Research Article

The Solar System: Favored for Space Travel

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Abstract

Here, we compare Earth to the most common type of exoplanet, the *super-Earth*, with respect to interplanetary space travel. The typical super-Earth should have higher gravity and atmospheric pressure at its surface. These factors pose significant challenges to rocket launches and to reentering spacecraft. In addition, the Solar System is compared to exoplanetary systems with respect to interstellar travel. It is easier to launch an interstellar spacecraft from a planet in the circumstellar habitable zone of the Sun than from planets in the circumstellar habitable zones of less massive stars. In the larger context of the Milky Way galaxy, our Solar System is in the best location to initiate interstellar missions. In summary, we here confirm and expand upon recent studies that argue that the Earth and the Solar System are rare in the degree to which they facilitate space exploration.

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INTRODUCTION

The discovery of over 4,000 exoplanets has changed the direction of scientific research and motivated scientific questions previously entertained only in science fiction. For instance, there is now serious consideration of sending an interstellar probe to the closest star, Proxima Centauri, in order to study its planet [1]. Questions relating to the habitability of exoplanets are no longer merely speculative, and the question of life beyond Earth is undoubtedly the strongest motivation for those involved in exoplanet research.

Exoplanets and their host stars span a wide range of properties [2]. This fact has prompted astrobiologists to expand their horizons beyond Solar System analogs. While the planets in the Solar System are highly diverse, they span a much smaller range of properties compared to exoplanets. In particular, there is a class of exoplanets called super-Earths that is not represented in the Solar System. While there is no single agreed upon definition of super-Earths, generally a planet is classed as a super-Earth if it ranges in mass from just over one Earth mass to about 10 Earth masses [3]. However, mass is not the only parameter relevant to their classification. Some super-Earths might resemble the terrestrial planets Earth or Venus while others resemble Neptune or Uranus more closely, depending on their volatile content. Much better classification is possible if both the mass and the radius are known. Most uses of the term "super-Earth" imply planets resembling Earth more closely than Neptune [4].

There is still much to learn, but we now have enough examples to begin addressing space travel from exoplanetary systems. Two research papers were published in 2018 [5,6] addressing the question. Hippke considered space travel from the surface of a super-Earth asking, "Can 'Super-Earthlings' still use chemical rockets to leave their planet? This question is relevant for SETI and space colonization." Lingam and Loeb focused on escape from a planetary system once escape from a planet is achieved. These three authors are the first to explore the possibility of space travel from the perspective of hypothetical extraterrestrials from known exoplanetary systems. While quantitative, their studies were brief and left out relevant details. My purpose here is to fill in some of those missing details.

THEORETICAL BACKGROUND

Escape from the planet

The Tsiolkovsky equation [7, 8] gives the maximum change in velocity (delta-V) applicable to a simple single stage rocket or a single stage in a multistage rocket:

$$\Delta v = v_e \ln \frac{m_0}{m_f} = I_{sp} g_E \ln \frac{m_0}{m_f} \quad (1)$$

where m_0 is the initial total mass, m_f is the final mass without the propellant, v_e is the exhaust velocity, I_{sp} is the specific impulse, and g_E is the acceleration due to gravity at the Earth's surface. The argument of the natural log is called the *mass fraction*. The mass fraction is an exponentially increasing function of delta-V relative to the exhaust velocity. In other words, to achieve greater delta-V an increasingly larger fraction of the rocket mass must be propellant.

Rearranging equation 1, we can solve for the propellant mass fraction as a function of delta-V:

$$m_{prop,f} = \frac{m_{prop}}{m_0} = 1 - \frac{m_f}{m_0} = 1 - e^{-\Delta v / v_e} \quad (2)$$

From these equations we note that the propellant mass fraction approaches unity as delta-V increases.

The delta-V value needed to escape from a planet's surface (or near surface) is called the escape velocity and is given by:

$$v_{esc} = \sqrt{\frac{2GM_p}{R_p}} = 11.2\sqrt{\frac{M/M_E}{R/R_E}}\,\text{km s}^{-1} \quad (3)$$

where M_p and R_p are the mass and radius of the planet in mks units, and M and R are the corresponding variables in Earth units. In order to calculate v_{esc} for a super-Earth, then, we just need to know its mass and radius. These quantities have been determined for a number of exoplanets. It has been found that exoplanets reach a peak density near 1.5 Earth radii [9].

