"There and Back Again"
A Layman's Guide to Ultra-Reliability for Interstellar Missions

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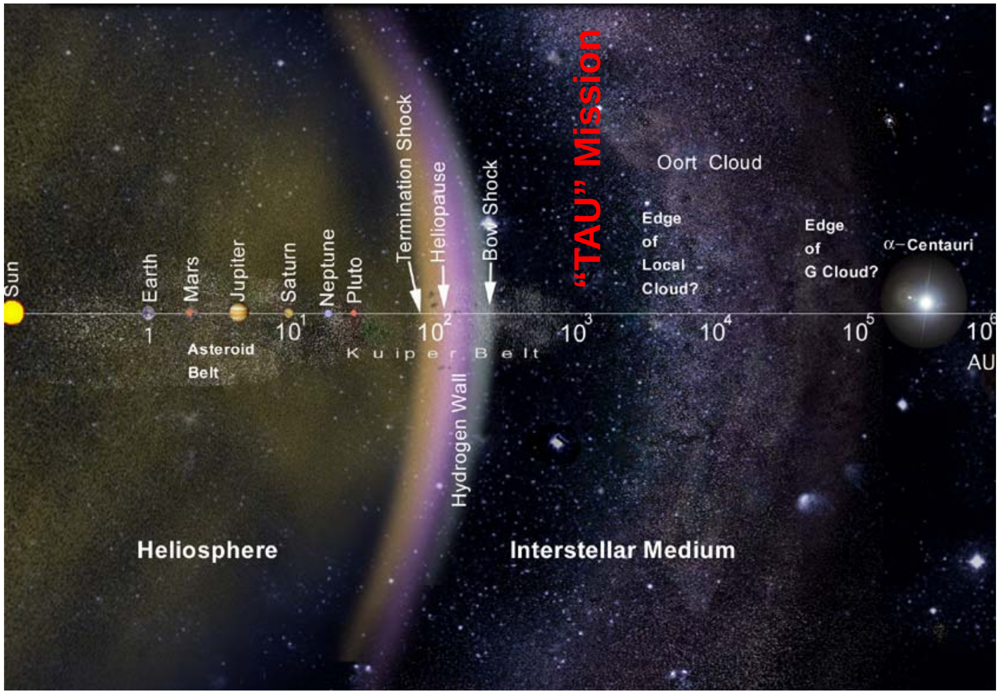
AGENDA

- – Background on Interstellar Flight
- – Reliability Concerns
- – Key Issues
- – References

Why Do We Want to Go?



Relative scales in the Nearby Interstellar Medium and the Solar System

(Sarah Gavit and Paulett Liewer,1999)

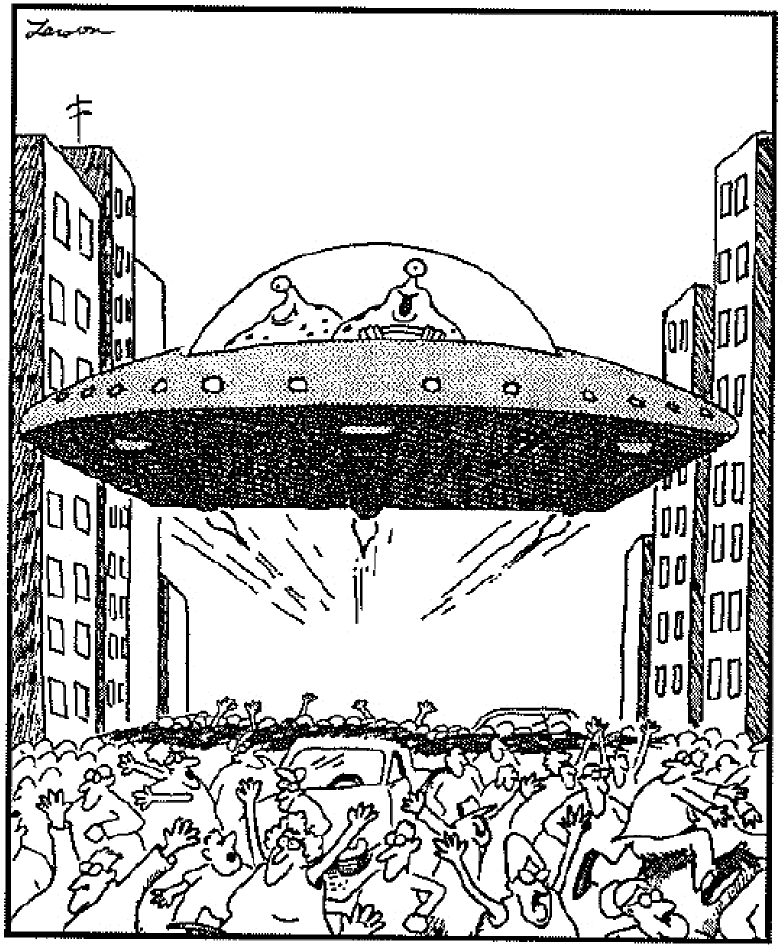
Short Term Science Objectives

1. Explore the nature of the interstellar medium and its implications for the origin and evolution of matter in our Galaxy and Universe.
2. Explore the outer solar system in search of clues to its origin and to the nature of other planetary systems.
3. Explore the influence of the interstellar medium on the solar system.
4. Explore the interaction between the interstellar medium and the solar system as an example of how a star interacts with its local galactic environment.

For The Future…

1. Search for "New Worlds for Mankind"
2. Search for Life
3. "To boldly go where no man has gone before!"

The True Purpose of Interstellar Travel!!



"YEEEEEHAAAAAAAAA!"

Where do We Want to Go?

