TECH BRIEF:
SATELLITE INNOVATION FOR CISLUNAR INFRASTRUCTURE

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Cislunar: An Introduction

- Why has Cislunar missions and technology become so important ?
  - Commercial & Government technology and cost advances have reached a point where space commerce & manufacturing are possible
- The First Step: Permanent human operations on the Moon to support mining and manufacturing
  - Lunar operations includes manufacturing, communications, location/liming, & transportation between the moon and orbital logistics stations
  - The Cislunar economy/infrastructure will bring exploration and colonization of mars and asteroid mining both economically and technically possible

The Vision: Cislunar is the first step in humankind's permanent expansion across the Solar System

NASA ARTEMIS Program Lunar GATEWAY

Contents:

- The three body problem
  - Orbital mechanics in the Earth <> Moon <> Sun System
- Communications, Location, and Time Distribution
  - Regulatory, Environmental, Technology considerations
- Cislunar Transport System

  Materials and Fuel

The Three Body Problem
Orbital mechanics in the Earth <> Moon <> Sun System

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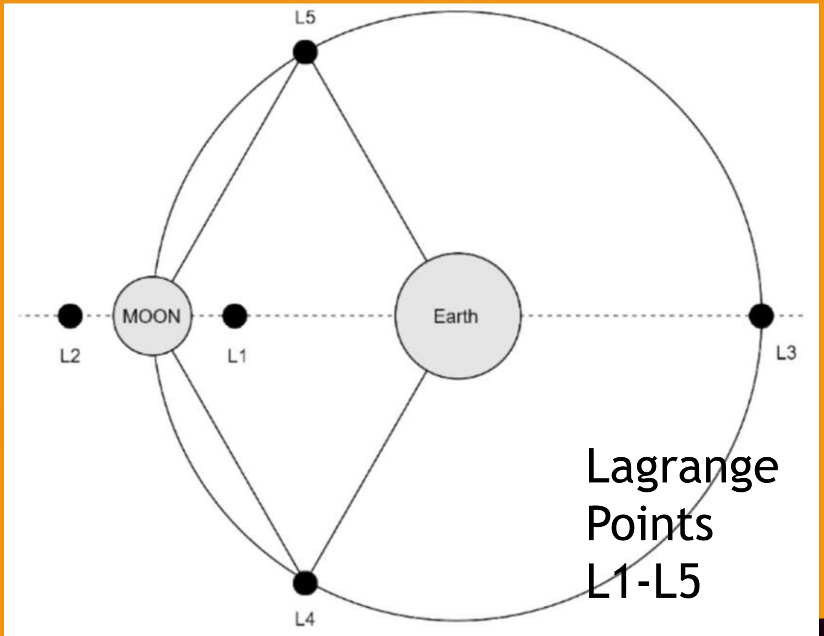
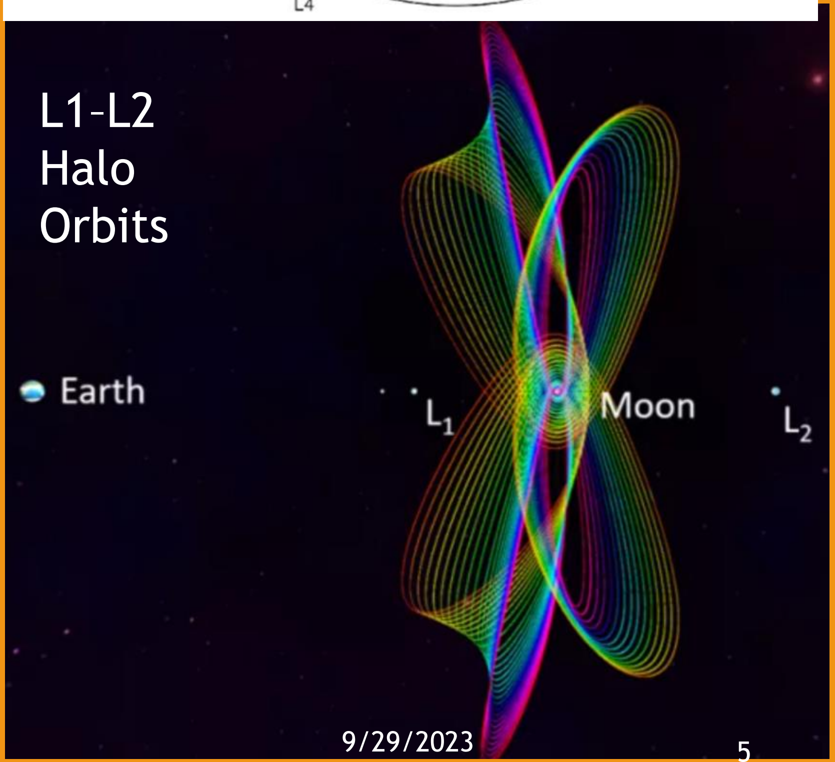
Lagrange Earth-Moon Equilibrium Points