Above this size, the typical density of an exoplanet rapidly declines, which is interpreted as increasing volatile fraction [9, 10, 11]. The fact that we can detect the increased size of a planet from the effects of its thicker atmosphere/deeper oceans above 1.5 Earth radii implies that even exoplanets below this limit will have a large volatile inventory compared to Earth, which has a mass fraction of water of only 0.1% [12]. In addition, for super-Earths less than 1.5 Earth radii (R_E), we cannot just assume constant density; self-compression becomes increasingly important with increasing planet mass. Scaling the Earth up to a super-earth, then, requires modeling terrestrial planet interiors [4]. In principle, super-Earths can also differ in the interior compositions. They can range, for example, from pure iron, to Earth-like, to pure rock, to pure water [9].

For the purposes of the present work, we adopt the super-Earth interior models for Earth-like composition [13]. This choice is not arbitrary. We know that an Earth-like interior composition and structure makes for a habitable terrestrial world (at least for Earth size); for example, a significant metal core would be required for magnetic field generation, which enhances habitability [14]. Also, the extreme end members in the modeling of Hakim et al. ("bare-core" and "Mercury-like") do not provide a good match to observations of exoplanets [13; Figure 7, panels c and d]. Their equation relating planet radius to mass is [13]:

$$R/R_E = 1.02\left(M/M_E\right)^{0.252} \quad (4)$$

The equation is applicable to super-earths just above one Earth mass to 10 times Earth's mass.[1] Note, a constant density relation would give an exponent of 1/3; the full range of the exponents in Table 2 of Hakim *et al.* for all the planet types is 0.218 to 0.270, and the coefficient ranges from 0.82 to 1.08. Exoplanet observations are consistent with both the "Earth-like" and "Moon-like" compositions [13]. The effects of uncertainties in the equation of state for iron are less important but not negligible [13].

[1] Note that the "1.02" factor in their equation means that the answer will not be strictly correct for the Earth. Their equation was derived for super-Earths more massive than Earth.

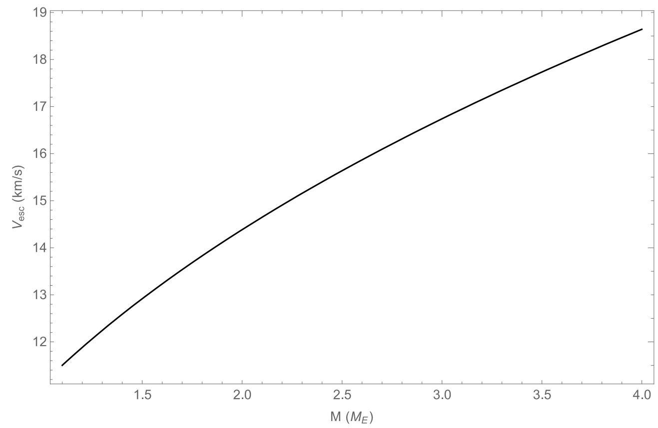

Figure 1: Escape velocity for super-Earths as a function of mass. **doi:**10.5048/BIO-C.2020.1.f1

We can substitute this relation for R into equation 3 to determine v_{esc} solely in terms of M:

$$v_{esc} = 11.1\left(M/M_E\right)^{0.374}\,\text{km s}^{-1} \quad (5)$$

From equations 4 and 5, then, an Earth-like planet twice the mass of the Earth would be 21% larger in radius and have an escape velocity of 14.4 km s^{-1}. Equation 5 is depicted in Figure 1.

We can also express the surface gravity, g, in terms of M for super-Earths:

$$g = \frac{GM_p}{R_p^2} = 9.8\frac{M/M_E}{\left(R/R_E\right)^2}\,\text{m s}^{-2} = 9.4\left(M/M_E\right)^{0.496}\,\text{m s}^{-2} \quad (6)$$

If we set delta-V equal to v_{esc} from equation 5 (keeping proper track of units), we obtain for the simple case of a single-stage rocket:

$$\ln\left(\frac{m_0}{m_f}\right) = \frac{11.1}{v_e}\left(\frac{M}{M_E}\right)^{0.374} \quad (7)$$

Taking a typical value of v_e to be 3.0 km s^{-1}, we plot the mass ratio as a function of planet mass in Figure 2.