ENGINEERING RESILIENT SYSTEMS

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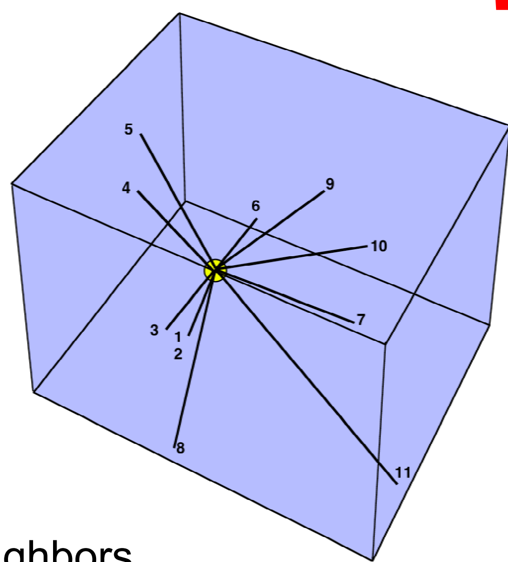
KEY	NAME	LIGHT YEARS	CLASS
1	Proxima Centauri	4.2	G2
2	Alpha Centauri A/B	4.3	G0/K5
3	Barnard	5.9	M5
4	Wolf 359	7.6	M6e
5	Lalande 21185	8.1	M2
6	Sirius A/B	8.7	A0/WH DW
7	Luyten 726-8 A/B	8.9	M6e/M6e
8	Ross 154	9.4	M5e
9	Ross 248	10.3	M6e
10	Epsilon Eridani	10.6	K2
11	Gliese 876 *	15.4	M4

* Closest star with planet (1.9 x Jupiter's mass)

Sun = Class G2



Our interstellar neighbors (courtesy R. H. Frisbee, 2003)

Evaluation of nearby target stars (Martin, 1978a). R1: stellar evolution; R2: likelihood of inorganic materials; R3: possibility of organic life; I: cumulative importance value.

Answer: α Centauri??

STAR	DIST (Ly)	Spectral Class	R1	R2	R3	I	RANK
Proxima	4.25	M5e	2	0	2	94.12	6
α Centauri A/B	4.3	G2/K6	7	10.7	10	644.19	1
Barnard's Star	5.9	M5	2	0	6	135.59	3
Wolf 359	7.6	dM8e	7	0	-1	78.98	8
Lalande 21185	8.1	M2	2	0.1	3	62.96	11
Sirius A/B	8.6	A1/wdA	12	0	-6	69.77	10
Luytens 726-8 A/B	8.9	dM6e/dM6e	12	0	-4	89.89	7
Ross 154	9.4	dM5e	2	0	2	42.55	12
Ross 248	10.3	dM6e	5	0	-1	38.83	13
ε Eridani	10.7	K2	2	3.3	9	133.64	4
61 Cygni A/B	11.2	K5/K7	6	0.1	10	143.75	2
ε Indi	11.2	K5	2	0.1	6	72.32	9
τ Ceti	11.9	G8p	6	3.6	6	131.09	5

But, Recent News May Suggest Other Destinations…

"*Gliese 581c* is ~50% bigger than Earth and ~5X more massive. It orbits Gliese 581, a red dwarf star located 20.5 light-years away that is about one-third as massive as the Sun…..It is located about 15 times closer to its star than Earth is to the Sun; one year on the planet is equal to 13 Earth days. Because red M dwarfs are about 50 times dimmer than the Sun and much cooler, their planets can orbit much closer while still remaining within the habitable zone." *Xavier Delfosse of Grenoble University, France.*

"Computer models predict *Gliese 581c* is either a rocky planet like Earth or a waterworld covered entirely by oceans. We have estimated that the mean temperature of this super-Earth lies between 0 and 40° Celsius and water would thus be liquid," said Stephane Udry of the Geneva Observatory, Switzerland. *MSNBCNews.com*

As of today, there are 784 know planets!! Of the newest, HD20794 at 19.8 light-years has 3 planets at 4.8, 2.7, and 2.4 Earth masses. The most massive (*HD20794d*) is in the "Goldilocks" zone…! *Exoplanet iPhone App, Hanno Rein (2009-2011)*

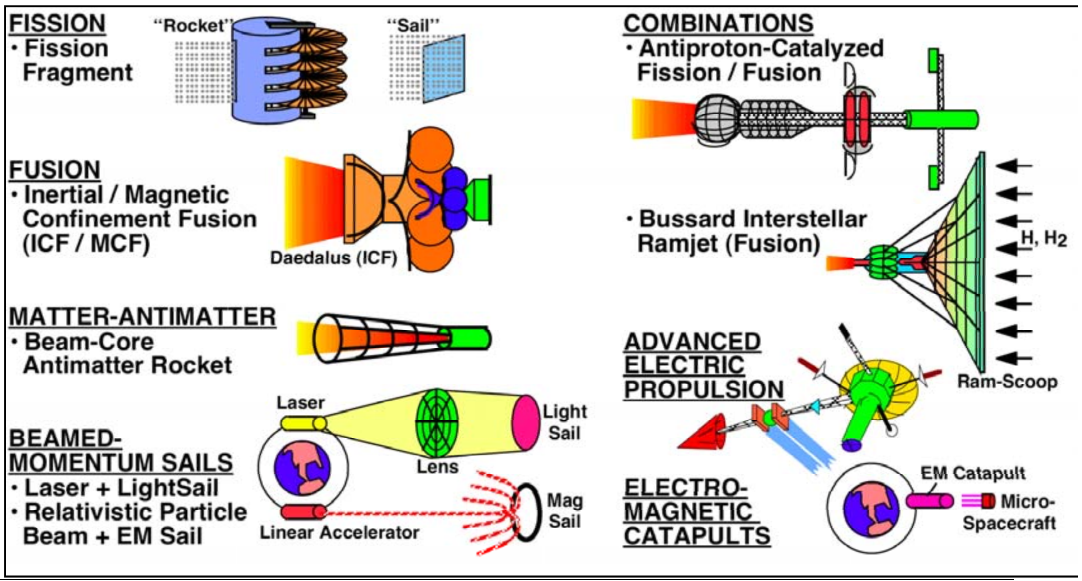
How do We Get There?

