International Journal of Astrobiology (2022), **21**:3 163–187
doi:10.1017/S1473550422000143

CAMBRIDGE
UNIVERSITY PRESS

RESEARCH ARTICLE

Migrating extraterrestrial civilizations and interstellar colonization: implications for SETI and SETA

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Received: 20 February 2022; **Revised:** 28 March 2022; **Accepted:** 31 March 2022; **First published online:** 28 April 2022

Keywords: Artefact, Cosmic Hitchhikers, extraterrestrial civilization, free-floating planet, flyby star, hypervelocity star, interstellar colonization, interstellar travel, SETA, SETI, terraforming

Abstract
Advanced extraterrestrial civilizations may produce observable technosignatures when they migrate inside their planetary systems and to other planetary systems. Collectively, the search for technosignatures produced by migrating extraterrestrial civilizations can be described as the search for migrating extraterrestrial intelligence (SMETI). I propose that extraterrestrial civilizations may use free-floating planets as interstellar transportation to reach, explore and colonize planetary systems. I propose possible technosignatures and artefacts that may be produced by extraterrestrial civilizations using free-floating planets for interstellar migration and interstellar colonization, as well as strategies for the search for their technosignatures and artefacts. I discuss technosignatures that may be produced by extraterrestrial civilizations using other methods of interstellar migration and colonization. As an example, I discuss the star GJ 433, which experienced a close flyby a few thousand years ago. I divide possible technosignatures of migrating civilizations into groups to highlight similarities and differences among technosignatures produced by civilizations using different methods of migration and interstellar colonization. It follows from the comparison, for example, that interstellar migration using flybys of stars can blend with interstellar migration using free-floating planets.

Contents

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Introduction

Advanced extraterrestrial civilizations may produce observable and distinctive technosignatures when they migrate to escape existential threats or for other reasons. Extraterrestrial civilizations may migrate inside planetary systems, away from their post-main-sequence stars. They may also migrate in the Galaxy. Extraterrestrial civilizations would most likely face serious or insurmountable technical problems when using spacecraft for interstellar migration of large populations. Therefore, they may use other methods of interstellar travel. Some extraterrestrial civilizations may build stellar engines (Shkadov, 1987, 1988; Shkadov *et al.*, 1989; Korycansky *et al.*, 2001; McInnes, 2002; Forgan, 2018). Some extraterrestrial civilizations may migrate to planetary systems of flyby stars (Hansen and Zuckerman, 2021).

I propose that extraterrestrial civilizations may also use free-floating planets as interstellar transportation to reach, explore and colonize other planetary systems. I discuss how extraterrestrial civilizations may travel from their home worlds to free-floating planets, and how they may transfer from their free-floating planets to other planetary systems. I propose possible technosignatures and artefacts that extraterrestrial civilizations may produce when using free-floating planets for interstellar migration. I propose strategies for the search for such technosignatures and artefacts. I also propose technosignatures that extraterrestrial civilizations may produce when migrating to flyby stars. This is in addition to a technosignature in the form of infrared excess proposed by Hansen (2022). As an example, I discuss the star GJ 433, which experienced a close flyby a few thousand years ago. I organize technosignatures of migrating civilizations in groups to facilitate their review and comparative analysis. I describe the search for technosignatures of migrating extraterrestrial civilizations as the search for migrating extraterrestrial intelligence (SMETI).

The search for extraterrestrial intelligence (SETI) and the search for migrating extraterrestrial intelligence (SMETI)

The circumstellar habitable zone has been an important unifying concept in astrobiology (Gonzalez, 2005). Similarly, searches for technosignatures of extraterrestrial civilizations often tend to focus on planetary systems with main-sequence host stars, preferably G- and K-type stars. The rationale for this choice is that the habitable zone of such stars remains relatively stable for a very long time. Therefore, living organisms have more time to evolve on planets or moons in such a habitable zone, and intelligent species existing in such a habitable zone are more likely to build advanced civilizations producing observable technosignatures. However, our human civilization demonstrates how with the advent of computer technologies, humans are spending more and more time in the cyberspace (Luciana, 2010). Some advanced civilizations, if such exist, might follow the same trend instead of engaging in far-reaching space exploration and producing observable technosignatures. Advanced extraterrestrial civilizations may also become less detectable at interstellar distances when their sciences and technologies allow them to integrate with their environments. For example, a qualitative classification of extraterrestrial civilizations was proposed to be based on the abilities of extraterrestrial civilizations to change their environment and to integrate with it. In this classification, class 3 civilizations can fully integrate with the environment, making it impossible to distinguish their technosignatures from natural phenomena (Ivanov *et al*., 2020).

Technological advancements of extraterrestrial civilizations may allow extraterrestrial civilizations to produce less and less noticeable technosignatures, especially when they are comfortably set in the relatively stable habitable zone of medium- and low-mass main-sequence stars. If this tendency is common among advanced extraterrestrial civilizations, then the search for their technosignatures in the habitable zone of main-sequence stars may require extensive efforts.

However, advanced extraterrestrial civilizations would have to engage in activities producing observable technosignatures in the times of hardship such as destructive cosmic events and disasters caused by actions of civilizations. To escape existential threats, large populations of extraterrestrial civilizations would migrate inside their home planetary systems or to other stars. Their migration and colonization of other cosmic worlds would produce distinctive technosignatures.

This provides SETI with an opportunity to expand its scope by including the searches for extraterrestrial civilizations and their intelligent technologies that are migrating inside planetary systems and in the Galaxy. For example, when a star becomes a red giant, its habitable zone moves outwards (Ramirez and Kaltenegger, 2016). Extraterrestrial civilizations would migrate in their planetary systems to follow the habitable zone moving to larger orbital distances and away from their host stars turning into red giants. Their migration and colonization of more distant planets and moons in their home planetary systems would produce observable technosignatures, including atmospheric technosignatures, infrared-excess technosignatures and communication technosignatures.

Some extraterrestrial civilizations may migrate from their home planetary systems to other planetary systems. They would most likely encounter serious or insurmountable technical problems when using spacecraft to transport large populations over interstellar distances. However, extraterrestrial civilizations may migrate among stars even if they do not have interstellar spacecraft designed to carry large populations. Studies relevant to the searches for such extraterrestrial civilizations are already in progress. For example, Hansen and Zuckerman investigated how extraterrestrial civilizations may migrate from their home planetary systems to planetary systems of other stars during close flyby events (Hansen and Zuckerman, 2021). In this paper, I propose a hypothesis describing how extraterrestrial civilizations may use free-floating planets as a means of interstellar travel to reach, explore and colonize other planetary systems.

Just as life on Earth takes any opportunity to expand to different environments, from deep regions in Earth's crust (Li *et al.*, 2020) and all the way up to stratosphere (DasSarma *et al.*, 2020), extraterrestrial civilizations may take different opportunities for interstellar migration that present themselves at the right time. Some advanced civilizations may send their populations or technologies to other stars during flyby events, some advanced civilizations may build stellar engines and some advanced civilizations may use free-floating planets as interstellar transportation to relocate their populations to other planetary systems. Various methods of interstellar migration and interstellar colonization may contribute to propagation of advanced extraterrestrial civilizations in the Galaxy, and each method of interstellar migration can produce a set of observable technosignatures. As a branch of SETI, the SMETI comprises the search for: (1) technosignatures of extraterrestrial civilizations migrating inside their home planetary systems and to other planetary systems; (2) technosignatures of intelligent machines sent to the outer regions of their planetary systems and to other planetary systems and (3) technosignatures of extraterrestrials colonizing and terraforming objects in planetary systems. SMETI shares some features with the search for technosignatures of civilizations inhabiting the habitable zone of main-sequence stars, and it includes other unique approaches to the search for technosignatures and artefacts of migrating extraterrestrial civilizations.