While this is an interesting result, it is not very realistic. The mass ratio for single-stage rockets is much larger than it is for multistage rockets. This means that multistage rockets require less propellant per kilogram of payload. For this reason, all rockets used to launch objects into low earth orbit (LEO) or interplanetary trajectories have been multistage rockets. In the following we will focus on multistage rockets and on the Saturn V rocket in particular. It is a helpful example of a successful (if costly) heavy-lift rocket. Saturn V has a total mass of 2.97 × 10^6 kg and can place 118,000 kg of payload into LEO or send 41,000 kg to the Moon; the mass that can be sent beyond the

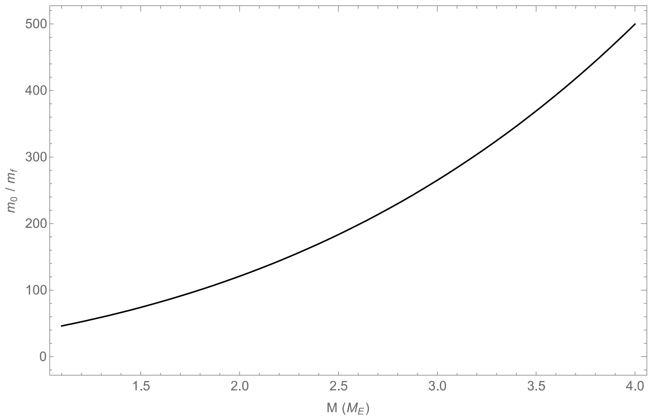

Figure 2: Mass ratio (equation 7) for a simple single-stage rocket as a function of super-Earth mass. **doi:**10.5048/BIO-C.2020.1.f2

Moon would be slightly less than 41,000 kg. The mass ratio for the payload that reaches escape velocity for the Saturn V is about 72.

For a multistage rocket, the total delta-V is equal to the sum of delta-V values for each stage from equation 1:

$$\Delta v_{tot} = \sum_{j=1}^{n} \Delta v_j = \sum_{j=1}^{n} v_{ej} \ln\left(\frac{m_{0j}}{m_{fj}}\right) \tag{8}$$

where m_{0j} is the total rocket mass when stage j begins burning, and m_{fj} is the rocket mass when stage j is exhausted but still attached [15]. The Saturn V rocket has three stages. The first stage uses RP-1 fuel (highly refined kerosene) and liquid oxygen as the oxidant, and the second and third stages are powered by liquid hydrogen and oxygen. From the full and empty masses of the three stages and the exhaust velocities of the engines (2.58 km s^{-1} for the first, and 4.13 km s^{-1} for each of the upper two stages)[2], we calculated each delta-V. They are 3.32, 4.46, and 3.32 km s^{-1} for the first, second, and third stages, respectively. These delta-V's sum to 11.1 km s^{-1}. It is important to remember that this estimate is the maximum ideal delta-V, which neglects air drag (see below).

Even this maximum delta-V value is still slightly less than the escape velocity from Earth's surface, 11.2 km s^{-1}. The delta-V deficit is more than made up if we remember to include the eastward tangential speed of the Earth's surface at the launch site. For launches from the Kennedy Space Center this is a significant 0.4 km s^{-1}. It is essentially free delta-V. If it were not available, the payload on the Saturn V would have to be decreased by about 25%.

If we set equation 8 equal to v_{esc} from equation 5 and apply it to super-earths for the case of the Saturn V, we can calculate the maximum payload mass as a function of planet mass. Doing so, we find that the maximum payload mass is reduced by about 40% for a super-earth only about 20% more massive than Earth. Beyond 1.65 Earth masses the Saturn V could not launch anything beyond the planet's atmosphere.

[2] The exhaust velocities were calculated from the minimum (sea level) specific impulse values for the F-1 engines in the first stage [16] and the J-2 engines in the second and third stages [17].

So far, we have presented the theoretical relations for rockets without considering the effects of an atmosphere. These effects are important for our purposes. First, the exhaust velocity of a rocket engine depends on the ambient pressure. The ideal exhaust velocity is given by the following equation [15]:

$$v_e = \sqrt{\frac{2k}{k-1}\frac{RT_c}{\mathcal{M}}\left[1-\left(\frac{P_e}{P_c}\right)^{(k-1)/k}\right]} \tag{9}$$

where k is the specific heat ratio, R is the universal gas constant, $\mathcal{M}$ is the mean molecular weight of the exhaust gases, T_c is the engine chamber temperature, P_c is the engine chamber pressure, and P_e is the pressure at the nozzle exit (which can be equated with the ambient pressure, see below). For the RP-1/oxygen mixture in the F-1 engines on the Saturn V's first stage, the values of these quantities are k = 1.24, $\mathcal{M}$ = 22.1 kg mol^{-1} (for an oxidizer to fuel mixture ratio of 2.27), $P_c = 6.65 \times 10^6$ Pa, T_c = 3572 °K [15]. From these values, we calculate an ideal exhaust velocity of 2.78 km s^{-1}. In actuality, the exhaust velocity of the Saturn V F-1 engines was 2.58 km s^{-1} at sea level. In the following we correct the ideal v_e by multiplying by an "efficiency factor" (0.93).