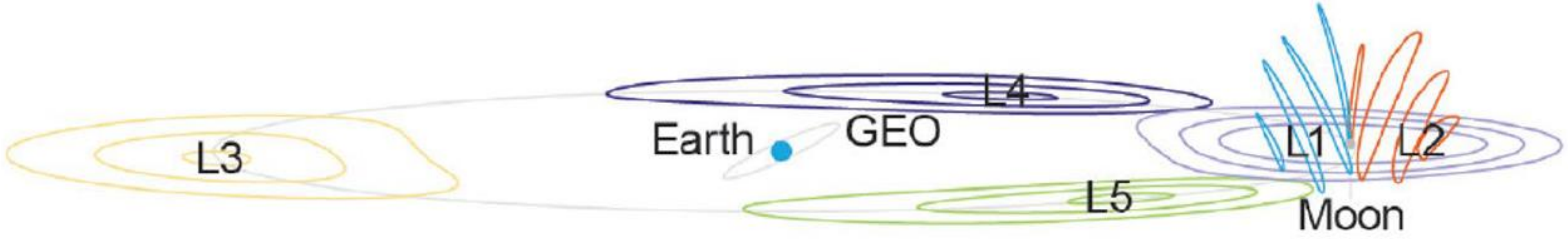
- In 1772, the French scientist Lagrange studied the Earth-Moon system and discovered five special gravitational equilibrium points L1 – L5
- Retrograde and Halo orbits around L1/2 allow spacecraft to reduce fuel consumption and remain in position while traveling around the Moon – These orbits are ideal for navigation and communications satellite constellations using the minimum number of satellites
- Test missions for Halo/DRO constellations are being conducted:
    - In June 2018, the Chinese lunar exploration project "Chang E-IV" mission relay satellite entered the Halo orbit around the Earth-Moon L2 LP, becoming the world's first satellite to operate in the L2 Halo orbit.
    - Chang E-V (CE-5) followed, entering service in 2022





