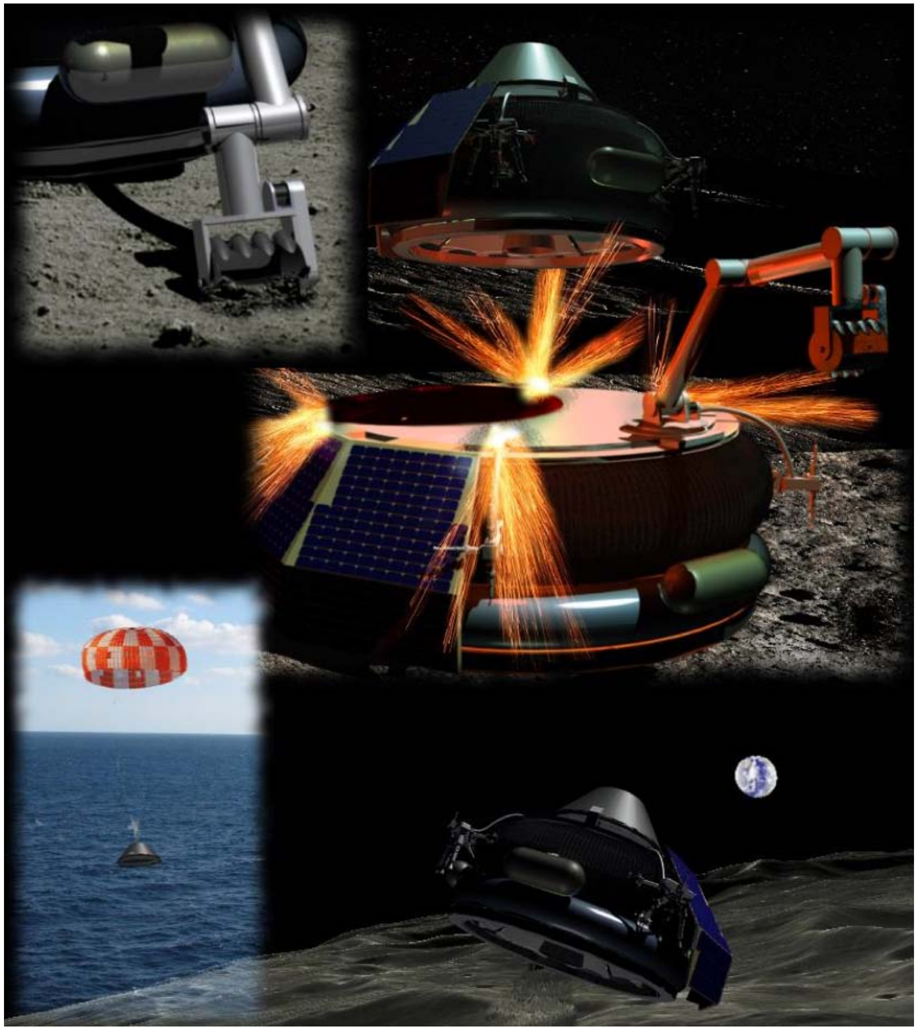
- MX-1 ascent vehicle
- Sample Return Capsule
- Sample acquisition, processing and transfer systems

Samples sold to private collectors, academia, enthusiasts, governments

Direct injection, direct entry

Water landing and recovery

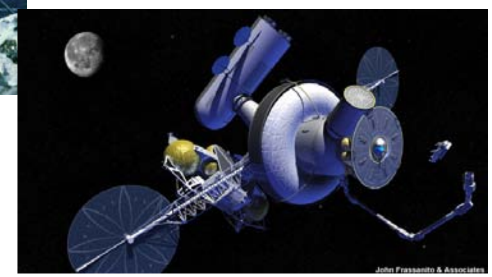
Sample Return	TLI to WSB	TLI Direct
Price per Mission	$275M	$275M
SRC Return Mass	43 kg	13 kg
Sample Mass	~8 Kg	~2 kg
Payload Power	10W (TBR)	10W (TBR)
Data Rate	100 kbps (min)	100 kbps(min)
Flight Duration	3 months + 4 day return	4 days + 4 day return
Surface Duration	2 weeks	2 weeks
Example LV	Falcon 9 / Dedicated	Falcon 9 / Dedicated
Launch Mass	2500 kg	2500 kg

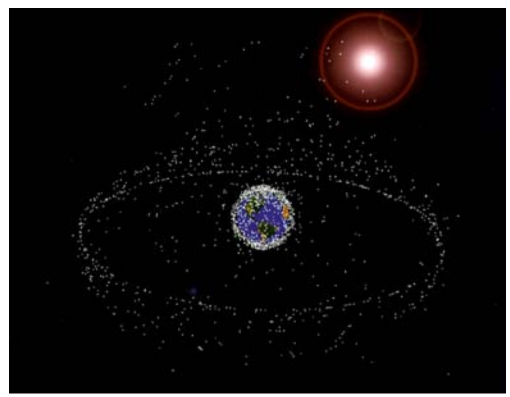


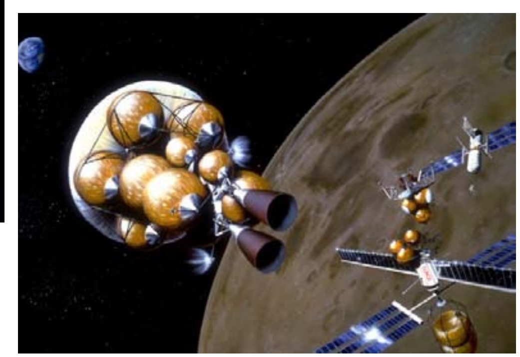
Back up

The Value of Lunar Resources

- Materials on the Moon can be processed to make hydrogen and oxygen for use on the Moon and for export to Earth-Moon (cislunar) space
- Propellant produced on the Moon can make travel within and through cislunar space routine
- This eventuality will completely change the spaceflight paradigm
- Routine access to cislunar space has important economic and strategic implications