From equation 9, we can see that v_e increases with decreasing ambient pressure. This means that v_e increases as the rocket ascends through the atmosphere. At half the surface pressure, v_e increases from 2.58 to 2.71 km s^{-1}. Conversely, if we double the surface pressure, v_e at liftoff would be 2.43 km s^{-1}. At three times the surface pressure, v_e would be 2.32 km s^{-1}.

The design of an engine nozzle for a given rocket stage is optimized for the altitude it will be operating within the atmosphere. The thrust force of a rocket engine is given by [15]:

$$F = \dot{m} v_e + A_e (P_e - P_a) \tag{10}$$

where $\dot{m}$ is the mass flow rate, A_e is the cross sectional area of the nozzle exit, and P_a is the pressure of the surrounding atmosphere. For a given engine nozzle design, the thrust is maximum when $P_a = 0$ in the vacuum of space and minimum when the rocket is at the surface. Thus, as the rocket ascends, its thrust increases [15].

From equation 9, however, we can see that v_e and P_e are inversely related. In addition, they both depend on the geometry of the engine nozzle, including A_e. At a given value of P_a the thrust is maximized when $P_e = P_a$ [15]. On a super-Earth with greater surface pressure, then, the thrust will be smaller, even when optimizing the engine nozzle for the higher pressure.

What can we say about the atmospheres of super-earths? As we noted above, beyond 1.5 R_E (or 4.6 M_E from equation 4) super-Earths have thick atmospheres and probably deep oceans. In addition, the surface relief of a super-Earth decreases with increasing mass, which follows from the increased surface gravity [18]; in other words, the solid surface is smoother, and mountains aren't as tall. For these reasons larger super-Earths are less likely to have dry land. Given these planets are likely to have thick hydrogen-dominated atmospheres, it is unlikely that super-earths more than ~50% larger than Earth would be habitable and that rockets could be launched from them even if they were.

It is still difficult to say whether Earth is an anomaly with respect to its volatile inventory. Venus is the only other terrestrial planet in the Solar System comparable in mass to Earth. Its surface pressure is 90 times that of Earth's. Earth could have been like Venus if our planet hadn't locked away most of its carbon in its crustal rocks over the course of its history. For lack of a better model, we will assume in the following that the mass of the atmosphere of a super-earth scales with the mass of the planet.

With this working assumption, the surface pressure of a super-earth, P_p, can be calculated with the following equation:

$$\frac{P_p}{P_E} = \left(\frac{M}{M_E}\frac{g}{g_E}\right)\left(\frac{R}{R_E}\right)^{-2}$$

Using equations 4 and 6, we can express this equation in terms of M:

$$\frac{P_p}{P_E} = 0.92\left(\frac{M}{M_E}\right)\left(\frac{M}{M_E}\right)^{0.496}\left(\frac{M}{M_E}\right)^{-0.504} = 0.92\left(\frac{M}{M_E}\right)^{0.992} \quad (11)$$

The pressure as a function of height above the surface, z, is given by:

$$P = P_0 \exp\left(-\frac{z}{H}\right) \quad (12)$$

where P_0 is the surface pressure and H is the scale height, given by $kT/\mu g$, where μ is the mean molecular mass (4.81×10^{-26} kg). This equation applies to an isothermal atmosphere, but it is a good approximation if it is applied to a section of the atmosphere. The value of T corresponding closest to the observed decline in pressure with height in Earth's atmosphere is 260 K; H is 7.6 km in the lower atmosphere. We assume for simplicity the same composition and temperature structure for super-earth atmospheres as for the Earth.[3]

Given these assumptions, H (scale height) will vary from planet to planet solely from the g dependence. Since H is inversely proportional to g, H is smaller in super-earth atmospheres compared to Earth's atmosphere:

$$H = 7.9\left(\frac{M}{M_E}\right)^{-0.496} \text{ km} \quad (13)$$

While a super-earth has a higher surface pressure, the pressure declines with height more rapidly than it does in Earth's atmosphere. Combining equations 11, 12, and 13, we can calculate the height profile of pressure for super-Earths compared to Earth. We show the resulting plots in Figure 3 for three values of planet mass.

