Though physically possible, interstellar travel will be exceedingly difficult. Both the known laws of physics and the limits of our current understanding of engineering place extreme limits on what may actually be possible.

Our remote ancestors looked at the night sky and assumed those tiny points of light were campfires around which other tribes were gathered – and they dreamed of someday making the trip to visit them. In our modern era, we’ve grown accustomed to humans regularly traveling into space and our robots voyaging ever-deeper into the outer edges of our solar system. Traveling to those distant campfires (stars) has been made to look easy by the likes of Captains Kirk and Picard as well as Han Solo and Commander Adama.

Our understanding of physics and engineering has not kept up with our imaginations and many are becoming frustrated with the current pace at which we are exploring the universe. Fortunately, there are ideas that may one day lead to new physical theories about how the universe works and thus potentially make rapid interstellar travel possible – but many of these are just ideas and are not even close to being considered a scientific theory or hypothesis.

Absent any scientific breakthroughs, we should not give up hope. Nature does allow for interstellar travel, albeit slowly and requiring an engineering capability far beyond what we now posses. Antimatter, fusion and photon sail propulsion are all candidates for relatively near-term interstellar missions.

The plenary lecture will discuss the dreams and challenges of interstellar travel, our current understanding of what may be possible and some of the “out of the box” ideas that may allow us to become an interstellar species someday in the future.
Interstellar Propulsion Research
Realistic Possibilities & Idealistic Dreams

Les Johnson
Deputy Manager, Advanced Concepts Office
NASA George C. Marshall Space Flight Center
Who am I to talk about Interstellar Propulsion?

- Managed Interstellar Propulsion Research Project in the late 1990’s and early 2000’s for NASA
- Managed In-Space Propulsion Technology Project which included technologies that might one day enable us to reach the stars
- Deputy Manager for Advanced Concepts Office
- Advocate of solar sails as a propulsion system - and believe they have the potential to take us to the stars
- And
I watched Star Trek ...

And I believe it is a future open to us
The challenge is great (distance!!!)
Today
Voyager I (launched April 1977)
(Launch + 32 Years)
Distance:
10 billion miles
108 Astronomical Units (AU)
Speed:
17 km/sec
(3.7 AU/Year, 0.006% c)
Time to Travel
150 AU: 40 Years
4.3 Light Years: 74,000 Yrs

Today plus 74,000 years
Alpha & Beta Centauri will be ours!
(If Voyager were going in the right direction...)

Distance:
10 billion miles
108 Astronomical Units (AU)
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17 km/sec
(3.7 AU/Year, 0.006% c)
Time to Travel
150 AU: 40 Years
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Interstellar Propulsion Research: Near Term, Far Term & Beyond

- **Near-Term**
  - Several “do-able” missions have been proposed
    - Interstellar Probe (250 AU)
    - Gravity Lens Mission (550 AU)
    - TAU Mission (1000 AU)

- **Far-Term**
  - Technologies that might enable missions to another star (4.3 LY min.)

- **Beyond**
  - Will physics allow us to build a warp drive?
Near Term
Interstellar Probe Mission

- The first mission to beyond the Heliopause
  - 250 AU minimum (500 AU desired)
  - Reach 250 AU within 20 years from launch
  - 15-20 AU/year target velocity

The Heliopause is a barrier where charged particles from the sun cannot go beyond because cosmic rays from deep space force them back.

- Three propulsion approaches appear to be possible in the “near” term
  - Chemical with Jovian and Solar Close Approaches (25 - 30 years required)
  - Solar Sails (via close solar approach)
  - Nuclear Electric (fission reactor)
Solar Sail Propulsion

- Solar sails use photon “pressure” of force on thin, lightweight reflective sheet to produce thrust; ideal reflection of sunlight from surface produces 9 Newtons/km² at 1 AU
- Net force on solar sail perpendicular to surface
- One component of force always directed radially outward
- Other component of force tangential to orbit (add/subtract $V_o$)

[<0.2 oz per football field]
Candidate Solar Sail Trajectory

15 Year Solar Sail to 200 AU

- Delta-II class launch to Earth escape
- Sail unfurled with 1800 N-sec impulse for spin up to 12 rpm
  - Final spin rate of 0.3 rpm (after deployment)
- Heliocentric trajectory inbound to 0.25 AU for maximized solar photon pressure
- Sail jettisoned on outbound near 5 AU (low solar pressure beyond this point)
  - 14 AU/year final coast velocity achieved