ENGINEERING RESILIENT SYSTEMS

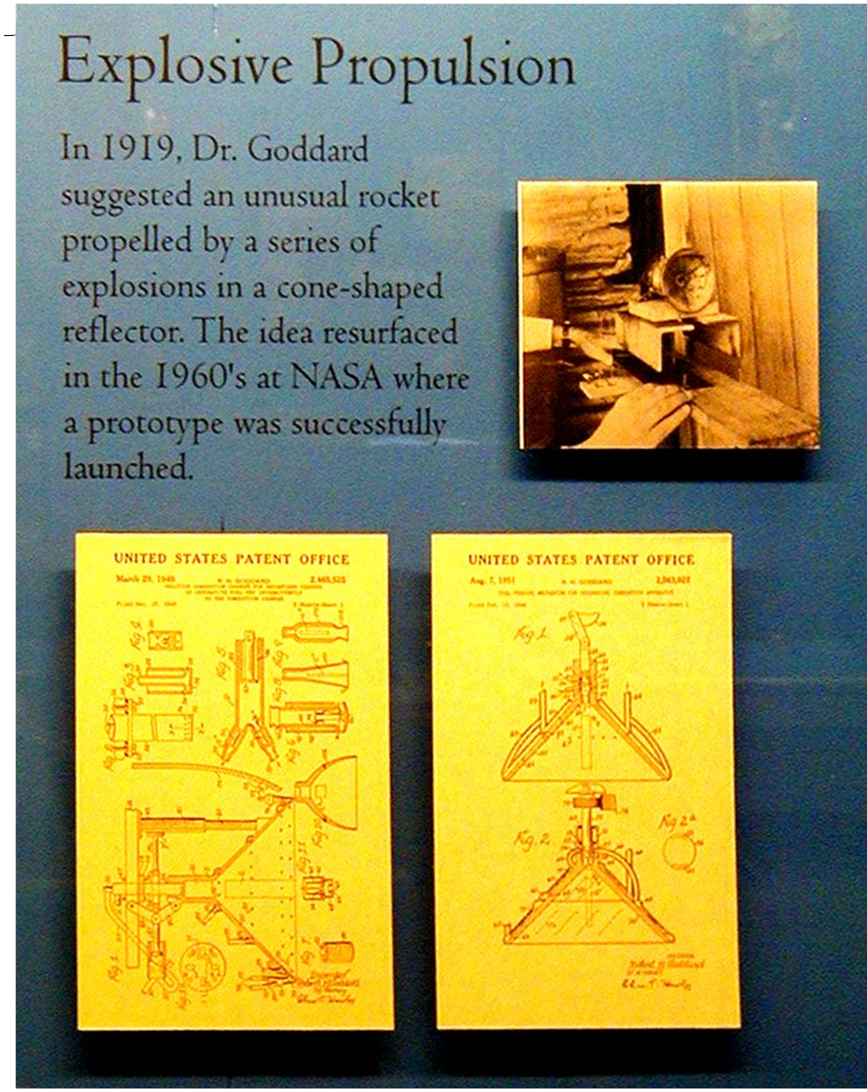
Propulsion Concept	Mission	Source
- Traditional	Pioneer 10,11	NASA
	Voyager 1,2	NASA
	Pluto-Kuiper Belt	NASA
- Sail	Interstellar Probe	NASA
	Beamed Power	Forward
- Electric Propulsion		NASA
- Fission/Fusion	Anti-matter	
	Nuclear Bomb	
	Fusion Bomb	(Daedalus)
- Beamed power	Laser	Forward
	Particles	Forward
	Microwave	Forward
- Brussard Fusion Ramjet		Brussard

Cartoon of the various types of interstellar propulsion being considered (Frisbee, 2003).

In principle, a "slow" (<10% c) ship might be "feasible" but would likely require all the Earth's resources for generation(s)…



Nothing New Under the Sun!!



Robert Goddard holds the patent on an explosion-based interstellar drive…

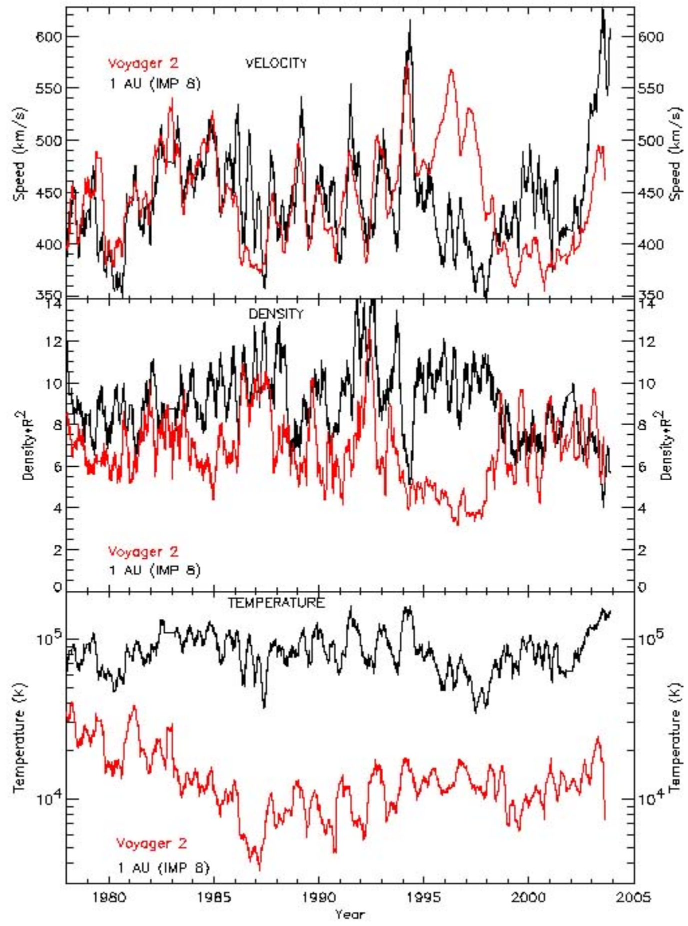
Roswell, NM--the First Interstellar Space Port (for real!)

Can We do it?

We're already doing it…. Pioneer and Voyager are already on the way!

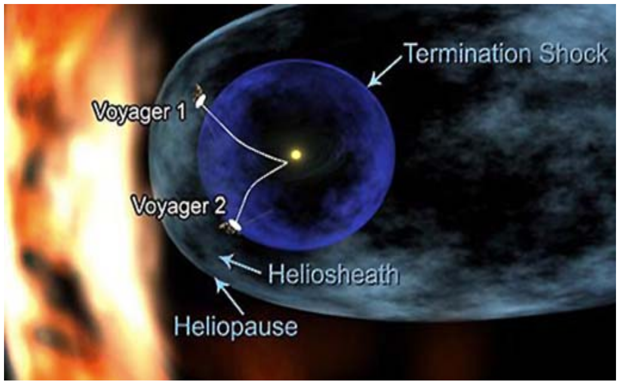
Spacecraft:	Pioneer 10	Pioneer 11	Voyager 1	Voyager 2
Launch Date:	3-Mar-72	3-Apr-73	20-Aug-77	5-Sep-77
Star:	Ross 248	AC+79 3888	AC+79 3888	Sirius
Travel Time:	32,600 yr	42,400 yr	40,300 yr	497,700 yr

