Interstellar Propulsion: Challenges and Developments 30 Years After Daedalus.

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The Challenges of Interstellar Missions

What is ‘wrong’ with current rocket propulsion technology?

~25 star systems in 4 parsec radius
Common measure of rocket efficiency:

Specific Impulse

\[ I_{sp} = \frac{V}{g} \]

Tells us how much Impulse (force x time) per unit mass of propellant expelled.

<table>
<thead>
<tr>
<th>Propellant</th>
<th>I(secs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen-Flourine</td>
<td>528</td>
</tr>
<tr>
<td>Hydrogen-Oxygen</td>
<td>460</td>
</tr>
<tr>
<td>O$_3$H$_2$</td>
<td>607</td>
</tr>
<tr>
<td>F$_2$Li-H$_2$</td>
<td>703</td>
</tr>
<tr>
<td>O$_2$/Be-H$_2$</td>
<td>705</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>I(secs)</th>
<th>Mass Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>1.3x10$^{1328}$</td>
</tr>
<tr>
<td>1,000</td>
<td>1.1x10$^{664}$</td>
</tr>
<tr>
<td>5,000</td>
<td>6.5x10$^{132}$</td>
</tr>
<tr>
<td>10,000</td>
<td>2.6x10$^{36}$</td>
</tr>
<tr>
<td>50,000</td>
<td>1.9x10$^{13}$</td>
</tr>
<tr>
<td>100,000</td>
<td>4.4x10$^{6}$</td>
</tr>
<tr>
<td>200,000</td>
<td>2.1x10$^{3}$</td>
</tr>
</tbody>
</table>

One-way Proxima Centauri Fly-through mission

\[ V_{cruise} = 5\% \ c \]

\[ t_{trip} \sim 86 \ yrs \]
Rocket Alternatives

Chemical

\[ I_{sp} \approx 1,000 \text{s} \]
Rocket Alternatives

Electric

\[ I_{sp} \approx 2,500 - 10,000 \text{s} \]
Rocket Alternatives

Nuclear Fission

Solid Core

\[ I_{sp} \approx 500 - 1,100\,s \]

Liquid Core

\[ I_{sp} \approx 1'300 - 1'600\,s \]

Gas Core

\[ I_{sp} \approx 3'000 - 7'000 \]
Rocket Alternatives

Nuclear Fusion

\[ I_{sp} \approx 2'500 \text{–} 200'000 \text{s} \]
Rocket Alternatives

Antimatter

3 Possibilities

i. Use AM annihilation products for propulsion

ii. Heat a working fluid for propulsion.

iii. Heat a fluid to generate electricity to power electric spacecraft.

2 Typical Reactions

\[ p\bar{p} \] Charged mesons

\[ e^- e^+ \] Gamma rays

\[ I_{sp} > 10^6 \text{s} \]
Fusion Principles

Fusion an attractive option

- Fusion well understood
- High specific impulse
- Produces less radiation than a fission rocket
- Greatest energy density (neglecting matter/antimatter)

Principles

\[ D + T \rightarrow He + n + 17.6\text{MeV} \]
Fusion Principles

Coulomb Force
Infinite range, repulsive

\[ \vec{F} = \frac{kq_1q_2}{r^2} \hat{r}_{21} \]

Nuclear Force
Short range, attractive

\[ V(r) = -g^2 e^{-mr} \]

British Interplanetary Society 2009
To overcome the Coulomb potential we need to make energetic nuclei

\[ P(E)dE \propto \sqrt{E}e^{-E/KT}dE \]

\[ v_{mp} = \sqrt{\frac{2KT}{m}} \]

\[ v_{rms} = \sqrt{\frac{3KT}{m}} \]
Particles need sufficient thermal energy to exceed Coulomb repulsion

\[ \frac{3}{2} k_B T > \frac{ke^2}{r_{\text{nuc}}} \]

Thermal and Coulombic energies

Rearrange

\[ T > \frac{2ke^2}{3k_B r_{\text{nuc}}} \]