Cislunar Orbits – an Expanded View

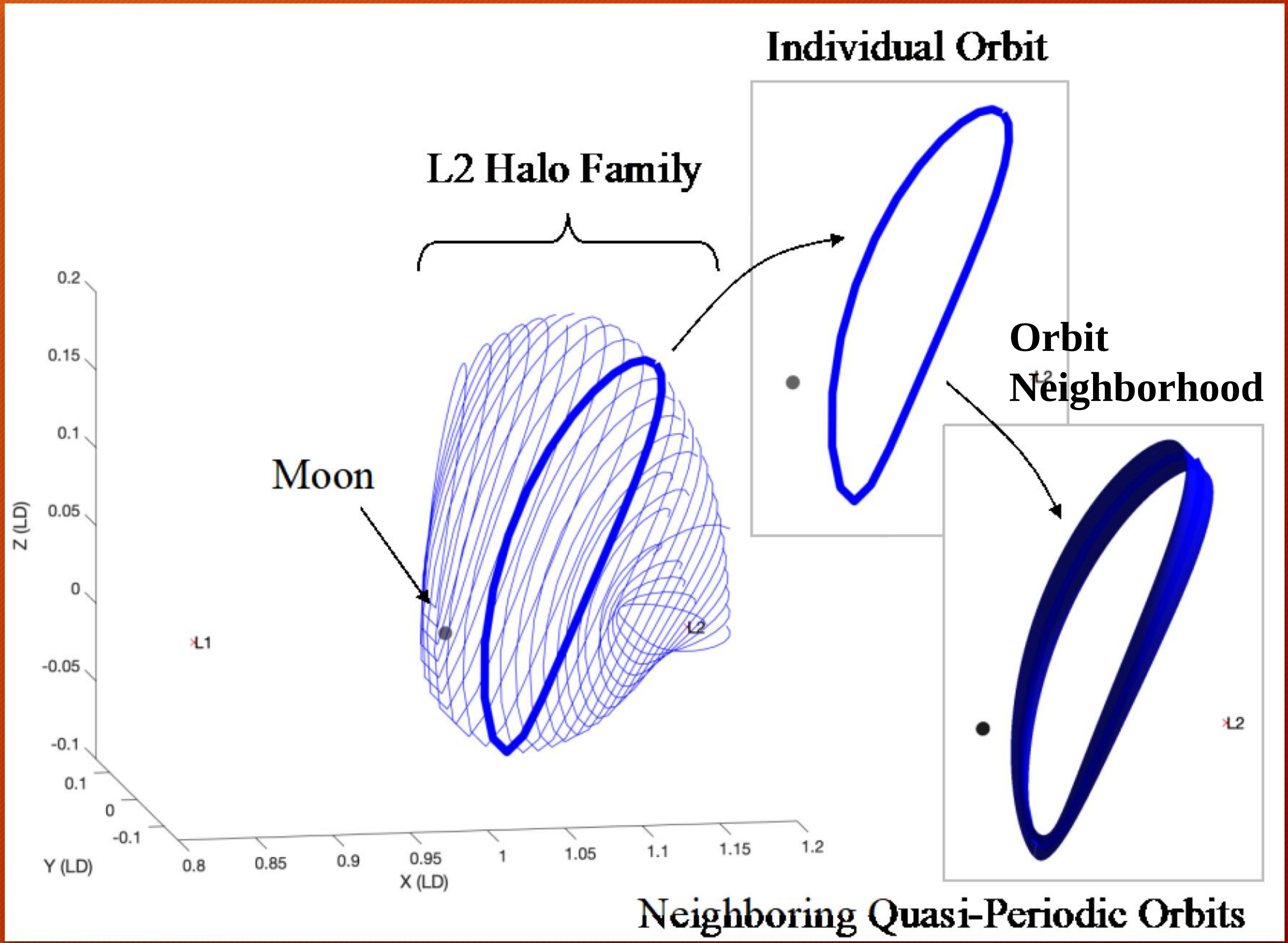
- Halo orbits travel above and below the Earth – Moon orbital plane
  - James Webb Telescope is in a L2 Halo Orbit
- Lyapunov orbits lie entirely in the Earth – Moon orbital plane



Halo orbits (examples shown here in blue and orange about L1 and L2, respectively) exhibit motion above and below the moon's orbit plane, which enables visibility to the lunar poles. L2 halo orbits offer a unique location for a communication relay, with continuous visibility to both Earth and the far side of the moon.

