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RESEARCH ARTICLE

Von Neumann probes: rationale, propulsion, interstellar transfer timing

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Abstract
A Von Neumann probe is a self-reproducing intelligent device with interstellar capabilities. A space-faring civilization could conceivably use such constructs to occupy much or all of the Milky Way galaxy and perhaps the entire universe. This paper presents several reasons that a civilization might decide to produce and deploy Von Neumann probes. Physically possible interstellar propulsion methods for such devices are discussed, as is a launch strategy minimizing the duration of an interstellar transfer. Various solar system locations could be investigated to determine whether Von Neumann probes are present in our vicinity.

Contents

Introduction: what is a Von Neumann probe? Why build them?

The possibility of self-replicating interstellar probes was introduced by John Von Neumann and has been further developed by other researchers (Von Neumann, 1966; Rose and Wright, 2004; Borque and Hein, 2021). Conceptually, the Von Neumann probe is a very simple device (Tipler, 1994). It is a self-sufficient spacecraft endowed with sufficient intelligence to cross from the planetary system of the civilization that constructs it to a neighbouring planetary system. At this destination, one of its functions is to reproduce itself using in-space resources or resources available on planets, dwarf planets and satellites. These 'daughter' probes would then depart the planetary system of the 'parent' Von Neumann probe to ultimately expand through (and perhaps) beyond the galaxy.

Because interstellar transfers by nuclear fusion (Kezerashvili, 2021) and photon sailing seem feasible (Vulpetti *et al*., 2015) in the near future, the vast interstellar distances may not deter the designers of such devices. Nanotechnology may certainly allow for very-low mass intelligent interstellar spacecraft (Lubin, 2016).

From a technological point of view, there seems to be no obstacle to the ultimate terrestrial construction of Von Neumann probes. But why should a space-faring society decide to attempt the robotic occupation of the entire galaxy? What are the advantages and disadvantages of various possible interstellar propulsion options for these constructs? Is there a potential launch strategy to minimize the complexity and duration of second-generation and later Von Neumann probes? What locations in our solar system might telescopes and spacecraft explore for signs of local Von Neumann probes constructed by non-humans? The next section of this paper considers propulsion options. Other issues are addressed in subsequent sections of this paper.

Propulsion options for Von Neumann probes

This section begins with unpowered giant-planet gravity assists, the only interstellar propulsion techniques that have been applied so far to human-constructed extra-solar probes. Progressively more advanced propulsion techniques are considered in turn.

It must be noted that one major issue must be addressed by a civilization constructing Von Neumann probes, no matter which propulsion method is selected. Because no terrestrial spacecraft has survived in the deep-space environment for more than about five decades, the difficulties in designing probes that can survive the temperature extremes, cosmic-ray impacts and other environmental hazards of outer space for centuries or millennia should not be minimized.

Unpowered giant-planet gravity assists

Five space probes, all launched by NASA, have utilized this technique to achieve solar-system escape velocities. These are Pioneer 10/11, Voyager 1/2 and New Horizons. The fastest of these, Voyager 1 is currently about 155 Astronomical Units (AU) from the Sun (https://voyager.jpl.nasa.gov/mission/status/) and is cruising through the local interstellar medium at ~3.5 AU/year (Mallove and Matloff, 1989). If it were travelling in the direction of our nearest stellar neighbour, Proxima/Alpha Centauri at a distance of 4.3 light years (~ 270 000 AU), it would reach that star in ~ 70 000 AD.

In conducting an unpowered giant-planet gravity assist, a spacecraft performs a close fly-by of the giant planet to redirect its velocity vector relative to the planet (Minovich, 1961*a*, 1961*b*). The planet's solar-orbital velocity is reduced by an infinitesimal amount during the manoeuvre.

The trajectories of human extra-solar probes launched to date have been optimized for science, not for interstellar cruise velocity. Many extra-solar planets have been discovered that are more massive than Jupiter (Mason, 2008). In the discussion that follows, it will be assumed that the optimized interstellar velocity of a Von Neumann probe exploiting this propulsion option will be sufficient to traverse one light year (1 ly) in 15 000 years. Although this is the slowest of the interstellar propulsion options considered here, it is by far the easiest to implement.

