Terraforming of Terrestrial Earth-sized Planetary Bodies

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Abstract

This investigation into chemically altering, and thus geologically changing the nature of a planetary atmosphere and its surface provides new scientific predictions, insight, and numerical theories into the feasibility of technologically inducing the habitability of other worlds. Innumerable permutations of potential planetary evolution pathways exist due to large variations in the astrophysical, atmospheric, and geologic properties of a given world, dictated by unique planetary formation, dynamics, and evolution. Surface interactions that give rise to habitable climates are driven by geochemical reactions and geomorphic processes that can act in feedbacks to either promote or decay the climactic habitability of a planetary atmosphere and surface. Using the TerraGenesis iPhone application created by Alexander Winn, we simulate and track 19 different technologically induced planetary evolution scenarios. I present numerical-game simulation modeling of our solar system's real terrestrial bodies: Mercury, Venus, Earth, the Moon, and Mars, Jupiter's moons: Io, Europa, Ganymede, Callisto, Saturn's moons: Tethys, Dione, Rhea, Titan, and Iapetus, Uranus's moon Oberon, and Pluto. I also test a range of four hypothetical exoplanets to colonize: Bacchus, Pontus, Ragnarok, and Boreas. We consider the approach for future exoplanet studies including terraforming of TRAPPIST-1 planets. Calculations in this application are taken out with simple, coupled numerical rules, with model years into C.E., the Common Era. The user of this application 'controls' the terraformation process by manipulating the temperature, atmospheric pressure, oxygen content, sea level, and biomass, limited by the available economic resources. Technologically induced terraforming in this numerical model produced all tested habitable worlds, and reached stability within 1,000–3,000 mission years. Through testing the efficacy of terraforming technologies to combat modern climate change on the Earth, this study additionally shows that it is at least feasible to achieve stable habitability on Earth before (or after) a global climate catastrophe: reversing the effects of modern climate change may take on the order of ~100 to ~1,000 years. This paper also reviews and condenses the current literature in the year 2017 on terraforming as well as recent developments and advancements.

Keywords: Terraforming, planetary engineering, geochemistry, astrobiology, astrophysics, climate change, planetary evolution, atmospheric sciences, numerical analysis, planetary geology, iPhone application development, software development, exoplanet geoscience, computer modeling, terraforming, comparative planetology, numerical simulation, cryospheric science, geomorphology, and space exploration.

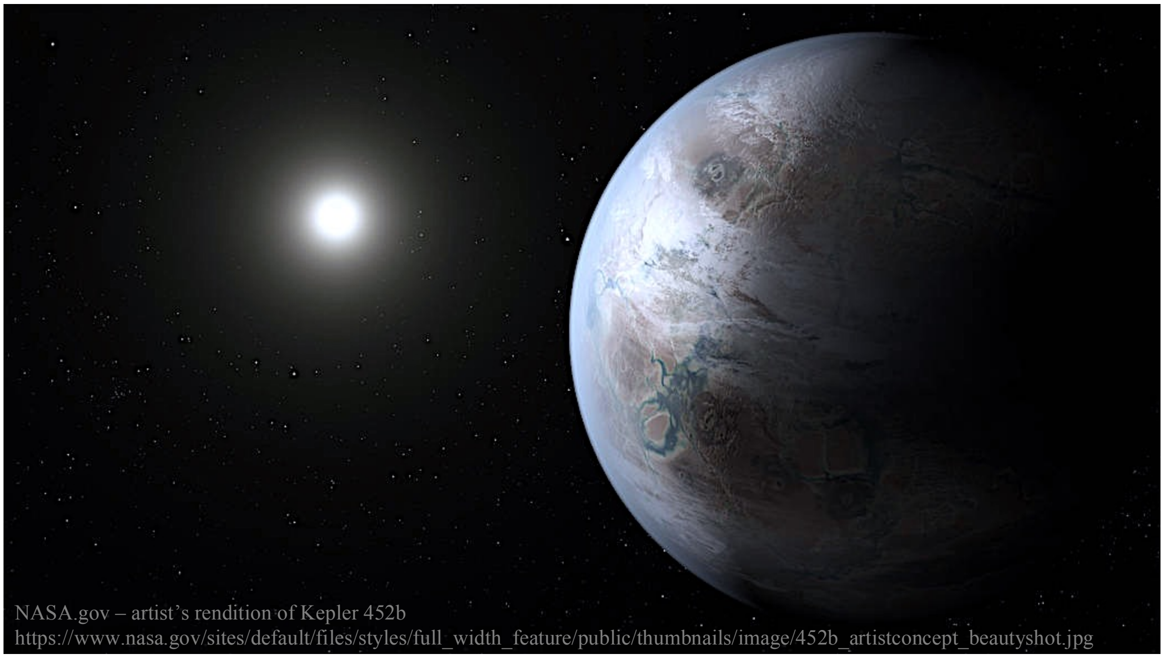
Table of Contents Page #

1 Introduction and background

The word terraforming literally translates to the ‘Earth-shaping’ of a planet, moon, or other celestial body, which I define as the hypothetical process of deliberately altering the atmosphere, temperature, surface topography, and ecology by technological means to artificially induce the habitability of another world, and ultimately enabling life to flourish (e.g., Fogg 1995; Kahwaji and Ghantous 2011, McKay 2011). The word terraforming was first coined by the science fiction writer Jack Williamson and can be defined as a process by which a barren extraterrestrial planetary environment can be altered to one that is suited for life (Hiscox and Fogg 2001). According to Moores and Melo (2003), terraforming is the intentional application of anthropogenic forcing to a planetary environment in order to effect a desired climactic change. Terraforming can also be thought of as creating an Earth-like world through planetary engineering (Todd 2006). Based on the nature of climate change on Earth, we now have substantial evidence that the environment and climate of a planet can be accidentally or deliberately altered on human timescales given the right (or wrong) technological and economic circumstances (e.g., Cervantes et al., 2011; Fogg 1995; Hiscox and Fogg 2001; Kahwaji and Ghantous 2011; McKay et al., 1999). The exact feasibility, however, of creating an unconstrained planetary environment that mimics the Earth’s is unknown. Ecopoiesis, coined by McKay (2008), describes the initiation of a living, self-sustaining ecosystem in a planetary environment (Todd 2006). Ecosynthesis refers to the development of an ecosystem that includes succession, i.e., ecosystem maturation by the replacement of orgnisms (Todd 2006). Planetary biology is therefore made of four components: planetary protection, the search for life, human life support, and ecopoiesis/terraforming (Todd 2006).

Altering the conditions of the planet Venus was initially suggested by Carl Sagan in the journal *Science* (Sagan 1961). The planetary engineering of Venus was imagined through a process of seeding its atmosphere with algae, converting water, nitrogen and carbon dioxide into more complex organic molecules (Sagan 1961). Removing CO_2 from the atmosphere, and reducing its pressure would cool Venus and reduce its greenhouse effect until surface temperatures reached near-habitable conditions, in the range stable for liquid water: 273–373 K (e.g., Sagan 1961; Dyson 1989). The possibility of heating Mars and accelerating the alteration of its atmosphere has been historically the most popular option for human colonization in terms of its proximity to the Earth, and its technological feasibility (e.g., Cervantes et al., 2011; Hiscox and Fogg 2001; McKay et al., 1991; Sagan 1973a; 1973b; Zubrin and McKay 1997). Carl Sagan was a proponent of planetary engineering of Mars in an article he published in the journal *Icarus* (Sagan 1973a). NASA first used the term "planetary ecosynthesis" when they addressed the issue of planetary engineering officially (Sagan 1973a), which concluded that it was indeed possible for Mars to support life and be made into a habitable planetary ecosystem (e.g., Sagan 1973a; 1973b). Now with the abundant evidence of ancient water and oceans on Mars (e.g., Fogg 1995; 1998; Hiscox and Fogg 2001; McKay 1982; 1993; 2004; 2008) we know that it would be relatively simple to convert the red planet into greens (biomass) and blues (water). The long timescales, ethical nature, logistics, politics, and economic practicality of terraforming are heavily debated (e.g., Haqq-Misra 2012; Hickman 1999; McKay and Zubrin 2002; McMahon 2016; Zubrin 2001) and are discussed in the concluding chapters of this paper.

The research in this paper shows that if we assume the technological capabilities and economic resources are readily available, the ability of a spherical planetary body to be technologically transformed depends mostly on its initial conditions of astrophysical, atmospheric, and geologic parameters. I use data derived from model runs in the application TerraGenesis version 3.0+ (Winn 2017) to track the planetary engineering of 19 Earth-sized planets, exoplanets, and moons, until they reach habitable conditions and complete colonization. In this case of technologically induced terraforming, the dynamic model TerraGenesis allows us to control the planet's temperature, atmospheric pressure, hydrologic–cryospheric cycle, and the mining resources available to derive the evolution of each planetary body on human timescales. I test how the varied initial conditions can change the average time it takes to reach habitability and subsequent colonization. This research investigation aims to provide deeper insight into the colonization of other worlds by considering the timescales, population growth, technological complications, and the hydrologic–topographic changes involved to help humanity explore the potential that exists on the life-less worlds of our solar system and beyond. We also consider what exoplanets are possible for future colonization by humanity. The methods involved in this research include geochemistry, astrobiology, astrophysics, climate change, planetary evolution, atmospheric sciences, numerical analysis, planetary geology, iPhone application development, computer modeling, numerical simulations, cryospheric science, geomorphology, comparative planetology, and exoplanet geoscience.



NASA.gov – artist's rendition of Kepler 452b
https://www.nasa.gov/sites/default/files/styles/full_width_feature/public/thumbnails/image/452b_artistconcept_beautyshot.jpg

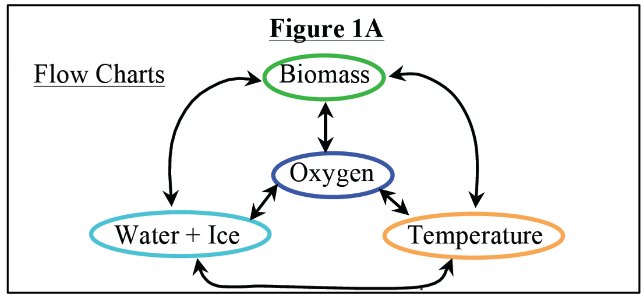
1.1 Planetary characteristics and nomenclature

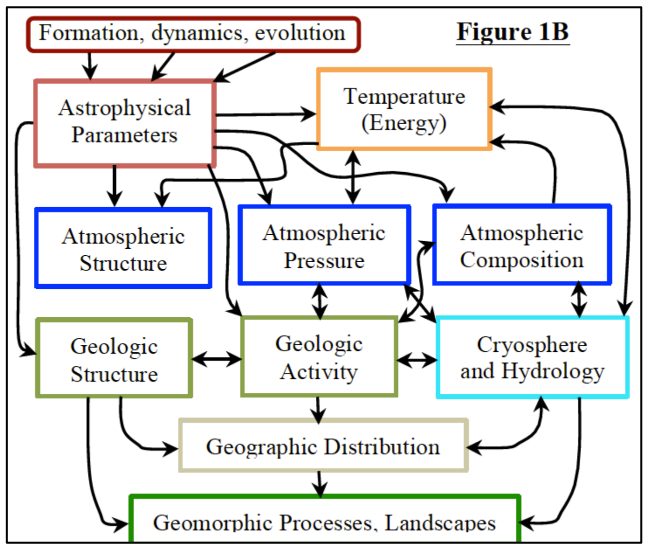
What makes a planet or moon habitable for our definition of life (see section 1.6) is a specific set of qualities and characteristics that differ that celestial object from other bodies. Narrowing down these qualities to their basal representations and interconnections, we see there are three main groups or categorizes through which these parameters can be sorted: astrophysical, atmospheric, and geologic. Each of these categories has numerous characteristics that affect the state of a planet's interior, surface, and atmosphere. The following table shows the various parameters associated with each general category.

