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Apr 27th, 2:00 PM - 5:00 PM

Paper Session I-C - Interstellar Transportation- An Enabling Technology for Interstellar Civilizations

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Scholarly Commons Citation

Bennett, Gary L., "Paper Session I-C - Interstellar Transportation- An Enabling Technology for Interstellar Civilizations" (1993). *The Space Congress® Proceedings*. 10.
https://commons.erau.edu/space-congress-proceedings/proceedings-1993-30th/april-27-1993/10

INTERSTELLAR TRANSPORTATION: AN ENABLING TECHNOLOGY FOR INTERSTELLAR CIVILIZATIONS

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Abstract

In order to realize interstellar civilizations in which the vast distances between star systems must be spanned in times much less than the lifetimes of the crew and the people remaining on the planets there must be a revolution in transportation technology. This paper surveys the general field of interstellar flight including concepts based on nuclear energy (both fission and fusion), antimatter, interstellar ramjets, beamed power, vacuum energy fluctuations and various forms of faster-than-light (FTL) travel.

Introduction

Most futurists and certainly most science fiction writers assume that the human race will expand beyond the Solar System. Certainly the territorial/exploration imperative which seems to be wired into the genes of the human race argues that eventually the human race will go to the stars. As James Strong expressed it: "To me, star flight appears as one of the great challenges of Nature, for I see the universe of stars as an arena that has been set for countless eons, patiently awaiting all comers. At any moment in time, any race--human or alien--that feels moved to pick up the gauntlet may do so. To whoever wins, the reward is survival." [Strong 1965]. However, before any exploration missions or even migrations can be attempted there must be a transportation system. This paper surveys the general field of interstellar flight based on the assumption that an interstellar civilization would want trip times much less than the lifetimes of the crew, passengers, and the people on the embarkation and destination worlds (hence ruling out, for the purposes of this paper, suspended animation and generation ships). The term "interstellar civilization" is not explicitly defined but for the purposes of this paper it is assumed that such a civilization would consist of several star systems with separation distances on the order of 5 to 10 light years (ly) (~4.8 x 10^{13} km to ~9.5 x 10^{13} km). As Mallove and Matloff have observed: "But the dawn of starflight cannot be that ambitious. For the moment, we should be satisfied with the domain out to perhaps 21 ly. This is a convenient measure, for within a sphere of that radius lies the nice round figure: 100 *known* stars contained within 75 star systems" (emphasis in the original) [Mallove and Matloff 1989].

Transportation Background

A key consideration for human exploration beyond the Solar System is mission travel (or transit) time, which encompasses the biological effects of extended exposure to microgravity, the psycho-social effects of long-duration confinement, the increased radiation doses from galactic cosmic rays (GCRs), and the likelihood of equipment failures during extended flights. To give some idea of the interrelationship of travel time and propulsion requirements consider a trip to the nearest star beyond the Solar System, Proxima Centauri, a spectral class M star, which is 4.3 light years from the Sun. Traveling at a constant velocity of 50 km/s, which is about the velocity of the fastest robotic spacecraft and fast enough to escape the Solar System, would take 250 centuries to travel that distance. This time can be contrasted with the 15 centuries since the fall of the Roman Empire or the 50 centuries since the construction of the Pyramids [Chaisson 1988].

To reduce the transit time to a more manageable 50 years would require a velocity addition ("delta-v" or "Δv") of (c)(4.3 y)/(50y) or 26,000 km/s (neglecting any relativistic corrections), where c is the velocity of light (~3 x 10^5 km/s). To complete the trip in 10 years would require $\Delta v \approx$ 129,000 km/s! Even more demanding, to reach Proxima Centauri in one year of elapsed time on Earth would require going 4.3 times the speed of light -- a condition which we will see is not allowed by the special theory of relativity.