Powered solar gravity assists

Another approach to achieving solar-system escape velocity is a powered solar gravity assist, also called the 'Oberth Manoeuvre' after German rocket pioneer Hermann Oberth (Oberth, 1972). This technique works because a powered manoeuvre deep within a massive celestial object's gravity well is more efficient that a similar manoeuvre performed in a gravity-free space (Matloff, 2005).

An example of the Oberth manoeuvre is a spacecraft that flies by the Sun at a perihelion distance of 0.01 AU. If the spacecraft's velocity relative to the Sun is increased by 2 km s^{-1} at perihelion, it departs the solar system at about 41 km s^{-1} or 8.7 AU per year, more than twice the interstellar cruise velocity of Voyager 1 (Matloff, 2005). It will therefore be assumed that this approach can result in an interstellar trajectory that traverses one light year in 7000 years.

Nuclear fission and fusion

Controlled nuclear fission, which is currently feasible, releases energy in the splitting of massive atomic nuclei. Controlled nuclear fusion releases energy in the combination of low-mass atomic nuclei and is currently approaching feasibility. Both approaches are currently utilized in nuclear and thermonuclear weapons.

One form of fission propulsion is the nuclear-electric rocket. The energy released by an on-board fission reactor is used to ionize and accelerate fuel particles. In the mid-1970's, a NASA/JPL symposium determined that it might eventually be possible to launch a nuclear-electric probe to 1000 AU with a flight time of 50 years (Mallove and Matloff, 1989). At 40 AU per year, this craft is about 4.5× faster than the powered solar gravity assist in the previous section. It will traverse one light year in about 1500 years.

A controlled fusion rocket would operate using an on-board fusion reactor to heat and expel reaction fuel at exhaust velocities of 100 km/s or higher (Kezerashvili, 2021). If the probe's interstellar cruise velocity is equal to its exhaust velocity, it will traverse one light year in less than 3000 years.

Fission and fusion rocket performance can be increased by supplying more fuel, reducing payload and structure mass, etc. But it should be noted that fission and fusion fuel sources are rare in space. The lunar concentration of uranium and thorium respectively is ~0.3 and ~1.2 ppm. Helium-3 is also found in trace quantities in the lunar regolith (Bruhaug and Phillips, 2013). Fusion fuel is also found in the solar wind. The deuterium/proton ratio in the solar wind is 1.4×10^{-5}. Helium-3 is also found in the solar wind. The solar-wind ratio of Helium-3 to Helium-4 is approximately 4.1×10^{-4} (Bochsler *et al*., 1990). Doubly ionized Helium nuclei comprise 3–6% of solar wind ions (Neugebauer, 1981).

Propelling second or subsequent generation Von Neumann probes with fission or fusion will not be easy. A substantial in-space industrial infrastructure will be required.

Photon and electric sails

These two in-space acceleration approaches make use of solar system resources and require no on-board propellant. The photon sail accelerates by absorbing or reflecting solar or laser photons (Lubin, 2016; Vulpetti *et al*., 2015). Electric sails accelerate by using electromagnetic fields to reflect solar wind particles (Janhunen, 2004).

Contemporary solar photon sails, several of which have flown in space, are typically multi-layered. A reflective layer (usually aluminium) faces the Sun and is mounted on a plastic substrate. An emissive layer is often mounted on the substrate layer oriented away from the Sun.

It is possible to achieve better performance by using a monolayer metallic sail. A 20-nm aluminium sail unfurled at the 0.2-AU perihelion of a parabolic solar orbit could achieve a solar system escape velocity in excess of 300 km/s. Such a sail could traverse one light year in about 1000 years (Matloff and Kezerashvili, 2008).

Beryllium solar-photon sails are generally faster (Matloff, 2006). Ultimate solar photon sails may be constructed of atom-thick graphene (Matloff, 2012).

Aluminium is far more abundant in solar system resources that beryllium (Ehmann and Morgan, 1970; Quandt and Herr, 1974). Production of graphene in quantity has not yet been achieved.