Extraterrestrial civilizations using free-floating planets for interstellar migration and interstellar colonization

Some free-floating planets may host simple life forms and deliver them to planetary systems (Stevenson, 1999; Abbot and Switzer, 2011; Badescu, 2011; Schulze-Makuch and Fairen, 2021). I propose that free-floating planets may enable interstellar travel of extraterrestrial civilizations and technologies, delivering them to planetary systems. Extraterrestrial civilizations' biological species, post-biological species or their technologies become Cosmic Hitchhikers when they ride free-floating planets to reach, explore and colonize planetary systems.

Free-floating planets can provide constant surface gravity, large amounts of space and resources. Free-floating planets with surface and subsurface oceans can provide water as a consumable resource and for protection from space radiation. Technologies can be used to modify the motion of free-floating planets. If controlled nuclear fusion has the potential to become an important source of energy for humankind (Ongena and Ogawa, 2016; Prager, 2019), then it may also become a source of energy for interstellar travellers riding free-floating planets.

Extraterrestrials could use free-floating planets to transport large groups or populations escaping oncoming existential threats, to misplace unwanted populations, to send large numbers of post-biological species to explore distant worlds or to spread populations of their species to several planetary systems to preserve the continuity of their civilization. Extraterrestrial civilizations could also send Cosmic Hitchhikers in the form of smart machines, probes and other technologies to survey stars, planetary systems and interstellar medium.

Post-biological species may be machines with artificial intelligence, machines with 'uploaded' intelligence of biological species or species composed of both organic and biomechatronic body parts (Ćirković, 2018). Space radiation is one of the important issues in the design of electronic components of space systems built by humankind; and one of the most effective solutions is using shielding from space radiation to protect sensitive electronic parts (Daneshvar *et al.*, 2021). Post-biological species might be designed to withstand space radiation for years or centuries. However, without shielding, space radiation may deteriorate their condition over the course of thousands of years of space travel.

Free-floating planets can provide them with additional protection from space radiation. Post-biological species may also use resources of free-floating planets to generate energy; make repairs; manufacture technologies for space travel, colonization of planetary systems and for their own self-replication. Advanced civilizations may also send biological and post-biological species to ride free-floating planets together.

Here, four scenarios describe how Cosmic Hitchhikers may travel from their home worlds to free-floating planets.

Scenario A: using free-floating planets that pass by home worlds of extraterrestrial civilizations

Cosmic Hitchhikers may travel to free-floating planets passing close by their home planetary systems. The frequency of flybys of free-floating planets would depend on the number and distribution of free-floating planets in the Galaxy, which in turn depends on how free-floating planets originate. It is considered that numerous free-floating planets should originate and reside in star clusters. However, computer simulations of the Orion Trapezium star cluster demonstrated that about 80% of its free-floating planets would promptly escape the cluster upon being unbound from their host stars (van Elteren *et al*., 2019). Stars with 1–7 times solar mass undergoing the post-main-sequence evolution, as well as a supernova from a 7–20 times solar mass progenitor, can eject Oort-cloud objects from their systems (Veras *et al*., 2011) so that such objects become unbound from their host stars.

There are billions of stars in the Galaxy, and some stars can pass close by the Solar System. For example, the closest known flyby of a star to the Solar System was that of the W0720 system approximately 70 000 years ago (Mamajek *et al*., 2015). Studies predicted that there may be billions of free-floating planets (Veras *et al*., 2011; Ginsburg *et al*., 2012; Veras and Tout, 2012; Barclay *et al*., 2017). Therefore, some free-floating planets may pass near Oort clouds of planetary systems or through the Oort clouds, as stars sometimes do. If the number of free-floating planets in the Galaxy is greater than the number of stars, then flybys of free-floating planets should be more common than flybys of stars. Extraterrestrial civilizations may take advantage of close flybys of free-floating planets and send their species or their technologies to the free-floating planets.

When travelling at 1.6 light years from the Sun, for example, a free-floating planet would be travelling through the outer region of the Oort cloud of the Solar System. For a spacecraft sent from the inner Solar System to the free-floating planet, that would be compatible with interstellar travel. However, there may be other ways for an advanced extraterrestrial civilization to reach a flyby free-floating planet passing through the Oort cloud of the civilization's planetary system. For example, if the civilization colonizes its planetary system, including its Oort cloud, then its spacecraft may transport its populations from their locations in the Oort cloud to the free-floating planet passing through the Oort cloud. The distance travelled by the spacecraft would be less than interstellar distances.

Otherwise, if a civilization has spacecraft to transport its populations to distances of up to ~80 AU from its host star, it may send the spacecraft with its populations to an object similar to 2015 TG387 when it is close to its periastron of ~ 65 AU. (2015 TG387's aphelion distance is about 2100 AU (Sheppard *et al*., 2019).) The object will deliver the space travellers to the inner Oort cloud at about 2100 AU from the host star. Propulsion systems attached to the object and gravity assist events involving other objects of the Oort cloud will change the object's orbit and bring it closer to a free-floating planet passing through the Oort cloud. Then, the space travellers may use their spacecraft to transfer from that Oort-cloud object to the free-floating planet.

When in the end of its interstellar travel, the extraterrestrial civilization riding the free-floating planet in the interstellar space approaches an Oort cloud of another planetary system; the civilization may use its spacecraft to transfer from the free-floating planet to a selected object of that Oort cloud. That object with a high-eccentricity orbit will carry the extraterrestrials inwards, from the outer edge of the Oort cloud and towards the major planets of the planetary system. When that object approaches its periastron, the extraterrestrials may use their spacecraft to transfer from the object to the major planets.

Scenario B: using free-floating planets steered towards extraterrestrial civilizations' home worlds by means of astronomical engineering

The term 'astronomical engineering' describes methods and technologies used to change the motion of cosmic objects (Korycansky *et al.*, 2001; McInnes, 2002; de la Fuente Marcos and de la Fuente Marcos 2003). Usage of a propulsion system to change the orbit of an Oort-cloud object, as described in scenario A, is an example of astronomical engineering. Advanced extraterrestrial civilizations might also use technologies to steer passing by free-floating planets towards the civilizations' planetary systems so that the civilizations' species or technologies could travel to the flyby free-floating planets.

Scenario C: using free-floating planets ejected from planetary systems by means of astronomical engineering

Cosmic Hitchhikers may settle on cosmic objects native to the outer regions of their planetary systems and use technologies to eject the objects from their planetary systems, thus artificially turning them into free-floating planets. Such objects could be similar to Sedna. Sedna has a highly eccentric orbit that resides beyond the Kuiper Belt (Brown *et al.*, 2004). Objects similar to Sedna may have highly eccentric orbits that would take the objects from 60 to 70 AU from their host stars to the inner edge of their Oort clouds. Here, the estimate is that the inner edge of the Oort cloud of our Solar System is located at about 2000 AU from the Sun (Fouchard *et al.*, 2017). Civilizations capable of doing so would be advanced civilizations that already have their planetary systems explored to the distances of at least 60 AU from their host stars.

In planetary systems with main-sequence stars, civilizations would not attempt ejecting planets located at distances less than ~50 AU from their host stars because that would destabilize other planets' orbits. For example, if Earth were removed from the Solar System, the orbits of Venus and Mercury would be destabilized within a relatively short time (Innanen *et al.*, 1998). The orbits of Jupiter and Saturn would also change (Korycansky *et al.*, 2001). Advanced extraterrestrial civilizations in planetary systems with post-main-sequence host stars would be residing in the outer regions of their planetary systems farther away from their host stars. They would be already positioned to reach Sedna-type objects. Therefore, for civilizations in planetary systems with main-sequence stars and post-main-sequence stars, objects similar to Sedna would be the objects of their choice to travel to the Oort cloud and in the Oort cloud.