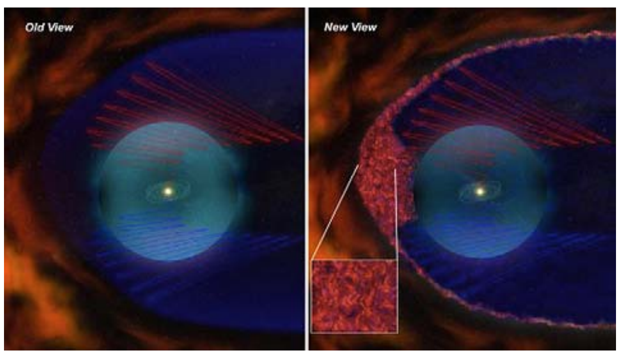
Travel times for current "interstellar missions" to reach nearby stars (Sheffield, 2003)



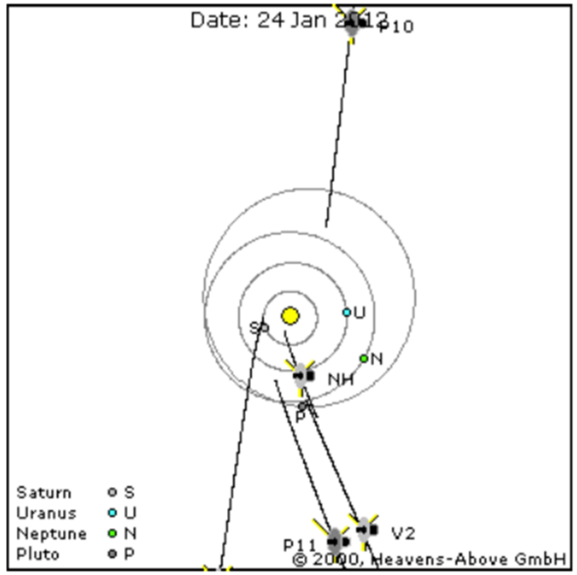
Solar wind plasma--IMP- 8 in Earth orbit (black line) vs Voyager 2 at 72 AU (red line). 50-day running averages (ref. MIT Space Plasma Group; *http://web.mit.edu/afs/athena/org/s/space/www/index.html)*

Where are we now?

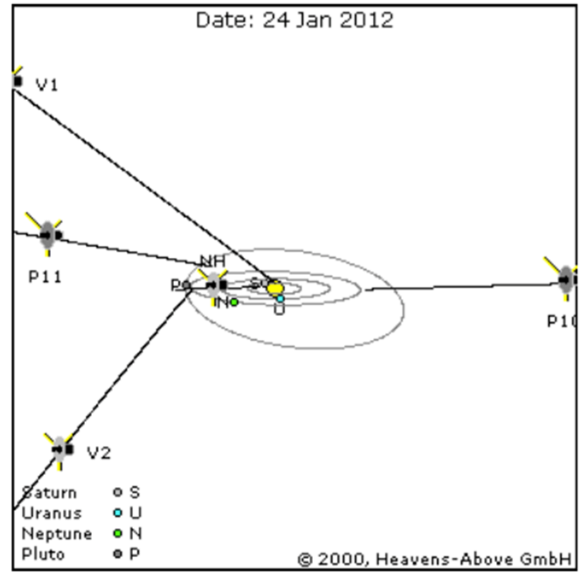




Voyager at the Heliopause—a New Vision



View of orbit from above ecliptic plane



View from 10 degrees above ecliptic plane

	Pioneer 10	Pioneer 11	Voyager 2	Voyager 1	New Horizons
Distance from Sun (AU)	105.088	84.910	97.522	119.552	22.270
Speed relative to Sun (km/s)	12.047	11.392	15.448	17.051	15.498
Speed relative to Sun (AU/year)	2.541	2.403	3.259	3.597	3.269
Ecliptic Latitude	3.0°	14.3°	-33.9°	35.0°	1.8°
Declination (J2000)	25.88°	-8.85°	-55.27°	11.97°	-21.25°
Right Ascension (J2000)	5.094 hrs	18.752 hrs	19.869 hrs	17.183 hrs	18.787 hrs
Constellation	Tau	Sct	Tel	Oph	Sgr
Distance from Earth (AU)	104.407	85.791	98.311	120.082	23.172
One-way light time (hours)	14.47	11.89	13.63	16.64	3.21
Magnitude of Sun from spacecraft	-16.6	-17.1	-16.8	-16.3	-20.0
Spacecraft still functioning ?	No	No	Yes	Yes	Yes
Launch date	Mar 3, 1972	Apr 6, 1973	Aug 20, 1977	Sep 5, 1977	Jan 19, 2006

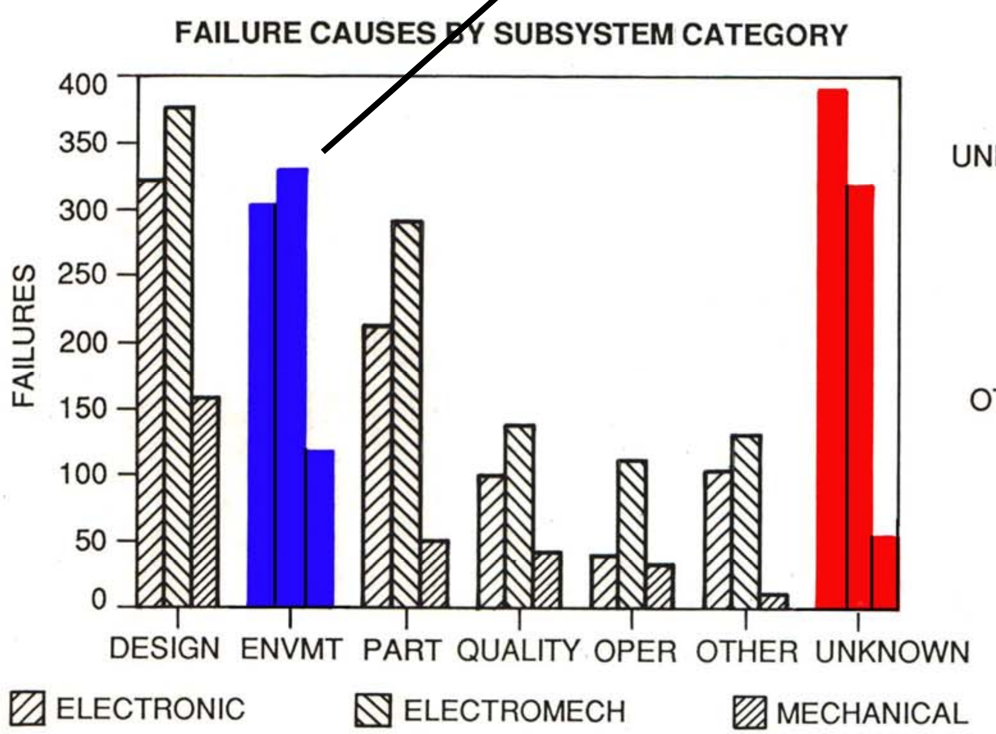
Courtesy Chris Peat, Heavens-Above GmbH (http://heavens-above.com/solar-escape.asp)