Halo Orbit Families

- Complications of earth-moon-sun 3 body gravity create infinite repeating natural orbits:
  - These repeating orbits are grouped into sets of families.
  - For each individual repeating natural orbit in a family, there are infinite neighboring quasi-periodic orbits (QPOs)
  - QPO's have bounded motion , they stay within the neighborhood) but never exactly repeat their trajectories.
- Repeating natural orbits possess great utility in cislunar space. They are currently featured in NASA's Lunar Gateway design



Communications, Location, and Technology Time Distribution

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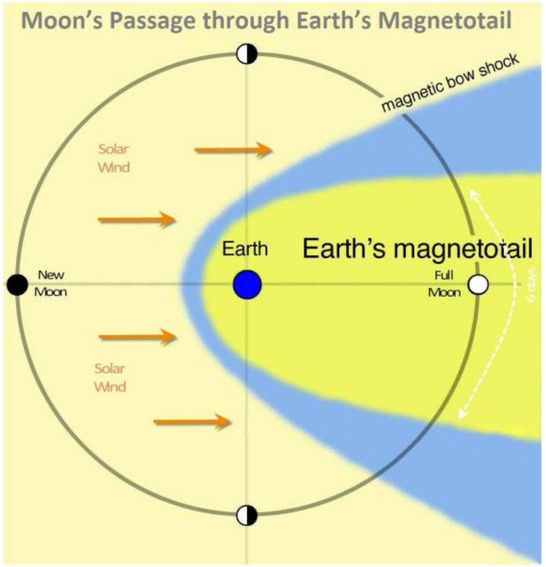
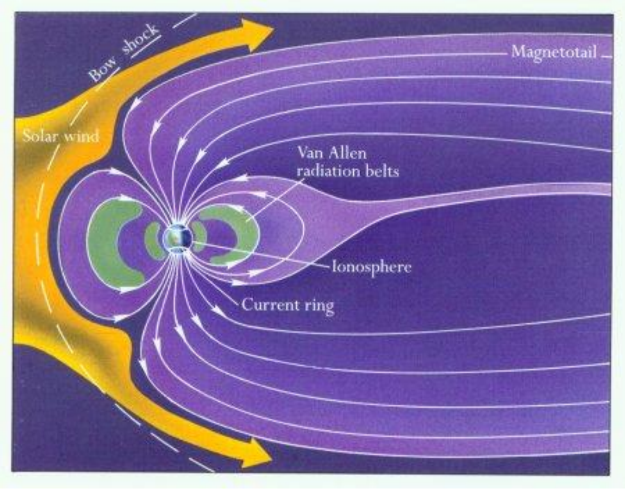
Communications & GNSS
Just Like on Earth - **Only Different!**

- Just like on Earth
  - Communications coverage requires at least on satellite be within line of site at all times
  - Global Navigation Satellite System (GNSS) for location/time distribution require 3 & ideally 4 satellites be in line of site
- Costs for deployment, station keeping resources, and replacement/spares require minimum satellite constellations
  - A 5 satellite constellation with 3 Halo orbit and 2 DRO (Distant Retrograde Orbit) satellites provide 100% lunar coverage
  - A 14 satellite constellation with 8 halo orbit and 6 DRO satellites provides 100% lunar navigation, timing , & Comms coverage
  - Additional Communications links between the Moon, L1, L2, L4, & L5 will be required

Communications and GNSS:
Regulatory, Environmental, Technology considerations

- Positioning calculations will be greatly complicated by the complex ephemeris of the Earth<> Moon<> sun satellite orbits.
- Radio Frequency Regulation for Cislunar Systems
  - Assumption is that ITU (International Telecoms Union) rules will apply
  - Distance between Earth and Moon is great enough that terrestrial frequency bands can be reused.
- Radiation shielding will critical - the moon has a negligible magnetic field and is protected by the earths magnetic field <70% of the time
  - Interplanetary missions (Mars, asteroids, etc.) have the same problem - little or no protection
- Mass of satellite other cislunar systems is critical
  - Initial infrastructure will have expensive Earth to cislunar launch costs
  - Economical orbits to minimize station keeping fuel budgets