The air drag force, F_D, is proportional to the air density, ρ, and the rocket velocity squared [15]:

$$F_D \propto \rho v^2 \quad (14)$$

The dependence of air density on z is the same as the dependence of P on z. Although a rocket on a super-earth might begin moving more slowly immediately after launch, soon after it must achieve greater velocity to escape a super-earth. The air drag will be greater during much of its early trajectory. There is a complex interplay among the sensitive dependence of air drag on velocity, the smaller scale height for more massive planets, and the greater escape velocity for more massive planets. We illustrate this roughly in Figure 4.

In these figures we assumed super-Earth atmospheres have the same composition as Earth's atmosphere. However, above some mass limit the typical super-Earth atmosphere will be hydrogen-dominated. The mean molecular mass is smaller for a hydrogen-dominated atmosphere, resulting in a larger scale height. In such an atmosphere a rocket will experience large drag forces even at high altitude.

The Apollo missions to the Moon were manned. The Saturn V was designed to bring the astronauts safely back to Earth. That means they had to survive reentry. The reentry speed is approximately equal to the escape velocity, and the thermal energy generated is proportional to the square of the reentry speed. Reentry in super-Earth atmospheres therefore will occur at higher speeds, which would require stronger shielding (and thus greater vehicle weight). Heat generated during reentry in a

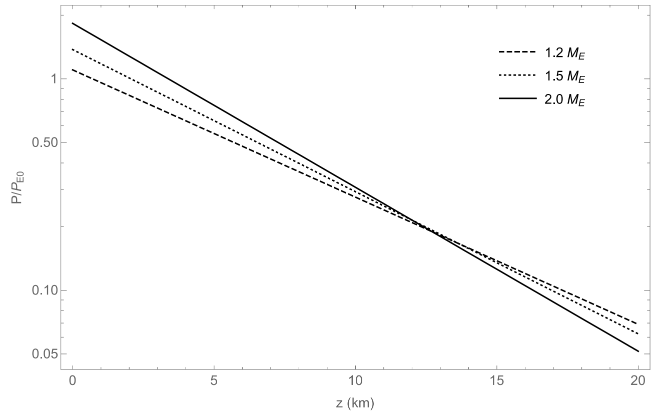

Figure 3: Pressure as a function height above a planet's surface for three super-Earth mass values. Pressures are normalized to Earth surface pressure. Notice the steeper decline with height for the more massive planets. **doi:**10.5048/BIO-C.2020.1.f3

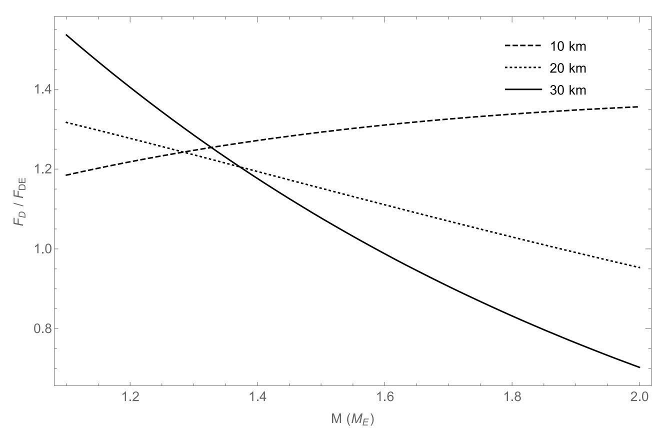

Figure 4: Drag force as a function of planet mass at three altitudes. Super-Earth values are normalized to Earth values. The curves were calculated from equation 14 with the velocity set equal to the escape velocity. **doi:**10.5048/BIO-C.2020.1.f4

[3] If super-earth atmospheres do retain more hydrogen, then the mean molecular mass would be smaller, which would result in a larger scale height.

hydrogen-dominated atmosphere will be significant at a higher altitude.

Escape from the planetary system

Once a rocket achieves escape velocity from a planet, it could continue on and visit a moon, another planet within the planetary system, or it could escape the system altogether. How difficult is it to escape a planetary system? Manasvi Lingam and Abraham Loeb [6] explored the possibility of escape from planetary systems with host stars of different mass. We follow their derivation here.