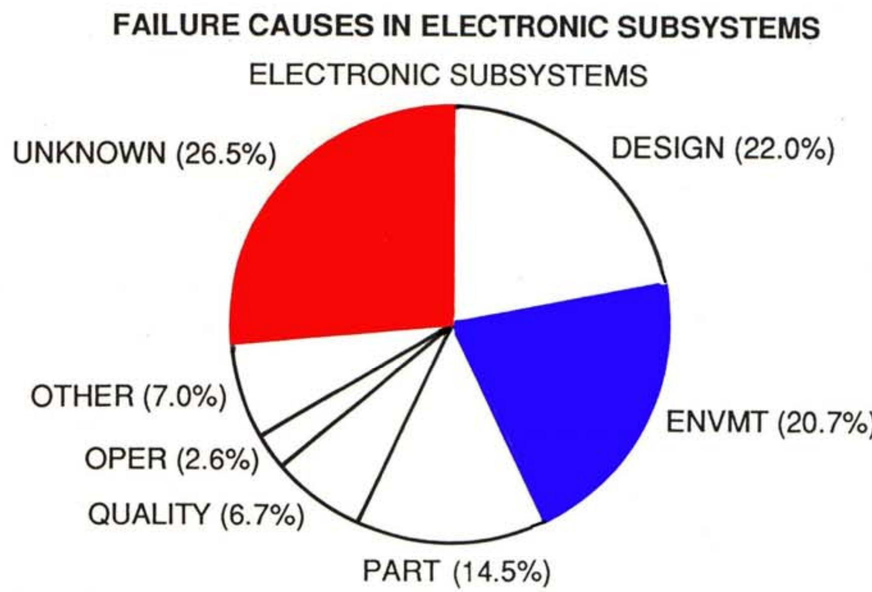
What are the Key Reliability Concerns?

1. Environmental Exposure
2. Propulsion Systems
3. Electronic Systems
4. Mechanical Systems
5. Materials
6. Thermal Control
7. Infrastructure
8. Mission Assurance
9. Software
10. Integrated Systems Health Management
11. Navigation and Attitude Control

What are the Major Subsystem In-Flight Failure Causes?

Environmental Failures





(Hecht, 1985)

What has the Impact of the Environment been on Space Systems?[†]

Distribution by Anomaly Diagnosis

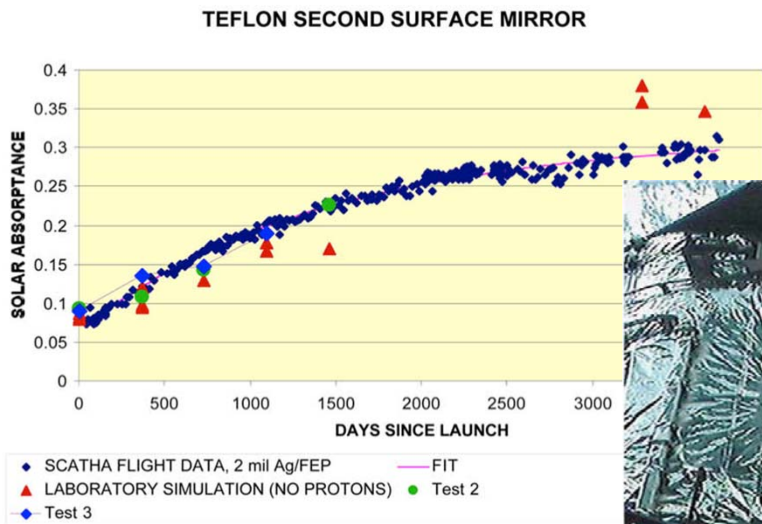
Diagnosis	Number of Forms
ESD - Internal Charging	74
ESD - Surface Charging	59
ESD - Uncategorized	28
Surface Charging	1
Total ESD & Charging	**162**
SEU - Cosmic Ray	15
SEU - Solar Particle Event	9
SEU - South Atlantic Anomaly	20
SEU - Uncategorized	41
Total SEU	**85**
Solar Array - Solar Proton Event	9
Total Radiation Dose	3
Materials Damage	3
South Atlantic Anomaly	1
Total Radiation Damage	**16**
Micrometeorid/Debris Impact	10
Solar Proton Event - Uncategorized	9
Magnetic Field Variability	5
Plasma Effects	4
Atomic Oxygen Erosion	1
Atmospheric Drag	1
Sunlight	1
IR background	1
Ionospheric Scintillation	1
Energetic Electrons	1
Other	2
Total Miscellaneous	**36**

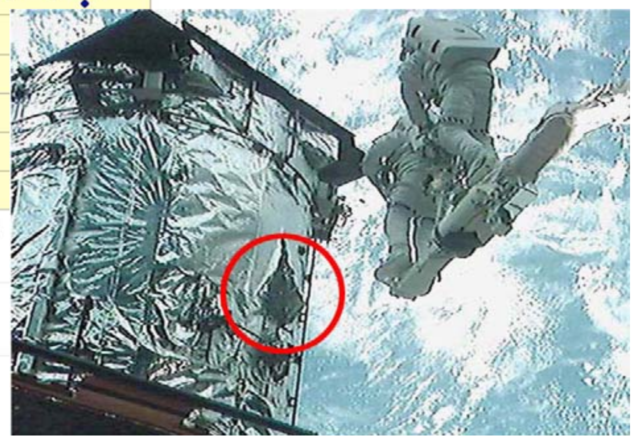
Missions Lost/Terminated Due to Space Environment

Vehicle	Date	Diagnosis
DSCS II (9431)	Feb 73	Surface ESD
GOES 4	Nov 82	Surface ESD
DSP Flight 7	Jan 85	Surface ESD
Feng Yun 1	Jun 88	ESD
MARECS A	Mar 91	Surface ESD
MSTI	Jan 93	Single Event Effect
Hipparcos*	Aug 93	Total Radiation Dose
Olympus	Aug 93	Micrometeoroid Impact
SEDS 2*	Mar 94	Micrometeoroid Impact
MSTI 2	Mar 94	Micrometeoroid Impact
IRON 9906	1997	Single Event Effect
INSAT 2D	Oct 97	Surface ESD

[†]Koons, H.C., J. E. Mazur, R. S. Selesnick, J. B. Blake, J. F. Fennell, J. L. Roeder, and P. C. Anderson, "The Impact of the Space Environment on Space Systems", presented at Charging Conference, Nov 1998.