Energy required to change the speed of major planets located at <40 AU from their host star is significantly greater than energy required to change the speed of Sedna-type objects at distances >500 AU. To change the orbital speed of Earth to the speed needed to escape the Sun's gravity, work done to change Earth's kinetic energy (ΔK_E) would be $\approx 1.4 \times 10^{33}$ joules. For an object with its mass similar to the mass of Sedna, $m_O = 4.5 \times 10^{21}$ kg and its location in the inner Oort cloud at a distance of 2000 AU, changing its orbital speed to the escape speed would correspond to a change in its kinetic energy, $\Delta K_O \approx 5.0 \times 10^{26}$ joules $\approx 3.6 \times 10^{-7}\ \Delta K_E$. This amount of energy is still huge. However, we can place this in perspective. A little more than 300 years ago, horses were a main mean of transportation for humans on land, with a power output of about 1 horsepower per horse. In modern times, the overall power of a space shuttle at takeoff reached about 16 million horsepower. A civilization, which is several hundred years or millennia ahead of humankind in its technological development, may use advanced propulsion technologies and gravity-assist events to convert Oort-cloud objects to free-floating planets.

For example, an advanced civilization may send spacecraft with its populations and technologies to a Sedna-type object, which has its mass, periastron and apastron similar to those of Sedna (i.e. (1.7–6.1) $\times 10^{21}$ kg, 76 AU and 937 AU). When the Sedna-type object is approaching its periastron, they land on the Sedna-type object, build subsurface habitats and infrastructures and attach propulsion systems to it. They fire the propulsion systems when the Sedna-type object reaches its periastron to increase its apastron distance. The modified orbit of the Sedna-type object will take it to the Oort cloud. At apastron, they may fire the propulsion systems again to get the Sedna-type object to a higher

https://doi.org/10.1017/S1473550422000143 Published online by Cambridge University Press

circular orbit in the Oort cloud. In the Oort cloud, their Sedna-type object will pass by giant wide-orbit planets and other objects in the Oort cloud and gain energy via the gravity assist mechanism. The gravity-assist events will allow the Sedna-type object to gain enough energy to become unbound.

Gravity-assist events for the Oort-cloud object would require advanced mapping of the regions of the Oort cloud. Careful planning took place for gravity-assist events for Voyager 1 and several other robotic spacecraft, for example. A civilization, which is several centuries or millennia more advanced in its technological development than humankind, may accomplish something similar on the scale of a Sedna-type object or an object similar to 2015 TG387 moving in its Oort cloud.

Scenario C has commonality with scenario A in terms of the need to change the orbit of an Oort-cloud object. Scenario B may require changes in the orbital motion of an Oort-cloud object in the way similar to that in scenario A. In scenario A, the Oort-cloud object is sent to its rendezvous with a flyby free-floating planet. In scenario C, the Oort-cloud object is sent to escape the planetary system and to become a free-floating planet.

After the Sedna-type object is converted to a free-floating planet in scenario C, the propulsion systems may steer it towards a star of their choice. It may be a star located light years away. It may be a flyby star. Some migrating civilizations might be able to use propulsion systems on their free-floating planet to change its motion so that it would enter an orbit around another star, in the outer regions of its planetary system (to avoid destabilization of the orbits of pre-existing planets of that system). Later, they may travel from their free-floating planet, which they turned into a bound planet of another star's planetary system, to colonize planets of that planetary system. Otherwise, they may transfer from their free-floating planet to the Oort cloud of that star's planetary system, as described in scenario A.

Regarding wide-orbit giant planets with stable orbits near the Oort cloud and in the Oort cloud, mechanisms of formation have been proposed for their orbits: (a) a free-floating planet may bind to a star located in a stellar cluster (Perets and Kouwenhoven, 2012) and (b) passing stars can interrupt planet–planet scattering, creating stable wide-orbit giant planets in Oort clouds (this mechanism operates in planetary systems that experienced planet–planet scattering while the host star was in a stellar cluster) (Bailey and Fabrycky, 2019).

In our Solar System, Sedna is one of inner Oort-cloud objects with its perihelion greater than 50–60 AU. Examples of other similar objects are 2012 VP113 and 2015 TG387 (Sheppard *et al.*, 2019). Even without firing a propulsion system at its perihelion, 2015 TG387 could take space travellers from its perihelion at about 60 AU from the Sun to the inner edge of the Oort cloud at about 2100 AU from the Sun over the course of 18 000–20 000 Earth years. The processes, which shaped the orbits of Sedna, 2012 VP113 and 2015 TG387 in our Solar System, may also be in place in other planetary systems. Therefore, similar objects may exist in other planetary systems.

Scenario D: using cosmic objects ejected from extraterrestrial civilizations' home worlds by their host post-main-sequence stars

Objects of Oort clouds can be dynamically ejected during the post-main-sequence evolution of their host stars of 1–7 solar mass (Veras *et al.*, 2011). The critical semimajor axis in the Solar System within which an orbiting body is guaranteed to remain gravitationally bound to the dying Sun is $a_{cr} \approx 10^3$–10^4 AU (Veras and Wyatt, 2012). If Sedna maintains its orbit until the Sun leaves the main sequence, then Sedna will remain bound during the post-main-sequence evolution of the Sun; the fate of objects near or beyond the critical semimajor axis would significantly depend on their locations along their orbits when the Sun would experience mass loss during its post-main-sequence evolution (Veras and Wyatt, 2012).

Extraterrestrial civilizations may ride Oort-cloud objects of their planetary systems, which become free-floating planets after being ejected by their host stars during the red giant branch (RGB) evolution and the asymptotic giant branch (AGB) evolution. For example, if a host star is a sun-like star and the critical semimajor axis $a_{cr} \approx 1000$ AU, then extraterrestrials may use spacecraft to travel from their home planet to an object similar to 2015 TG387, when it is close to its periastron ~60–80 AU.

https://doi.org/10.1017/S1473550422000143 Published online by Cambridge University Press

They would ride that object, and they would leave the object when it would reach its apastron ~2100 AU. Then, they would use their spacecraft to transfer to another object of the Oort cloud that would be later ejected by its post-main-sequence star.

For all the above scenarios, free-floating planets may not serve as a permanent means of escape from existential threats. Because of the waning heat production in their interior, such planets eventually fail to sustain oceans of liquid water (if such oceans exist). Also, free-floating planets provide less resource than planetary systems. Therefore, instead of making free-floating planets their permanent homes, extraterrestrial civilizations would use the free-floating planets as interstellar transportation to reach and colonize other planetary systems.

An extraterrestrial civilization riding one free-floating planet may establish its colonies in more than one planetary system. Populations of the same civilization may also ride more than one planet-like object ejected from their planetary system. Therefore, they may establish colonies in a few planetary systems. Cosmic Hitchhikers in the form of automated probes may keep transferring from one free-floating planet to another, populating a growing number of free-floating planets and exploring the Galaxy.

Space colonization and the number of civilizations in the Galaxy

When an advanced civilization (i.e. a *parent-civilization*) establishes colonies on cosmic objects of their home planetary system and in other planetary systems, its colonies may become the 'seeds' growing into new autonomous civilizations (i.e. *daughter-civilizations*) that differ from their parent-civilization. The reasons for this belong to two categories: socio-economic reasons and reasons relevant to cosmic and planetary conditions and environments. The second category includes the environments and orbital parameters of colonized planets and moons, properties of their host stars, interplanetary environments and interstellar environments. Shaped by its own unique circumstances, cosmic and planetary environments, each daughter-civilization may eventually assert its distinctiveness and autonomy. In this way, the parent-civilization may create unique and autonomous daughter-civilizations inhabiting different planets, moons or regions of space.

