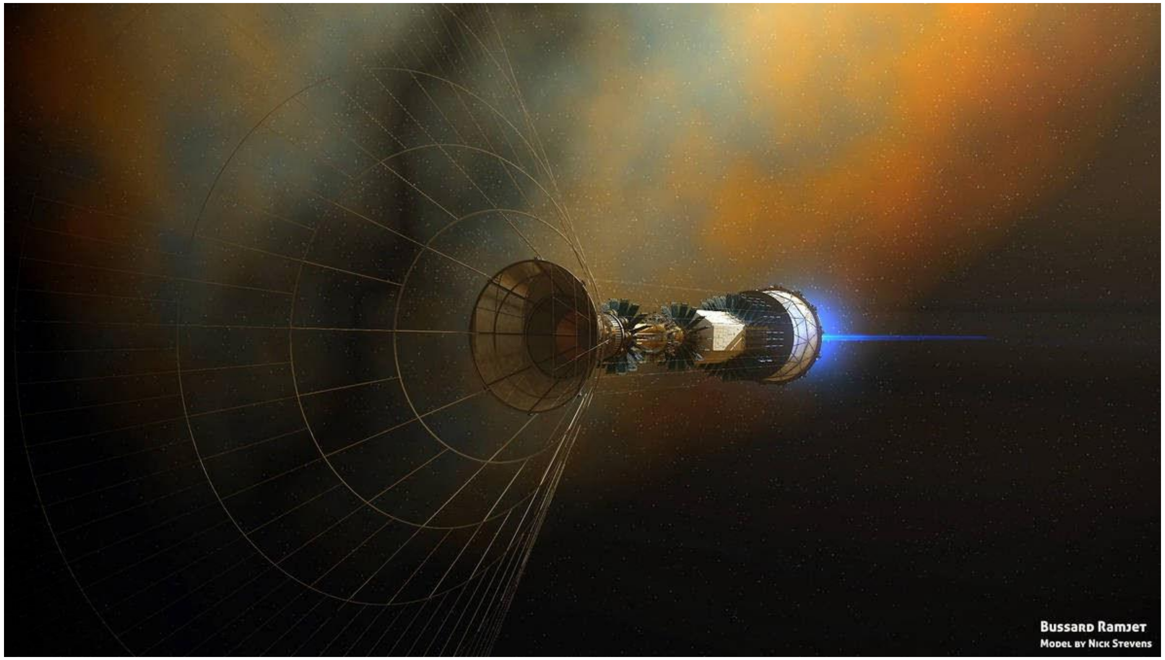

The Interstellar Ramjet: Engineering Nightmare

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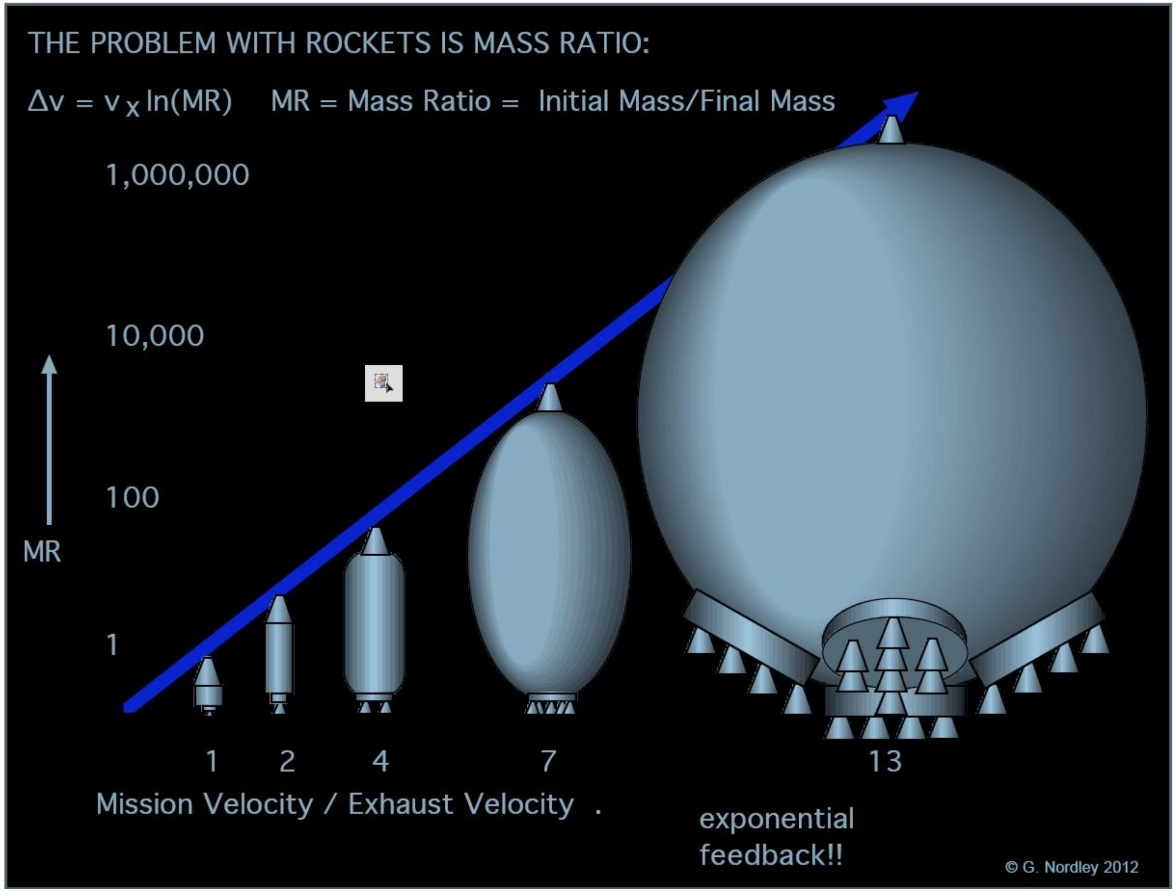
“Its hard to be lite and travel near the speed of light”

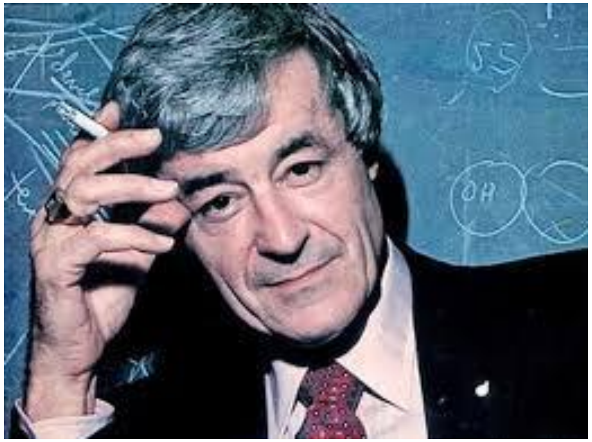
The mass ratio problem



Eugen Sänger

Les Shepherd

Solving the mass ratio problem with the interstellar ramjet.



Robert Bussard
1928 - 2007

John Ford Fishback
1947 -1970

R.W. Bussard, “Galactic Matter and Interstellar Flight”,
Astronautica Acta, VI, (1960) 179-195,.

J. F. Fishback, Relativistic interstellar spaceflight,
Astronautica Acta 15 (1)
(1969) 25-35

The Fishback solenoid (1969)

Just one assumption: adiabaticity $\frac{dB}{dt} T_c \ll B$ i.e. during one gyration period T_c the B field changes slowly. With the cyclotron frequency $\omega_c = eB/m_p = 2\pi/T_c$

$$\Rightarrow \quad \frac{dB}{ds}\frac{ds}{dt}\frac{2\pi m_p}{eB} \ll B = \epsilon B$$

s=s(t) ... path of the proton
m_p ... proton rest mass
e ... electron charge
ε < 1 ... adiabatic constraint
$v_{||} \approx v_0 = \beta$ c ... proton speed