Figure 1: Spacecraft Trajectory, Baseline Option
Minimum Perihelion 0.25 AU—15 yr to 200 AU
Technology Status:
- Two competing teams designed, fabricated, and tested solar sails and performed system level ground demonstrations:
  - 10 m system ground demonstrators were developed and tested in 2004.
  - 20 m system ground demonstrators designed, fabricated, and tested under thermal vacuum conditions in 2005.
- Developed and tested high-fidelity computational models, tools, and diagnostics.
- Multiple efforts completed: materials evaluation, optical properties, long-term environmental effects, charging issues, and assessment of smart adaptive structures.
Near-Term Solar Sail Applications Lead to Interstellar Capability with Laser Sails

- Solar Powered
- Laser Powered

Areal Density (Sail Mass/Sail Area)

Near-Term Solar Sail Applications

- 2010 - 2015
  - 10 m²
  - NanoSail-D

Mid-Term Sail Demo

- 2015 - 2025
  - ~ 100-m DIA = 10 g/m²
  - TECH DEV

Interstellar Medium Exploration

- 1-km DIA = 0.1 g/m²
- 500 - 800-m DIA = 1 - 2.5 g/m²
- TECH DEV

- 1000-km DIA = 0.1 g/m²
- TECH DEV

- INTERSTELLAR PROBE
- EUROPA LANDERS
- COMET SAMPLE RETURN
- SOLAR POLAR IMAGER
- MERCURY ORBITER
- NON-KEPLERIAN EARTH ORBITS

- OORT CLOUD

Interstellar Probe Flyby

- 4.5 LY

Interstellar Probe Rendezvous

- 40 LY

TRAVEL WITHIN SOLAR SYSTEM: DAYS TO WEEKS
Electric Propulsion

Is an In Space Propulsion technology that utilizes electrical energy to produce an electrostatic reaction (with a propellant) to obtain thrust. May utilize Solar or Nuclear generated power.
Solar Electric Propulsion Status

Solar powered DAWN mission is flying to Asteroids Ceres & Vesta

Hall thrusters are in use on multiple orbital spacecraft
Nuclear Electric Propulsion
For the Interstellar Probe Mission

**Small Reactor:**
- **180 kWe, 335 kg**
- **32 cm x 35 cm core**

**Payload:**
- **(250 kg)**

**Thermal Radiators**

**Electric Thrusters**
- **(13,300 s Isp)**

**Power Conversion**

**Radiation Shield**

**Thrusters**
- **(13,300 s Isp)**

**2500 kg dry mass**

**5500 kg propellant**

**Mid-course maneuvering**

- **30 a.u. in 6 yrs**
- **250 a.u. in 15 yrs**
- **500 a.u. in 26 yrs**

- **123 km/s;**
- **26 au/yr;**
- **0.4 milli-c**

Sandia National Laboratories
Cruise Velocity

<table>
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<tr>
<th>Trip Time (Years)</th>
<th>km/s</th>
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<tbody>
<tr>
<td>10</td>
<td>0.1 c</td>
</tr>
<tr>
<td>100</td>
<td>0.3 c</td>
</tr>
<tr>
<td>1,000</td>
<td>1.0 c</td>
</tr>
</tbody>
</table>

- **ALPHA CENTAURI (4.5 LY)**
- **40 LIGHT-YEARS**

**Kinetic Energy of 1,000 kg Spacecraft**

- Energy Output of Humanity for: 1 Month
- 1 Day
- Tunguska (1908) Impact
- 1 M-Ton H-Bomb
- Saturn V First Stage

**Interstellar Mission**
- Required cruise velocity ~ 0.5 c
- Total mission velocity change \(\Delta V \sim 1.0 \, c\) for rendezvous mission (start & stop)
Far Term: Extending Our Reach Demands Extraordinary Methods of Propulsion

• Matter-Antimatter (Highest Energy Density Propellant)
  – Production, handling and storage
  – Converting energy to exhaust

• Fusion Ramjet (Refueling on the Road)
  – H-H fusion
  – Large area magnetic scoops “Drag-free” fusion

• Beamed Energy (Propellantless Propulsion)
  – Very high power lasers with large apertures
  – Precision pointing
  – Large, low density sails
Antimatter Propulsion Concept

