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Comet Riders - Nuclear Nomads To the Stars

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Abstract

This paper describes the potential role of an evolutionary family of advanced space nuclear power systems (solid core reactor, gas core reactor, and thermonuclear fusion systems) in the detailed exploration of Solar System comets and in the use of interstellar comets to support migratory journeys to the stars by both human beings and their smart robot systems.

Introduction

It has been suggested that there are two roads to the stars: the first involves the use of "fast" interstellar ships and the second involves the use of interstellar comets as a resource base on long nomadic journeys (several thousand generations in duration) to neighboring star systems.[1] Perhaps the greatest obstacle facing either approach is **energy** - which is very scarce in interstellar space.

Nuclear energy sources, especially in the form of advanced fission reactors, controlled thermonuclear reactors, and matter-antimatter annihilation systems have been extensively suggested as the key to the "fast" interstellar ship approach - an approach which involves directed journeys of some 40 to 60 years to neighboring star systems, reaching a maximum mission velocity of perhaps 0.1c to 0.2c (c being the velocity of light).[2]

These same nuclear energy sources also represent the energy key to the nomadic, more gradual approach to the diffusion of human beings and their smart exploring machines throughout the Galaxy. In this nomadic approach to the stars, a robotic payload or advanced human habitat takes full advantage of the material resource base represented by an interstellar comet. While such an interstellar journey might take several thousand generations, this slower interstellar migration process could fill the Galaxy in perhaps 500,000,000 years.[1,2] Interstellar comets are thought to have random velocities of about 10 km/s to 20 km/s, essentially mimicking the random velocities of the parent stars that ejected them. It is estimated that a "comet-riding" nomadic band of humans would require about one megawatt per person on the long journey through interstellar space. Advanced gigawatt-class nuclear power systems, developed initially for energy for Earth, could provide the deep space energy sources needed to make such nomadic interstellar journeys possible.[3]

The Interstellar Imperative

The dictionary defines "imperative" as a command or obligation. The **interstellar imperative** might, therefore, be defined as a deeply rooted, perhaps genetic, drive that urges intelligent creatures to explore the unknown - initially across their home planet's surface, then out into their solar system, and ultimately across the interstellar void to neighboring star systems. According to some scientists, intelligent life in the Galaxy might be thought of as experiencing three basic levels or types of technical civilization, when considered on an astronomical scale.[2,4] The Soviet astronomer, N.S. Kardashev (in examining of question of information transmission by extraterrestrial civilizations in 1964), first postulated these three types of technologically developed civilizations on the basis of their ability to use and control energy resources. As a TYPE I civilization begins to emerge from its home planet and expands out into the solar system around its parent star, this TYPE I civilization also transitions into the initial phases of a TYPE II civilization.[2,4] A **TYPE** I civilization would represent a

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planetary civilization similar to the technology level found on Earth in the mid- to late- 20th Century. This TYPE I civilization would command the use of somewhere between 10^{12} and 10^{16} watts of energy - the upper limit representing the amount of solar energy being intercepted by an ecologically suitable planet in orbit around its parent star. A TYPE I civilization could experience the simultaneous development of nuclear energy and space flight - a circumstance that would gently stimulate a primitive response to the **interstellar imperative**.

A maturing **TYPE II** civilization would engage in advanced deep space exploration activities and in feats of planetary engineering, emerging from its home planet through sophisticated developments in space technology. During this expansion process, the TYPE II civilization would extend its energy and material resource bases throughout the local star system by capturing much if not all of the energy output of the parent star (i.e., some 10^{26} to 10^{27} watts for a star like our Sun) and by developing multi-gigawatt and terawatt class advanced nuclear energy systems which would function as mobile energy centers (if you will, portable "artificial stars") for applications in the outer regions of the home solar system.[2-4] Once this level solar system civilization is achieved, the search for additional resources and the pressures of continued growth could encourage interstellar migrations: using both the "fast" interstellar ship and the nomadic comet-riding approaches to crossing the interstellar void. This migration process would then mark the start of a TYPE III civilization.