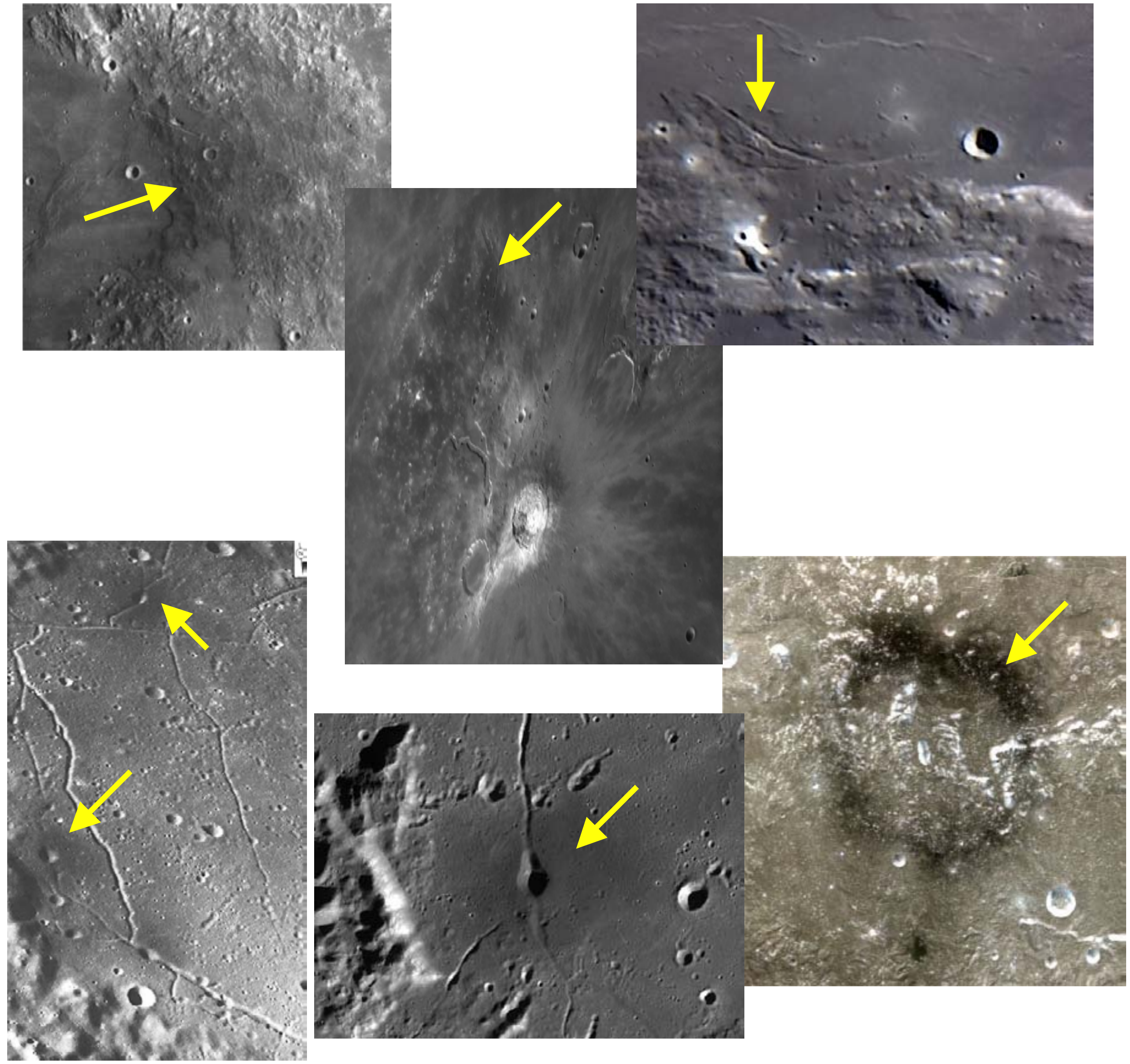
Examples: Lunar Pyroclastic Deposits

Regional

- Sulpicius Gallus
- Rima Bode
- Aristarchus Plateau
- Littrow

Localized

- Alphonsus
- Schrödinger
- Orientale dark ring



Pyroclastic materials

Apollo 15 green glass

- Emerald green glass, primitive magma from extreme depth within the Moon (~ 400 km)
- Very fine-grained (~50 micron spheres)

Apollo 17 orange and black glass

- Buried for more than 3 billion years; excavated by impact that made Shorty crater
- Orange and black glass have same titanium-rich composition
- Surface coatings of volatile elements (S, Pb, Zn)