Helium-3 Mining Aerostats in the Atmospheres of the Outer Planets

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Imagine an Interplanetary Future
Where -

• d-He3 fusion produces most of Earth’s energy needs without radioactivity or carbon emissions

• Space transportation has been revolutionized by an efficient fusion propulsion system with exhaust velocity up to 0.088 c

• Space commerce is stimulated by the existence of an interplanetary cargo worth $3-M a kilogram

• Unmanned probes travel to the nearest star systems with flight times less than a human lifetime
He-3 Fusion for Energy & Propulsion

\[ \text{d} + \text{He}3 \rightarrow \text{p} + \text{He}4 \]

- reactants are stable and storable
- products are energetic, charged and stable
  - Efficient electrical generation from MHD
  - No activation and embrittlement of reactor vessel
  - Efficient conversion to thrust with exhaust velocity up to 0.088 c --> ~50 yr interstellar flight using known physics.
- \(3.6 \times 10^{14}\) J/kg of d-He3 mixture = \(1.0 \times 10^8\) kWh/kg
  - Fuel is about 20% of the kWh cost of electricity
  - If electricity is 15¢/kWh then He3 has a value of $3M/kg

\[ \text{He-3 is one of the few commodities worth interplanetary freight costs} \]
Why Outer Planets for He-3?

- Earth: breeding of tritium from either isotope of lithium by neutron bombardment, tritons decay to He-3.
  - Containment, waste problems same as d-t fission.
  - USA has no current capability.
  - Lithium inventory?
- Moon: solar wind implanted in regolith, 10 ppb (10^{-8}) by mass in uppermost few meters. ~1000 yr of 2001 energy needs- a starter catalyst?.
- Outer planets: primordial He3, ~10 parts per million (10^{-5}), ~10^9 yr of 2001 energy needs- the ultimate energy source?.

Which Outer Planet-Jupiter

Pro:
• Closest to Earth and Sun

Con:
• Huge gravity means return vehicle has mass ratio >20 (nuclear thermal $I_{sp} = 900$ s)
  – No mass budget left for cargo!

• A lot hotter at a any given density
  – Galileo probe killed by heat not by pressure
Which Outer Planet - Saturn

Pro:
• Not as far as Uranus and Neptune
• Rapid rotation substantially reduces $\Delta V$ to orbit

Con:
• Seen as depleted $\sim$5x in Helium compared to other outer planets
  – reanalysis of Voyager data 20 yr later restores that 5x - maybe
  – won’t know for sure until we send an entry probe
• Rings as a navigation hazard
  – need close-in, co-orbiting mission to look
Which Outer Planet-Uranus

Pro

• Primordial He3 abundance?
• ΔV to orbit requires mass ratio < 5
• Closer than Neptune

Con

• Axial tilt complicates interplanetary travel
• Twice as far from Earth as Saturn

_Uranus may be the closest planet without major possible problems -- but we must return to both Saturn to be sure_
Do we really know how much He3 is there?

- He3/He4 cannot be measured by remote sensing
- He3/H₂ and He3/He4 ratios have been measured *in situ* only by *Galileo* at Jupiter
- He3/He4 ratio of $10^{-4}$ to $1.5 \times 10^{-4}$ from meteors, solar wind, cosmology
- Use *Galileo* results for He3/He4 = $10^{-4}$ and Voyager results (?) for He4/H₂
He-3 Mining with Balloons

- Balloon diameter: 80 m
- Total Plant mass: 146 tonnes
- Return vehicle: 59 tonnes
- Total lift needed: 205 tonnes
Notional Distillation Plant Concept

Thinking Big about our Space Cryogenics Future

X₃ = He-3/He-4 ratio
G = gas
L = liquid

HeRV propellant
LH₂ 17 K
LH₂ 22 K
GH₂ 60 K

CH₄ Ar

pump

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Energy Economics
He3/H₂ = 10 ppm

Table 1

<table>
<thead>
<tr>
<th>Stage</th>
<th>Process</th>
<th>Energy (J)/g He₃</th>
</tr>
</thead>
<tbody>
<tr>
<td>1, 2, 3</td>
<td>cool atmosphere to 16 K</td>
<td>7.2x10⁷</td>
</tr>
<tr>
<td>3</td>
<td>liquify H₂ at 16 K</td>
<td>3.2x10⁸</td>
</tr>
<tr>
<td>5</td>
<td>cool He from 16 K to 4.2 K</td>
<td>1.3x10⁷</td>
</tr>
<tr>
<td>5</td>
<td>liquify He at 4.2 K</td>
<td>1.1x10⁷</td>
</tr>
<tr>
<td>6</td>
<td>cool LHe from 4.2 to 1.2 K</td>
<td>1.2x10⁷</td>
</tr>
<tr>
<td>total</td>
<td></td>
<td>4.3x10⁸</td>
</tr>
</tbody>
</table>

Transportation on 2 yr trajectory: 5x10⁷ J/g He₃
Energy released: 6x10¹¹ J/g He₃
Theoretical energy payback: ~1000
The most valuable interplanetary commodities are refined He-3, deuterium, and heavy metals.
Next Steps

• Jupiter Icy Moons Orbiter (JIMO)
  – nuclear fission-powered
  – electric propulsion flight system
  – Big deal: 20 tonnes, >$4 B, 10 kWe
  – First of a series: Project Prometheus

• Saturn Ring Observer

• Uranus/Neptune Orbiter with Probes

• Self-deploying balloon probes for Mars, Titan

• Discovery/New Frontiers missions to other resource sites (Moon, asteroids, comets) for interplanetary commodity economy

http://www.jpl.nasa.gov/jimo/gallery.cfm
A Trial Balloon?

Scientific balloon missions to outer planets, using Pu RTGs and/or O₂ burners, to study

- He₃/He₄ and He/H₂ ratio
- pressure vs. temperature for 1 < p < 100 bar
- trace gas composition
- entry, deployment, and telemetry engineering experiments

A science balloon could be as small as 2.8 m diameter, and use at most 7 kg of Plutonium as a heat and power source