Atmospheric	Astrophysical	Geologic
Pressure	Equilibrium temperature	Activity, volcanism, tectonics
Structure	Planet composition	Structure (surface and interior)
Temperature	Planet size and gravity	Geography (distributions)
Scale height	Planet mass and density	Hydrology and cryosphere
Thermal gradient	Magnetic field strength	Albedo and emissivity
Weather and climate	Stellar age, type, radiation	Radiogenic heat flow
Equilibrium (loss/gain)	Rotation speed / day length	Mass, size, gravity (geoid)
Size and total mass	Orbital period / velocity	Composition, density
Carbon/oxygen cycles	Orbital size (radius)	Geomorphic processes
Nitrogen cycles	Orbital eccentricity	Economic resources
Biosphere cycles	Tides and resonances	Geochemistry
Composition	Impactor flux	Biosphere

1.2 Flow charts of main concepts

The diagrams below show the connections between each key parameter involved in planetary engineering. We consider key parts of these parameters to be biomass, oxygen, temperature, water and ice, atmospheric structure, pressure, and composition, geologic structure, and geologic activity. The positive and negative feedbacks are not explicitly listed in these diagrams. Each directional arrow is a coupling of two related parameters. A single-directional arrow leaving the parameter means only one affects the other, while a bi-directional arrow denotes a coupling where both parameters affect each other (equally or unequally). You can think of the arrows as meaning that one is dependent on the other, or that one affects the other arrow. Figure 1A shows the simple coupling of changing temperature, oxygen, biomass, and total water content vs. total ice content. Each parameter affects one another in this flow chart. If you change one parameter, it may effect the others ability to retain a state of equilibrium. Steady-state conditions are an end goal of such engineered planetary climates. These conditions are largely described by the parameters in the second flow chart (see Figure 1B) with categories discussed before represented as the rows. It is important to recognize that all of the connecting arrows initially emerge from the astrophysical parameters. Figure 1B shows us that the cryosphere and hydrology are coupled with geographic distribution and geomorphic processes, which eventually lead to each unique planetary landscape. From this we can see that the initial conditions of astrophysical parameters are the fundamental quantities that dictate the planetary formation and evolution.



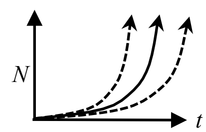


These couplings and groupings help us to better understand the interconnections between different planetary atmosphere-surface-interior interactions. Although the physics of these connections have largely been explored and are developed, the exact chemical, physical, and biological recipe can lead to planets that are well outside of the human realm of imagination. A given planetary surface is the product of a complex history dictated initially by its astrophysical parameters, and later by atmospheric, geologic, and potentially biologic processes. These categories/variables are what I consider the fundamental parameters of planetary formation and evolution. From the quantities in this paper, we are most interested in modeling the evolution of planetary population, total biomass, pressure, oxygen, temperature, and water level.

1.3 Dynamics of terraforming planetary bodies

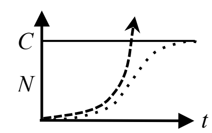
The combination of complex physics, chemistry, and geology of planetary surfaces dictate the specific environmental conditions of that surface and its atmosphere. This is a multi-component system that is strongly inter-coupled with each individual component – that is: one depends on the others and/or they all affect one another (as seen in the flow chart arrows above in section 1.2). These dynamics can be defined quantitatively with mathematical equations and physical relationships, and more qualitatively with theoretical graph predictions. The shape and mathematics of a growing global population (N) as a function of time (*t*), with an initial population (N_0), a growth rate (r_G), and a carrying capacity (C) is:

$$\frac{\partial N}{\partial t} = r_G N \quad \therefore \quad N(t) = N_0 \exp(r_G \cdot t)$$



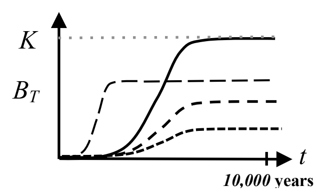
and

$$\frac{\partial N}{\partial t} = r_G N \left(\frac{C - N}{N} \right)$$



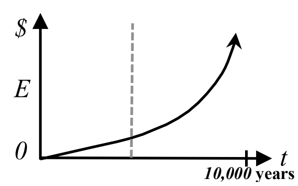
The dotted lines in the first graph are varying growth rate ranges. The second graph is population growth (dotted) with a capacity, and the dash is an uncapped population. Following this mathematics, biomass growth and economic growth both follow the same form of the exponential equation, written as:

$$\frac{\partial B_T}{\partial t} = r_B B_T \left(\frac{K - B_T}{B_T} \right)$$



Where K is the biomass capacity (proportional with planet size), dictated by surface area and chemical recycling rates. The dotted lines give various growth rate values and temporal scales for theoretical planetary bodies. Total biomass (B_T) is given a specified growth rate (r_B), and the economic growth (*E*) as a function of time (*t*) is simply proportional to the population growth as a function of time equation:

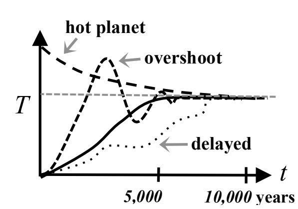
$$E(t) \propto N(t) \text{ ; geologic and energy rescources}$$



These fundamental mathematical relationships can be found in nature, however, from planet-to-planet can vary in both magnitudes and growth rates. The above is what we will assume for economic growth and resource availability. The dotted gray line is an economic-energy production threshold for a civilization to reach. Temperature and pressure are of course a strongly coupled system, important to planetary dynamics. Dynamics for planetary temperature (*T*) are given below, and described further on the next page:

$$T_{EQ} = \left[\frac{(1-\alpha)}{4} T_{SUN}^4 \left(\frac{R_{SUN}}{R_{ORB}} \right)^2 \right]^{1/4} \qquad T_S \approx \left[\frac{(1-\alpha)}{4\varepsilon\sigma} F_S S_O \right]^{1/4} + (19.5 + 20.4 F_S)\, pCO_2^{1/2}$$

$$T(t) \propto pGHG(t) \text{ ; eccentricity ; obliquity ; tidal forcing}$$

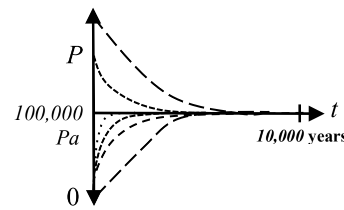


Where T_{EQ} is the planetary equilibrium temperature, and T_S is the greenhouse-corrected surface temperature including typical constants for emissivity, albedo, orbital radius, planetary radius, stellar size, and flux. The levels of greenhouse gasses and anthropogenic energy balance change of a planet are grouped into the parameter of planetary temperature. The dynamics for pressure (P) involves the height above the surface (z), surface pressure at $z = 0$ (P_0), and the scale height (z_*), determined by the planets average temperature (T), and the Boltzmann constant (k), divided by gravity (g) and average atmospheric molecular mass (m).

$$P(z) = P_0 \exp\left(-z / z_*\right) \quad ; \quad z_* = kT / mg$$

$$P(t) \approx E_R \cdot t \quad \text{(artifical emission rate)}$$

$$\mathrm{M_T} \approx \frac{P \cdot A}{g}$$

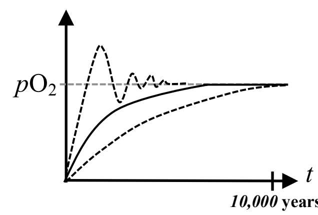


To find the total atmospheric mass ($\mathrm{M_T}$), you need the surface pressure (P) times the surface area of the planet (A), divided by the gravitational acceleration of the planet (g). The pressure as a function of time depends on the technological ability to produce artificial gasses, at an emission rate of E_R. Partial pressure of pO_2 (or pCO_2) follows a similar trend, but can have instabilities upon initial atmospheric genesis due to surface geochemistry and biomass-related couplings and interactions:

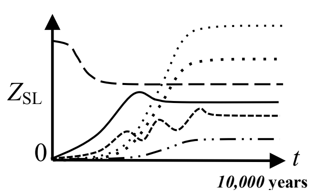
$$C + O_2 \Leftrightarrow CO_2 \quad ; \quad CO_2 + 2H_2O \Leftrightarrow 2O_2 + CH_4 \quad \text{(biomass coupling)}$$

$$2Al_2Si_2O_8 + 2CO_2 + 4H_2O \Leftrightarrow 2CaCO_3 + Si_4O_{10}Al_4(OH)_8$$

$$\therefore \quad CO_2 + CaSiO_3 \Rightarrow SiO_2 + CaCO_3$$



This graph of oxygen as a function of time could also start above the steady state line, and be forced into a state of less total oxygen as would be required on theoretical worlds Boreas and the third world of Trappist-1, Huanca. Sea level (S_L) is strongly coupled with temperature (T) and total water content (W_T). The shape of the sea level surface and total depth varies spatially across a planetary surface. This is driven by differences in geographic feature distribution, the gravity field, and groundwater storage potential.



$$Z_{SL} \propto \text{geography, geoid, and total water as a function of time}$$

$$W_T = w_I + w_O + w_L + w_G \quad \text{total water summation}$$

$$Z(t) = \dot{M} \cdot t - \dot{F} \cdot t + \dot{R} \cdot t - \dot{L} \cdot t \quad \text{where} \quad \dot{M}\ ,\ \dot{F} \propto T(t)$$

Where the total amount of water in the system is the ice (w_I) plus oceans (w_O) plus land-water (w_L) plus groundwater (w_g). The average elevation of the water (z) as a function of time (t) is simply the melt rate (m) minus the freeze (f) rate, plus net loss rate (L) and gain rate (R) to and from the planetary system.

The mathematics and validity of the physics is in what we expect to see in the model runs, and many of these graphs are simply initial conditions, perturbed by a function that pushes the quantities into steady state. These PDE's can all be effectively classified as damped over time or as a damped exponential over time. Each one has many permutations of different forcings toward and away from steady state, and that is what makes accurate and detailed planetary modeling so difficult and numerically time-consuming.

1.4 Terraforming technologies and climate change

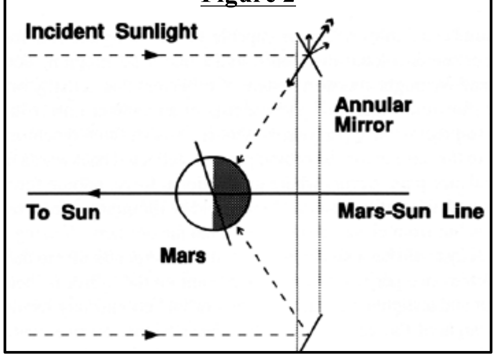
Theoretical technologies and modern technologies are the two different groups of terraforming or planetary engineering related technology. For our theoretical modeling of the evolution and feasibility of terraforming a planet or moon, we assume that the necessary technology is both acquired and used, without limitation of recourses, and that it follows the economic growth curve from before that is based ultimately on population growth. Every planet in the TerraGenesis application has a finite amount of resources, from which the economy is derived. After colonization, infinite clean energy (fusion) is assumed and the economic growth and population growth follow the same rate. If you assume a much more rigorous approach, the feasibility of global planetary engineering will remain plausible, but the timescales may be lengthened. Planetary engineering is the application of technology for the purpose of influencing the global properties of a planet, while geoengineering is planetary engineering applied specifically to Earth, by affecting the greenhouse effect, atmospheric composition, solar insolation or impact flux (Sagan 1973). Terraforming will eventually be facilitated through a mixture of these types of mega-scale engineering and biological planetary engineering technologies. The end goal is specifically directed at enhancing the capacity of an extraterrestrial planetary environment to achieve habitability and creating an open planetary ecosystem that is capable of self-regulation (e.g., McKay 2008).

On the other hand, paraterraforming is engineering that involves the construction of a large-scale habitable enclosure, like the Biosphere 2 experiment here on Earth, a closed-ecosystem environment in a dome-structure (Taylor 1992). Some proposed terraforming methods include creating orbital mirrors (Figure 2 on the next page) that will reflect sunlight and heat the desired planet's surface, greenhouse gas-producing factories to trap solar radiation, and Importing volatiles through asteroid or comet impacts to create volatile release (Early 1989; Zubrin and McKay 1997; Clacey et al. 2005). Other viable technologies suggested by the aforementioned authors include artificial super greenhouse gasses PFC's, albedo reduction, and biological seeding. Freitas (1985) suggests that a machine self-replicating systems (SRS) could robotically induce the habitability of a world. Terraforming via SRS involves planting a small "seed" unit near the surface of the body to be altered, which self-replicates into a megascale factory complex capable of permanent planet modification (Freitas 1985).

Climate change on Earth suggests that other planets might experience similar runaway effects associated to rising temperatures and ecosystem overexploitation, leading to catastrophic shifts on short time scales (e.g. Sole et al., 2015). Remediation scenarios capable of counterbalancing these effects involve geoengineering and sustainable practices and carbon sequestration, but are not enough to achieve the desired restoration of safe boundaries (Sole et al., 2015). Synthetic organisms with the appropriate engineering design could be used to safely prevent declines in some stressed ecosystems and help by improving carbon sequestration (Sole et al., 2015). The implications of this study reveal that testing this designed organisms can be achieved by using controlled bioreactor models and accurate computational models including different scales – from genetics, metabolic pathways, to population dynamics.