Expression for temperatures

\[ T > 10^{10} K \]
Fortunately Quantum Mechanics Comes to the Rescue

\[ \Delta x \Delta p_x \geq \frac{h}{4\pi} \]
Important Fusion Cycles

\[ D + ^3He \rightarrow p(14.68\text{MeV}) + ^4H(3.67\text{MeV}) \]

\[ D + T \rightarrow n(14.07\text{MeV}) + ^4H(3.52\text{MeV}) \]

\[ D + D \rightarrow n(2.45\text{MeV}) + ^4H(0.82\text{MeV}) \quad 50\% \]
\[ \quad \rightarrow p(3.02\text{MeV}) + T(1.01\text{MeV}) \quad 50\% \]

\[ ^3He + ^4He \rightarrow 2p + ^4He \quad 12.86\text{MeV} \]

\[ p + ^{11}B \rightarrow ^3He \quad 8.7\text{MeV} \]

\[ p + ^6Li \rightarrow ^3He(2.3\text{MeV}) + ^4He(1.7\text{MeV}) \]

\[ D + ^6Li \rightarrow \text{5 Primary reactions} \]
Fusion Cycles

\[
D + \text{\textsuperscript{3}}He
\]
Large fraction of charged particles

\[
D + T
\]
Lowest burn temperature

\[
D + D
\]
Fuel is most plentiful on Earth

Legend
- Charged Particle
- Neutron Power
- Thermal Radiation

Power densities for important fusion fuel cycles
Achieving Fusion

Detonation of Atomic Weapon

Magnetic Confinement

ICF
Magnetic Confinement

Tokamak

Heating Achieved via:

• Ohmic Heating
• Neutral Beam Injection
• Magnetic Compression
• RF Heating

20 Tokamaks Currently Operating

30 Years Program
Production of 500 MW for 1,000 s
0.5g Deuterium/Tritium Mix
840m$^3$ Reactor
Scheduled to be switched on in 2018
Produce steady-state plasma $Q > 5$
Magnetic Confinement

- Z-pincha
- Stellarator
- Fusora
Inertial Confinement

ICF Principles

- High energy beams of laser/ions/e^{-}
- Pellet (usually D/T)
- Capsule ablation

Ablation

- Absorption
- Energy Transport
- Compression and burn

Aim

To generate sufficient Temperature/Pressure for fusion process. Preferably gain.
Inertial Confinement

- **Direct Drive**
  - Spherical fuel pellets
  - Heated by driver

- **Indirect Drive**
  - Fuel pellet placed inside Hohlraum
  - Hohlraum heated via driver, then re-radiates x-rays to heat fuel

- **Fast Ignition**
  - Target compressed using laser driver
  - Implosion reaches maximum density
  - 2\textsuperscript{nd} ultra-short PW pulse heats core
Nuclear Spacecraft

- Orion

- 1958-1965
- Nuclear Pulse Propulsion
- Interplanetary
- 3-5% c (fission)
- 8-10% c (fusion)
- Earth to Pluto and back in less than a year!

\[ I_{sp} = \frac{C_0 V_e}{g} \]

\( C_0 \) Collimation factor

\[ I_{sp} = 2000 - 6000 \text{s} \]

\[ I_{sp} = 10,000 - 20,000 \text{s} \]
Nuclear Starships

- **Daedalus**
  - 1973-1978
  - Fusion Pulse Propulsion
  - Barnard’s star
  - 12% c

Numerous advantages over Orion:
- Does not require large size associated with Orion
- No radioactive pollution

\[ I_{sp} = 10^6 \text{s} \]
The Propulsion Process

1. Propellant carried as spheres at cryogenic temperatures in disposable tanks.
2. Pellets injected into reaction chamber, at high velocity.
3. Pellet hit by high powered $e^-$ beams.
4. Ablation of outer layer, fuel is compressed and shockwave heated. Core reached fusion temperatures.
5. Resulting plasma ball directed axially via the field arrangement.
6. Plasma KE stored in magnetic field. Plasma direction is reversed and ejected at high velocity along the engine axis.
7. Momentum is transferred into the reaction chamber and thrust is generated.