We assume that a rocket payload just barely achieves escape from a planet in the circumstellar habitable zone of its host star and is orbiting the star in the same direction as the planet. The circular speed of the planet around the star is:

$$v_c^* = \sqrt{\frac{GM_*}{a_*}} \tag{15}$$

where M_* is the mass of the star, and a_* is the distance of the planet from the star. The escape velocity from the system, v_{esc}^*, from the same orbit is simply $\sqrt{2}v_c^*$. The required delta-V is then

$$(\sqrt{2}-1)v_c^* = \left(1 - {}^{1}/_{\sqrt{2}}\right)v_{esc}^*.$$ [4]

For example, Earth's orbital speed is 30 km s^{-1}, and the escape velocity from its orbit is 42.1 km s^{-1}. The required delta-V at Earth's orbit is therefore 12 km s^{-1}. This must be achieved by the final rocket stages that escape from the Earth.

The escape velocity from the orbit of a planet in the circumstellar habitable zone of its host star in terms of the host star properties is:

$$v_{esc}^* = \sqrt{\frac{2GM_*}{a_*}} = 42.1\sqrt{\frac{M_*/M_S}{a_*/a_S}}\,\text{km/s} = 42.1\sqrt{\frac{M_*/M_S}{\left(L_*/L_S\right)^{1/2}}}\,\text{km/s}$$

where L_* is the luminosity of the star, L_S is the luminosity of the sun, M_S is the mass of the sun, a_S is the radius of Earth's orbit, and we made use of the fact that for a planet receiving the same insolation as the Earth, $a_* \propto \sqrt{L_*}$. We can express v_{esc}^* solely in terms of the mass of the star by making use of the mass-luminosity relation for main sequence stars [19]:

$$L_*/L_S = \left(M_*/M_S\right)^4 \tag{16}$$

This equation is most accurate for stars with mass in the range

$$0.43 \le M_*/M_S < 2.0.$$

Substituting for L_*/L_S above, we obtain for the escape velocity:

$$v_{esc}^* = \frac{42.1}{\sqrt{M_*/M_S}}\,\text{km/s} \tag{17}$$

[4] In their paper [6] Lingam and Loeb mistakenly state concerning this equation, "…where the additional factor has been introduced to account for the boost from gravitational assists." They are referring to the factor with the square root of 2. They do go on to correctly explain the derivation of this equation, but it has nothing to do with gravity assists, which we describe below.

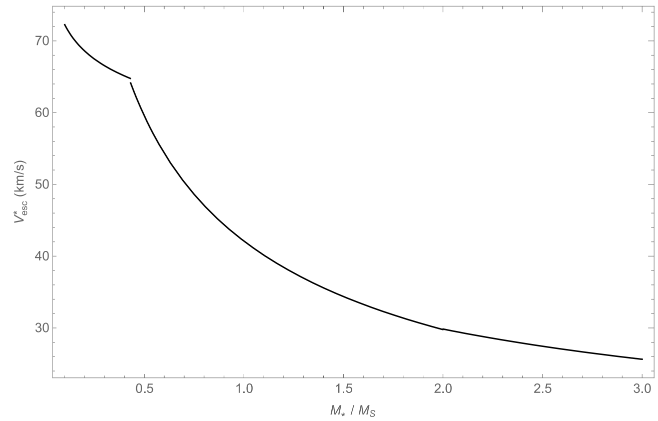

Figure 5: Escape velocity for leaving the circumstellar habitable zone of a star. The piecewise function uses equation 16 over its range of applicability (0.43 M_S to 2.0 M_S). Portions outside that range are plotted according to the treatment of Duric and Nebojsa [20].

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A plot of v_{esc}^* against stellar mass is shown in Figure 5.

Five spacecraft have escaped our Solar System: *Pioneers 10* and *11*, *Voyagers 1* and *2*, and *New Horizons*. Each is a relatively lightweight robotic probe. For example, each *Voyager* probe has a mass of only 722 kg [21]. Soon after launch, at 200 km above Earth's surface, *Voyager 1* had an Earth-centric velocity of 18.3 km s^{-1} [22]; at a large separation from Earth, its Earth-centric velocity would have been 14.5 km s^{-1}, enough to escape the Solar System when added to Earth's orbital speed.

These deep space probes benefitted from maneuvers involving close planetary encounters. So-called gravitational assists (or slingshots) can boost the speed of a rocket with relatively little fuel [23]. Thus, planetary neighbors make it easier for inhabitants of a planetary system to escape it. As an illustration, the *Galileo* probe had two close flybys of Earth in 1990 and 1992 before heading off for Jupiter (with a flyby of Venus between the two Earth flybys). Its first Earth flyby increased the probe's heliocentric velocity from 30.1 to 35.3 km s^{-1}, and the second one increased it to 39 km s^{-1} [24]. Instead of going on to Jupiter, *Galileo* could have been programmed to escape from the Solar System from the vicinity of Earth's orbit with an additional modest delta-V of 3 km s^{-1}.