A solar mirror (i.e. Figure 2) has been proposed to vaporize portions of the Martian regolith, liberating trapped volatiles including O_2, N_2, CO_2 and H_2O (Birch 1992), and then it would be ready and stable to complete atmospheric changes by introducing photosynthesis. Zubrin and McCay (1997) believe that only by initiating a certain change process of global warming, for instance in the context of Mars that requires a 4ºC increase in temperature to activate a global warming effect, we will be able to trigger a snow-ball effect global warming phenomenon. This would be achieved by placing giant space mirror in orbit (Figure 2) built with the most up to date materials in order to achieve the best efficiency in relation to the weight (Zubrin and McCay 1997). It would require a mirror with a radius of ~25 km and a weight of ~2x10^5 tons, is difficult but remains theoretically feasible (e.g., Zubrin and McCay 1997). A technology that will need further research in the future is a tool to evaluate terrestrial planets interior structure (i.e., Luther et al. 2010) – a key to future space exploration classification of exoplanets

Figure 2



Over the past 30 years the concept of planetary engineering, more popularly known as terraforming, has moved from the arena of science fiction towards serious scientific attempts to determine its future practicality (Hiscox and Fogg 2001). Humans have deliberately caused an increase in the mean global surface temperature of between 0.5 and 1.0ºC since pre-industrial times due to our emissions, so it is clearly possible to alter the climate system (e.g., Hiscox and Fogg 2001). Fogg (1995) also talks about other potential technologies such as nuclear mining and solar heating via mirrors. Another technology considered ecopoiesis produces an anaerobic biosphere suitable for bacteria and primitive plants (Fogg 1995). A major hurdle to this is like on Earth, recycling of atmosphere, water, wastes, and the supply of food is largely an automatic process (Fogg 1995), and therefore running the life support system is now a task similar to that of civilized terrestrial agriculture.

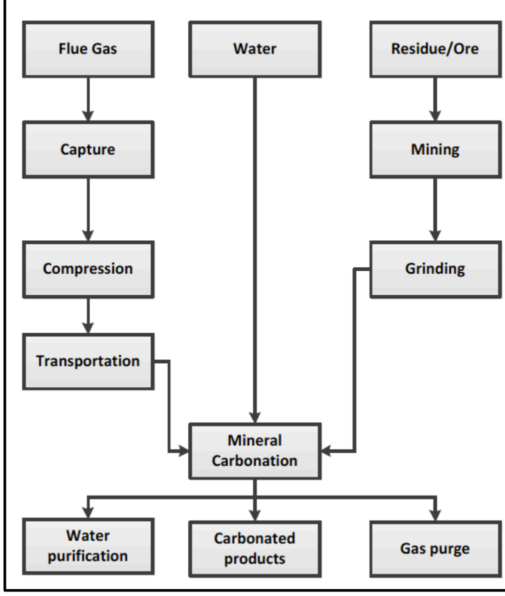
Carbon sequestration plants are the ideal terraforming technology that needs more research – being that my home planet Earth is being deliberately heated with it due to our own ignorance and comfort. If we are able to remove carbon dioxide from the atmosphere, we are likely able to stop the heating of our atmosphere. If this is true for one gas, why not for any gas, and we could also add a gas if required with such technology. My ideal version of how to power these carbon-sequestration plants is with solar (clean battery backup), wind, nuclear (fusion one day), and geothermal (oil-reclaimed borehole) energy sources. The hurdle is to separate CO_2 from N_2, Ar, and other trace gasses. Mineral carbonation is a possible technique for the long-term storage of CO_2, and the basic geochemical reactions for this can go as follows:

$$CaO + CO_2 \Leftrightarrow CaCO_3$$
$$CaSiO_3 + CO_2 \Leftrightarrow CaCO_3 + SiO2$$
$$2MgO + CaCO_3 + CO_2 \Leftrightarrow CaMg(CO_3)$$
$$2Al_2Si_2O_8 + 2CO_2 + 4H_2O \Leftrightarrow 2CaCO_3 + Si_4O_{10}Al_4(OH)_8$$

Humans add about 7.5 GtC/year in total to the Earth system and it is simply spread between reservoir components (atmosphere [3], forest regrowth [0.5], fertilization [2], oceanic uptake [2]). So for steady state, we would have to be removing 7.5 GtC/year from the atmosphere and into rocks, such as carbonates to make new cement and building foundations.

Actual proposals from McKay and Zubrin (2002) for the system process of mineral carbonation are given to the right in Figure 3. It really is a very common idea in the field of geoengineering is to inject CO_2 from the atmosphere into a reservoir, whether underground or in the ocean (Keitha et al., 2009). Anthropogenic activities have led to substantial increases in CO_2, contributing to heightened concerns of global warming, and in the last decade alone CO_2 emissions increased by 2.0 ppm/yr globally (Mohammad 2012). Seasonal variation and net increase in the concentration of CO_2 has been steadily increasing at the station on Mauna Loa in Hawaii (NOAA 2014). CO_2 capture and sequestration has been recognized as promising solutions to mitigate CO_2 emissions from fossil fuel based power. Typical techniques for carbon capture include post-combustion capture, pre-combustion capture and oxy-combustion capture, which are under active research globally (Mohammad 2012). Scaling of this size of project with present day technologies leads to a reduction in the net amount of CO_2 captured due to offset by emissions. In the coming decades, we are likely to see a surplus in innovative energy engineering – for example, scientists from the University of Bristol Cabot Institute recently produced a diamond battery that generates electricity and is made from up cycled radioactive waste (Weforum 2017). Ultimately, to achieve the goals of sequestration, we would need renewably powered sequestration plants, capable of net removal from the atmosphere.

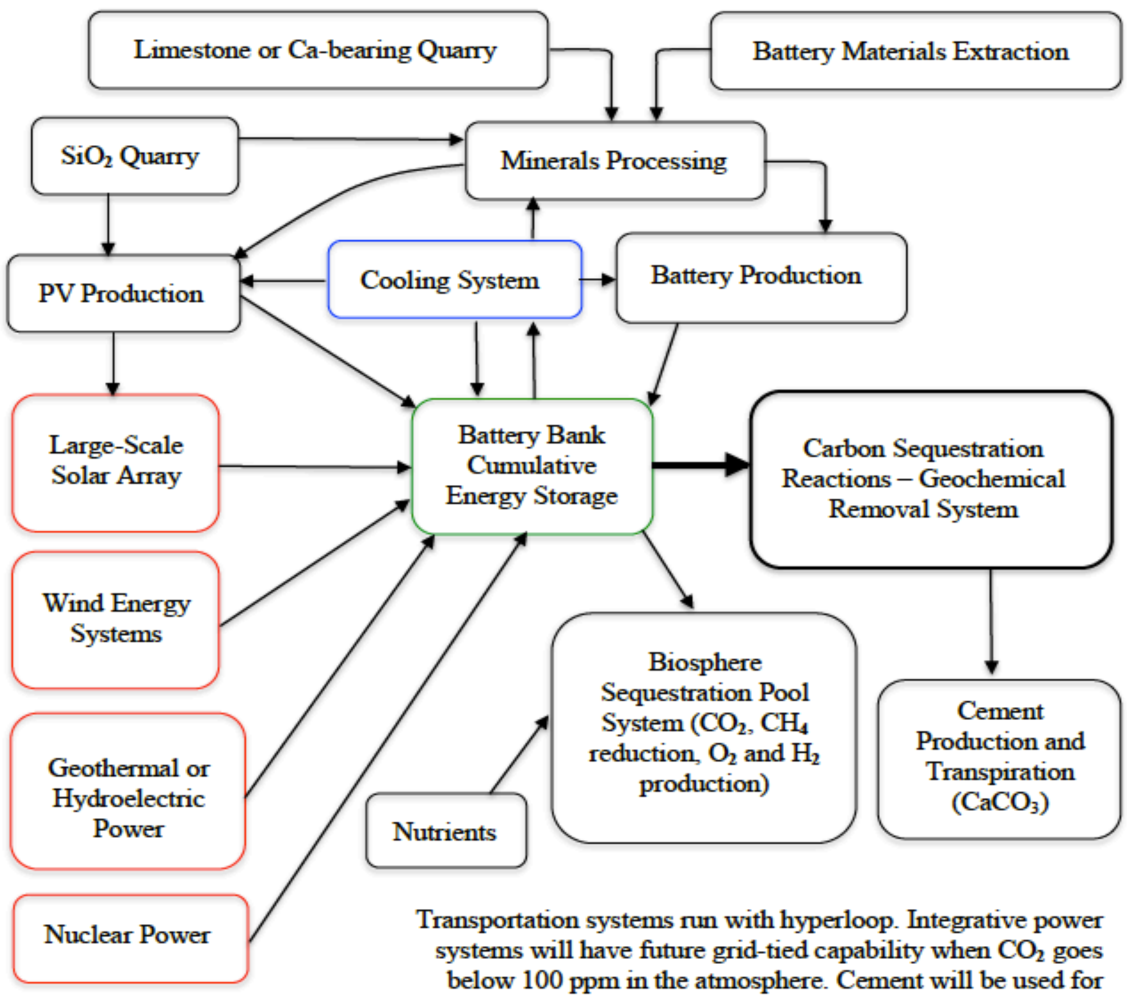
Figure 3



The potential for carbon sequestration projects to succeed is unknown. However, after careful thought and using a sustainable systems approach, I have devised the following engineering flow chart (Figure 4). The impressive speed at which humanity has grown technologically and industrially in the past ~100 years has led us to a catastrophic situation, if left unresolved, that will extremely alter the planetary biosphere and global planetary climate conditions will become unsuitable for natural human life. This planetary engineering solution would be initiated through globally funded mega-scale engineering projects, namely, 15 renewably powered greenhouse gas sequestration plants, powered in a self-sustaining mechanism.

Figure 4

Mega-Scale Self-Sustaining Systems Approach to Industrial Carbon Sequestration



Transportation systems run with hyperloop. Integrative power systems will have future grid-tied capability when CO_2 goes below 100 ppm in the atmosphere. Cement will be used for industrialization and oxygen, hydrogen production will be integrated into propellant production for SpaceX projects.

Ultimately, this method aims to buy humanity enough time to solve enough problems and reduce our emissions to near zero. Terraforming theory of this scale requires fundamentally understanding how planets form, evolve, and can be changed through manipulation of their various essential parameters.

1.5 Planetary formation and geochemistry

Solar systems are derived from molecular clouds (Figure 6), regions of the interstellar medium (ISM) with sufficient gas densities to allow molecule formation (Frank 2014). When the internal outward pressure of a region of the cloud fails to counter balance its gravity, that segment will collapse under its own mass (Frank 2014). By the conservation of angular momentum, it forms a rotating circumstellar disk around the protostar (Frank 2014). Dust grains then gravitationally clump together to form increasingly large particles, eventually forming planets (Frank 2014) through a snowball-effect process. For our solar system, this process began 4,568.5 ± 0.5 Ma, as recorded in the oldest components of the calcium aluminum-rich inclusions (CAI's) found in chondritic meteorites (Frank 2014). Figure 5 shows total mass delivered by three main impact events in the early-Earth history for which there are still records (Frank 2014). Figure 6 shows the condensation process of terrestrial-gas world planetary system formation. These three events dominated the mass addition to the early Earth. These events could have been potentially catastrophic to any developing life because even if it was one impactor or multiple, it is clear that the iteration of life from which we originate must have arisen no earlier than the Late Veneer (Frank 2014). The Late Veneer was the last recorded impact event capable of melting the Earth's crust—and extinguishing any extant life (Frank 2014). These mass-delivering impacts likely provided all of the necessary hydrocarbon compounds required for primordial life to emerge, as well as un-quantified periods, probably coinciding with the Late Veneer and the LHB, of extensive water delivery from comets from beyond the frost-line during formation.