RADIATION EFFECTS ON MATERIALS

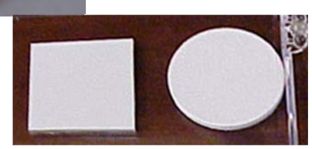




Silver Teflon: Flight Data

Tedlar: 3-4 Yrs GEO Test Exposure

White Paint: GEO Test Exposure



Materials suffer from UV/EUV and particle radiation (Grads on surfaces!) through changes in:

- Dimensions
- Tensile strength
- Conductivity
- Transmission
- Reflectance
- Decomposition

Adapted from Meshishnek et al., 2004
Courtesy of the Aerospace Corporation

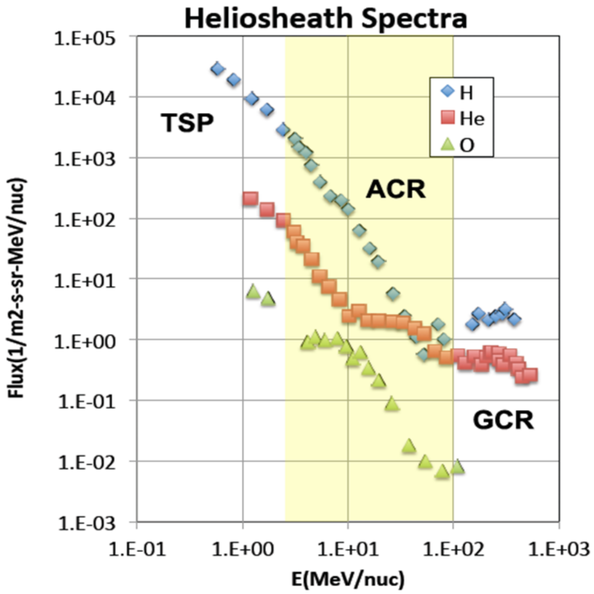
INTERPLANETARY RADIATION ENVIRONMENTS

Mission	Dominant Species	Total Dose (krad/yr) With 100mil Al	Total Dose (krad/yr) With 400mil Al	Total SEU Risk (Relative)	SEU Susceptibility (bit-flip/Gbits/yr) [1] Trapped Protons	Cosmic Rays [2]	Solar Protons [3] 100mil Al	Solar Protons [3] 400mil Al
LEO	p+	<1	<<1	Low	+	10^{-2}	0	0
LEO-Polar	p+	6	1	Moderate	+	10^{-2}	10^{-2}	10^{-5}
MEO	e - (soft)	200-2000	10-100	Severe	++	10^{-2}	10^{-3}	10^{-4}
GEO	e - (soft)	<100	<1	Moderate	0	10^{-2}	10^{-3}	10^{-4}
Jup-Galileo	e - (hard)	250	25	Severe	++	10^{-2}	0	0
Jup/Europa	e - (hard)	1500	800	Severe	++	10^{-2}	0	0
Interplanetary	p+	<1	<<1	Low	0	10^{-2}	10^{-1}	10^{-3}
DOD/Nuclear	e - (soft)	50-10000	1-100	Severe	NA	NA	NA	NA

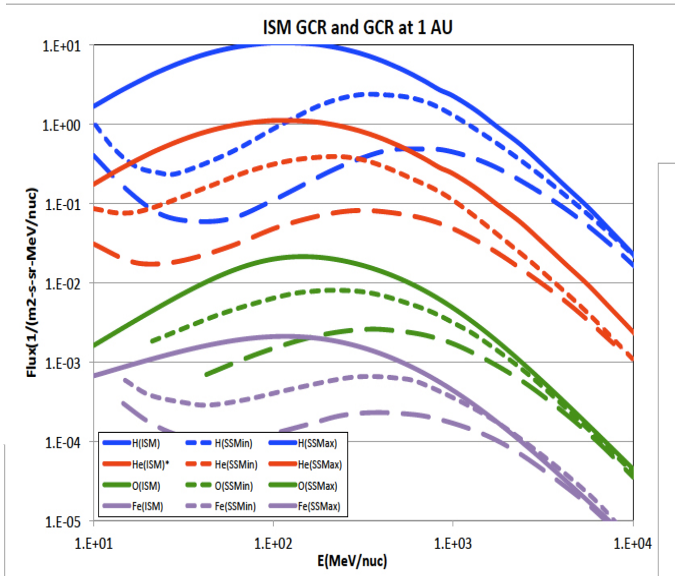
Notes:
1 For devices with LET = 10 MeV-cm²/mg
2 For Adams' 90% Worst Case GCR (Galactic Cosmic Rays)
3 For 99th percentile Solar Flare Events

Representative radiation environments for different regions near the Earth and in the solar systerm.

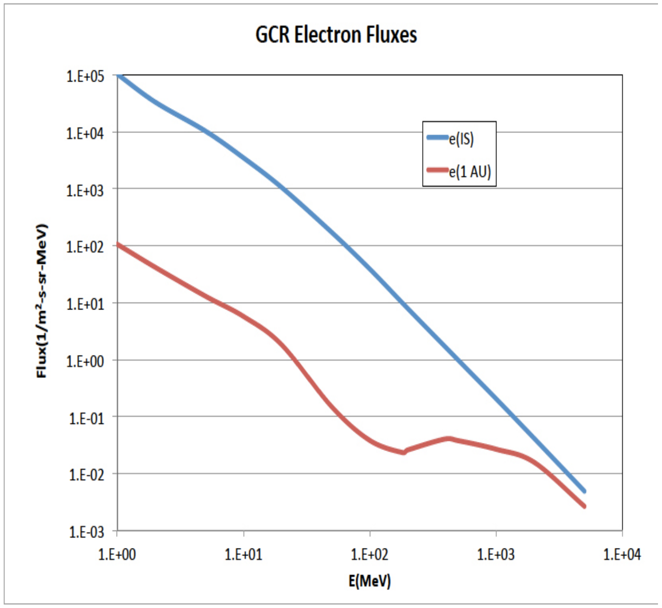
Cosmic Ray Spectra at 1 AU and in Interstellar Space…



The ACR ions near the TS showing the TSP, ACR, and GCR energy ranges.