Space travel to date has been accomplished exclusively with chemically fueled rockets. However, these rockets are limited by the energy available in chemical bonds, as in the equation for the exhaust velocity (which, in metric units, is also the specific impulse) of a chemical propulsion system:

$$v_e^2 = 2\,\eta\,\Delta h$$

where

v_e = exhaust velocity

η = efficiency of converting thermal energy released into directed kinetic energy of the jet

Δh = energy release (from chemical reactions) per unit mass of propellant

The best operational chemical systems can produce $v_e \sim 5$ km/s and with exotic chemical systems the exhaust velocity may approach 20 km/s to 30 km/s [Garrison and Stocky 1988]. Clearly, chemical propulsion is not of interest for transporting members of an interstellar civilization. In fact, Strong has observed that "The successful orbital flights of Soviet and American astronauts have tempted more than one space travel enthusiast to compare them with the pioneering days of heavier-than-air flight at the beginning of this century. The analogy is misleading if it leads others to conclude that, sixty years from now, space-liners will be crisscrossing the Solar System with the same ease and regularity as jet aircraft link the cities of the world today. Men's first ventures into space would be better described as comparable to the clumsy, hot-air balloon ascents of the brothers Montgolfier in the eighteenth century" [Strong 1965].

The following table shows the relative theoretical propulsion performance in terms of the exhaust velocity (or specific impulse) of several advanced (but plausible) chemical and nuclear energy sources [Garrison, Frisbee, and Pompa 1982].

Propellant	Ideal Specific Impulse (km/s)
Standard chemical	≤ 5

Free radical and/or metastable	≤ 30
Fission	$\leq 1.1 \times 10^4$
Fusion	$\leq 2.5 \times 10^4$
Antimatter	3×10^5

Other concepts such as interstellar ramjets and beamed power, while they may have certain engineering advantages, do not improve upon the theoretical performance of antimatter, which has the highest available specific impulse or exhaust velocity (speed of light) based on "classical" relativity theory [Bennett and Stone 1989, Forward 1985 and 1986, Garrison et al. 1982, Garrison and Stocky 1988, and Mallove and Matloff 1989].

As the velocities increase relativistic effects must be considered. Generally, the four-dimensional, spacetime momentum of a relativistic transportation system can be written as

$$\mathbf{p} = m_r \mathbf{v}$$

where **p** is the four-vector momentum and **v** is the velocity. By using this form the preservation of the four-dimensional configuration requires that the relativistic mass be written as

$$m_r = m_o/(1 - \beta^2)^{1/2}$$

where m_o is the proper or so-called rest mass and $\beta = v/c$, the ratio of the velocity of the transportation system to the velocity of light. As can be seen from this equation as the velocity of the transportation system increases to approach the velocity of light the value of β approaches unity and hence the relativistic mass appears to approach infinity which indicates the inertia to be overcome to approach the velocity of light. Equations such as this have led to the assertion that nothing can travel faster than the speed of light which would imply that the fastest transit time we could hope to achieve to Proxima Centauri would be 4.3 years. (More will be said about this later.) Similarly, the preservation of the four-dimensional structure requires that

$$\Delta t_r = \Delta t_s/(1 - \beta^2)^{1/2}$$

where Δt_r is the "moving" time interval and Δt_s is the "stationary" time. What this equation says is that there will be a "dilatation of time", that is, the time interval of the "moving" clock will be slower than that of a "stationary" clock. (The interested reader is referred to Bergmann 1976, Einstein 1961, Goldstein 1959, and Rindler 1969 for further discussions of these points. There are also many excellent popular discussions of these topics.)

"Meta" Relativity

In 1962, O. M. P. Bilaniuk, V. K. Deshpande, and E. C. G. Sudarshan proposed a scheme in which FTL particles might exist without violating the basic ideas of special relativity. In what they termed "meta" relativity the particles always travel at a velocity greater than light. As they stated: "For such a particle to have physical significance its energy

$$E = m_0 c^2/[1 - (v/c)^2]^{1/2}$$

and its momentum

$$p = m_0 v/[1 - (v/c)^2]^{1/2}$$

must be real. This implies imaginary 'rest mass' for this particle, which may seem to disqualify the whole idea right from the start. One should recall, however, that in classical mechanics the mass m_0 is a parameter which *cannot* be measured directly even for slow particles. As Max Jammer puts it, mass 'does not do what it does because it is what it is, but it is what it is because it does what it does.' Only energy and momentum, by virtue of their conservation in interactions, are measurable, therefore, must be real. Thus the imaginary result for the rest mass of the hypothetical 'meta' particles offends only the traditional way of thinking, and not observable physics". Similar arguments can be made for measurements of length and time [Bilaniuk et al. 1962].