Figure 5

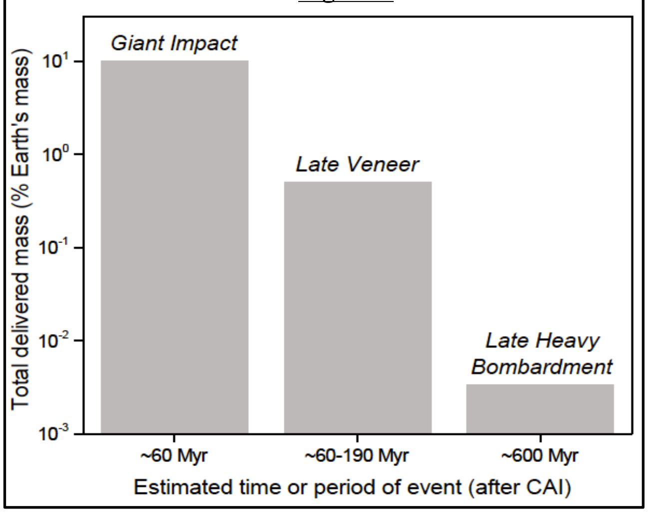
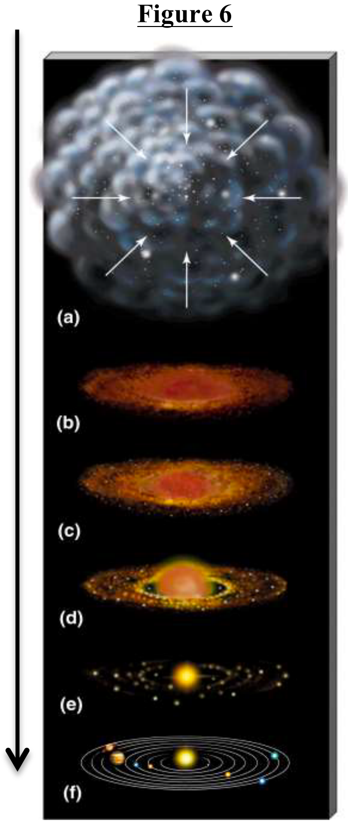


Figure 6



This goes to show that it is generally accepted that silicate-metal ('rocky') planet formation relies on coagulation from a mixture of sub-Mars sized planetary embryos and (smaller) planetesimals that dynamically emerge from the evolving circumsolar disc in the first few million years of our Solar System (Brasser et al., 2016). Once the planets have, for the most part, assembled after a giant impact phase, they continue to be bombarded by a multitude of planetesimals left over from accretion (Brasser et al., 2016). The dynamically and geochemically self-consistent scenario from Brasser et al. (2016)

requires that future N-body simulations of rocky planet formation either directly incorporate collisional grinding or rely on pebble accretion. For this analysis, we assume that other planets in their protostellar disc form in a similar fashion to the accepted formation history of the planets of our solar system. This includes the assumptions that exoplanetary systems will mostly only vary in their metallicity, host star type, number of planets, and total mass of the disc. Future analysis of the connections between exoplanet atmospheres and their subsequent geologic processes will teach us a wealth of other new physics, chemistry, and dynamics involved in forming planetary atmospheres, surfaces, and interiors.

1.6 Astrobiology and habitability

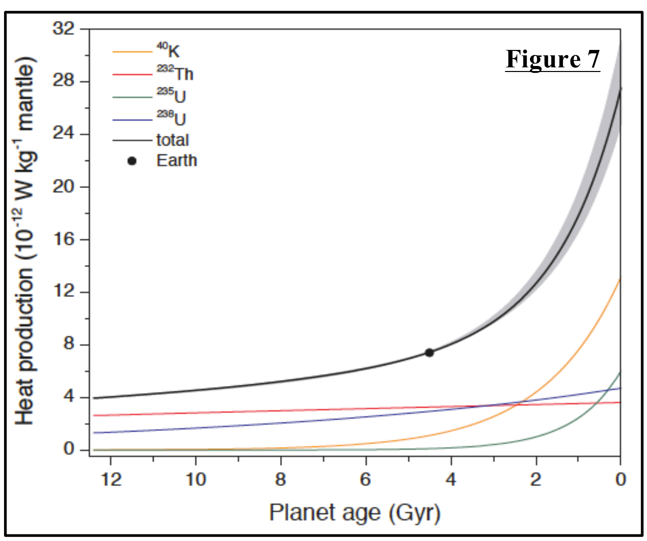
To determine the basic general definition of life, I turn to what I have learned from my previous research advisor Dr. Stephen J Mojzsis and from Dr. Carl Sagan in their life's work. For the context of this research, I consider life to be defined as a self-contained chemical system that is capable of undergoing Darwinian evolution over time. Darwinian evolution in this case is considered to be the process of change in life in response to natural selection pressures. Albert Branscomb once said: "life is not a means of aggregating 'building blocks', but instead is concerned with developing nanoengines (not mere catalysts) that can couple thermodynamically opposed processes, in order to create one disequilibrium at the expense of dissipating another." For this study, we consider the 5 definitions for life to be:

1. physiological – growth and development, response to environment
2. thermodynamics – order (decreased entropy)
3. biochemical – reproduction (distinct chemistry) DNA
4. genetic definition – evolutionary adaptation (evolution by natural selection)
5. metabolic – energy utilization

Metabolic life can also be classified into: photoheterotrough, chemoautotrough, photoautotrough (plants), and chemoheterotrough (animals). Specific requirements for life include: sunlight energy, mostly chemical (e.g. $H_2 + CO_2 = CH_4 + H_2O$), carbon, liquid water, and other elements such as N, P, and S (McKay et al., 1991). Chemically, the requirements for life break down to the abundant elements required for life's chemical reactions: S, P, O, N, C, and H. Any terrestrial world post-terraformation will likely be able to chemically recirculate these elements into any artificial biosphere. Organic chemical building blocks necessary for the origin of life can be obtained by: 1) sunlight energy and lightning can facilitate generation of complex organic molecules and amino acid, 2) delivery directly from comets, asteroids, and interplanetary dust, and/or 3) deep-sea vents can synthesize organic molecules in the presence of water and minerals. Another classification scheme is called the seven pillars of life: 1) program - genetic blueprint, 2) improvisation - evolution, 3) compartmentalization, 4) energy, 5) regeneration, 6) adaptability - response to stimuli, and 7) seclusion - biochemical specifics.

Barge et al., (2016), argues that life only emerges when and where particular planetary-scale conditions of chemical disequilibria are produced through the interactions of the atmosphere-hydrosphere complex with fresh mafic to ultramafic oceanic crust continually replenished by active partial melting of the mantle. One might then ask, when is too soon for life to arise on a planet, and when is it too late for it to continue? The epoch of habitability on a rocky world is dictated by the suite of geological events and processes it experiences (Frank 2014). Life always seems to find a way – there are many different types of extremophiles and single-celled organisms on the Earth that can thrive in nearly any environment we have tested them in. Some of these include piezophile, halophile, lithophile, thermophile, and psychrophile. The limits on the long-term dormancy of organisms on a biologically dormant planet are thermal decay, amino acid racemization, radiation, and degradation of organics (McKay and Marinova 2002).

Limits for habitability on Earth-like planets can be defined by extracting Earth's history from the geochemical record to infer that of the rocky planets lying far beyond the reaches of our solar system (Frank 2014). Planetary accretion stymies the emergence of life, but geophysics might provide its eventual demise. A requirement for the development of life in a natural process requires plate tectonics. It is necessary for life – it recycles older rock into new rock, which is a source of material to build life, and it recycles the earth's CO2 in what is called the global carbon cycle (and further stabilizes the atmosphere). Plate tectonics modulate the Earth's energy budget and globate climate, keeping Earth's surface temperate stable (Frank 2014). Figure 7 gives exoplanet radiogenic heat production curves against time since the planet formed. The total energy budget of a terrestrial Earth-sized planet depends strongly on its quantity and



composition of radioactive isotopes (i.e., Frank 2014). Geological activity of a planet is maintained largely by the long-lived, heat-producing radionuclides ^{40}K, ^{232}Th, ^{235}U, and ^{238}U, whose concentrations decline as Earth ages (Frank 2014). The gray band shows the range of heat production of ^{40}K depending on the relative proportions of primary versus secondary contributions. Eventually, these isotopes will no longer be able to provide the heat required for mantle convection, and plate tectonics will shut down, calling into question Earth's ability to maintain habitability on a global scale. Frank (2014) showed that age is key in the long-term thermal regimes of conventionally defined terrestrial Earth-like exoplanets.

Provided with limits on the reign of life on Earth, the habitability of rocky exoplanets can be evaluated: those that are too young will still be experiencing biological sterilizing impact events, while those that are too old will possess cool mantles incapable of sustaining geological activity that supports the only life we know of in the Universe. Ultimately, it is the geological processes that generate planetary atmospheres, capable of sustaining sufficient energy balance circulation and the conditions that are right for life to evolve and flourish. Geochemical and astrophysical criteria must be met before the surface of an astronomical body is to be considered habitable. The first and foremost requirement for life is an energy source, followed by a liquid medium to undergo chemical changes. NASA (2017) defines the criteria for habitability as extended regions of liquid water, conditions favorable for the assembly of complex organic molecules, and energy sources to sustain metabolism.

The astrophysical requirements are that the host star is a main-sequence star and lacks any irregular radiation phenomena. The planet must receive a low variation in insolation, with low orbital eccentricity ranging from ~0.2 and 0. The axial tilt of the planet must be no greater than 45º for normal habitability conditions to exist. The Earth's 23.5º, gives us nice seasonal variations that create a cyclic 'heartbeat' of the biosphere. The most important factors, as far as human beings are concerned, are gravitational acceleration, surface pressure and surface temperature (Moores and Melo 2003). These three factors are connected: any suitable body must be sufficiently massive to prevent the thermal escape of the major atmospheric constituents (Moores and Melo 2003). This results in a buildup of surface pressure and an increase in the insulating properties of the atmosphere which affects the surface temperature (Moores and Melo 2003). Important to consider for extrasolar habitability is the concept of a galactic habitable zone (GHZ), defined as an annulus in the galactic disk that is sufficiently metal-rich to form rocky planets and has a relatively temperate environment for life to develop, particularly in the context of nearby supernovae rates (Frank 2014). In addition to sufficent water, requirements for human habitability, from McKay et al., (1991), are:

1. Global Average Temperature between 273 K and 303 K
2. Total Atmospheric Pressure between 0.5 bar and 5 bar
3. Less then 10 mbar of Carbon Dioxide (toxic above this level)
4. Greater then 300 mbar of inert buffer gas (such as Nitrogen or Argon)
5. Oxygen Partial Pressure between 130 mbar and 300 mbar
6. Gravitational acceleration or the length of the day-night cycle (e.g. Moores and Melo 2003)

While the habitability requirments for a plant-based biosphere, according to McKay et al., (1991), are:

1. Total Atmospheric Pressure greater than 10 mbar
2. Carbon Dioxide partial pressure greater than 0.15 mbar (photosynthesis limit)
3. Greater than 10 mbar of Nitrogen (nitrogen fixation)
4. Greater then 1 mbar of Oxygen (Plant respiration), 20 – 50 mbar

Atmospheres are a critical requirement for the classification of a habitable world. During the initial stages of planet formation, outgassing from volcanism creates atmospheres of H_2O, CO_2, N_2, SO_2, H_2S, NH_4, CH_4, and NO_3. Airapetian et al., (2017) showed that the atmospheres of a significant fraction of Earth-like exoplanets around M dwarfs and active K stars exposed to high XUV fluxes will incur a significant atmospheric loss rate of oxygen and nitrogen, which will make them uninhabitable within a few tens to hundreds of Myr, given a low replenishment rate from volcanism or cometary bombardment. Atmospheric loss affects exoplanetary habitability in terms of surface water inventory, atmospheric pressure, the efficiency of greenhouse warming, and the dosage of the UV surface irradiation (Airapetian et al., 2017). Atmospheres of exoplanets in the habitable zones around active young G-K-M stars are subject to extreme X-ray and EUV (XUV) fluxes from their host stars that can initiate atmospheric erosion (Airapetian et al., 2017). Thermal escape models suggest that exoplanetary atmospheres around active K-M stars should undergo massive hydrogen escape, while heavier species including oxygen will accumulate forming an oxidizing atmosphere (Airapetian et al., 2017).

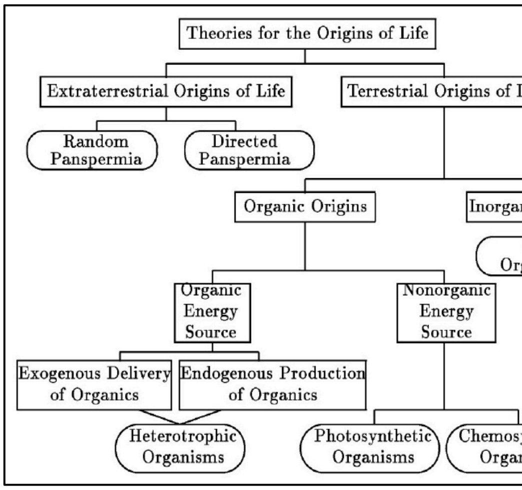


Figure 8

Theories for engaging a self-sustaining biosphere on another planet can be guided by the theories on the origin of life (Figure 8). The tree of life (Davis and McKay 1996) shows how heterotrophic, chemosynthetic, and photosynthetic life forms developed. Terrestrial analogue studies underpin almost all future planetary missions and their use is essential in the exploration of our Solar system and in assessing the habitability of other worlds (Preston and Dartnell 2014). Non-traditional habitable zones within the aqueous environments of the icy moons of Europa and Enceladus and potentially in the hydrocarbon lakes of Titan were explored in the work of Preston and Dartnell (2014). Such analogue sites offer critical ground-truths for astrobiological studies on the habitability of different environmental parameter sets, the biological mechanisms for survival in extreme environments and the preservation potential and detectability of biosignatures (Preston and Dartnell 2014). It is clear from that terrestrial analogue sites can be applied to multiple terrestrial Earth-sized planetary bodies, thereby increasing their value for future exploration.