A civilization of Cosmic Hitchhikers would act as a 'parent-civilization' spreading the seeds of 'daughter-civilizations' in the form of its colonies in planetary systems. This applies to both biological and post-biological species.

Free-floating planets: are they rare or common?

To detect free-floating planets with low surface temperatures, astronomical observations use gravitational microlensing requiring a special and rare condition of alignment between a free-floating planet and a background star. Such microlensing events are difficult to detect because they have small angular Einstein radii and extremely short timescales; frequent photometric observations (about ten observations per night per site or higher) are required (Mróz *et al*., 2020). Consequently, a limited number of detected free-floating planets with low surface temperature is related to the challenges of their detection, and not to their actual space density.

Infrared imaging surveys discovered free-floating planets with high atmospheric temperatures (Zapatero Osorio *et al*., 2000). A population of Jupiter-like free-floating planets was discovered in the Upper Scorpius young stellar association. These young planets are hot enough to be detected in optical and near-infrared wavelengths (Miret-Roig *et al*., 2022). Their discovery nearly doubled the total number of free-floating planets already known.

Free-floating planets may originally form around a host star and in multiple-star systems, and then they may be scattered away. Free-floating planets may form in isolation through direct collapse of clouds of gas and dust (Gahm *et al*., 2007). According to simulations of terrestrial planet formation around a solar-type star, about 2.5 terrestrial-mass planets per star become free-floating planets after they are ejected during the planet formation process; their population is likely composed of

Mars-sized planets (Barclay *et al*., 2017). Gravitational microlensing survey observations were used to estimate that there are two Jupiter-mass free-floating planets per each main-sequence star (Sumi *et al*., 2011), though this estimate may be re-evaluated. Another study predicts that per each main-sequence star, there may be up to 10^5 unbound objects in the mass range of 10^{-8}–10^{-2} solar mass (Strigari *et al*., 2012).

Free-floating planets can be produced in the process of ejection of fragments from a perturbed protoplanetary disc (Vorobyov and Pavlyuchenkov, 2017). They can be ejected by interactions with another star (Hurley and Shara, 2002). For post-main-sequence stars: (a) objects of Oort clouds and wide-separation planets may be dynamically ejected from 1–7 times solar mass parent stars during the RGB and AGB evolution; (b) most of the planetary material that survives a supernova from a 7–20 times solar mass progenitor will become dynamically ejected from the system and (c) planets orbiting >20 times solar mass black hole progenitors may survive or be ejected (Veras *et al*., 2011). Free-floating planets can be ejected by scattering interactions in a multi-planet system (Veras and Raymond, 2012).

Veras and Tout conservatively estimated that: (a) planetary material, which is located beyond a few hundred AU while orbiting multiple stars each more massive than the Sun and whose minimum separation is less than 100 solar radii, is likely to be ejected during its stars' post-main-sequence evolution; (b) Oort-cloud objects of post-main-sequence multiple-star systems could escape and (c) planets at a few tens of AU from the central concentration of stars may escape. These systems may significantly contribute to the free-floating planet population (Veras and Tout, 2012). If planet formation around binary stars is efficient, then circumbinary planetary systems might be producing free-floating planets (Smullen *et al*., 2016).

The speeds of free-floating planets vary. Free-floating planets with the transverse speed of 75 km s^{-1} were detected (Stefano, 2012). Very rare hypervelocity free-floating planets are predicted to have a speed of $\sim 10^4$ km s^{-1} (Ginsburg *et al*., 2012). The speed of free-floating planets forming through direct collapse of an interstellar cloud of gas and dust should be different from that of free-floating planets ejected by post-main-sequence stars.

Interstellar spacecraft versus free-floating planets as interstellar transportation

The ability to travel on a spacecraft to other stars is determined by the laws of mechanics, propulsion system, vehicle mass and means of life support and protection from space radiation and the interstellar medium. Spacecraft operations can be negatively affected by space radiation, interstellar gas and dust, temperatures variations and more. A relativistic spacecraft can be seriously damaged by its interactions with the interstellar medium (Hoang *et al*., 2017).

If a world ship, which is a hypothetical interstellar spacecraft transporting large populations, was travelling at less than 1% the speed of light, it would deliver its passengers to another planetary system over the course of several centuries. Passengers' health and their ability to transfer knowledge and skills to next generations on the ship would require a very large number of passengers. Up to 44 000 people would be needed to survive in good health 150 years of an interstellar journey (Smith, 2014). Other studies considered a population of a world ship of ~250 000 people (Bond and Martin, 1984). The greater the number of passengers, the more massive their world ship would be and the more challenging or, perhaps, impossible it would be to build it and send it other stars.

Advantages of using free-floating planets as interstellar transportation for interstellar migration are discussed below.

Advantage 1: plentiful amounts of space for habitation, technologies and resources for in-situ *resource utilization*

Free-floating planets may supply large amounts of resources and space for habitation and technologies. Some free-floating planets may have a surface or subsurface ocean sustained by radiogenic and primordial heat (Lingam and Loeb, 2020a).

https://doi.org/10.1017/S1473550422000143 Published online by Cambridge University Press

Advantage 2: availability of liquid water for space radiation shielding

Water can be used for space radiation shielding (DeWitt and Benton, 2020). Extraterrestrials riding free-floating planets with oceans of liquid water may use that water for space radiation shielding.

Advantage 3: constant surface gravity

Free-floating planets can provide constant surface gravity for interstellar travellers, which may differ from that of the travellers' home world. Extraterrestrial civilizations may apply biotechnologies to adapt to it.

Advantage 4: possibilities of applications of astronomical engineering

Advanced civilizations may use propulsion technologies to modify the motion of free-floating planets.

Interstellar migration using close flybys of stars

Hansen and Zuckerman investigated how extraterrestrial civilizations may use spacecraft to migrate to flyby stars passing unusually close by the home planetary systems of the extraterrestrial civilizations (Hansen and Zuckerman, 2021). In the solar vicinity, one would expect appropriate close passages of other suitable stars (about 100 times smaller than typical stellar separations) to occur at least once during a characteristic time of a Gyr (Hansen and Zuckerman, 2021). Close passages of stars of any type happen more often. The closest known flyby of a star to the Solar System was identified to be that of the W0720 system, which passed through the Oort cloud about 70 000 years ago (Mamajek *et al*., 2015). Scholz's star (W0720) is a binary system that includes an active M dwarf star and its companion, a possible brown dwarf. Such M dwarf stars have been observed to produce V-band flares to exceed 9 mag (Schmidt *et al*., 2014).

Perturbations by passing stars on Oort-cloud comets can be the source of long-period comets visiting the planetary region of the Solar System (Oort, 1950; Rickman, 2014) and producing extinction events on Earth (Davis *et al*., 1984; Mamajek *et al*., 2015). Close flyby events should affect the Oort clouds of both stars involved in the flyby events. Therefore, they may negatively affect the habitability of planets orbiting the flyby star when comet showers reach the planets, although it takes extensive amounts of time for the comet showers to reach the planets (Loibnegger, 2021).

Technosignatures produced by extraterrestrial civilizations using free-floating planets for interstellar colonization

Extraterrestrial civilizations riding free-floating planets and colonizing planetary systems may produce distinctive technosignatures discussed below.