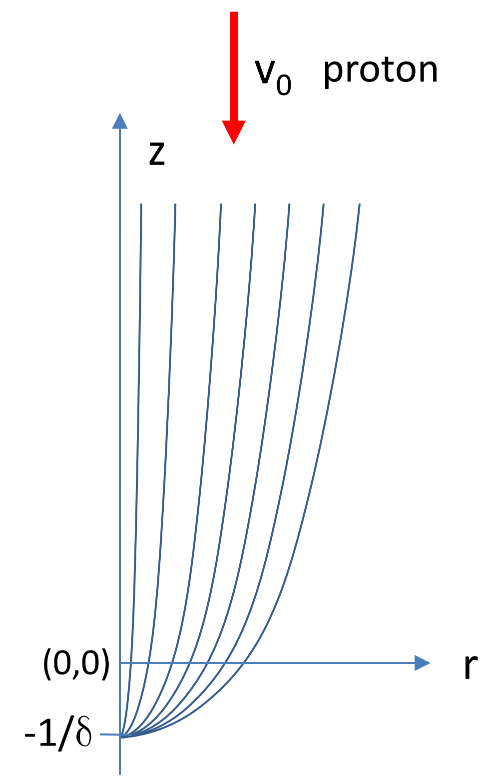
- Solve this differential Eq. for r=0 in cylindrical coordinates (z,r): Br(z)=0 by symmetry,

$$B_z(z) = B_0 \frac{1}{1+\delta z}$$

$$\delta = \frac{\epsilon e B_0}{2\pi m_p v_{\|}} = \frac{\epsilon e B_0}{2\pi m_0 \beta\gamma c}$$

$$\nabla \vec{B} = 0 \quad \Rightarrow \quad B_r = B_0 \frac{\delta\, r}{2(1+\delta z)^2}$$

$\Rightarrow$ **Field lines are bundles of parabolae**

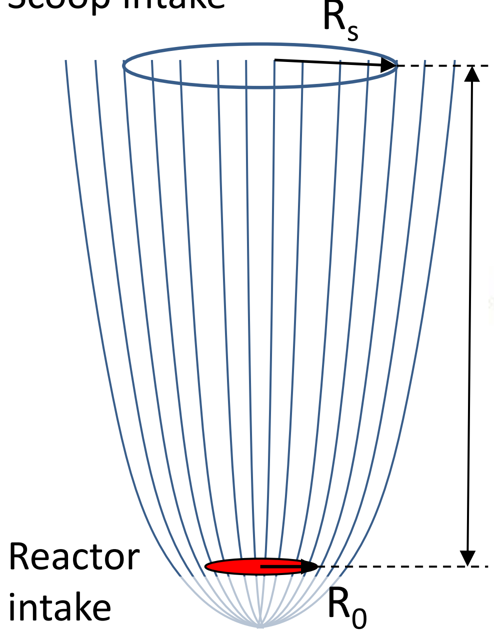


Consequences of adiabaticity

- Field lines are bundles of parabolae
- Protons gyrate over a field line to reactor intake
- Angular momentum = const.

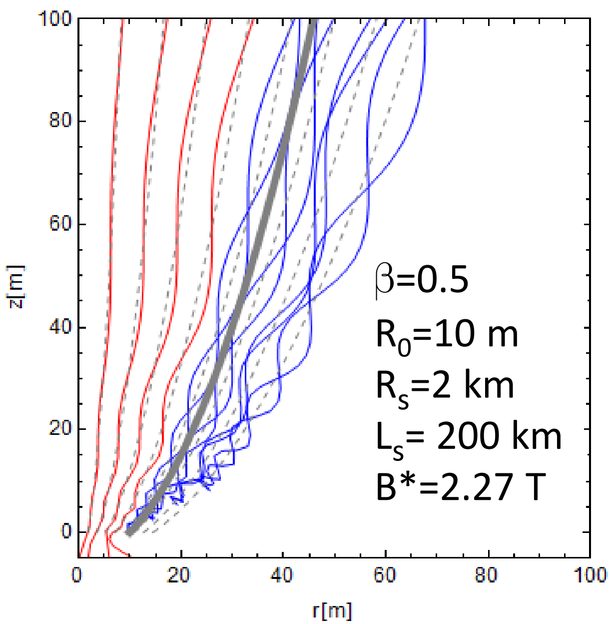
⇒

- Well defined relation between scoop intake radius R_s, reactor intake radius R_0 and extension L_s of the field
- Field at reactor intake $B_0 > B^*$ in order to guarantee small gyration radius
- Confirmed by numerical simulation