Propellant Tanks

Antimatter Storage and Feed System

- Trap Magnets
- LH2 Feed System (Magnets)
- Pressure Isolation System
- Extraction System (Levitation Lasers)

Engine System

- Refrig (<1K)
- Vac Pump (<10^-14 atm)
- Radiation Shield

Thruster

Solid Anti-H2 (Diamagnetic Trap)
Intermediate Returns on Antimatter Infrastructure And Propulsion Investment

Solar System Boundary & Interstellar Medium

Birthplace of Comets

Hydrogen Clumps, Brown Dwarfs

Nearby Stars and Planetary Systems

α-Centauri and Beyond

4.5 - 40 LY
10 - 100 yrs

~ 1 T

~ 1000 T

Heliopause, Kuiper Belt, Interstellar Medium
1,000 AU
10 yrs

Oort Cloud, 10,000 AU
10 yrs

100,000 AU
10 yrs

Medical / Industrial Applications

- Imaging & Treatment - e.g., Detect & Destroy Cancer Tumors
- Basic research

Additional Space Applications

- 4-Month R/T to Mars - Deliver/Retrieval 100 M-tons (TAU)
- < 4-Weeks travel to any place in the Solar System (TTAU)

Basic Science Return

Antimatter Production

~100 ng

~ 1 mg
Nuclear Fusion Propulsion

- Fusion concepts will enable human exploration beyond Mars to the moons of the outer planets.

- Antimatter-catalyzed fusion looks promising for space applications
  - Might be the first real application of fusion technology

- Insufficient energy density to enable true interstellar travel -- unless Bussard ramjet proves feasible
  - Must collect enough interstellar hydrogen to work ($v > 0.6c$ required)
  - Most interstellar hydrogen is not the correct isotope and therefore will not likely work at all!
**Interstellar Light Sail Concept**

**INTERSTELLAR FLYBY**
- Laser (1.5µm)
- Transmitter
- Optics
- Light Sail
- 100 km Diameter
- 1000 km Diameter
- 2 L.Y.
- Coast Rest of Way to Star

**INTERSTELLAR RENDEZVOUS**
- Laser (0.5µm)
- Transmitter
- Optics
- Light Sail
- 300 km Diameter
- 6 L.Y.
- 300 km Diameter
- 2nd Stage (300 km Dia.) Stops at Star
- 1st Stage (1000 km Dia.) Accelerated Out of System

**Advantages**
- Perform interstellar missions in 50 - 100 years
- Only competitor is antimatter
- Use as a solar sail once in orbit about target
- Use solar power satellite as driver for robotic flybys

**Disadvantages**
- Very high laser / microwave powers (0.1-1,000 TW)
- Very large optics (100-1,000 km)
- Far-term concept, but one of the few ways to do "fast" interstellar missions
Laser Sails Are Big

LightSail for 40 LY Rendezvous Mission
- 100 Year Trip Time
- 0.2 gees Max Accel.
- 936 km Dia
- 3,000 TW Beam

LightSail for 4.5 LY Rendezvous Mission
- 20 Year Trip Time
- 0.2 gees Max Accel.
- 117 km Dia
- 47 TW Beam

Beamed-Energy Transmitter Array
- 1,000 km Dia
- 1 μm Wavelength

Courtesy: Robert Frisbee
Cue Breakthrough Inspirations

- 1880, P. Grec, "Antigravity"
- 1928, E.E. Smith, "FTL"
- 1931, J. Campbell, "Hyperspace"
- 1935, N. Schachner, "Space Warp"
- 1951, M. Gibbs, "Warp Drive"

1956, Forbidden Planet
1966, Star Trek
1977, Star Wars
1978, Douglas Adams
Infinite Improbability Drive

1984, Buckaroo Banzai
1993, Babylon 5
1999, Galaxy Quest

© Paramount Pictures
© Dreamworks Video
© LucasFilms

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Ingoing Premise - History Repeats Itself

limits prior technology

different technology

(Foster, Innovation - The Attacker’s Advantage, 1986)

![Diagram showing the relationship between performance and resources, with lines for pioneers and masters.](image-url)
Propulsion’s Next S-Curve

- Propulsion *technology*, even when at its upper limit, is inadequate for *timely* interstellar flight