A **TYPE III** civilization would be an interstellar civilization consisting at first of several star systems and at maturity of a Galaxy-wide community of numerous intelligent species scattered over millions of star systems. In concept, a mature TYPE III civilization would be capable of harnessing the material and energy resources of an entire galaxy (typically containing some 10^{11} to 10^{12} stars). Using our Milky Way Galaxy as a model, a fully-developed TYPE III civilization would be capable of commanding energy levels of between 10^{37} and 10^{38} watts.[2,4]

A "fast" starship is a space vehicle capable of traveling the great distances between star systems. Even the closest stars in our Galaxy are often light-years apart. By convention, the word "starship" is used here to describe "fast" interstellar spaceships capable of carrying intelligent beings to other star systems; while robot interstellar spaceships are called "interstellar probes".[2] Perhaps the most important performance requirement for a starship or interstellar probe is that the vehicle be capable of traveling at a significant fraction of the speed of light (c). Ten percent of the speed of light (0.1c) is often considered as the lowest acceptable speed for a starship (or fast interstellar probe) - while cruising speeds of 0.9c and beyond are considered highly desirable. This "optic velocity" cruising capability is considered necessary to keep interstellar voyages to reasonable lengths of time, both for the home civilization and for the starship crew or robotic payload.

A starship should also provide a comfortable living environment for the crew and passengers (in the case of a "fast" interstellar ark) as well as adequate amounts of radiation protection for the crew, passengers, and sensitive equipment.

One major engineering technology needed to make the "fast" starship a technical reality is an effective propulsion system. Despite the tremendous engineering difficulties associated with the development of a "fast" starship propulsion system, several concepts have already been proposed. These include: the pulsed nuclear fission engine (Orion Project concept), pulsed nuclear fusion (Project Daedalus study), the interstellar ramjet, and the photon rocket. These theoretical systems are briefly described in **Table 1** along with their potential advantages and disadvantages.[2]

However, "fast" starship travel may prove to be too technically challenging, or else prohibitively expensive (i.e. each "ship" costing a significant fraction of the wealth of a solar system civilization). If this is found to be the case, our descendants may chose to cross the interstellar void using another road to the stars - via nomadic journeys in which interstellar comets provide a material resource base and advanced nuclear energy systems an energy source for the leisurely migration (several thousand generations in duration) through interstellar space.

This paper will now discuss two important aspects of this nomadic approach to interstellar migration: advanced space nuclear power systems and advanced deep space comet rendezvous and sampling missions (including robotic probes into the Oort Cloud).

PULSED NUCLEAR FISSION SYSTEM (Project Orion)

- Principle Of Operation: Series of nuclear fission explosions are detonated at regular time intervals behind the vehicle; special giant pusher plate absorbs and reflects pulse of radiation from each atomic blast; system moves forward in series of pulses.

- Performance Characteristics: Very low efficiency in converting propellant (explosive device) mass into pure energy for propulsion; limited to number of nuclear explosives that can be carried on board; radiation hazards to crew (needs heavy shielding); probably limited to a maximum speed of about 0.01 to 0.10 the speed of light.

- Potential Applications: Most useful for interplanetary transport (especially for rapid movement to far reaches of Solar System); not suitable for a starship; very limited application for an interstellar robot probe; possible use for a very slow, huge interstellar ark (several centuries flight time). INTERPLANETARY VERSION COULD BE BUILT IN A DECADE OR SO; LIMITED INTERSTELLAR VERSION BY END OF 21st CENTURY

PULSED NUCLEAR FUSION SYSTEM (Project Daedalus)

- Principle of Operation: Thermonuclear burn of tiny deuterium/helium-3 pellets in special chamber (using laser or particle beam inertially confined fusion techniques); very energetic fusion reaction products exit chamber to produce forward thrust.

- Performance Characteristics: Uses energetic single step fusion reaction; thermonuclear propellant carried onboard vessel; maximum speed of about 0.12c considered possible.

- Potential Application: Not suitable for starship; possible use for robot interstellar probe (fly-by) mission or slow interstellar ark (centuries flight time). LIMITED SYSTEM MIGHT BE BUILT BY END OF 21st CENTURY (INTERSTELLAR PROBE).

INTERSTELLAR RAMJET

- Principle of Operation: First proposed by R. Bussard; after vehicle has an initial acceleration to near-light speed, its giant scoop (thousands of square kilometers in area) collects interstellar hydrogen which then fuels a proton-proton thermonuclear cycle or perhaps the carbon-cycle (both of which are found in stars); thermonuclear reaction products exit vehicle and provide forward thrust.

- Performance Characteristics: In principle, not limited by amount of propellant that can be carried; however, construction of light-mass giant scoop is major technical difficulty; in concept, cruising speeds of from 0.1c up to 0.9c might be obtained.