As Nick Herbert has noted: “Special relativity does not in itself outlaw superluminal motion. What relativity does say is that certain kinds of superluminal motion lead directly to time travel, that is to signals that can go back into the past, signals that are capable of changing events that, by conventional reckoning, have already happened. To eliminate the possibility of time travel via superluminal signaling from the laws of nature, physicists attempted to make the weakest assumption possible that would do the job--the COP” (causal ordering postulate) [Herbert 1988]. Herbert goes on to list 14 things that move faster than light:

Scissor-blade intersection
Searchlight beam
Eclipse shadow
Perfectly rigid rod
Galloping waves
Quasar expansion
Plasma phase velocity
Marquee lights
Comet tail
Riptide
Oscilloscope trace
Neptune and Pluto
Expansion of space-time
“Practical speed” of NAFAL ship [NAFAL means “nearly-as-fast-as-light”]

While no “meta” particles (sometimes called “tachyons”) have been discovered and the causality violation issues seem formidable the exciting aspect of this work is that it has led to serious thinking by physicists about how FTL could be accomplished and still be consistent with the “laws” of physics as we now know them. It may be that there is a mechanism analogous to quantum tunneling in which a spacecraft could penetrate the “luxon barrier” into the metarelativistic universe of FTL travel (see, for example, the fictional account in Bennett 1980).

Wormholes and Tunnels

Almost from the beginning of relativity theory there have been proposals for devising wormholes or tunnels through space to overcome the perceived prohibition against FTL. Some of these spacetime tunnels have involved the use of black holes, although these, too, can present causality problems not to mention lethal doses of radiation and the possibility that the tunnels will pinch off. Perhaps the most successful recent attempt to develop a wormhole solution to the problem of FTL without invoking black holes has been that of Michael Morris and Kip Thorne [Morris and Thorne 1988 and Parker 1991].

Morris and Thorne listed the desirable properties of traversable wormholes [Morris and Thorne 1988 and Parker 1991]:

- They had to have small tidal forces
- They had to be two-way, which meant that they could not have a horizon
- Transit times through them had to be reasonable, both from the points of view of the traveler and the people outside the tunnel
- Radiation effects had to be minimal
- The wormhole should be capable of being constructed with reasonable materials and within a reasonable period of time

A key factor in maintaining a wormhole is threading the tunnel with "exotic", negative energy matter to prevent pinching off the tunnel. As Morris summarized their work: "We asked the question: Do the equations of general relativity allow you to have a wormhole that is everything the science fiction novelists dream of? And the answer is: Yes, but you're going to have to build it out of exotic matter . . which may or may not exist. It's up to the particle physicists to tell us whether or not it can exist." [Parker 1991].

Summary and Conclusions

This paper began with the premise that an interstellar civilization will depend on fast, i.e., $\beta > 1$, travel. The paper then listed some of the possible methods to construct FTL physics. A good beginning has been made by simply asking what would have to be done to relativity theory to retain its known physical consistency if FTL is assumed to be possible. Just as it took paradigm shifts to move beyond 19th century physics to describe the quantum physics and relativistic physics of the 20th century so it will take another paradigm shift to achieve FTL. In the author's opinion the key may lie, as John Wheeler has indicated, in quantum physics: "The quantum is the 'crack' in the armor that covers the secret of existence" [Parker 1991]. Perhaps the astronomer J. Allen Hynek said it best with his statement that "There is a tendency in the 20th century to forget that there will be a 21st century science, and indeed a 30th century science, from which vantage points our knowledge of the universe may appear quite different. We suffer, perhaps, from temporal provincialism, a form of arrogance that has always irritated posterity" [*Time* 1967].

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