Unexplained emissions of electromagnetic radiation and astrophysical phenomena of unknown origin

Astronomical observations may mistakenly identify signals originating in the Solar System as signals from distant astronomical objects. For example, The Wow! signal was detected on 15 August 1977, in the constellation Sagittarius (Sgr). Some interpretations claimed the Wow! signal was made by extraterrestrials. Others associated it with stellar activity. Paris and Davies used observational data to propose that the Wow! signal was a natural phenomenon generated by Comet 266P/Christensen (Paris and Davies, 2015).

Because free-floating planets are not readily observable, technosignatures produced on free-floating planets may be mistakenly interpreted as technosignatures originating in planetary systems, groups of

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stars, galaxies or empty regions of space. This may occur when at the time of observations a free-floating planet is located along the line of observations of a planetary system, group of stars, galaxies or empty regions of space. Later, the technosignatures may not be detected along the line of observations because the free-floating planet moves away from it. Therefore, the search for free-floating planets is recommended in the regions where unexplained emissions of electromagnetic radiation or unusual cosmic phenomena are detected as described above.

Emissions of electromagnetic radiation detected relatively close to free-floating planets

Magnetic sails may be used to manoeuver, accelerate or decelerate spacecraft (Andrews and Zubrin, 1990). Zubrin examined the possibility of detecting extraterrestrial civilizations by means of searching for the spectral signature of their interstellar transportation. He concluded that the most detectable form of radiation would be the low-frequency radio emissions of cyclotron radiation caused by interaction of the interstellar medium with a magnetic sail (Zubrin, 1994).

When, hypothetically, a free-floating planet carrying extraterrestrials approaches a planetary system, the extraterrestrials may board their spacecraft and travel to the planetary system. If the free-floating planet moves faster than the planetary system, they may use a magnetic sail to decelerate and manoeuver the spacecraft, producing a technosignature in the form of the low-frequency radio emissions of cyclotron radiation caused by interaction of the interstellar medium with the magnetic sail. Then, the technosignature may be observed in the region where the planetary system and the free-floating planet are located.

Unusual emissions of electromagnetic radiation detected relatively close to free-floating planets may be also produced by other technologies used by extraterrestrials during their interstellar travel. The characteristics of the emissions might be detailed by any future hypotheses describing such technologies.

Unusual infrared emissions and other emissions on free-floating planets

Infrared imaging surveys have been used to discover free-floating planets with high atmospheric and surface temperatures (Zapatero Osorio *et al.*, 2000; Miret-Roig *et al.*, 2022). Theoretical studies predicted observables related to water latent heat release on free-floating planets with low surface temperatures (Tang *et al.*, 2021).

Technological activities of extraterrestrial travellers on free-floating planets may produce emissions of electromagnetic radiation that can serve as technosignatures. For example, waste heat generated by their technologies on the free-floating planets may emit electromagnetic radiation in mid-infrared wavelengths. Therefore, unusual infrared emissions originating on free-floating planets with low surface temperatures may be technosignatures of technological activities of interstellar travellers on the free-floating planets. The unusual characteristics of such emissions could be in the form of relatively large amounts of the emissions (i.e. infrared excess) or unusual changes in the intensity of the emissions. Otherwise, technological sources of the emissions may be unevenly distributed over a free-floating planet, which may become noticeable if the planet spins. The emissions may also include various types of electromagnetic radiation in addition to infrared radiation. The distribution of the energy of the emissions across the spectrum of electromagnetic radiation may differ from what would be expected for low-temperature free-floating planets.

Similar technosignatures produced in more than one planetary system

SETI studies are advancing to include the search for atmospheric technosignatures on exoplanets (Kopparapu *et al.*, 2021). Atmospheric technosignatures and other technosignatures produced in the process of colonization of planets may be indicators of terraforming. The search for groups of planetary systems with similar indicators of terraforming (e.g. the same anomalous atmospheric composition,

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atmospheric and surface temperatures), biosignatures and technosignatures may test the proposal that extraterrestrials riding one or more than one free-floating planet may colonize more than one planetary system. For example, they may ride a few free-floating planets ejected from the Oort cloud of their home planetary system. When colonizing different planetary systems, they would produce similar technosignatures in the planetary systems.

Strategies for the search for technosignatures and artefacts produced by extraterrestrials using free-floating planets for interstellar colonization

Technosignatures and artefacts of extraterrestrial civilizations engaged in interstellar migration and interstellar colonization may be more likely found in certain locations in the Galaxy as follows.

Oort clouds of RGB stars and AGB stars

Objects of the outer regions of planetary systems can be dynamically ejected during the post-main-sequence evolution of their host stars of 1–7 solar mass (Veras *et al*., 2011). To increase chances of survival or to increase the extent of interstellar colonization, an extraterrestrial civilization may ride one or more than one planet-like object ejected from its Oort cloud by its host post-main-sequence star or with the help of technologies, as discussed in scenarios D and C (Section 'Extraterrestrial civilizations using free-floating planets for interstellar migration and interstellar colonization' of this paper). Therefore, technosignatures may be produced in the Oort cloud in the form of communication signals, emissions produced by propulsion systems or infrared and other emissions produced by technological activities on the Oort-cloud objects that are ejected or about to be ejected.

According to our understanding of evolution of life, the expectation is that the search should focus on post-main-sequence stars that evolve from main-sequence stars with the habitable zones remaining relatively stable for billions of years (e.g. G- and K-type stars).

Stellar neighbourhoods of RGB stars, AGB stars and white dwarfs

Extraterrestrial civilizations riding Oort-cloud objects ejected from their home planetary systems with post-main-sequence host stars may reach, explore and colonize planetary systems in their stellar neighbourhoods. Therefore, stellar neighbourhoods of post-main-sequence stars should be searched for their technosignatures. The prime candidates for the search should be stellar neighbourhoods of RGB stars, AGB stars and white dwarfs that formed from G- and K-type stars in single-star systems. This is because such main-sequence stars maintain the habitable zone remaining relatively stable for billions of years.

Region of space in proximity to white dwarf binaries and neutron star binaries

Advanced civilizations may use Dyson slingshot to accelerate free-floating planets that they ride. Dyson slingshot is white dwarf binary gravitational assist (Dyson, 1963). The same idea was extended to binaries with neutron stars and black hole binaries (Kipping, 2018). Some extraterrestrials riding free-floating planets might use technologies to steer their free-floating planets towards binary systems to have them further accelerated via Dyson slingshot. Their technosignatures may be detected near white dwarf binaries and neutron star binaries.

Stellar neighbourhoods and Oort clouds of main-sequence stars

Advanced extraterrestrial civilizations are expected to inhabit their home planetary systems with main-sequence host stars capable of keeping relatively stable habitable zones for billions of years. If such

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civilizations use technologies to eject their Oort-cloud objects or if they hitch a ride on flyby free-floating planets passing through their Oort clouds, then their Oort clouds and their stellar neighbourhoods may harbour their technosignatures.

Planetary systems with gravitationally captured free-floating planets

Free-floating planets can become gravitationally captured by planetary systems (Perets and Kouwenhoven, 2012). If extraterrestrials riding free-floating planets can modify the motion of their free-floating planets, then they can make their free-floating planets become captured by planetary systems of their choice. Therefore, wide-orbit exoplanets orbiting stars, which might be gravitationally captured free-floating planets, should be candidates for SETI studies. A word of caution is that many wide-orbit exoplanets might form or become captured during early formation of planetary systems in star clusters.