Cislunar Transportation System

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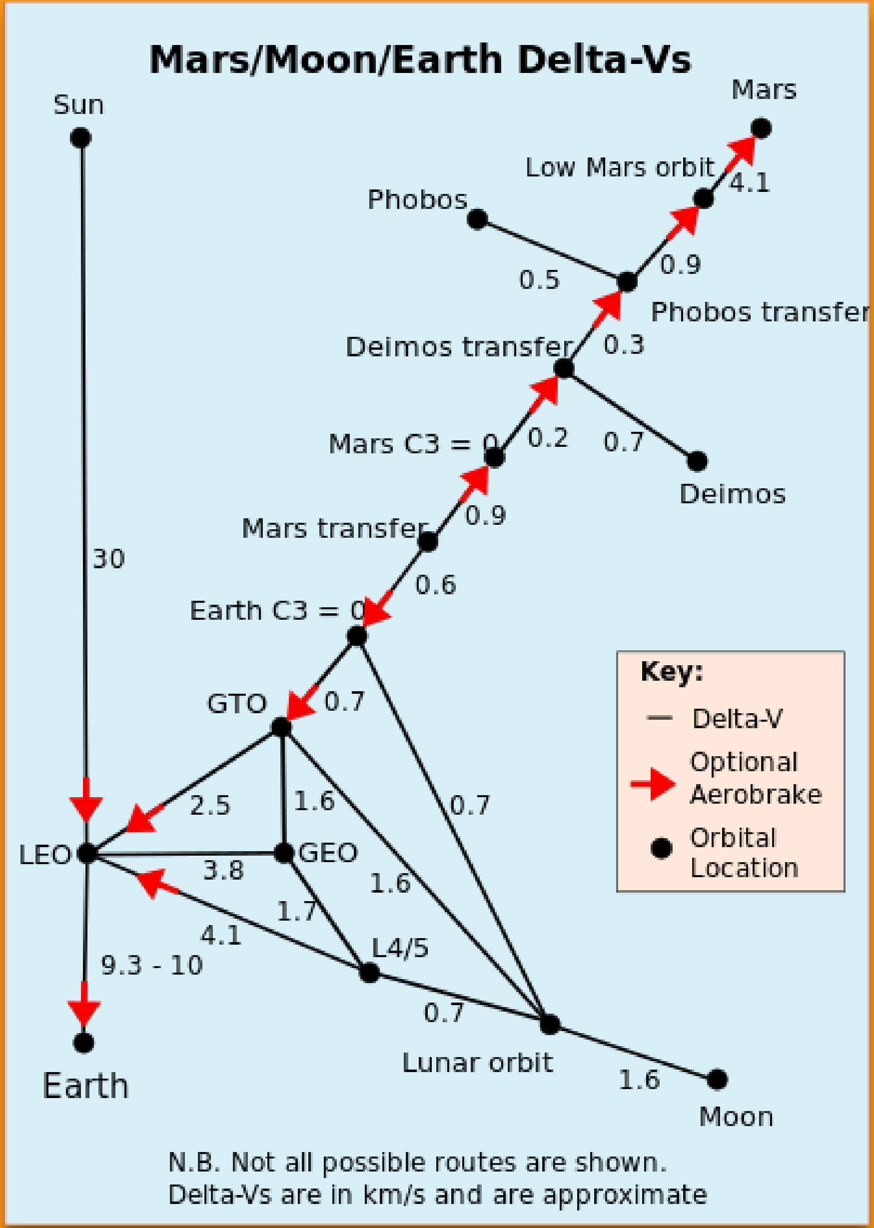
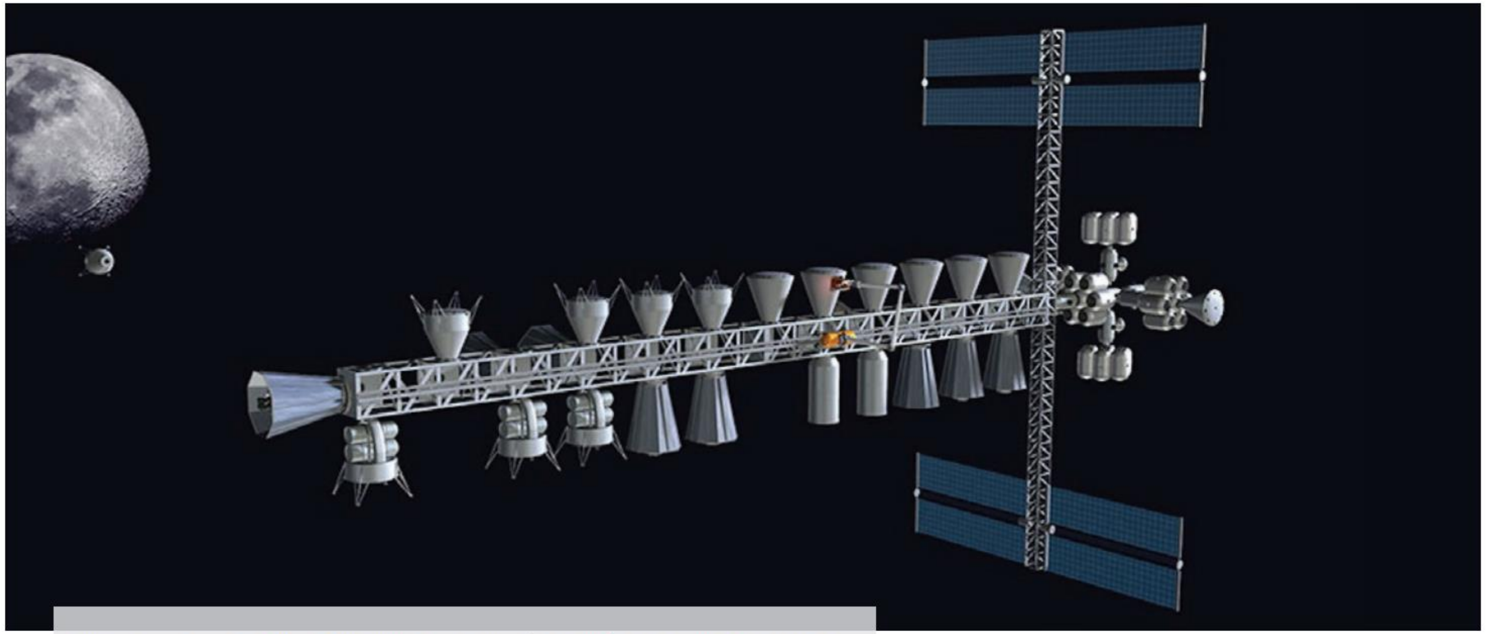
Transportation:
Its all about Delta-V