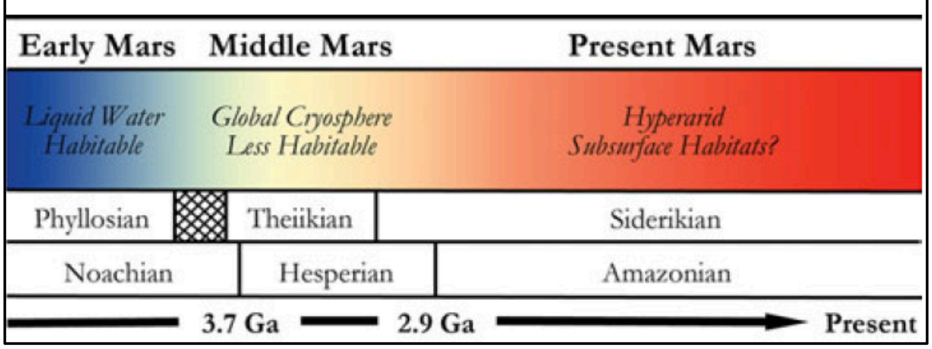
Early terraforming colony on the Moon
www.yalescientific.org/wp-content/uploads/2013/04/Image-2C.jpg

2 Terraformable worlds

2.1 Mars

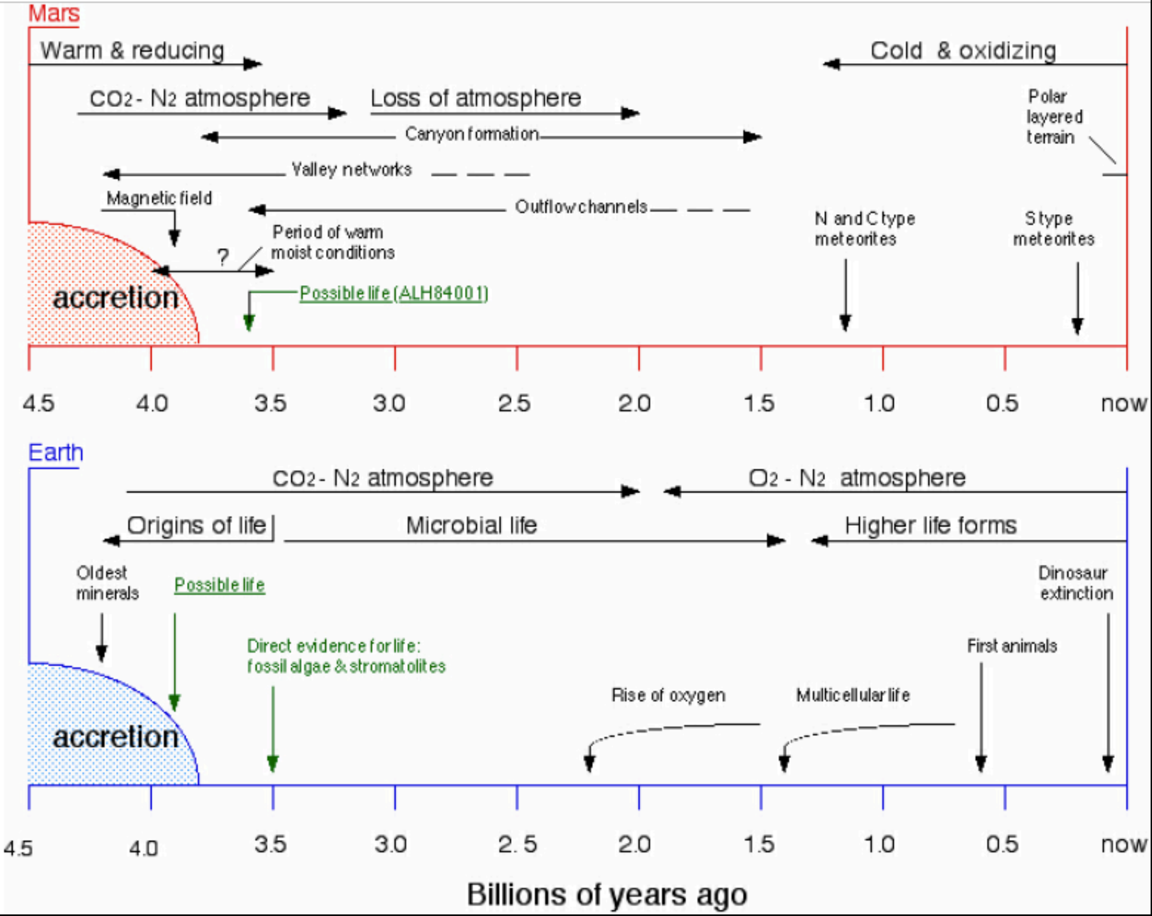
The planets of the night sky have always fascinated humans, in particular: Mars. This world, close to home, and reminiscent of the Earth's past and future, gives us a peak into planetary evolution, habitability, and colonization potential. Terraforming Mars could mark the beginning of our ability to long‐term survival as a species (Cervantes et al., 2011). Mars is a potentially habitable planet given the appropriate planetary engineering efforts (Barsoum 2014). Although cold and dry today, this red world holds all of the essential elements that are needed for our definition of life to exist. Mars is the most Earth-like planet in the

Figure 9



Solar System and we know now that it once had a more habitable environment early in its history, with a thicker atmosphere and abundant water that was lost due to atmospheric escape over hundreds of millions of years. Mars's magnetic field ceased early in its history, allowing the atmosphere to be stripped early on. The planet Mars, while cold and arid today, once possessed a warm and wet climate, as evidenced by extensive fluvial features observable on its surface. It is believed that the warm climate of the primitive Mars was created by a strong greenhouse effect caused by a thick CO_2 atmosphere (Zubrin and McKay 1997). Mars lost its warm climate when most of the available volatile CO_2 was fixed into the form of carbonate rock due to the action of cycling water (Zubrin and McKay 1997). Figures 9 and 10 (Zubrin and McKay 1996; 1997), show the timelines for both the mineralogical and climactic evolution of Mars.

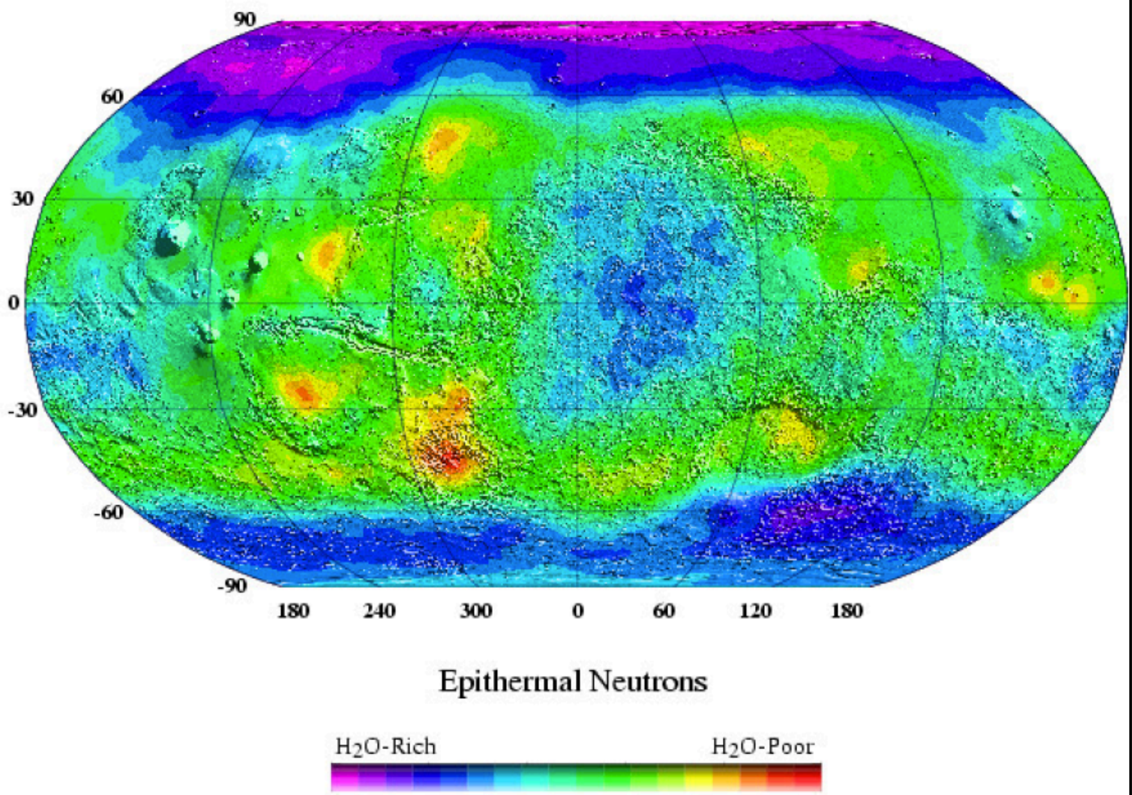
Figure 10



It is believed, however, that sufficient CO_2 to form a 300 to 600 mb atmosphere may still exist in volatile form (Zubrin and McKay 1997), which can be seen in Figure 11 (next page). This CO_2 may be released by planetary warming, and as the CO_2 atmosphere thickens, positive feedback is produced which can accelerate the warming. Through a positive feedback reaction, the sublimation of the volatile southern polar ice cap on Mars can increase global temperatures and pressures to the benchmarks set for minimum acceptable survivable human conditions (Barsoum 2014). Raising of 4–5° C surface temperature south pole of Mars, could release into the atmosphere from 50–100 mbar of CO_2, which would be sufficient to start the regolith massive degassing, generating a temperature positive feedback in the atmosphere regolith system, increasingly raising the surface temperature of Mars (e.g., Cervantes et al., 2011; Budzik 2001).

A mathematical model from Zubrin and McKay (1997) of the Martian CO_2 system shows this potential of positive feedback to accelerate terraforming efforts. It is shown that by taking advantage of the feedback, the requirements for planetary engineering can be reduced by about 2 orders of magnitude relative to previous estimates (Zubrin and McKay 1997). Thus, they, (Zubrin and McKay 1997), conclude that by taking advantage of the positive feedback inherent in Mars' atmosphere/regolith CO_2 system, that engineering efforts can produce drastic changes in climate and pressure on a planetary scale. Figure 11 shows the volatile content on Mars with a global neutron map revealing water-rich and -poor regions.

Figure 11



Fogg (1992) considers a habitable environment on Mars would be one in which: 1) the yearly average global temperature of a planetary body should be between 0° and 30°C, with a maximum seasonal daily average of not less than –10°C and not much more than 40°C, 2) available fresh water levels should be in the area of 10 L/person/day (including drinking, cooking, and cleansing estimates), 3) a global average of 130 to 300 mbar of O_2, 0.1 to 1 mbar of CO_2, and enough N_2 in order to act as a buffer for the atmosphere (though at least 10 mbar is needed), and 4) an overall atmospheric pressure between 0.25 and 2.55 bar. The terraforming of Mars could also be broken down into two stages: 1) technological – the first stage would consist of raising the average temperature above the freezing point of water, while increasing the atmospheric pressure, and 2) biological – the second stage would consist of introducing organisms that produce the oxygen required by most plants and animals to live (Cervantes et al., 2011).

A synergetic approach to terraforming Mars was adopted by Fogg (1992). The first point is that a runaway CO_2 greenhouse effect is not ideal and may produce too much CO_2 for subsequent photosynthetic processing into a breathable atmosphere (Fogg 1992). Trace greenhouse gases currently appear to be capable of providing only about half of the 60ºC warming needed, and most of the chemicals proposed so far would be too short-lived and destructive to ozone (Fogg 1992). He goes on to discuss space-based mirrors could increment the Martian insolation to an Earth like value (Fogg 1992). Other devolatilization methods, such as focused sunlight, nuclear mining and impacts, have their own distinct problems or unknowns that render them less than fully applicable for the provision of a substantial atmosphere and hydrosphere (Fogg 1992). He finishes with considering that unmanaged Antarctic-type ecosystems appear to be wholly inadequate at the task of oxygenating the atmosphere and transforming Mars into an aerobic planet (Fogg 1992). They found that this synergetic approach could make it possible to obtain estimated values of 280K (~60K increase), >400mbar total pressure (from ~7mbar initial), an approximate 40% reduction in UV flux, ~70m global depth of water (at 10% surface coverage, with a Boreal Sea up to 1km deep), and plant coverage of approximately 25% of the surface in basic plants with some higher order plants present (Fogg 1992). This shows that their synergetic approach to terraforming effectively initiates a habitable environment within a much faster timeframe than estimated by any single approach.