In general, when the speed of a spacecraft and the planet are comparable, the following equation gives the post-encounter speed of the spacecraft orbiting a star:

$$v_2 = v_1\sqrt{5 + 4\cos\theta} \tag{18}$$

where θ is the pre-encounter angle between the velocity vectors of the spacecraft and planet, v_1 is the pre-encounter speed, and v_2 is the post-encounter speed (all in the reference frame of the star) [25]. The average value of θ corresponding to *Galileo*'s two Earth encounters is about 204 degrees; this is confirmed from inspection of the *Galileo* trajectory plot [26].

If we replace v_1 in equation 18 with the circular speed of a planet in the circumstellar habitable zone, then we obtain for a gravity assist post-encounter speed:

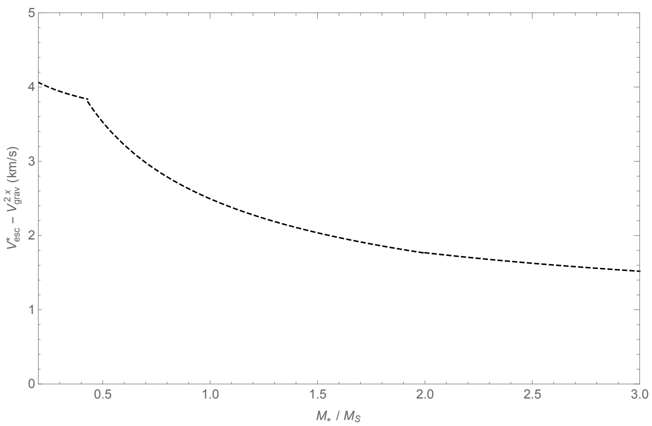

Figure 6: Difference between the escape velocity for leaving the circumstellar habitable zone of a star (from Figure 5) and velocity resulting from two gravity assists from a planet within that zone. **doi:**10.5048/BIO-C.2020.1.f6

$$v_2 = \frac{30\sqrt{5+4\cos\theta}}{\sqrt{M_*/M_S}}\ \text{km/s} \tag{19}$$

We plot the difference between v_{esc}^* and v_2 from two gravity assists of a planet in the circumstellar habitable zone (like *Galileo* with Earth) in Figure 6. From this, it is evident that v_2 resulting from two gravity assists cannot keep pace with increasing v_{esc}^* for decreasing stellar mass. We agree with Lingam and Loeb that it is more difficult to launch interstellar missions from the circumstellar habitable zone of a low mass star, but it is not as difficult as they argue if you include realistic delta-V boosts resulting from typical gravity assists.

ADDITIONAL CONSIDERATIONS

There are key prerequisites for a civilization to contemplate starting a space program. The construction and launch of a rocket like the Saturn V requires a high level understanding of metallurgy, chemistry, and electronics. These technologies, in turn, require a planet with dry land containing concentrated mineral ores that are economically feasible to mine, including fossil fuels. Not just any planet will have these resources [27].

Any complex metazoan is going to need an oxygen rich atmosphere for its basic metabolism [28]. In addition, the atmosphere must have enough oxygen to allow the planet's inhabitants to harness fire, which is the starting point for advanced technology [28]. Photosynthesis produced nearly all the oxygen in Earth's atmosphere, and it rose to near present levels when the sources overwhelmed the sinks just over 2 billion years ago. [29] Photosynthesis only requires a translucent atmosphere. Interestingly, an oxygen-rich atmosphere tends to be transparent in the optical part of the electromagnetic spectrum. Earth's transparent atmosphere provides its inhabitants with clear views of the starry heavens.

Our ability to see the Moon, planets and stars is an important prerequisite for developing a space program. Imagine living on a world like Venus, where only a small fraction of the sun's light filters through the atmosphere to the surface. On such a planet one would know about the day/night cycle but little else about the celestial realm. Inhabitants wouldn't even know that anything existed beyond their world or that there might be nearby planets or even other worlds. There would be little motivation for space travel.

The Saturn V employed kerosene/oxygen for its first stage and hydrogen/oxygen for the upper two stages. Although hydrogen/oxygen may be the best propellant for chemical rockets, in some cases others are preferable. For example, hydrogen is very low density, requiring large tanks. This, in turn, requires more mass of non-propellant material for the rocket. Therefore, it is sometimes advantageous in a rocket stage design to reduce rocket weight and air drag to use a propellant with smaller thrust. While Earth's atmosphere is hydrogen-poor, hydrogen is readily available in the hydrosphere, extractable from water with electrolysis. Of course, fossil fuels require a long history of life on a planet and the right kind of geology.