$$L_s = \frac{1}{\delta}\left(\frac{\delta^2 R_s^2}{4} - 1\right) \approx \frac{R_s^2}{2R_0}$$

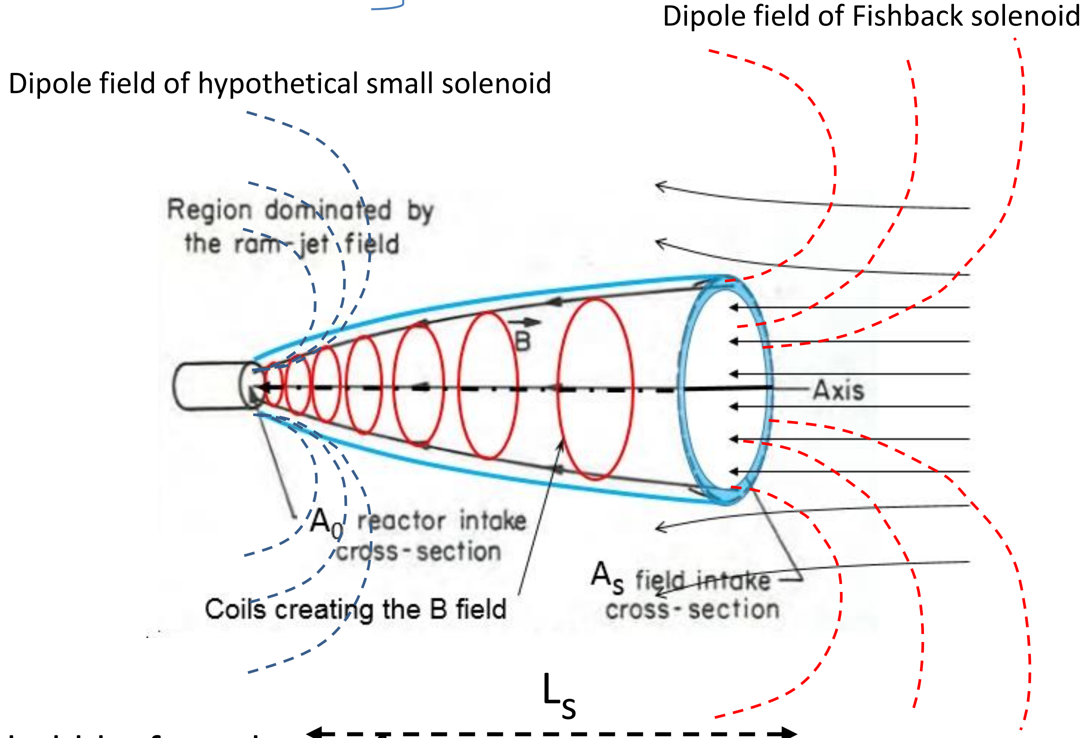
$$B^* = \beta\gamma\frac{4\pi m_0 c}{R_0 \epsilon e}$$



Solenoid shape

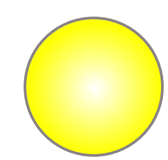
- B fields become dipolar @ z > dimension of the solenoid
- Dipolar fields don't fulfil the adiabaticity condition

→ The Fishback solenoid must cover the entire length L_s



In the local bubble, for a thrust of $\approx 10^7$ N @ β=0.5 one needs $R_s \approx 2000$ km. With R_0 = 20 m $L_s \approx 10^8$ km