Figure 12 shows an artists rendition from devinart.com of a future terraforming technology that will be used for heating the atmosphere, adding gasses, and potentially driving propellant production (see Musk 2017) for spaceflight. Technologies for producing the initial warming on Mars to drive the terraforming include the stationing of orbiting mirrors, the importation of natural volatiles with high greenhouse capacity from the outer solar system, and the production of artificial halocarbon greenhouse gases on the Martian surface through in-situ industry (Zubrin and McKay 1997). Mars would be habitable if it were warmer and had a denser O_2 or N_2 atmosphere, but previous terraforming proposals have been incomplete or have described very slow processes (Birch 1992). Other methods such as using dark, carbonaceous Martian moon material to alter the overall average albedo of the polar ice cap has been proposed (Barsoum 2014), and by covering roughly 10% of the Martian polar ice cap with dark carbonaceous material, the required energy for terraformation can be obtained.

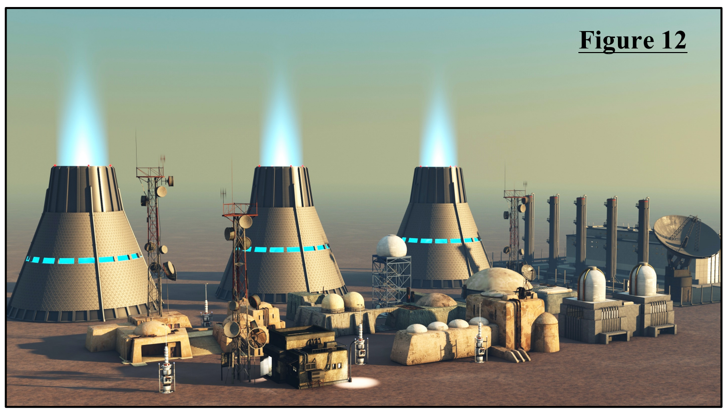


Figure 12

Graham (2003) thinks that the process of the biological terraforming of Mars can be compared to the process of primary ecological succession on terrestrial barren rocks. Each stage in the succession alters the environment in such a way that the next stage in the process becomes possible (Graham 2003), like any good positive feedback. The initial stage in terraforming Mars will be dominated by microorganisms and lichens (Graham 2003). This would require removing carbon dioxide from the Martian atmosphere, adding oxygen and nitrogen, and adding organics to the regolith to produce a true Martian soil (Graham 2003). The second stage will be dominated by bryophytes, simple plants such as mosses and liverworts, which will draw down the carbon dioxide level of the Martian atmosphere and raise the level of oxygen (Graham 2003). The critical limiting factors for the introduction of flowering plants are the level of oxygen in the atmosphere and the lack of animal pollinators (Graham 2003). The majority of flowering plants require a minimum oxygen level of 20 to 50 mbar (Graham 2003), and certain aquatic plants and arctic plants, however, are highly tolerant of anoxic conditions.

Figure 13 shows an artists rendition of the Martian surface, post-terraformation (sea level stable, cryosphere developed, and the biosphere has taken hold). Notice the polar sea ice and glacial caps on the Tharsis region volcanoes. The difficulties in terraforming Mars are that we are dealing with a radiative

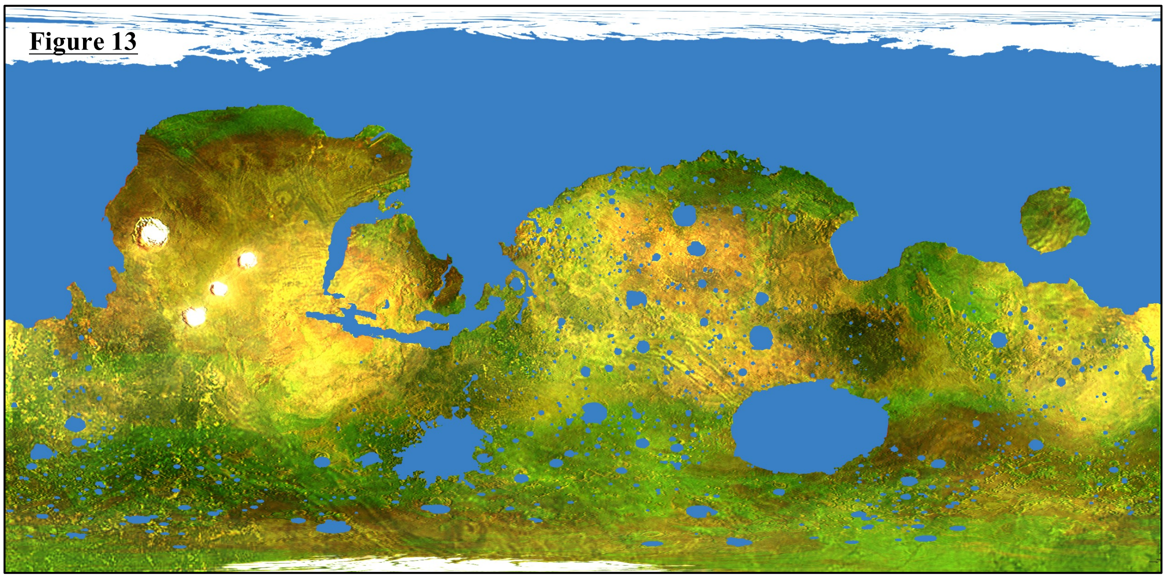
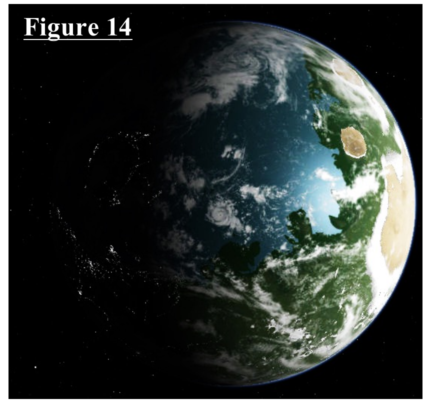


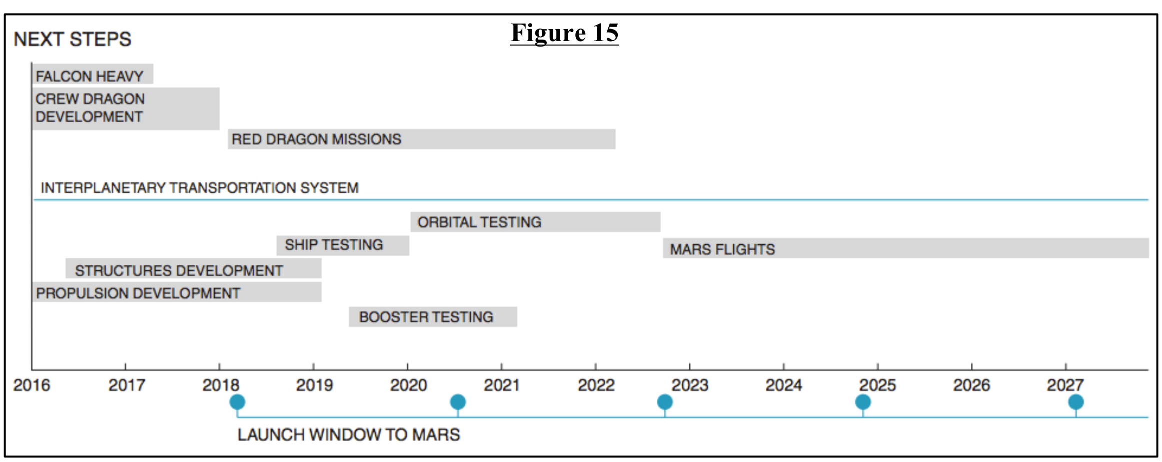
Figure 13

deficit, compounded by a lack of resources (Moores and Melo 2003). This suggests that a number of techniques will be required to act synergistically in order to improve the habitability of the planet. Additionally, the initial contamination of a planet with Earth life is to be minimized in order to facilitate a search for planetary life (Todd 2006). In order to sustain human life there needs to be large-scale modifications of the planetary environment (i.e., Todd 2006). The main considerations for terraforming Mars are how to change the temperature, water level, atmospheric composition, and atmospheric pressure. Environmental change on the Earth is imminent from anthropogenic causes and will also occur on a longer timescale from natural climate cycles – such as ice ages (McKay 2011). These natural changes make the eventual geo-engineering of the Earth inevitable. The question is not if, but, when and how. A habitable Mars is not necessarily a "lifeboat" for the Earth (McKay 2011), but it would help us understand the colonization of geochemically and biologically dead planets, while providing deep and useful insights into the potential biospheres of planets and moons.

A drastic modification of Martian conditions can be achieved using 21st century technology (Zubrin and McKay 1997). The Mars so produced will closely resemble the conditions existing on the primitive Mars (Zubrin and McKay 1997). Humans operating on the surface of such a Mars would require breathing gear, but pressure suits would be unnecessary (Zubrin and McKay 1997). With outside atmospheric pressures raised, it will be possible to create large dwelling areas by means of very large inflatable structures (Zubrin and McKay 1997). Average temperatures could be above the freezing point of water for significant regions during portions of the year, enabling the growth of plant life in the open (Zubrin and McKay 1997). The spread of plants could produce enough oxygen to make Mars habitable for animals in several millennia (Zubrin and McKay 1997). More rapid oxygenation would require engineering efforts supported by multi-terrawatt power sources (Zubrin and McKay 1997). The desire to increase the speed of the terraforming of Mars (i.e., Figure 14) will be a driver for developing such advanced and megs-scale technologies, which in turn will define a leap in human power over nature as we advanced toward a type-1 civilization.



Ultimately, the exploration of Mars will be the first step for humanity in the colonization of other worlds, and we will do this within the next 100 years (Musk 2017). The two most important factors in the quest to colonize and eventually terraform Mars are reducing the cost by increasing reusability and propellant production on the surface (Musk 2017). SpaceX's recent achievements of reducing their costs through reusability has shown us that the feasibility of colonizing our nearest neighbor is possible, today more than ever, this is extremely relevant to our fate as a species. Each day on Earth that brings us closer to climate change, overpopulation and accelerating industrialization will eventually bring humanity to a state of crisis. We must continue researching viable technologies in the realm of planetary-scale engineering, as well as the eventual cost-allowing (200,000 USD/person) shipment of a nearly 100,000 person human colony to Mars (Musk 2017) within the century. Ever-increasing problems are global increase in average temperature by 1°C (1.8°F), sea ice melting, coral reefs dying, and ecosystems collapsing, and now we only have 3 years left to prevent a full blown climate catastrophe (Figueres et al. 2017). A Summary of Elon Musk's SpaceX presentation at the 67th International Astronautical Congress in Guadalajara, Mexico can be found in the references as Musk (2017). The timescale below (Figure 15 from Musk 2017) suggesting we should send at least a total of 5 fleets of ships by 2027 – in just 10 years to quickly colonize Mars.



2.2 Venus

Altering the conditions of the planet Venus was initially suggested by Carl Sagan in the journal *Science* in 1961. He imagined planetary engineering through a process of seeding the atmosphere with algae, converting water, nitrogen and carbon dioxide into more complex organic molecules (Sagan 1961). Removing CO_2 from the atmosphere, and reducing its pressure would cool Venus and reduce its greenhouse effect until surface temperatures reached near-habitable conditions, around 273–373 K (e.g., Sagan 1961; Dyson 1989). Terraforming Venus requires 2 major changes; removing most of the planet's dense 9 MPa carbon dioxide atmosphere and reducing the planet's 450 °C (723.15 K) surface temperature (Birch 1991). These goals are closely interrelated, because Venus's extreme temperature is thought to be due to the greenhouse effect caused by its dense atmosphere (Birch 1991). The atmospheric structure of Venus compared to the Earth and Mars is given in Figure 16 below.

The work of Birch (1991) laid out the general foundations for the terraforming of Venus, including the economic considerations, population growth, and megascale environmental engineering. The low end of the timescales for cooling Venus are within ~200 years, suggested by Birch (1991), but the upper limit suggested it could take as long as 10,000 years. I show that a more reasonable timescale is in between the two around 3,000–4,000 years for Venus. Another common proposal is purely sequestering of the atmospheric carbon in order to solve the temperature problem (e.g., Birch 1991; Dyson 1989). Removing its massive atmosphere is the single greatest obstacle in terraforming Venus (e.g., Fogg 1987). Another potential method – transforming Venus by induced overturn – was first suggested by Smith (1989). Gillett (1991) suggests that stabilizing Earth-like conditions will be difficult, but suggests that using little water and hypersaline seas, to reduce the vapor pressure of water, are possible solutions. Speculations resulting from the observations of Robins et al., (2015) suggest that life's origin could have been intimately related to chemical/physical processes occurring where volcanic sources discharged iron through highly porous siliceous substrates and into the primitive ocean. The diverse community also provides a potentially useful ecosystem for Mars terraforming experiments (Robins et al., 2015). Figure 17 shows two different stages in the future evolution of the planet Venus after atmospheric removal, post-terraformation.