If advanced extraterrestrial civilizations may ride free-floating planets, then there may be an extremely small non-zero probability that over the last 4 billion years, some free-floating planets populated with advanced extraterrestrial civilizations, their technologies or artefacts may have passed close by the Solar System or other planetary systems in our stellar neighbourhood and some of those free-floating planets may have been captured by the gravity of the Sun or other stars in our stellar neighbourhood. If such captured free-floating planets discovered, they should be candidates for SETI studies.

A free-floating planet of Earth-like composition, age and mass approximately equal 3.5 times Earth mass could sustain a subglacial liquid ocean and it could be detected using reflected solar radiation if the planet were to pass within 1000 AU of Earth (Abbot and Switzer, 2011). Surveillance probes could be sent to gravitationally captured free-floating planets in the Solar System and in other planetary systems in our stellar neighbourhood if such free-floating planets were ever discovered.

Technosignatures produced using other methods of interstellar migration and interstellar colonization

Interstellar migration and interstellar colonization using close flybys of stars

Hansen proposed that an extraterrestrial civilization migrating from its planetary system to a planetary system of another star during its close flyby would produce a technosignature of infrared excess due to the construction of spacecraft that would transport materials and individuals to the flyby star's planetary system (Hansen, 2022). Hanson searched the GAIA database of stars within 100 pc and identified 132 pairs of stars with either a better than 1% chance of passing within 104 AU of one another; no evidence of infrared excess around unbound pairs of stars featuring Sun-like stars was found (Hansen, 2022).

I propose that a civilization migrating from its planetary system to a planetary system of a flyby star may produce technosignatures after the flyby is over and the stars are moving away from one another. That is, if the civilization migrates to the flyby star's planetary system, it may terraform its planets, creating observable atmospheric technosignatures and other terraforming technosignatures. For example, among other pairs of stars, Hanson considered a pair of stars that includes the star GJ 433 and a binary system with a K0V star and a white dwarf, Hanson estimated that the closest approach occurred for this pair a few thousand years ago (Hansen, 2022). If a civilization migrated during the closest approach of GJ 433 and the binary system a few thousand years ago, then by the time of the current observation, the civilization would have spent a few thousands of years on its new home planet, creating atmospheric technosignatures and other terraforming signatures on the planet it colonized.

Therefore, the search for technosignatures of civilizations engaged in migration during close flybys of stars must not be limited to the search for infrared-excess technosignatures in the ongoing flybys of stars. The search needs to include investigations of pairs of stars that have already experienced closest approach and have been moving away from one another for a few centuries or a few thousand years. This could be sufficient time for a civilization to migrate to a flyby star's planetary system and terraform a planet chosen for colonization, potentially producing atmospheric technosignatures. Technosignatures

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could be produced if the civilization would use technologies to change the orbit of the colonized planet to change the amount of stellar energy reaching it. Extraterrestrials may also produce communication technosignatures among their own species.

In addition to spacecraft or instead of spacecraft, advanced extraterrestrial civilizations may use free-floating planets as space transportation to migrate from their home planetary systems to the planetary systems of close flyby stars. A civilization would use technologies to eject a planet-like object from the outer region of its planetary system, turning it into a free-floating planet, and the civilization would modify the motion of the object to make it captured by the flyby star.

This 'blend' of migration to flyby stars and migration using free-floating planets could also become a contingency plan for a migrating civilization. If anything would go wrong during the civilization's spacecraft travel to the flyby star's planetary system, the civilization could be in jeopardy, running out of consumables. On the other hand, when riding a free-floating planet ejected from its Oort cloud, the civilization would have huge amounts of resources at its disposal on the planet while transitioning to the flyby star's planetary system. Then, a technosignature could be produced by technologies modifying the motion of the migrating planet.

Interstellar migration and interstellar colonization using stellar engines

Some extraterrestrial civilizations may use stellar engines (i.e. technologies engineered to accelerate stars) to modify the motion of their host stars and migrate with their planetary systems in the Galaxy (Shkadov, 1987, 1988; Shkadov *et al*., 1989; Korycansky *et al*., 2001; McInnes, 2002; Forgan, 2018). Lingam and Loeb proposed that hypervelocity stars can be candidates for stellar engines (Lingam and Loeb, 2020d).

Interstellar migration of post-biological intelligence

Post-biological species may engage in interstellar migration and interstellar colonization. Self-replicating probes described by Von Neumann (1966) could be an example of migrating extraterrestrial intelligence. Osmanov examined a scenario of von Neumann probes moving in the HII clouds and determined that by encountering the interstellar protons the von Neumann probes may be visible at least via infrared emissions (Osmanov, 2020).

Interstellar migration and interstellar colonization using interstellar spacecraft

Extraterrestrial civilizations may send interstellar spacecraft with small groups of explorers or machines, producing technosignatures that were discussed by Zubrin (1994). Lingam and Loeb investigated how massive stars, micro quasars, pulsar wind nebulae, supernovae and active galactic nuclei could power spacecraft with solar sails; they determined that such spacecraft's communication radio signals could be detectable; the spacecraft could produce cyclotron radiation by magnetic sails, Doppler shifts due to light sails and radiation produced by interactions with cosmic microwave background photons (Lingam and Loeb, 2020c).

Interstellar migration of extraterrestrial civilizations and its implications for the search for extraterrestrial artefacts (SETA)

Potentially, evidence of the existence of extraterrestrial species or technologies riding free-floating planets may exist in the form of technological artefacts in planetary systems. Various hypothetical extraterrestrial artefacts potentially existing in the Solar System have been proposed (Freitas and Valdes, 1985). They include hypothetical extraterrestrial technology existing in the Solar System and surveying humankind without our knowledge, as well as inactive extraterrestrial technology remaining on planets, our Moon or in the interplanetary space of our Solar System (Arkhipov, 1995, 1998*a*, 1998*b*;

Haqq-Misra and Kopparapu, 2012; Davies and Wagner, 2013). An earlier reference to the idea of an ancient extraterrestrial artefact left on the Moon is found in Arthur C. Clarke's science fiction story, 'The Sentinel' (Clarke, 1951). Other hypotheses describe extraterrestrial observing probes or 'Lurkers' potentially existing in our Solar System (Benford, 2019, 2021).

I propose that artefacts of Cosmic Hitchhikers may be as follows.

Robotic surveillance probes sending transmissions to their recipients on free-floating planets

Benford discussed how extraterrestrial civilizations may send robotic surveillance probes (Lurkers) to the Solar System, place them on nearby co-orbital objects to observe Earth and have the probes sending surveillance data back to their origin. One of the approaches proposed by Benford to study Lurkers is sending robotic probes and manned missions to inspect them (Benford, 2019). If extraterrestrials riding free-floating planets send their robotic surveillance probes to nearby planetary systems, then their probes may be similar to Lurkers.

Suppose that Lurkers were discovered in the Solar System. Automated missions or manned missions could examine them and retrieve records with timestamps of their transmissions. Analysis of the timestamps, locations of the Lurkers for those timestamps and directions of the transmissions could determine the apparent path of the receiver of transmissions and predict its current apparent location. The search for a free-floating planet could be conducted to test if the transmissions were sent to recipients on the free-floating planet. This very low-probability scenario would need a set of hypothetical conditions to be realized. However, it may be one of many tools that may potentially support SETI. Alternatively, surveillance technology of Cosmic Hitchhikers might be located on the Moon. Potential existence of extraterrestrial artefacts on the Moon was earlier discussed by Arkhipov (1995, 1998*a*, 1998*b*) and Davies and Wagner (2013).