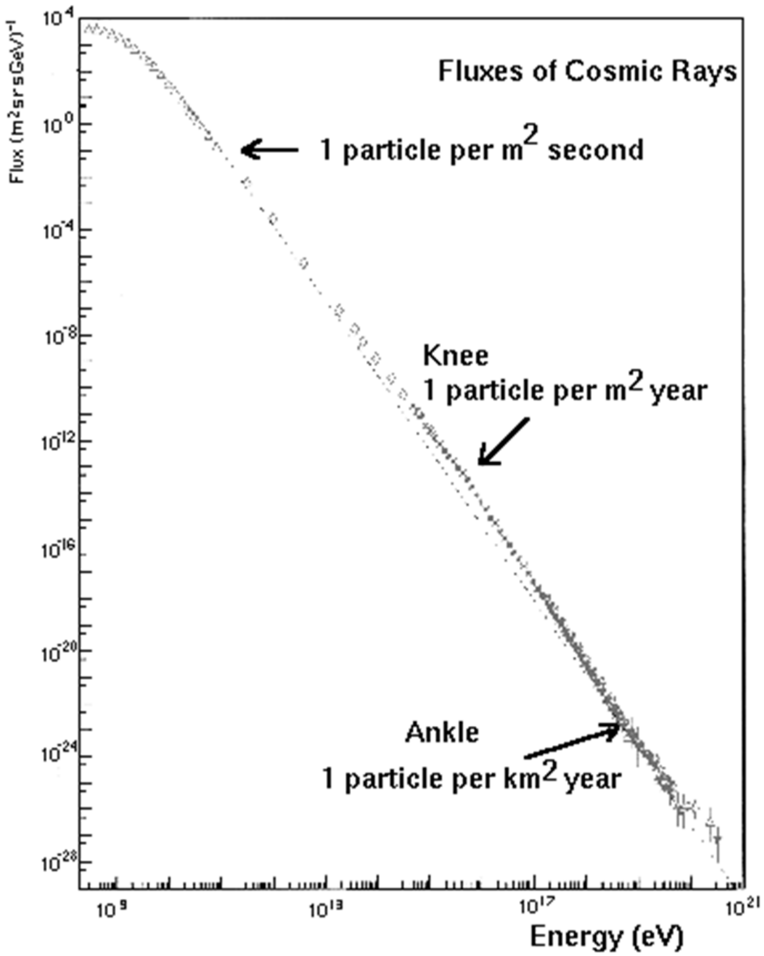


Estimates of the GCR ions at 1 AU for SSMin and SSMax and in Interstellar Space (after R. Mewaldt and others).

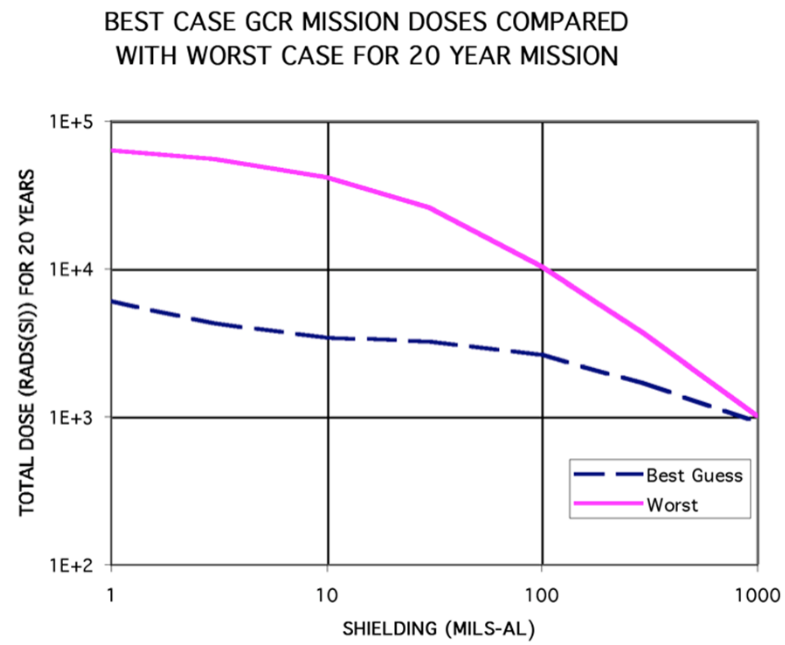


Estimates of the GCR electrons at 1 AU and in Interstellar Space (after R. Mewaldt and others).

Space Environments-Radiation



Galactic Cosmic Ray Environment



Total Ionizing Dose from Galactic Cosmic Rays as a Function of Aluminum Shielding Thickness Graph*. Units are Rad(Si) vs Mils(Al)

*Calculations are for a 4π steradian view factor and for a solid sphere. The "Worst" case is for 20 years at the IS fluences.

Space Environments-Gas and Dust

Number Density of Interstellar gas:	
- Clouds	10^7-10^9 m^{-3}
- Intercloud Regions	2-3x10^5 m^{-3}
- Solar Neighborhood	10^6 m^{-3}
Density of Gas:	1.67x10^{-21} kg m^{-3}
Mass Density of Interstellar Grains:	
- Mean	1.4x10^{-23} kg m^{-3}
- Intercloud Regions	(?)10^{-25} kg m^{-3}
- Solar Neighborhood	(?)10^{-24} kg m^{-3}
Mean Mass of Grains:	10^{-16} kg