If a Von Neumann probe can be nano-miniaturized and if an in-space solar-pumped laser array is powerful enough, the probe can reach relativistic velocities (Lubin, 2016). But unlike the solar-photon

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option, it cannot utilize the sail to decelerate at the destination star. Constructing such a laser array would require a substantial in-space industrial infrastructure.

The solar-electric sail has not yet been tested in space. Because the solar wind is highly variable (unlike the solar photon flux), it is unclear what the interstellar cruise velocity of a Von Neumann probe propelled by this technique will be. But it certainly won't exceed the solar wind velocity, which is typically 300–800 km s^{-1} (Cox *et al*., 2000).

The ultimate possible interstellar cruise velocity of a sail-propelled Von Neumann probe will depend upon various factors. Conservatively, it is assumed here that a 300 km s^{-1} interstellar cruise velocity is possible for this propulsion option and that one light year can be traversed in 1000 years.

Antimatter/matter rockets

If human technology could produce antimatter in sufficient quantities and store it safely for years or decades, the annihilation of antimatter with matter would provide the most powerful possible rocket fuel (Forward, 1985; Matloff, 2005). Sadly, our most efficient antimatter factories could deliver nanograms of the stuff per year if they were devoted to the task. And storing antimatter ions or atoms for sufficiently long periods of time would be a major technological challenge.

But if Von Neumann probes can be nano-miniaturized as suggested by Tipler (1994), there is another possibility. Bickford (2006) has discussed the possibility that natural antiprotons might be found in small quantities stored in the magnetospheres of giant planets.

If an advanced technology could tap is a potential resource, antimatter could allow for nano-miniaturized Von Neumann probes travelling at relativistic velocities. The total conversion of antimatter/matter fuel to energy could therefore enable a technological species to spread beyond its home galaxy (Tipler, 1994).

A Von Neumann probe expansion strategy

It is possible to develop a conservative estimate of the expansion rate of a civilization's Von Neumann probes. To minimize the duration of probe interstellar transits, Von Neumann machines might be programmed to 'reproduce' when a star makes a close approach to the parent probe's planetary system. An analysis based upon the second data release of the European Gaia space observatory reveals that a star of approximate solar mass will pass within one light year of the Sun at intervals of ~ 500 000 years (Bailer-Jones *et al*., 2018). Such close stellar encounters may be more frequent because Gaia underestimates the number of dim, low-mass red dwarfs.

One can easily estimate how long it would take civilization to occupy most stellar systems in the Milky Way galaxy using a simple mathematical technique. If we denote each subsequent probe migration generation by 'n' and the number of occupied stellar systems by P, the following equation can be applied:

$$P \approx 2^n, \tag{1}$$

At time = 0, $n = 0$ and $P = 1$. At time = 500 000 years, $n = 1$ and $P = 2$. When $n = 36$ and time = 18 million years, $P = 68.7$ billion. This approach is only an approximation: not all stellar systems will be suitable for occupation by Von Neumann probes and some close stellar encounters will be repeated. But it does indicate that not many long-lived space-faring civilizations that deploy Von Neumann probes are required to occupy the galaxy. Even if the slowest interstellar propulsion technique presented above – unpowered giant-planet gravity assists – is the one selected by ET, the required galactic-occupation time is not substantially increased.

Reasons for Von Neumann probes

Propulsion is necessary for ET to attempt galactic occupation. An ~18 million-year time frame for the effort might not daunt a long-lived civilization. But why would anyone launch a Von Neumann probe? This section presents some possible answers to this query.

Life after death

We have no idea regarding the lifespan of advanced extraterrestrial civilizations and the reasons for their ultimate demise. An advanced space-faring civilization, recognizing its own imminent demise, might pepper the galaxy with probes describing its existence and accomplishments. In this manner, it might live on in the minds of citizens of successor civilizations.