Figure 16

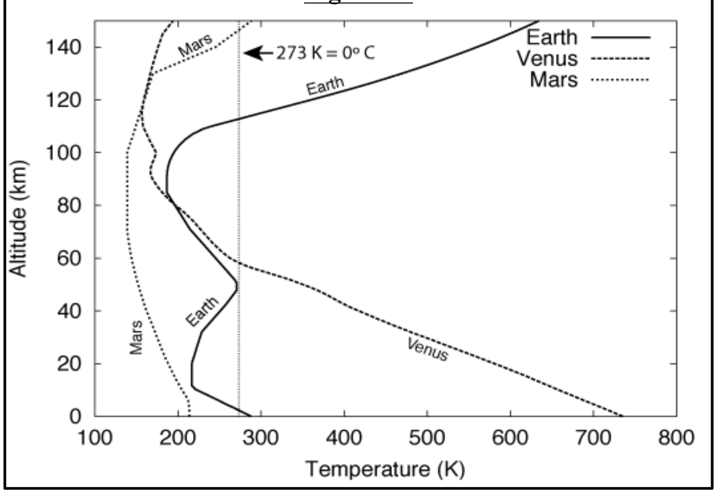


Figure 17

The terraforming of Venus after the removal of nearly ~6.9 MPa of atmosphere would initially include the addition of the oceans, which would collect at the poles of Venus, since the equatorial region is highest in elevation. Figure 18 is a table using data from NASA.gov that shows all of the governing planetary characteristics (discussed in section 1.1) of the 5 main Terrestrial worlds of Sol. This table is what we can consider for the initial conditions, mission year zero, for terraforming.

Figure 18

Planetary Parameter	Mercury	Venus	Earth	Moon	Mars
Mean Surface T (ºC)	167	460	15	-31	-60
Mean Radius (km)	2440	6053	6371	1738	3390
Surface Pressure (Pa)	0	9.5E+06	101230	0	600
Scale Height (km)	–	15.9	8.5	–	11.1
Atmosphere	Trace	CO_2, N_2, SO_2	N_2, O_2, Ar	Trace	CO_2, N_2, O_2
Surface	Rock	Rock, lava	Water, rock, ice	Rock	Rock, ice
Mass (kg)	3.30E+23	4.87E+24	5.97E+24	7.30E+22	6.42E+23
Density (kg/m^3)	5427	5243	5515	3344	3933
Surface Gravity (m/s^2)	3.7	8.9	9.8	1.6	3.7
Magnetic Field	None	Dormant	Strong	Trace	Dormant
Bond Albedo	0.068	0.77	0.306	0.11	0.25
Topographic Range	7	13	20	13	30
Stellar Flux (W/m^2)	9083	2601	1361	1361	586
Orbital Radius (km)	5.791E+07	1.082E+08	1.496E+08	1.496E+08	2.279E+08
Orbital Period (days)	87.97	224.7	365.26	29.53	686.98
Rotation Period (hrs)	4222.6	3039.7	23.9345	27.3217	24.6229
Obliquity (º)	0.034	177.4	23.4393	6.68	25.19
Eccentricity	0.2056	0.0068	0.0167	0.0549	0.0935

2.3 Earth

Our home planet is the reference point to which we consider a planet habitable. There are likely countless other possibilities for 'habitability' and the ability to host life, such as varying the atmospheric chemistry, and geology of terrestrial planets and moons. For human life, we consider planetary engineering to habitable and stable conditions to be called terraforming – or Earth-shaping. The Earth is undergoing dramatic climate shifts due to anthropogenic forcing of the climate (i.e., IPCC 2014; NASA 2017). In order for us to save the planet from extreme changes, I hope you would agree that we must act quickly and cooperatively. We do have the technology and the means to save the planet from extreme changes that would result from our current course and direction. To save the planet, we can break the steps down to more easily tackle the problem. In order to reverse the effects of climate change on the Earth, I propose these 5 steps, in chronologic order, for stopping, or reversing the effects of global climate change:

1. Net growth of the biosphere (natural removal of CO2)
2. Increased renewable resources (to power steps 3–5)
3. Net technological removal of CO2 (equilibrium at ~100 ppm)
4. Net reduction of increasing emission rates of CO2
5. Net removal of CO2 from the oceans

For the purpose of this paper, climate change is the term used to describe the temporal evolution of a planetary atmosphere. This is essentially a game of atmospheric equilibrium with the geochemistry of the surface, ocean, and biosphere. Atmospheric pressure, temperature, continental land mass distribution, ocean currents, atmospheric currents, and total energy balance (or budget) are the main things that dictate the evolution of a planetary atmosphere. The Earth experiences 'natural' (meaning non-anthropogenic) climate change forcings due to slight variations in solar irradiance, the eccentricity, obliquity, and precession of the Earth. The energy distributed throughout a planet's oceans is constrained by the orientation, shape, and bathymetry of the continents. The modern shape of the continents leads to the Earth's modern ocean-energy climate distributions (such as El Nino and La Nina). The forcing that humans are creating is adding energy to the atmosphere in the form of greenhouse gasses. The 2 most important of these to talk about are carbon dioxide (CO_2) and methane (CH_4). These are being anthropogenically added to our atmosphere everyday, and they ultimately lead to a net increase of Earth's average global temperature. Simply due to the increased energy 'budget' of the Earth, locally, climates will be shifted into extreme heat waves, extreme cold, droughts, forest fires, flooding, extreme storms, and likely costal drowning.

Technologies for reversing the effects of climate change, which would also be used in terraforming, are carbon sequestration plantations (i.e. Pazar 2017). On the Earth, we would need to remove ~700 billon metric tons. This is not that unrealistic for humans to technologically convert into carbonate rock if we power them with 100% renewable energy. For example, from 2011 to 2014, China produced 640 billion metric tons of cement in three years alone, driven by rapid industrialization (i.e., supply and demand). So we are therefore tasked with removing ~7 billion metric tons per year of carbon, which becomes a feasible task if we want to remove ~700 billion metric tons in the next ~100 years. This is of course after assuming the economic cost reductions and sufficient renewable power supply. This application modeling research suggests that humans could do it in less than 100 years, if we cooperate and act quickly.

2.4 Mercury, dwarf planets, and moons

Other possible candidates for terraforming include Titan, Callisto, Ganymede, Europa, the Moon, Mercury; Saturn's moon Enceladus, and the dwarf planets Ceres and Pluto. The main problem facing the colonization and sustainability of these worlds is their low gravity presents a challenge in their ability to retain an atmosphere. It is possible however, that if the technological and artificial rate of gas emissions produced from the surface is able to counter-balance the atmospheric erosion and escape from the top of the atmosphere, that in theory, the net pressure could remain fixed and suitable for human colonization. On small worlds, this obviously may not remain sustainable for long time scales, but still remains a possibility for hopping to-and-from different moons and planets in hopes of temporary colonization and/or resource extraction. Planets such as Mercury present a threat to future colonization because of the extremely high temperatures and high levels of radiation at the surface. In contrast, worlds at the edge of the solar system would have a hard time harnessing solar energy and would likely be powered by nuclear and geotherm energy sources in order to sustain high enough temperatures on future potential colonies.

Figure 19 below shows two tables that give data from NASA.gov and shows all of the governing planetary characteristics (previously discussed in section 1.1) of the 10 additional moons and dwarf worlds of our solar system. This table is what we consider for the initial conditions, mission year zero, for terraforming.

Figure 19

Planetary Parameter	Io	Europa	Ganymede	Callisto
Mean Surface T (ºC)	-155	-170	-160	-155
Mean Radius (km)	1821.5	1560.8	2631.2	2410.3
Surface Pressure (Pa)	1.00E-04	1.00E-07	1.00E-07	7.50E-07
Scale Height (km)	–	–	–	–
Atmosphere	Trace, CO_2, SO_2	Trace, O_2	Trace, O_2	Trace, CO_2
Surface	Rock, lava	Ice	Rock, ice	Rock, ice
Mass (kg)	8.93E+22	4.80E+22	1.48E+23	1.08E+23
Density (kg/m³)	3530	3010	1940	1830
Surface Gravity (m/s²)	1.80	1.31	1.43	1.24
Magnetic Field	Possible	Weak	Normal	Trace
Albedo	0.62	0.68	0.44	0.19
Topographic Range (km)	8	1	6	2
Stellar Flux (W/m²)	50.26	50.26	50.26	50.26
Orbital Radius (km)	4.22E+05	6.71E+05	1.07E+06	1.88E+06
Orbital Period (days)	1.769138	3.551181	7.154553	16.689017
Rotation Period (hrs)	42.459312	85.228344	171.709272	400.536408
Inclination (º)	0.04	0.47	0.18	0.19
Eccentricity	0.004	0.009	0.001	0.007

Planetary Parameter	Tethys	Dione	Rhea	Titan	Iapetus	Oberon
Mean Surface T (ºC)	-187	-187	-197	-179	-163	-198
Mean Radius (km)	538	562	763	2575	735	761
Surface Pressure (Pa)	–	–	–	146700	–	–
Scale Height (km)	–	–	–	40	–	–
Atmosphere	Trace	Trace, O_2	Trace, CO_2, O_2	N_2, CH_4, H_2	Trace, CO_2, O_2	Trace
Surface	Ice	Ice	Ice	Ice, methane	Ice, rock	Rock, ice
Mass (kg)	6.18E+20	1.10E+21	2.31E+21	1.35E+23	1.81E+21	3.01E+21
Density (kg/m³)	985	1480	1240	1880	1090	1630
Surface Gravity (m/s²)	0.15	0.23	0.264	1.352	0.223	0.346
Magnetic Field	Trace	Trace	Trace	Trace	Trace	None
Albedo	0.67	0.7	0.7	0.22	0.05–0.5	0.2
Topographic Range (km)	12	3	3	2	20	4
Stellar Flux (W/m²)	14.82	14.82	14.82	14.82	14.82	3.69
Orbital Radius (km)	2.95E+05	3.77E+05	5.27E+05	1.22E+06	3.56E+06	5.84E+05
Orbital Period (days)	1.887802	2.736915	4.518212	15.945	79.3215	13.463234
Rotation Period (hrs)	45.307248	65.68596	108.437088	382.68	1903.716	323.117616
Inclination (º)	1.12	0.019	0.345	0.349	15.47	0.07
Eccentricity	0.0001	0.0022	0.0013	0.0288	0.0286	0.0014

2.5 Hypothetical worlds

Hypothetical exoplanetary candidates are also considered for purposes of applying the terraforming models to new knowledge that has emerged of the diversity and unique properties of the potential exoplanets all over the galaxy. We consider a range of four hypothetical exoplanets (Figure 20 next page) to colonize that are named Bacchus, Pontus, Ragnarok, and Boreas. We will go over these four planet's characteristics starting from the one closest to the star and moving outward. Each one has unique properties that are theorized based on their size and astrophysical parameters that governed their theoretical evolution.

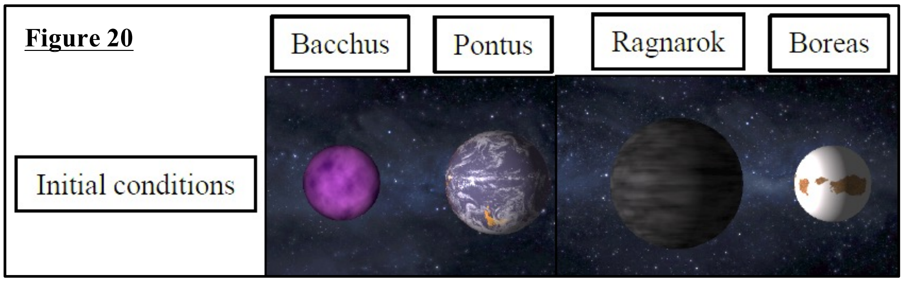


Figure 20

Bacchus is a beautiful world of purple color and complicated rock formations, created by the unique composition of the planet's crust and the gravitational influence of nearby planets. We expect colonization to be fairly straightforward following the same pathways as it took to colonize Mars. This world is only slightly larger than the Earth, and closest to its host star. Pontus is a super-Earth water world. The goal initially on this planet is to reduce sea level that would reveal new lands for colonization and new planet for humanity to colonize. Ragnarok is a super-Earth world as well; over three times the size of the Earth. It is incredibly rich with metals and minerals, and is in technically in the habitable zone for liquid water. However, this world is ridden with a dark thick atmosphere full of ash and poisonous volcanic gasses. There are lava-exposed rifts on the surface, created by an unstable core and mantle. This planet also has a strong magnetic field, preventing much atmospheric erosion and protecting the surface from harmful radiation. The last world, lingering on the outer edge of its solar system is Boreas. The coldest world yet to be targeted for colonization, where massive polar ice caps cover most of its surface, with only small amounts of land exposed around the equator. These worlds, while hypothetical in nature, provide insight into the potential for future colonization and terraforming, as well as the diversity of planets in the galaxy.