Artefacts on free-floating planets gravitationally captured by planetary systems

If a free-floating planet carrying extraterrestrial species or their technologies were gravitationally captured by a planetary system with the help of extraterrestrial technologies, then the captured free-floating planet would keep interstellar travellers or their artefacts. Therefore, extraterrestrial artefacts might exist on some captured free-floating planet residing as wide-orbit planets in the outer regions of planetary systems. If wide-orbit planets as potentially captured free-floating planets ever discovered in the Oort cloud of the Solar System or in the Oort clouds of nearby planetary systems, then probes should be sent to investigate them and to search for extraterrestrial artefacts.

Artefacts of technologies used for surveillance or colonization of oceans

Some free-floating planets may have a liquid ocean (Abbot and Switzer, 2011; Lingam and Loeb, 2020a). Extraterrestrial civilizations riding free-floating planets would have to develop technologies to inhabit the oceans on their free-floating planets. Later, they could use these technologies to colonize oceans in the planetary systems, to which they would transition from their free-floating planets.

Lingam and Loeb estimated that in the habitable zone of stars, planets with a subsurface ocean could be 100–1000 times more common than rocky planets (Lingam and Loeb, 2019, 2020b). Having technologies for colonization of oceans would provide more colonization opportunities in planetary systems for migrating extraterrestrial civilizations. Extraterrestrials may also send surveillance probes from their free-floating planets to planetary systems for scientific purposes, to study the emergence of life in planetary oceans in order to test their theories of abiogenesis. Therefore, artefacts in oceans of a planetary system may exist even if colonization of the planetary system never occurred.

Extant and extinct oceans in our Solar System and in other nearby planetary systems (if such exist) should be candidates for the search for artefacts of extraterrestrial technologies designed for surveillance or colonization of oceans. Although the search for artefacts in the oceans of Earth, Jupiter's moon Europa or any captured free-floating planets would be beyond our current technological abilities, the task may be more realizable for extinct oceans. Potentially about 4 billion years ago, Mars had an ocean of liquid water on its surface (Dickenson and Davis, 2020). If Cosmic Hitchhikers sent probes to survey and explore the Martian Ocean at that time, then artefacts of that exploration could remain on Mars after its ocean became extinct. If relative geological inactivity on the surface of Mars can preserve important morphological features for billions of years (Dickenson and Davis, 2020), it can also preserve extraterrestrial artefacts in the ancient Martian Ocean if such artefacts ever existed.

Conclusion and recommendations

Advanced extraterrestrial civilizations may produce observable technosignatures when they migrate inside planetary systems and in the Galaxy. They may use free-floating planets as interstellar transportation for interstellar migration. Extraterrestrial civilizations may also send their intelligent technologies to ride free-floating planets and to survey interstellar space, stars and planetary systems. Extraterrestrial civilizations using free-floating planets for interstellar migration may produce technosignatures and artefacts as follows. Unexplained emissions of electromagnetic radiation observed only once or a few times along the lines of observation of planetary systems, groups of stars, galaxies and seemingly empty regions of space may be technosignatures produced on free-floating planets located along the lines of observation; the search for free-floating planets is recommended in regions where unexplained emissions or astronomical phenomena occur. Technological activities on free-floating planets can produce technosignatures as infrared and other electromagnetic radiation. A technosignature in the form of low-frequency radio emissions of cyclotron radiation can be produced by interaction of the interstellar medium with a magnetic sail of a spacecraft carrying extraterrestrials from their free-floating planet to a planetary system they wish to colonize. A civilization using free-floating planets may colonize more than one planetary system, producing similar indicators of terraforming in the colonized planetary systems. As potentially gravitationally captured free-floating planets, some wide-orbit exoplanets should be searched for extraterrestrial technosignatures or artefacts.

If Lurkers discovered in the Solar System, their records may pinpoint the location of the recipient of their transmissions; the search for a free-floating planet at that location should be conducted. Artefacts of migrating civilizations might exist on gravitationally captured free-floating planets, as well as in extant and extinct oceans in planetary systems.

Technosignatures of civilizations using free-floating planets to reach and colonize planetary systems may be produced in: (1) the outer regions of planetary systems of post-main-sequence stars evolved from main-sequence stars of preferably G- or K-type; (2) in stellar neighbourhoods of post-main-sequence stars and white dwarfs evolved from main-sequence stars of preferably G- or K-type; (3) regions of space in proximity to white dwarf binaries and neutron star binaries; (4) stellar neighbourhoods and Oort clouds of main-sequence stars of preferably G- and K-type and (5) planetary systems with gravitationally captured free-floating planets.

Atmospheric technosignatures and other technosignatures of terraforming can be produced by extraterrestrials colonizing planets of flyby stars. Emergence of such technosignatures could occur decades, hundreds or thousands of years after the flyby event would be complete. Therefore, searches for technosignatures should include stars that have already experienced close flyby and currently diverging from one another.

Various methods of migration in space and interstellar colonization may contribute to propagation of extraterrestrial civilizations throughout the Galaxy and produce technosignatures and artefacts. The search for their technosignatures constitutes a branch of SETI that can be described as the search for migrating extraterrestrial intelligence (SMETI). In the Appendix of this paper, possible technosignatures of migrating extraterrestrial intelligence are presented in groups according to their locale and methods of migration and interstellar colonization. The Appendix does not include all the possible technosignatures that migration in space and interstellar colonization may produce, as the list of technosignatures is extensive and keeps growing. However, it demonstrates a method of organizing information on technosignatures for further studies.

For example, Table 2 refers to civilizations using stellar engines to modify motions of their hypervelocity stars. Table 2 also refers to civilizations migrating during close stellar flyby. A connection can be made that a civilization using a stellar engine may steer its hypervelocity star to a close flyby with another star; some of the civilization's populations may migrate to that star's planetary system. For civilizations migrating during 'natural' close flybys of stars and civilizations migrating from their hypervelocity stars to other stars' planetary systems during 'artificially-arranged' flybys, their migration during close flybys of stars may be followed by terraforming of the colonized planetary systems with the emergence of atmospheric and other terraforming technosignatures. Therefore, planetary systems that a hypervelocity star, as a potential stellar engine, passes in the Galaxy should be studied for terraforming and communication technosignatures.

For interstellar migration of civilizations using a close flyby of a star and interstellar migration of civilizations using free-floating planets, a connection can be made using Tables 2 and 3 that instead of or in addition to using spacecraft, extraterrestrials may ride objects ejected from their Oort cloud to migrate to the planetary system of the flyby star. Therefore, the method of migration during flybys of stars can blend with the method of migration using free-floating planets.

Table 3 refers to migration using free-floating planets and migration using hypervelocity stars-stellar engines. A connection can be made that a civilization inhabiting a planetary system with a hypervelocity stars-stellar engine may eject planet-like objects from its Oort cloud and steer them to nearby planetary systems. There may be an exchange of communication signals between such objects and the civilization inhabiting the planetary system with the stellar engine. Therefore, SETI should include the search for free-floating planets close to the path of hypervelocity stars. SETI should also include the search for technosignatures produced on such free-floating planets by technologies modifying the motion of the free-floating planets and sending communication signals.

Acknowledgement. I thank the anonymous reviewers for their careful reading of my manuscript and their comments and suggestions.

Financial support. No funding has been provided for this research.