- Potential Applications: Starship; interstellar robot probe; giant space ark; WOULD REQUIRE MANY MAJOR TECHNOLOGICAL BREAKTHROUGHS—SEVERAL CENTURIES AWAY, IF EVER.

PHOTON ROCKET

- Principle of Operation: Uses matter and antimatter as propellant; equal amounts are combined and annihilate each other releasing an equivalent amount of energy in form of hard nuclear (gamma) radiation; these gamma rays are collected and emitted in a collimated beam out the back of vessel, providing a forward thrust.

- Performance Characteristics: The best (theoretical) propulsion system our understanding of physics will permit; cruising speeds from 0.1c to 0.99c.

- Potential Applications: Starship; interstellar probes (including self-replicating machines); large space arks; MANY MAJOR TECHNOLOGICAL BARRIERS MUST BE OVERCOME—CENTURIES AWAY, IF EVER.

Table 1 Characteristics of Possible Starship Propulsions Systems

Advanced Space Nuclear Power Systems

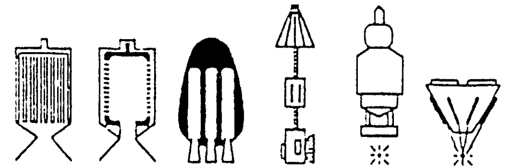
A significant number of advanced missions have been identified that need versatile, high capacity space nuclear power systems.[5-8] These missions include: manned planetary outposts and bases requiring hundreds of kilowatts to megawatt power levels for sustained operations; interplanetary electric propulsion exploration and cargo vehicles with electric power requirements in the 2 to 5 megawatt range; and Earth-oriented applications (such as very high capacity communications and information processing platforms in geostationary orbit) with anticipated requirements of hundreds of kilowatts-electric. **Figure 1** describes the planetary surface power requirements for a variety of future manned missions to the Moon and Mars.[3,5-9]

The entire spectrum of "classical" nuclear propulsion concepts is also being given renewed interest and study - both in support of human expeditions to Mars and in support of human expeditions to Mars and in support of advanced robotic missions to the outer regions of the Solar System and beyond (e.g., the Thousand Astronomical Unit (TAU) mission).[8-11] **(See Figure 2)**

Mission	Power Level	Duration
Human-Tended Lunar Observatory	< 100 kWe	Years (Sustained)
Human Outpost	100-600 kWe	Years (Sustained)
Human Base (With In-Situ Resource Processing)	2 - 20 MWe	Years (Sustained)
Human Settlement	100 MWe-1 GWe	Decades (Sustained)

Figure 1 Planetary Surface Power Requirements (Nuclear Reactor Applications)

The significant point here is simply this: the development of humanity's extraterrestrial civilization and the full and complete exploration of our Solar System will be accompanied by the extensive use of progressively more sophisticated space nuclear power systems, including advanced fission reactors and (in time) controlled thermonuclear fusion systems. Within the first few decades of the 21st century, a space technology infrastructure will emerge which will ensure the safe, efficient and beneficial operation of these space nuclear systems. Included in this infrastructure might be the **Nuclear Power Satellite (NPS)** - a spacebased energy center that uses the nuclear fission or nuclear fusion process to make available large quantities of energy in a very compact, mobile facility.[3] The Nuclear Power Satellite can not only provide prime electric power in large quantities (multigigawatt-electric regime), but also represents a source of process heat and a neutron source for radioisotope production and the breeding of additional fuels (such as tritium for fusion systems).



	FISSION SOLID CORE	FISSION PARTICLE BED	FISSION GAS CORE	FISSION ELECTRIC	FISSION PULSE	FUSION PULSE
THRUST (kN)	70	230	445	$< 10^{-2}$	3500	204
I_{sp} (m/s)	8430	9800	20,000	58,800	25,000	19,600
POWER (MW_t)	300	1100	4460	1-10 (th) 0.1-1 (el)	43,820	20,000
MASS (10^3 kg)	2.6	3.2	57	30-50 kg/kW_e	94	1427
THRUST/WEIGHT	2.7	7.3	0.8	$< 10^{-4}$	3.8	0.015

Figure 2 Nuclear Propulsion Systems

Figure 3 illustrates a one-gigawatt-electric class NPS based on an advanced gas core fission reactor.[3,12] In the system shown, the gas core reactor is dwarfed by its thermal radiator subsystem (each panel is about 50 meters by 27 meters), while the radio frequency (RF) transmitter array (to beam power to a space location or a terrestrial location) is on the order of a fifth of a kilometer in length and width.