Earth

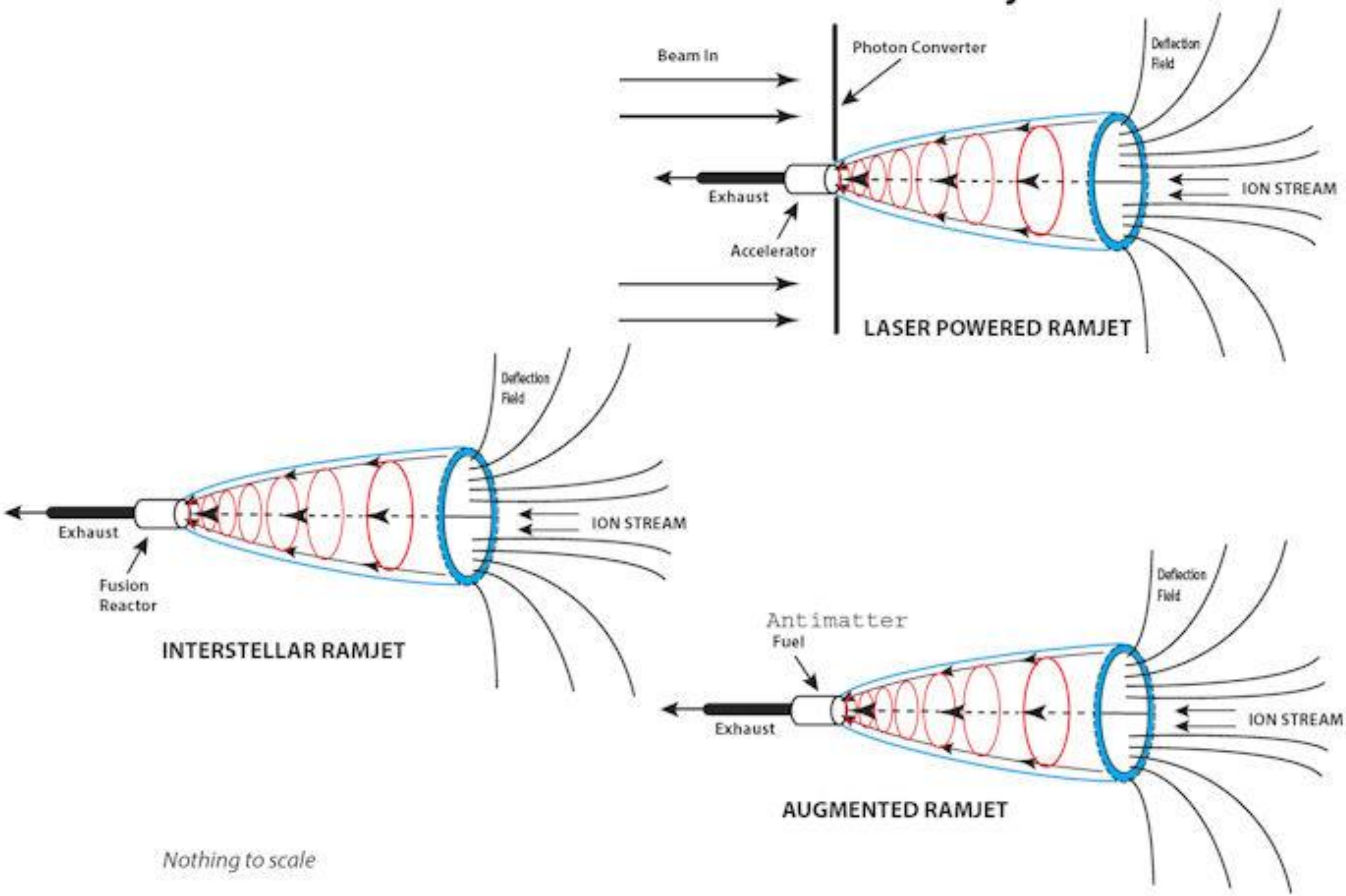

Sun

Limits on $\boldsymbol{\beta}$ as a function the material properties of the scoop field source for a 1 g vehicle.