- Since *Science* is the progenitor of *technology*…

- Seek new *physics* to circumvent *technological* limits
  - Even if impossible, spaceflight introduces new perspectives toward solving the lingering mysteries of physics
  - More optimistically, if new propulsion physics *is* discovered, a breakthrough class of technologies would result, revolutionizing spaceflight and enabling humanity to reach other habitable planets
**Stages of Progress**

<table>
<thead>
<tr>
<th>Conjecture</th>
<th>Speculation</th>
<th>Science</th>
<th>Technology</th>
<th>Commerce</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;I want to believe&quot;</td>
<td>Sci-Fi</td>
<td>Nature</td>
<td>Devices</td>
<td>Profitable Devices</td>
</tr>
</tbody>
</table>

- From theory to real nature
d- Not to hard

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Complications of Pursuing These Topics

• The Good
  - Intellectually stimulating topic
  - Easy to be a pioneer while others shy away – by simply doing an honest, competent job
  - Coworkers offer encouragement *(to watch the arrows in your back)*

• The Bad
  - Virtually no funding
  - Difficult on your management (*"It doesn't fit our plan!"*)
  - Revolutionary work is disruptive

• And The Ugly
  - Attracts the *Lunatic Fringe*
  - Pedantic reactions
Great Researchers & Important Problems
1986 lecture, Richard Hamming, distinctions between good and great researchers

- **Have courage to tackle** Important Problems
  - Grand challenges that will make a real difference, not just "safe" research
  - Attackable; there is a way to begin solving the problem
- **Start with independent thoughts and then collaborate**
- **Make steady progress, driven and focused**
- **Learn things beyond own work; "Knowledge is like compound interest"**
- **Redirect what is difficult to something easier (convert liabilities to assets)**
- **Honest with personal flaws & work to overcome (convert liabilities into assets)**
- **Tolerate ambiguity**
  - Believe in self enough to proceed
  - Doubt self enough to honestly see flaws
Overall Status

• Subjective Assessment
  - **State of Art** spans *defining problems* to *testing hypotheses* - pieces of the puzzle
  - Nothing yet at **TRL-1** (Basic principles observed and reported)
  - Numerous research options remain unexplored

• Facts
  - More than 16 approaches explored by NASA and others
  - Private $ exceeded NASA $, but with undisclosed results
  - Progress continues in small, isolated efforts, with publications in peer-reviewed journals
  - No funding currently exists to seek out and support the best prospects

• Hype Warning: “antigravity” and “free energy” claims
Book: *Frontiers of Propulsion Science*

- **AIAA Progress in Aeronautics and Astronautics Series**
- **Editors:**
  - Marc Millis (NASA GRC)
  - Eric Davis (Inst. Adv. Studies, Austin TX)
- **18 Authors**
- **22 Chapters**
  - Gravity control
  - Faster-than-light
  - Energy conversion
  - How to's
- **Publication Date:** 2009-Feb-2
Book - Table Of Contents

1. Foreword (Rutan)
2. Preface (Millis)
3. History (Gilster)
4. Propulsion technology limits (Frisbee)
5. Space drive prerequisites (Millis)
6. Review of gravity control theory (Davis)
7. Gravity / superconductor experiments (Hathaway)
8. Nonviable mechanical devices (Millis)
9. Yamishita null tests (Siegenthaler)
10. Lifter tests in air (Miller, et al)
11. Lifter tests in vacuum (Canning)
12. Thrusting against the quantum vacuum (Maclay)
13. Inertia as Stochastic Electrodynamics (Cambier)
14. Relativistic limits of spaceflight (Cassenti)
15. Faster-than-light in General Relativity (Davis)
16. Faster-than-light implications of Quantum Mechanics (Cramer)
17. Comparative space power technology (Bennett)
18. Extracting energy from quantum vacuum (Davis)
19. Sonoluminescence energy (Wrbanek et al)
20. Null tests of free energy claims (Little)
21. Computational tools (Maccone)
22. Prioritizing revolutionary research (Millis)
Today

Voyager I (launched April 1977)  
(Launch + 32 Years)

Distance:  
10 billion miles  
108 Astronomical Units (AU)

Speed:  
17 km/sec  
(3.7 AU/Year, 0.006% c)

Time to Travel  
150 AU: 40 Years  
4.3 Light Years: 74,000 Yrs

Tomorrow

A Galactic Empire!