Once a civilization succeeds in escaping their planetary home, they can explore nearby planetary bodies. Some planets may be easy to visit but difficult to return from. Venus and the gas giant planets are in this category. Moons would be relatively easy to visit and also depart from. Earth's moon, in particular, has served to inspire thoughts of space travel for countless generations. One inspired individual eventually succeeded [30].

Asteroids form a particularly interesting category. Hundreds of thousands of asteroids reside between the orbits of Mars and Jupiter. The largest one is Ceres, which has an escape velocity of 0.5 km/s. Most are rocky, but some are made of almost pure metals. Some are rich in volatile compounds, including water. We know from simple geometric principles that smaller bodies have greater surface area to volume ratio than larger ones. For example, blowing up an asteroid into one million equal size pieces increases the surface area to volume ratio by the same factor. This means that a given mass of ore is much closer to a surface of a small body than it is for larger ones. Asteroids of a required composition can be targeted ahead of time. Finally, the asteroid belt is still close enough to the sun that solar power is an effective energy source for spacecraft. A helpful overview of current ideas about asteroid mining is provided in *Asteroid Mining 101* by John S. Lewis [31].

Given these facts, it is much easier to build large structures in interplanetary space with raw materials from the asteroid belt than it is from any other type of body in a planetary system [32]. Not every planetary system will have a populated asteroid belt. Gas giants in exoplanetary systems are observed to range widely in their properties, implying that exo-asteroid belts do as well [33]. Our asteroid belt was heavily sculpted by the formation and dynamical history of Jupiter [34].

What about potential target systems? If the only constraint is the travel time, then the regions of the Milky Way galaxy with the highest density of stars would offer the closest targets. There are two general trends of star density with location in the galaxy. First, density declines with increasing distance from the galactic center. The Solar System resides within the disk of the

Milky Way; star density also declines with increasing distance from the disk mid-plane. Although the Solar System is located far from the center of the Milky Way galaxy, it is located almost exactly at the mid-plane of the disk [35]. In addition, the Solar System is near the closest point to the galactic center in its non-circular 220 million year orbit in the galaxy [36]. Taken together, these facts imply that the Solar System is currently surrounded by the highest stellar density of any point in its orbit in the Milky Way galaxy. There is no better time for us to engage in interstellar travel.

Given the higher density of stars surrounding the Solar System's current location, it would seem that those regions would be much better suited for interstellar travel. However, other factors come into play. In particular, the greatest threat to interstellar travel is interstellar dust. Impact with dust grains at high speeds would damage the surfaces of a spacecraft. The average interstellar dust density at a given galactocentric distance increases toward the galactic center before declining again very near the center [37]. Still, dust in the disk is patchy. It is more abundant within the major spiral arms. The Solar System is currently between two major spiral arms and within a "hole" with especially low interstellar dust density [38].

CONCLUSIONS

With the discovery of over 4,000 exoplanets, some astrobiologists are beginning to seriously consider the possibility of travel to the closest planetary systems. However, the most common type of exoplanet, the super-earth planet, poses severe, perhaps even insurmountable, challenges to any putative inhabitants contemplating launching rockets. Super earths in the circumstellar habitable zones of their host stars have higher surface gravity. Also, they are likely to possess atmospheres with higher surface pressure, possibly significant hydrogen, and deep oceans.

Furthermore, the most common type of star to host planets, M dwarfs, poses additional challenges for interstellar travel, as do systems lacking asteroid belts. In contrast, the Solar System seems tailor-made for space travel in multiple ways.

Although we have focused on space travel from super-Earths in the present work, it should be obvious that space travel from planets smaller than Earth should be easier, up to a point. Below some minimum mass, a terrestrial planet cannot maintain liquid water on the surface. However, it seems odd that the Earth is near the upper limit in mass for manned space travel.

Earth, in particular, provides its inhabitants clear views of the sun, moon, planets, and stars. Water, which is essential for life processes and for making Earth a habitable planet, also contains the two elemental ingredients needed for one of the best rocket propellants. Earth's crust contains the minable mineral and fossil fuel resources needed for a high-tech civilization, including the construction of rockets. Earth's planetary neighbors provide gravity assists to help spacecraft escape the Solar System. Even Earth's location in the Milky Way galaxy seems to be optimal for interstellar travel. Earth is much better for space travel than the many less habitable exoplanetary super-Earths that have been discovered.

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