Material	σ/ρ [10^6 Nm/kg]	$\beta\gamma_F$	$\beta\gamma_{ca}$	$B\gamma_c$	M_{cp}[ktons]	F_P[MN]	B_0 [T]
Aluminum	0.06	8.6	0.38	0.42	1.32	12.95	1.64
Steel	0.26	36.2	0.66	0.86	1.34	13.14	3.38
Pat. steel	0.53	73.6	0.83	1.23	1.34	13.17	4.83
Kevlar	2.5	*342*	1.28	2.67	1.35	13.2	10.5
Silica	3.31	460	1.38	3.07	1.35	13.2	12.08
Copper	4.36	605	1.48	3.53	1.35	13.2	13.87
Diamond	15.2	2100	1.99	6.58	1.35	13.2	25.89
Graphene	56.8	*7780*	2.66	12.73	1.35	13.2	50.05

Table 1: Cut-off speeds for several support materials. $(\beta\gamma)_{ca}$ is for a coordinate acceleration of 1 g, and $(\beta\gamma)c$ is for a proper acceleration of 1g. $(\beta\gamma)_F$ are results from Martin paper. B_0 is the maximum field at the reactor mouth, M_s the minimum mass of the coil support and F is the thrust at the cutoff speed. A scoop radius R_s of 2000 km and a reactor mouth R_0 of 10 m was assumed.

Schematic Constant Acceleration Ramjets



Example Interstellar Ramjets (see Appendix)

Initial Conditions

Proper Acceleration = 1 gravity

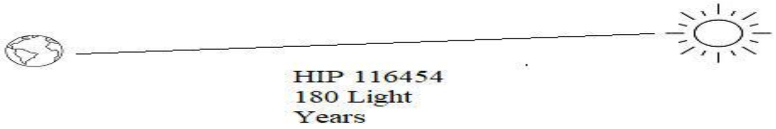
Payload = 1000 metric tons

Ship totally made of Graphene, density 2.2 gm/cc, tensile strength = 2.0×10^{12} dynes/cm2

Average Density Interstellar Medium = 1 H/cc   High Density HII Interstellar Medium = 10^6 H/cc

	pp	CNO	CNO	units
	Low Density	Low Density	High Density	
Characteristic scoop input radius	1721	1721	1.72	km
Characteristic scoop length	1.5×10^8	1.5×10^8	148	km
Scoop Support Mass	10	10	4	tons
Reactor length Mass = Payload + scoop	1.7×10^{15}*	53	53	km
Reactor Mass	$\sim2\times10^{17}$	1×10^7	1×10^7	tons
Corrected Scoop Support length		148	15,000	km

*Reactor Length   *180 light years! Distance to HIP 116454 (K0 star with a planet K2-02)



Conclusions

- The size and mass of the magnetic field scoop source is very large implying great difficulty with the engineering physics.
- For a 1g proper acceleration the attainable Lorentz factor is more strongly constrained than in the modeling by Fishback [4] and Martin[5]. Mission distances are thus constrained.
- Reactor design for the ‘pure’ Bussard Ramjet implies a totally unrealistic length for both low and high density regions of the galaxy.
- The Whitmire CNO reactor (augmented Ramjet [12]) reactor can be a reasonable size but the magnetic scoop is still and engineering problem. Even the antimatter augmented ramjet [13] is constrained.
- The Laser Powered Interstellar Ramjet has the same scoop scale problem.
- The material scoop and reactor are severe problems before radiation losses and structural strength in the reactor and the scoop.

Acknowledgements

P.S. acknowledges the support of the Austrian Science Fund under project P29687-N36 for parts of this work. The authors thank J. Benford and R. Heller for pertinent comments.