2.6 Exoplanets

Known existing exoplanets and exoplanet candidates are also considered in this analysis. We test with the TerraGenesis model the 7 worlds of the TRAPPIST-1 system, as well as considering what it would take and the timescales involved for the colonization of nearby exoplanets, such as the nearest one to the Earth, Proxima b. Perryman (2015) published an info graphic in July 2015 showing the detection of 1931 exoplanets: 1221 systems, 484 multiple, 1210 of which from transiting planets. As of October 2017, we have confirmed nearly 3000 exoplanets, with at least 30 earth-sized planets in the habitable zone for liquid water, and the number continues to grow as we comb through the data and confirm results from past observations (e.g., Witze and Krzysztofiak 2015; Gillon et al., 2017; Wittenmyer et al., 2014; Southworth et al., 2017). Countless fresh discoveries are being made, including the discovery of water and CO in an exoplanet atmosphere (Konopacky et al., 2013), water vapor absorption in the clear atmosphere of a Neptune-sized exoplanet (Fraine et al., 2014) and a temperate rocky super-Earth transiting a nearby cool star (Dittmann et al., 2017) to name just a few. Earth sized and super-Earth sized worlds are abundant and around Kepler 68, Kepler-68b has a 5.4 day orbit, with a mass of $8.3 \pm 2.4\ M_{\oplus}$, a radius of $2.31 \pm 0.09\ R_{\oplus}$, and density of 3.32 ± 0.98 g cm^{-3}, giving Kepler-68b a density intermediate between that of the ice giants

References

Abramov, O., Mojzsis, S. J., 2009. Microbial habitability of the hadean earth during the late heavy bombardment. Nature, 459, 419–422

Airapetian, V., Glocer, A., Khazanov, G., Liemohn, M. W., 2017. How Hospitable Are Space Weather Affected Habitable Zones? The Role of Ion Escape. The Astrophysical Journal Letters, 836, 1.

Barge, L. M., Branscomb, E., Brucato, J. R., Cardoso, S. S., et al., 2016. Thermodynamics, Disequilibrium, Evolution: Far-From-Equilibrium Geological and Chemical Considerations for Origin-Of-Life Research. Origins of Life, Evolution, Biospheres. Doi:10.1007/s11084-016-9508-z

Barsoum, C., 2014. The Thermodynamics of Planetary Engineering on the Planet Mars. Thesis. College of Mechanical and Aerospace Engineering and in The Burnett Honors College at the University of Central Florida, Orlando, Florida.

Birch P., 1992. Terraforming Mars Quickly. JBIS, 45, 331–340. Article.

Birch, P., 1991. Terraforming Venus Quickly. JBIS, 44, 157–167. Article.

Bouvier, A., Wadhwa, M., 2010. The age of the Solar System redefined by the oldest Pb–Pb age of a meteoritic inclusion. Nat. Geosci. 3, 637–641. doi:10.1038/ngeo941

Brasser, R., Mojzsis, S. J., Werner, S. C., Ida, S., 2016. Late veneer and late accretion to the terrestrial planets. Earth and Planetary Science Letters, 455.

Budzik, J. M., 2001. How to Terraform Mars: An Analysis of Ecopoiesis and Terraforming Research. Thesis.

Cervantes, S., Garcia, C. G., Mendoza, V. M., René, G., 2011. Terraforming Mars: Global Warming Scenarios using Different Combinations and Pressures of 5 Greenhouse Gases. Conference Paper.

Cover photo URL: http://4.bp.blogspot.com/-905v8SpAHKU/UybsSc_B2SI/AAAAAAAA4qU/-X_tD3a6Ijc/s1600/169128_Papel-de-Parede-Particao-oculta_1400x1050.jpg C8vgp6_UwAA1WaQ.jpg

Clacey, E., Gronstal, A., Grubisic, A., Pérez, J.E. A., Rogers, D., Bittner, T., et al., 2005. Visysphere Mars - Terraforming Meets Engineered Life Adaptation, Studies in the future of experimental terraforming techniques. Retrieved on researchgate.com.

Dittmann, J. A., Irwin, J. I., Charbonneau, D., et al., 2017. A temperate rocky super-Earth transiting a nearby cool star. Nature 544, 333–336. doi:10.1038/nature22055.

Dyson, F., 1989. Terraforming Venus. Correspondence in JBIS, 42, 593.

Early, J. T., 1989. Space-based Solar Shield to Offset Greenhouse Effect. JBIS, 42, 567–569. Article.

Fogg, M. J., 1987. The Terraforming of Venus. JBIS, 40, 551–564.

Fogg, M. J., 1989. The Creation of an Artificial, Dense Martian Atmosphere: A Major Obstacle to the Terraforming of Mars. JBIS, 42, 577–582.

Fogg, M. J., 1992. A Synergic Approach to Terraforming Mars. JBIS, 45, 315–329.

Fogg, M. J.,1995. Terraforming: The Engineering of Planetary Environments. SAE International.

Fogg, M. J., Terraforming Mars: A review of current research. 1998. Advances in Space Research.

Fraine, J., Deming, D., Benneke, B., Knutson, H., Jordan, A., Espinoza, N., Madhusudhan, N., Wilkins, A., Todorov, K., 2014. Water vapour absorption in the clear atmosphere of a Neptune-sized exoplanet. Nature 513, 526–529. Doi:10.1038/nature13785.

Frank, E. A., 2014. Temporal Limits on the Habitability of Rocky Worlds. University of Colorado Boulder, Boulder, Colorado. Doctoral Dissertation in the Department of Geological Sciences.

Freitas, R. A., 1985. Terraforming Mars and Venus Using Machine Self-Replicating Systems. JBIS, 36, 139–142.

Gillett, S. L., 1991. Establishment and Stabilization of Earthlike Conditions on Venus. JBIS, 44, 151–156.

Gilliland, R. L., Marcy, G. W., Rowe, J. F., et al., 2013. Kepler 68: Three Planets, One with a Density Between that of Earth and Ice Giants. The Astrophysical Journal, 766:40, 1–19.

Gillon, M., Triaud, A. H. M. J., Demory, B. O., Queloz, D., Jehin, E., Agol, E., et al., 2017. Seven temperate terrestrial planets around the nearby ultra cool dwarf star TRAPPIST-1. Nature.

Graham, J. M., 2003. Stages in the Terraforming of Mars: the Transition to Flowering Plants. AIP Conf. Proc. 654, 1284. http://dx.doi.org/10.1063/1.1541431

Haqq-Misra, J., 2012. An Ecological Compass for Planetary Engineering. Astrobiology. Article.

Hickman, J., 1999. The Political Economy of Very Large Space Projects. Journal of Evolution and Technology, 4.

Hiscox, J., Fogg, M. J., 2001. Terraforming Mars and the long-term habitation of mars. Space Science, 43.

Kahwaji, R., Ghantous, B., 2011. Terraforming, A Reality Or Science Fiction? 62nd International Astronautical Congress, 3.

Keitha, D., Lavoie, R., Eisingera, C., (2009), An overview of the wabamunarea co_2 sequestration project (wasp).

Konopacky, Q. M., Barman, T. S., Macintosh, B. A., Marois, C., 2013. Detection of Carbon Monoxide and Water Absorption Lines in an Exoplanet Atmosphere. Science, 339, 6126, 1398–1401.

Luther, R., Wagner, F. W., Sohl, F., Knapmeyer, M., 2010. A Tool for the Seismological Evaluation of Interior Structure Models of Terrestrial Planets. EPSL Poster.

McKay, C. P., 1982. Terraforming Mars. JBIS, 35, 427.

McKay, C. P., 1993. Restoring Mars to habitable conditions: Can we? Should we? Will we? Journal of the Irish Colleges of Physicians and Surgeons. Article.

McKay, C. P., 2004. Biology and The Future of Mars. NASA. Conference Paper.

McKay, C. P., 2008. Planetary Ecosynthesis on Mars: Restoration Ecology and Environmental Ethics. NASA Ames Research Center.

McKay, C. P., 2011. Planetary Ecosynthesis on Mars and Geo-Engineering on Earth: Can We? Should We? Will We? Article.

McKay, C. P., Toon, O. B. and Kasting, J. F., 1991. Making Mars Habitable. Nature, 352, 489–496.

McKay, C. P., Marinova, M. M., 2002. Astrobiology. NASA. Presentation.

McKay, C. P., Zubrin, R. M., 2002. Do Indigenous Martian Bacteria have Precedence over Human Exploration? On to Mars: Colonizing a New World, Apogee Books Space Series, ISBN 1-896522-90-4. 177–182.

McMahon, S., 2016. The Aesthetic Objection to Terraforming Mars. Retrieved from researchgate.com.

Michaelian, K., Simeonov A., 2017. Thermodynamic Explanation for the Cosmic Ubiquity of Organic Pigments. Journal of Astrobiology Outreach, 5, 1–10.

Mohammad, M., 2012. A Quantitative Investigation of CO2 Sequestration by Mineral Carbonation. Student Member, IEEE. Student Article.

Moores, J., Melo, S., 2003. Radiative Processes in Terraforming. Undergraduate Article.

Morgan, C. R., 1994. Terraforming with Nanotechnology. JBIS, 47, 311–318.

Musk, E., 2017. Making Humanity a Multi-Planetary Species. New Space 5, p 46–61. DOI: 10.1089/space.2017.29009.emu.

NASA, 2016. "Goal 1: Understand the nature and distribution of habitable environments in the Universe". Astrobiology: Roadmap.

Perryman, M., 2015. Exoplanet detection methods information graphic as of July 2015, Paris Observatory.

Preston, L. J., Dartnell, L. R., 2014. Planetary habitability: lessons learned from terrestrial analogues. International Journal of Astrobiology 13, 1, 81–98. doi:10.1017/S1473550413000396

Quintana, E. V., Barclay, T., Raymond, S. N., et al., 2014. An Earth-Sized Planet in the Habitable Zone of a Cool Star. Science, 344, 277–280. Doi:10.1126/science.1249403

Robbins, E., Kourtidou-Papadeli, C., Iberall, A. S., Sato, M., 2015. From Precambrian Iron-Formation to Terraforming Mars: The JIMES Expedition to Santorini. Article in Geomicrobiology.

Sagan, C., 1961. The Planet Venus. Science, 133, 3456, 849–58.

Sagan, C., 1973a. Planetary Engineering on Mars. Icarus, 20, 4, 513.

Sagan, C., 1973b. Climactic Change on Mars. Science, 181, 1045–1049.

Seifritz, W., 1989. Mirrors to Halt Global Warming? Nature, 340, 603. Article.

Sole, R., Duran-Nebreda, S., Martinez, R. M., 2015. Synthetic circuit designs for Earth terraformation. Biology Direct. Doi: 10.1186/s13062-015-0064-7.

Smith, A. G., 1989. Transforming Venus by Induced Overturn. JBIS, 42, 571–576.

Taylor, Richard L.S., 1992. Paraterraforming: The Worldhouse Concept. JBIS, 45, 341–352.

Todd, P., 2006. Planetary Biology and Terraforming. Gravitational and Space Research. Article.

Weidenschilling, S.J., 1977. Aerodynamics of solid bodies in the solar nebula. Mon. Not. R. Astron. Soc. 180, 57–70. doi:10.1093/mnras/180.2.57

Winn, A., 2017. TerraGenesis App., volume 3.0, an iPhone application and dynamic model interface.

Witze, A., Krzysztofiak, J., 2015. Exoplanets: The Next 20 Years. Infographic. Nature, 288, 527.

Wittenmyer, R. A., Tuomi, M., Butler, R. P., Jones, H. R. A., Anglada-Escudé, G., Horner, J., Tinney, C. G., Marshall, J. P., Carter, B. D., Bailey, J., et al., 2014. GJ 832c: A Super-Earth in the habitable zone. The American Astronomical Society. The Astrophysical Journal, 791, 2.

Zubrin, R. M., 1996. The Case for Mars: The Plan to Settle the Red Planet and Why We Must. Simon & Schuster/Touchstone, 248–249, ISBN 0-684-83550-9.

Zubrin, R., 2001. Entering Space: Creating a Space-Faring Civilization. Putnam.

Zubrin, R. M., McKay, C. P., 1997. Technological requirements for terraforming Mars. Journal of the British Interplanetary Society.