The space technology infrastructure created in the development of an evolutionary family of Nuclear Power Satellites provides immediate support to humanity's expansion into heliocentric space and beyond. For example, this evolutionary family of NPS systems represents the sustainable energy supply for a human civilization on Mars (including large-scale resource development efforts and initial planetary engineering projects); for the full-scale exploration and exploitation of the asteroid belt; and for the economic development of the resource-rich worlds of the Jovian and Saturnian systems. Finally, in its late 21st century configuration, an advanced NPS (perhaps burning helium-3/deuterium and positioned in the outer regions of the Solar System) will represent the enabling power/propulsion system for our first serious robotic and manned missions into "nearby" interstellar space - with particular goals of exploring and eventually establishing self-sustaining human outposts in selected regions of the Oort cloud.

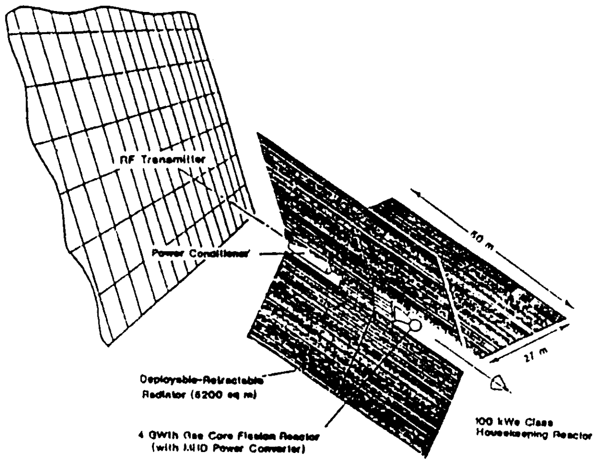


Figure 3 Nuclear Power Satellite (NPS)
(1 GWe Class)

Into The Oort Cloud

Comets are now thought to be small conglomerates of rock, ice, and dust - several kilometers in diameter and some 10^{12} to 10^{15} kg in mass, having been formed in the early year's of the Solar System's history.[2,13] Comets are by far the most numerous objects in our "solar family", with perhaps several trillion (i.e., 10^{12}) of these objects residing in the Oort Cloud (named after the Dutch astronomer Jan Hendrik Oort who first postulated it in 1950) - in loosely bound orbits at tens of thousands of astronomical units (AUs) from our Sun.[1,2,13] By convention, short-period comets (such as Halley's comet) circle the Sun in less than 200 years, while long-period comets travel along extremely elongated orbits that take 100,000 years to one million years or more to complete one orbit around the Sun. In fact, these long-period comets spend most of their time at distances of some 40,000 to 50,000 AU from the Sun in a region of "interstellar space" called the Oort Cloud.

It is also interesting to note that on occasion, a near encounter with another star perturbs the orbit of several comets in the Oort cloud. Some of these perturbed comets are sent off on trajectories into interstellar space (thereby becoming **interstellar comets**), while other perturbed comets are gently bumped toward the inner Solar System. Those comets entering the inner Solar System (some one million or so years later), might experience further trajectory modification if they gravitationally encounter one of the giant planets - thereby becoming either short-period comets or being sent out of the Solar System on interstellar trajectories.

If this process is common in single-star systems throughout the Galaxy - then interstellar space may actually have a significant population of interstellar comets, with an average spacing of some 10 AU (or 80 light-minutes).[1,2,13]

Perhaps the most well-known comet is **Comet Halley.** In March, 1986, an international armada of five spacecraft encountered this short-period comet as it made its periodic (approximately every 75 years) return to the inner Solar System. These scientific spacecraft included: two Soviet spacecraft (*Vega 1 and 2*); two Japanese spacecraft (*Suisei and Sakigake*); and the European Space Agency's *Giotto* spacecraft. The *Giotto* spacecraft passed through the outer comet/solar wind interaction layers and into the inner cometary coma, approaching the comet's nucleus as close as 500 km. Its instruments carried out a first order characterization of the solar wind interaction, a preliminary characterization of the density and composition of cometary gases, and a crude analysis of the elemental composition of cometary dust.[2,13] As a result of these highly successful international efforts to encounter Comet Halley, scientists have been able to initially confirm their previously postulated dirty ice/rock model of a comet's nucleus. But much more detailed data are still needed about the composition, characteristics and behavior of comets, if these interesting celestial objects are ever to play a significant role in mankind's migration to the stars.