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Appendix

Here, I present possible technosignatures of migrating extraterrestrial intelligence arranged in groups based their locale and methods of migration and interstellar colonization. Because there are no specific studies on possible technosignatures of interstellar spacecraft carrying large populations of extraterrestrial civilizations over many light years, I do not include such technosignatures. Information presented here does not include all the possible technosignatures that migration in space and interstellar colonization may produce, as the list of technosignatures is extensive and keeps growing. This presentation of information on technosignatures is one of the ways for organizing information on technosignatures (Tables 1–5).

https://doi.org/10.1017/S1473550422000143 Published online by Cambridge University Press

Table 1. *Technosignatures in home planetary systems of extraterrestrial civilizations*

Migration inside a planetary system	Interstellar migration using a close flyby of a star	Interstellar migration using free-floating planets as interstellar transportation	Interstellar migration using stellar engines
Technosignatures may exist as: • atmospheric technosignatures and other technosignatures due to terraforming of planets and moons in the outer regions of planetary system, • astronomical engineering technosignatures produced when potentially changing orbits of planets in the planetary systems. *Technosignatures may be observed in:* • the habitable zone of planetary systems existing at greater orbital distances because of the post-main-sequence evolution of host stars, • Oort clouds of planetary systems.	*Technosignature may exist (before and during close flybys) as:* • atmospheric technosignatures and other technosignatures due to terraforming of planets and moons in the outer regions of planetary system, • astronomical engineering technosignatures produced when potentially changing orbits of planets in the planetary systems, • infrared-excess technosignatures due to large-scale construction of spacecraft (Hansen, 2022). *Technosignatures may be observed in:* • the habitable zone of planetary systems existing at greater orbital distances because of the post-main-sequence evolution of its host star, • Oort clouds of planetary systems with post-main-sequence host stars, • in the regions of civilizations' home planetary systems where the construction of spacecraft takes place (Hansen, 2022).	*Technosignatures may exist as:* • atmospheric technosignatures and other technosignatures due to terraforming of planets and moons in the outer regions of planetary system, • astronomical engineering technosignatures. *Technosignatures may be observed in:* • the habitable zone of planetary systems existing at greater orbital distances because of the post-main-sequence evolution of its host star, • Oort clouds of planetary systems (e.g. technosignatures may be produced near and on planet-like objects that are to be ejected from the planetary systems).	*Technosignatures may exist as:* • technosignatures due to construction and operation of a stellar engine.

https://doi.org/10.1017/S1473550422000143 Published online by Cambridge University Press

Table 2. *Technosignatures in planetary systems, which are destinations of migrating extraterrestrial civilizations*

Migration inside a planetary system	Interstellar migration using a close flyby of a star	Interstellar migration using free-floating planets as interstellar transportation	Interstellar migration using stellar engines
N/A	*Technosignatures may exist as:* • atmospheric technosignatures and other technosignatures due to terraforming of planets and moons in the planetary system of a flyby star (e.g. search for this type of technosignatures should target the star GJ 433 and a binary containing a K0V star and a white dwarf that had their closest approach a few thousand years ago), • astronomical engineering technosignatures, spacecraft technosignatures and communication technosignatures. *Technosignatures may be observed:* • in the form of spacecraft technosignatures between two stars during a flyby event, • in a planetary system to which a civilization migrates, with terraforming technosignatures becoming observable decades, hundreds of years or thousands of years after the flyby event, • in more than one planetary system to which a civilization migrates, if the civilization keeps migrating during consecutive flybys of stars (in this case, terraforming signatures will be of different level of terraforming maturity due to the great intervals of time between consecutive flybys of stars).	*Technosignatures may exist as:* • atmospheric technosignatures and other technosignatures due to terraforming in one or more than one planetary system that an extraterrestrial civilization reaches when riding one or more than one free-floating planet (if a few planetary systems are colonized, then the planetary systems should have similar signatures of terraforming), • technosignatures of technologies used to modify the motion of cosmic objects in planetary systems, • technosignatures produced on gravitationally captured free-floating planets (e.g. atmospheric technosignatures, unusual infrared technosignatures, communication technosignatures).	*Technosignatures may exist as:* • atmospheric technosignatures and other technosignatures due to terraforming in one or more than one planetary system that an extraterrestrial civilization transitions to during a close flyby of its hypervelocity star- stellar engine, • communication technosignatures, • technosignatures of technologies used to modify the motion of cosmic objects in the colonized planetary systems.

Table 3. *Technosignatures produced on free-floating planets (or in space near free-floating planets) travelling in interstellar space or passing close by planetary systems*

Migration inside a planetary system	Interstellar migration using a close flyby of a star	Interstellar migration using free-floating planets as interstellar transportation	Interstellar migration using stellar engines
N/A	*Technosignatures may exist as:* • unusual infrared and other electromagnetic technosignatures due to technological activities of a civilization on a planet-like object ejected from its home Oort cloud, when the civilization uses such object instead of or in addition to spacecraft to migrate to the planetary system of a close flyby star, • technosignatures of technologies used to modify the motion of the Oort-cloud object turned into a temporary free-floating planet to carry the migrating civilization. *Technosignatures may be observed in:* • the Oort cloud of the civilization's home planetary system before and during a flyby event, or between two stars during their flyby event, • the planetary system to which the civilization migrates.	*Technosignatures may exist as:* • unusual infrared and other electromagnetic radiation emission technosignatures due to technological activities of civilizations on free-floating planets, • technosignatures of technologies used to modify motion of free-floating planets, • technosignatures of spacecraft (e.g. a magnetic sail of spacecraft producing low-frequency radio emissions of cyclotron radiation) used by extraterrestrials to travel from planetary systems to flyby free-floating planets and from free-floating planets to planetary systems that the free-floating planets pass close by. *Technosignatures may be observed on:* • free-floating planets travelling in interstellar space or passing close by planetary systems, with some technosignatures detected as unexplained emissions of electromagnetic radiation or astronomical events of unknown origin (because free-floating planets are not readily observed).	*Technosignatures may exist as:* • unusual infrared and other electromagnetic radiation emission technosignatures due to technological activities on free-floating planets, • technosignatures of technologies used to modify motion of free-floating planets, • communication signals. *Technosignatures may be observed on:* • Free-floating planets in the vicinity of hypervelocity stars, candidates for stars-stellar engines. That is, civilizations inhabiting planetary systems with stars-stellar engines could eject planets from their Oort cloud and direct them to passing by planetary systems for the purpose of studies, surveillance or migration. The ejected objects turned into free-floating planets could carry intelligent surveillance technologies.

Table 4. *Technosignatures produced in the regions of space near white dwarf binaries and neutron star binaries*

Migration inside a planetary system	Interstellar migration using a close flyby of a star	Interstellar migration using free-floating planets as interstellar transportation	Interstellar migration using stellar engines
N/A	N/A	*Technosignatures may exist as:* • technosignatures produced by extraterrestrials when they are riding free-floating planets and using technologies to modify the motion of their free-floating planets to have them further accelerated via Dyson slingshot, white dwarf binary or neutron star binary gravitational assist. *Technosignatures may be observed:* • near white dwarf binaries and neutron star binaries.	N/A

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Table 5. *Technosignatures produced in interstellar space*

Migration inside a planetary system	Interstellar migration using a close flyby of a star	Interstellar migration using free-floating planets as interstellar transportation	Interstellar migration using stellar engines
N/A	*Technosignatures may be produced* by extraterrestrial civilizations during close flybys of stars and specifically in the region of the close flybys of the stars.	*Technosignatures may be produced* by extraterrestrial civilizations riding free-floating planets and civilizations colonizing planetary systems in the stellar neighbourhoods of post-main-sequence stars and white dwarfs that formed from the host stars of the civilizations' home planetary systems. Some civilizations might leave planetary systems with main-sequence host stars and travel on free-floating planets. Some technosignatures may be in the form of unusual electromagnetic emissions in the vicinity of free-floating planets.	*Technosignatures may be produced in the form of:* • unusual electromagnetic emissions, • existence of hypervelocity stars moving at speeds of up to ~0.1 c, which might be attainable by stellar engines, as it is expected that natural astrophysical phenomena in the Galaxy are very unlikely to produce such speeds (Lingam and Loeb, 2020d).

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