References

[1] R. W. Bussard, Galactic matter and interstellar fight, Astronautica Acta 6 (4) (1960).
[2] P. Anderson, Tau Zero, Doubleday, 1970.
[3] C. Sagan, Direct contact among galactic civilizations by relativistic interstellar spaceflight, Planetary and Space Science 11 (1963) 485{498.
[4] J. F. Fishback, Relativistic interstellar spaceflight, Astronautica Acta 15 (1) (1969) 25{35.
[5] A. R. Martin, Structural limitations on interstellar spaceflight, Astronautica Acta 16 (6) (1971) 353{357.
[6] A. R. Martin, Magnetic intake limitations on interstellar ramjets, Astronautica acta 18 (1) (1973) 1{10.
[7] T. G. Northrop, Adiabatic charged-particle motion, Reviews of Geophysics 1 (3) (1963) 283{304. doi:https://doi.org/10.1029/RG001i003p00283.
[8] C. Semay, B. Silvestre-Brac, The equation of motion of an interstellar Bussard ramjet, European Journal of Physics 26 (1) (2005) 75{83.
[9] B. Cassenti, Design concepts for the interstellar ramjet, Journal of the British Interplanetary Society 46 (1993) 151{160.
[10] W. Rindler, Relativity, 2nd Edition, Oxford University Press, Oxford, 2006, p. 70.
[11] S. W. Kash, Minimum structural mass for a magnetic radiation shield, AIAA Journal 1 (6) (1963) 1439{1441.
[12] D. P. Whitmire, Relativistic spaceflight and the catalytic nuclear ramjet, Acta Astronautica 2 (1975) 497{509.
[13] A. A. Jackson , Some Considerations on the Antimatter and Fusion Ram Augmented Interstellar Rocket, Journal of the British Interplanetary Society, v33, 117,1980.
[14] D. Whitmire, A. Jackson, Laser Powered Interstellar Ramjet, Journal of the British Interplanetary Society Vol. 30pp. 223-226. 1977
[15] P. Schattschneider, A. Jackson , The Fishback Ramjet Revisited, in press Acta Astronautica, 2021

Appendix

Fisback derived an expression for the limiting Lorentz factor γ for a Bussard ramjet , Fishback (1969)

Fishback's limit was refined by Schattschneider and Jackson (2021)

$$(\gamma\beta)_S = \frac{\mu_0 encf(\beta)}{2\pi a B_0} \frac{\sigma_{max}}{\rho} \frac{1}{ln\left(\frac{B_0}{B_s}\right)}$$

$$f(\beta) = \beta(\sqrt{\beta^2 + 2\alpha(1-\beta^2)} - \beta)$$

β = velocity/c

$$\gamma = \frac{1}{\sqrt{1-\beta^2}}$$

e = charge on an electron

m_p = mass of proton

n = number density

a = proper acceleration

B_0=average galactic magnetic field

∝ = fusion energy yield

σ_{max} = support maximum tensile strength

ρ = density of support

μ_0 = vacuum permeability

Approximate ramjet dimensions (Whitmire, 1975 , Schattschneidera andJackson, 2021)

Assumptions: 100% efficiency in processes.
Radiation losses in reactor and scooping not included.

$$L = \frac{\beta\gamma a_p\, M}{\pi n^2 < \sigma v > R_0^2}$$

$$a_p = a^* f(\beta)\gamma^2$$

$$a^* = \frac{A_s \rho c^2}{M}$$

Approximate Mass of the Scoop

$$M_s \approx \frac{\pi B_0^2 R_0^3 \rho_s}{\mu_0 \sigma_s} \ln(\frac{R_s}{R_0})$$

Fusion rates at 10^9 K

For pp fusion $<\sigma v> = 6.6\text{x}10^{-39}$ cm^2 sec^{-1}

For CNO fusion $<\sigma v> = 2.1\text{x}10^{-22}$ cm^2 sec^{-1}

R_0 = Radius at reactor intake = 10 meters

R_s= Radius of the scoop intake

n = number density in reactor = 10^{20} per cc

a_p = proper acceleration of vehicle = 1g

α = fraction of scooped mass converted to energy = .007

M = Mass of reactor plus +payload + mass of scoop.

B_0 = magnetic field at reactor intake

ϱ = density interstellar space = 1H per cc (usually density), (10^6 High density HII regions)

A_s = Scoop entrance area.

$$\rho_s = density\ of\ 'solonoid'\ support$$

$$\sigma_s = tensile\ strength\ of\ the\ 'solenoid'\ support$$