Figure 4 presents an overall strategic vision for comet missions in the 21st Century that could lead to the "nomadic" diffusion pathway to the stars.

- Early Robot Missions (Within Solar System)
  - Rendezvous and Flyby
  - Sample Return
- Deep Space Missions (Beyond Solar System)
  - Oort Cloud Precursor (e.g., TAU)
  - Initial Oort Cloud Robotic Missions
    - Comet Population/Characteristics
    - Interstellar Comets
- First Human Missions To Oort Cloud
  - Interstellar Precursor (10-20 years)
- First Human Outposts Within Oort Cloud
  - Self-Sustaining Communities
  - Rise of An "Interstellar" Culture
- Use Of Interstellar Comets For Human Interstellar Migrations (Nomadic Pathway)
  - Small Population Groups (< 1,000)
  - Clustering of Interstellar Comets

Figure 4 Possible 21st Century Comet Missions (A Strategic Vision)

Early in the next century, nuclear-powered robotic comet rendezvous and comet nucleus sample return missions will provide our first detailed understanding of comets. For example, a typical comet rendezvous mission will follow a short-period comet through most of its inner Solar System passage, analyzing cometary dust and gas, energetic particles, as well as investigating in detail the structure and gross composition of the comet's nucleus. The next step, a robot sample return mission, will represent a "crude sample" return opportunity with the returned material retaining only the information about its basic elemental and isotopic composition.[13-14]

However, only precursor interstellar missions, such as the proposed Thousand Astronomical Unit (TAU) mission, can provide the technical heritage necessary to send robotic probes (and then manned vehicles) into the Oort cloud to determine the population and characteristics of the comets that reside many thousands of astronomical units from our Sun. For example, the nuclear powered/propelled TAU mission proposes to send a scientific payload some 1,000 astronomical units out into deep space on a mission of 50 years duration. **Table 2** describes some of the basic constraints and assumptions of this advance, nuclear-powered mission.[11]

Then, in the late 21st Century, if cometary resource data proves as interesting and favorable as is now speculated, advanced nuclear power/propulsion systems would be used to conduct the initial manned exploration of a short-period comet in deep interplanetary

- Launch 2005 - 2010
- Achieve 1,000 AU in 50 Years
- 1 Megawatt-Electric Nuclear Reactor
- Xenon Ion Engines
- 10 Year Thrust Phase
- Earth Spiral Departure
- 5,000 kg Spacecraft Mass (net).
- Heavy Lift Launch Vehicle

Table 2 TAU Baseline Mission (Constraints and Assumptions)

space (e.g., several years or so before or after perihelion). **(See Figure 5)** This historic mission would then be followed by precursor manned missions deeper and deeper into the space eventually reaching the comet-rich portions of the postulated Oort Cloud. At that point in human history, the "fast" ship approach toward interstellar migration would have been demonstrated to a satisfactory engineering level and economic assessment-- or else proven impractical. If "fast" ships prove feasible, then human outposts in the Oort Cloud could become the ports-of-embarkation for our first true interstellar migrations. However, should the "fast" ship approach proves impractical, our spacefaring descendants could still look at the comet population in the Oort Cloud and make the social and technical decisions necessary to take their advanced nuclear energy systems and harvest interstellar comet resources on a leisurely, nomadic diffusion pathway to the stars.

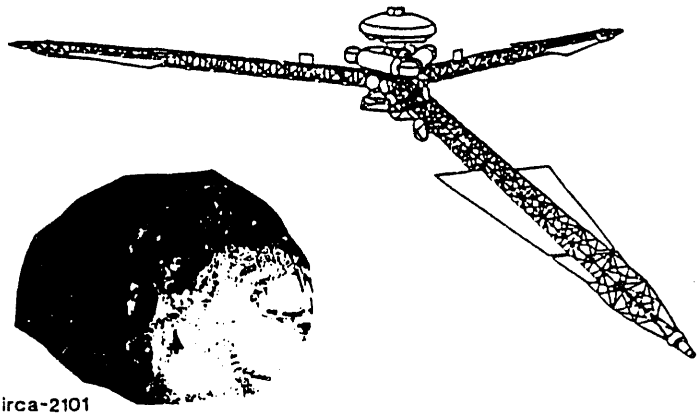


Figure 5 Advanced Manned Nuclear System (Exploring a Comet in Oort Cloud)

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