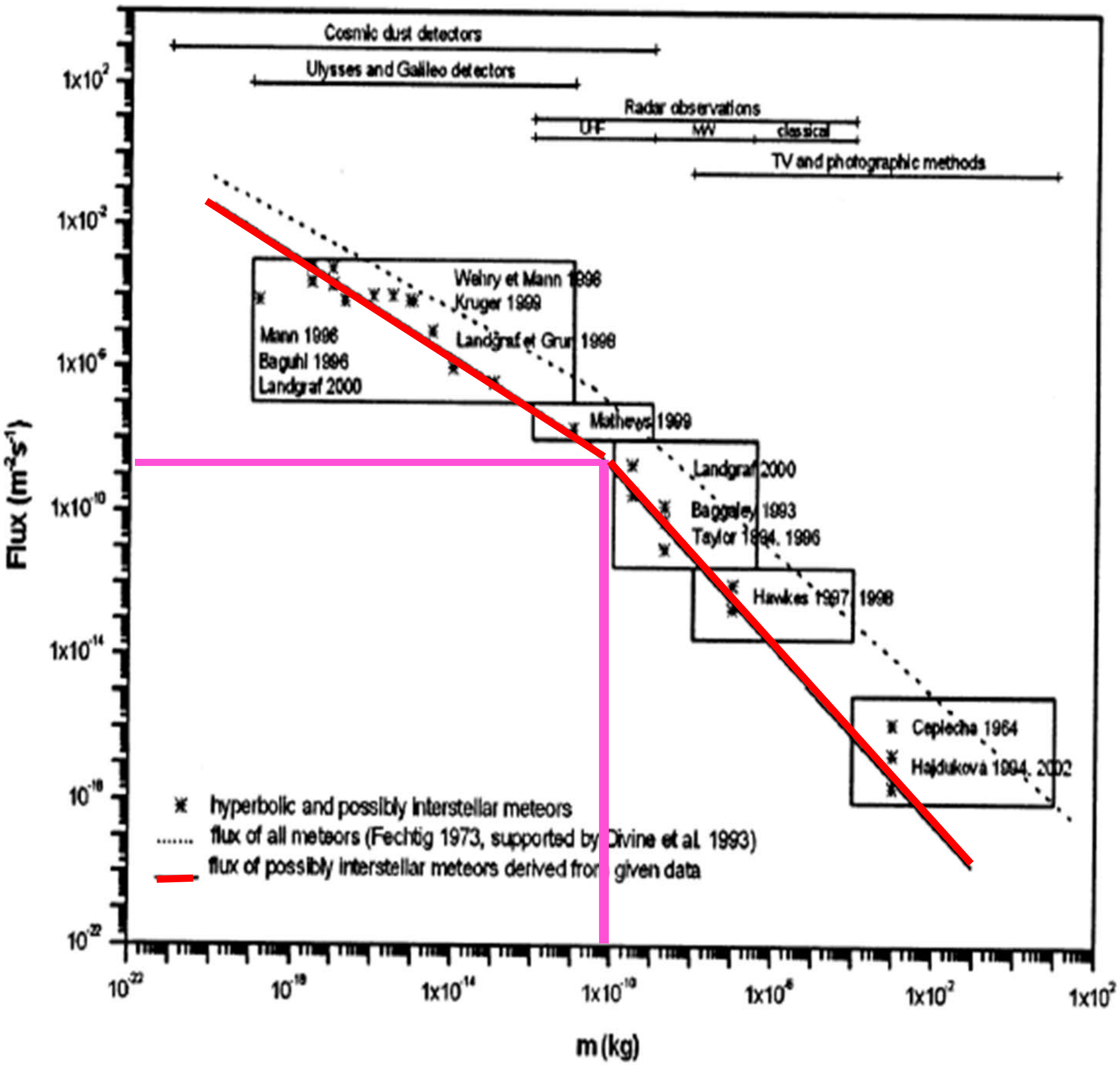
The particle environment in interstellar environment (Martin, 1978b). Note that impact velocities may approach 20% of c!

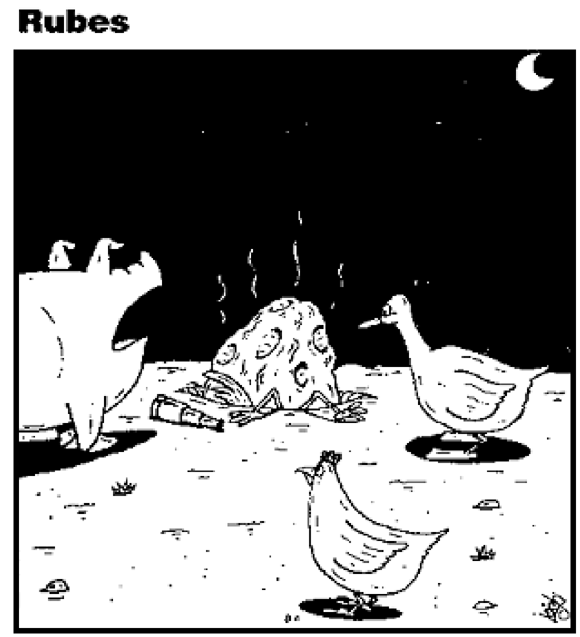
	m/A_o (kg m^{-2})	
β	$\rho=10^{-23}$ kg m^{-3}	$\rho=10^{-24}$ kg m^{-3}
0.05	1.8	0.18
0.10	7.32	0.73
0.15	16.68	1.67
0.20	30.27	3.03
0.25	48.72	4.87

Values of eroded mass per unit area (Martin, 1978b) for a 6 Light Year "Daedalus" mission for various light speeds ($\beta=v/c$).

At 20% c will Erode ~30 Kg/m² or ~1 cm of Al

Do Models or Observations of Interstellar Meteoroids Exist?





"Well, I'll be ... I guess the little chicken was right."

For a 10^{-10} kg particle the flux is $\sim 10^{-9}$/m^2-s or $\sim$1 impact/m^2 in 20 years

from Hajdukova and Paulech (2002) ACM, 173-176 and Hawkes et al., MEW (2007)

Reliability Concerns Unique to Interstellar Missions

Keck Institute for Space Studies

Engineering Resilient Systems

Will Need:

- **Advanced attitude control system for "beam riders" (laser or particle beams)**
- **Ultra-high levels of autonomy (9-40 yr command turn around) for control, health, and in-system scientific exploration and data return**
- **Ability for self-repair, system redundancy, and fault tolerance**
- **Careful consideration of flight spare vs functional redundancy.**
- **Robots capable of in-flight repairs—the ultimate integrated health management system!**
- **Development of common replacement parts strategy**
- **Means for actively regenerating key systems in-flight**
- **Advanced techniques for reconfiguring/reprogramming electronic systems in-flight**
- **New institutions for space research spanning ~50 years or more…(the "*Long Now Foundation*" proposes a 10,000 year timeline)**

Summary of Reliability Concerns for Interstellar Missions

Key Issues:

- We have already reached interstellar space and are capable of at least 35 year missions
- Propulsion to 10-20% the speed of light may be possible with current engineering methods…α Centauri at 4.3 Ly is a plausible target
- The major natural environment concern will be dust/meteroid impacts
- Will need to re-think our current maintainability procedures in light of 50 years and autonomous operations (e.g., common parts, in-flight repair/replacement, ability to reconfigure software, etc.)
- Will need to develop robots capable of in-flight repairs—the ultimate integrated health management system!
- Development of common replacement parts strategy
- Societal issues associated with maintaining a +50 year research mission…

INSTITUTE FOR SPACE STUDIES

References for Interstellar Travel

ENGINEERING RESILIENT SYSTEMS

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