Reproduction

As Tipler (1994) suggests, the ∼1000-year flight time between the Sun and our nearest stellar neighbours might mitigate against the deployment of generation ships carrying colonists to the stars. A Von Neumann probe could carry fertilized human ova to be raised robotically and populate in-space habitats circling nearby stars that would be constructed by the probe. A more advanced civilization might replace embryos with computer uploads of human ‘essences’.

Benign lurkers

As described by Benford (2021*a*, 2021*b*), ET might launch Von Neumann probes to construct ‘lurkers’ in planetary systems with life-bearing planets. When life on a planet in that system reaches the appropriate level, the ‘lurker’ might initiate contact or call home.

Malignant lurkers

A less optimistic scenario for Von Neumann probes has been developed by science-fiction author Fred Saberhagen. His ‘beserker’ probes would be distributed throughout the galaxy by a species desiring to protect itself from other space-faring species. At the first sign of suitably advanced life on a subject planet, the berserker would deploy an advanced arsenal to effectively sterilize that world (Saberhagen, 1967).

Life-spreading

If life turns out to be a very rare phenomenon in the universe, a space-faring civilization might deploy Von Neumann probes with a much happier purpose. Simple life forms might be ‘planted’ within oceans on sterile, water-bearing worlds to spread life through the universe.

Influencing or directing galactic/universal evolution

Tipler (1994) presents the grandest Von Neumann scenario of all. Perhaps megastructures constructed by Von Neumann machines could alter the physical course of galactic or universal evolution.

Where do we look?

The case has been made in this paper and elsewhere for the wide-spread application of self-replicating Von Neumann probes by advanced galactic civilizations. Unless humanity is the first space-faring civilization or we are under some form of quarantine, it is reasonable to wonder where such probes might be found in the solar system. Due to dynamic geophysical and meteorological processes, space might be a better place to search than Earth’s surface (Shostak, 2020).

Benford (2019, 2021*a*, 2021*b*) suggests inner-solar-system lurker sites. Searches might be conducted on the Moon (Arkhipov and Graham, 1995; Arkhipov, 1998), Earth Trojan asteroids and Earth co-orbital asteroids.

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Others suspect that our search for ET will have a better chance of success in the outer solar system. One possible (rather large) location is the Kuiper Belt (Matloff and Martin, 2005; Loeb and Turner, 2012; Matloff, 2019). An advantage of the Kuiper Belt for the construction of a subsequent generation of Von Neumann probes is the availability of resources including volatile materials. A disadvantage is the low solar flux available in the outer solar system

In a search for active or quiescent Von Neumann probes in the solar system, human science would contend with great uncertainty regarding the size of such objects. Some science-fiction authors contend that these devices might be the size of small planetary satellites (see for example L. Johnson, *Mission to Methone* and A. Reynolds, *Pushing Ice*). On the other hand, Haqq-Misra and Kopparapu (2012) believe that they may be in the 1–10 m size range of contemporary human space probes and these might be observable.

A search for local Von Neumann probes might turn up evidence of something even more dramatic than objects originating in distant planetary systems. Wright (2017) contends that very ancient pre-human terrestrial civilizations are not impossible and that early Venus or Mars could have hosted technological civilizations.

But there may be a limit to Von Neumann probe detection. If they can be nano-miniaturized as suggested by Tipler (1994), the solar system might swarm with them and detection efforts would likely fail.

Conclusions: possible limits to Von Neumann probes?

This paper has surveyed the range of propulsion options available to self-replicating Von Neumann probes. A possible expansion strategy for these devices has been considered. The subsequent discussion presented some reasons that an extraterrestrial civilization might choose to construct and deploy these devices. Finally, suggestions of where in the solar system to search for local Von Neumann probes were presented.

But one wonders if natural limits exist that prevent a space-faring civilization from occupying the galaxy. It is a well-known fact that radiation can result in human mutations. Perhaps the encoded instructions in a probes's computer bank might be altered by cosmic radiation and ultimately impair the probe's ability to reproduce.

Another possible limitation might be imposed by the amount of information encoded in an intelligent probe's computer. If this exceeds a certain complexity threshold, might the probes cease being very intelligent machines and develop consciousness? If this occurs, might the probe cease following directions and act in a volitional sense?

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