- Delta-V, the change in velocity to reach a specific location in the near earth/mars system in km/sec.
  - An Earth to Mars Mission requires a cumulative Delta-v of 19.5 Km/sec with ~50% (9.3 to 10 Km/sec used in Earth to LEO)
  - A lunar orbit to Mars mission requires just of 7.7 Km/sec or 40% of the Delta-v from earth
  - Getting materials from the moon to lunar orbit is only 1.6 Km/sec Delta-v which is ~17% of the cost
- It is all about cost and efficiency
  - Based Konstantin Tsiolkovsky's "ideal rocket equation" it takes 4.5kg of liquid propellent to reach LEO from earth
    - Note: it would take 20kg of solid propellent – hence why liquid is preferred
  - 1Kg payload to lunar orbit requires only 0.77 Kg of propellant
- Simple economics of Mass transfer are driving Cislunar expansion
- To achieve cislunar economics, a system of orbital manufacturing facilities, transfer tugs, and propellant depots is required.

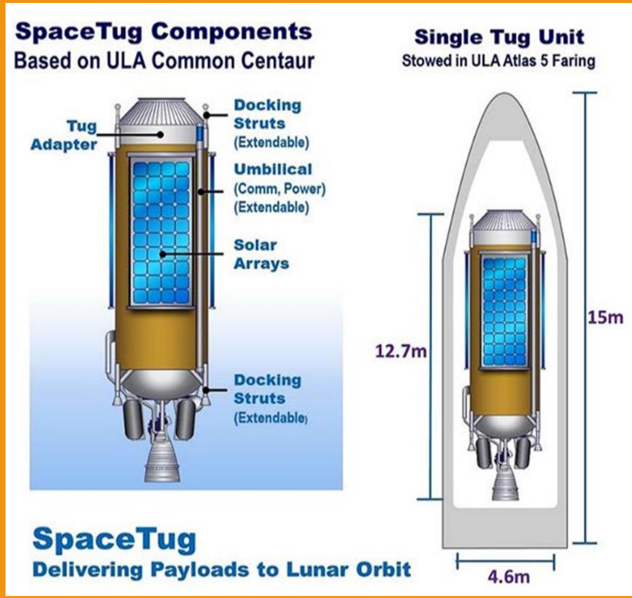


Transport System – Tugs, Depots, & Manufacturing

- The ground work for space transport has been under way for over a decade
  - Mission extension (refueling) and repair
  - Orbital reposition
  - Multiple satellite deployment
- Cislunar Transport System elements
  - Lunar orbit <> Lunar surface transport
  - Interorbital tugs
    - Between L1, L2, L4 & L5
    - Earth/Earth orbit
    - Mars/Asteroid supply
  - Fuel Depots/Manufacturing hubs
- Economical Mars/Asteroid missions
  - All fuel and vast majority of space craft infrastructure will be mined and manufactured in Cislunar facilities
  - Critical electronics/circuitry will be earth manufactured for foreseeable future

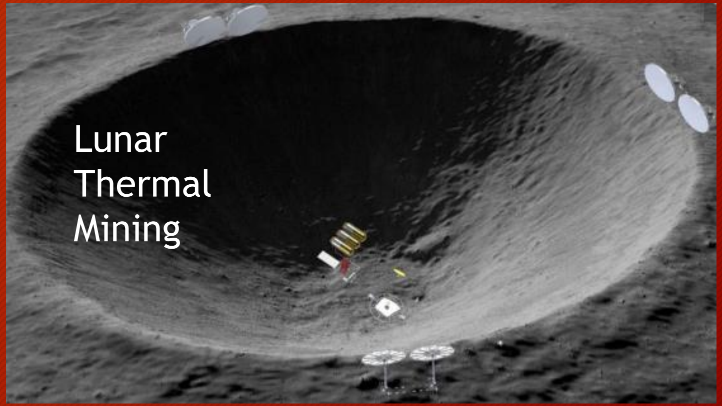


A logistics base at L1 with habitat modules (at right) and multiple docking ports for vehicles and propellant depots. Credit: Anna Nesterova



The O'Neill Mass Driver Concept

- In 1974, Princeton professor and space visionary Gerard O'Neill first proposed using an electromagnetic (EM) "railgun" to launch payloads from the moon
  - EM launcher will only be pointed in the right direction once a month
  - The launch window expands by using thruster system to provide correction steering and breaking
    - Repurpose transport system space tug technology
  - Abundant Solar Energy replaces propellant which is>50% of total lunar launch mass
- Propellant alone is big business:
  - NASA study estimates Cislunar ecosystem consuming 500 tons of propellant/year derived from harvesting lunar water - $2.4B
- Rather than waste nearly 50% of propellant/launch mass, thet mass driver is an interesting long term option



Final Thoughts

- The current satellite launcher and LEO orbit systems revolution is paving the way for the next wave of Cislunar expansion
- LEO revolution with its many competing technologies is systematically eliminating poor performing technology for later use:
  - Rocket/thruster technology
  - Zero-G manufacturing
  - Communications & GNSS
  - Observation technology – optical/hyperspectral and SAR
  - AI & Robotics – removing man from the loop – especially transport/mining
- Cislunar is driven by commercial economics, not government investment alone
- The most difficult problem – human susceptibility to cosmic and solar radiation