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Chosen problems of terraforming Mars

Abstract: Consideration was given to creating an atmosphere on Mars that would enable people to stay on the surface of Mars without spacesuits. The source of matter for this atmosphere are bodies brought from the outer zones of the Solar System. The Kuiper belt is the best source of these bodies. The energy needed to bring them was estimated. Depending on the variant, this energy ranges from 21% to 800% of the energy currently consumed by humanity annually.

Keywords: Terraforming; Mars; Kuiper Belt; Armstrong limit; Gravity assist

Introduction

The successes of astronautics bring us closer to the expedition to the "Red Planet". However, significant colonization is still a long way from the scientific expeditions of a few people. It will take several generations before there is a community for which Mars will be their home planet.

On Earth we still have uninhabited areas of the Arctic and Antarctica. There, potential settlers do not have to worry about breathing air and drinking water. They won't have such "luxuries" on Mars. If we think about mass emigration and a growing Earth colony on Mars, we need to think about those basic goods that we do not appreciate while living on Earth. This brings us to the idea of terraforming of Mars.

Atmospheres of Earth and Mars

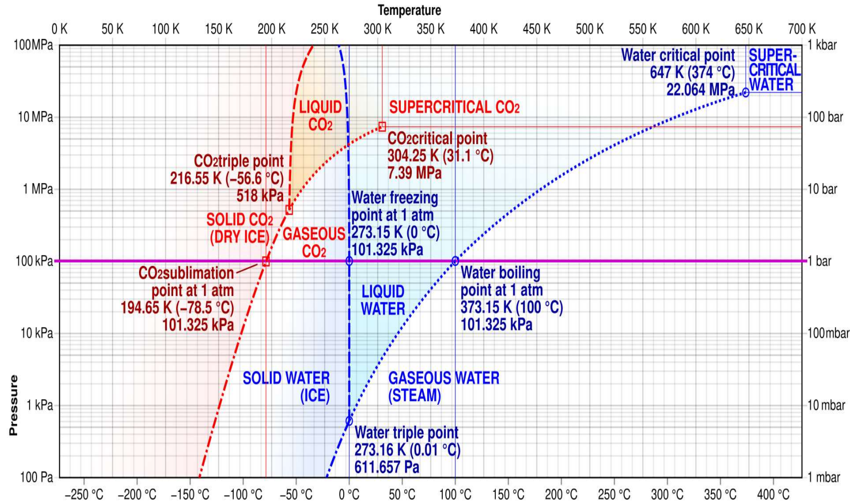
From the point of view of the colonization of Mars, the most important are the differences between the atmospheres of Earth and Mars. Atmospheric pressure on the surface of Mars ranges from 72 Pa at the top of Olympus Mons (Mars' highest mountain) to 1.16 kPa at the bottom of Hellas Planitia (Mars' lowest lowland). For the adopted reference level on Mars, the average value is 610 Pa [1]. At the top of Mount Everest on Earth, the pressure is 33.7 kPa, and for the reference level on Earth: 101.3 kPa.

Water at a pressure below 6.25 kPa boils at human body temperature. - Fig. **1.** This pressure value determines the so-called Armstrong limit. At lower pressure, the pressure suit is necessary. However, since we often have to operate at higher temperatures, it is worth adopting a slightly higher minimum pressure, e.g. p_{50} = 10 kPa. Then the water will boil only at ~50°C.

The current mass of Mars' atmosphere is 2.5×10^{16} kg [1]. Note that the pressure is proportional to the mass of the atmosphere. We are considering the terraforming variants described in Table **1.** The C parameter means how many times we must increase the mass of the atmosphere to obtain a given variant. The next column contains the mass. R_{1000} and R_{500} are the radii of the bodies needed to bring to Mars in a given variant, assuming body densities of 1000 kg m^{-3} and 500 kg m^{-3}, respectively.

Possible sources of volatile substances

For the terraforming of Mars, we should take care to import the right elements. The composition of the original gas and dust cloud from which the Solar System was formed is quite well known. It was determined from the composition of meteorites and the Sun's atmosphere (the layer that stored the initial composition of the cloud). We also have theoretical models of the formation of elements.



1. Phase diagrams of H_2O and CO_2. This figure is licensed under the Creative Commons Attribution-Share Alike 3.0 Unsorted license. Author. Cmglee Wikipedia

Tab. 1. Variants of terraforming considered in the paper

Variant	Description	C	Required mass [kg]	R_{1000} [m]	R_{500} [m]
v1	Armstrong l. at Hellas	5,4	1,096E+017	29696	37415
v2	p_{50} at Hellas	8,6	1,905E+017	35696	44974
33	Armstrong l. at h=0	10,2	2,311+017	38072	47967
v4	p_{50} at h=0	16,4	3,848E+017	45123	56851
v5	Pressure 101,3 at Hellas	87,3	2,1581E+018	80168	101005
v6	Pressure 101,3 at h=0	166,1	4,1266E+018	99503	125366

Celestial bodies orbiting far from the Sun have large amounts of volatile substances, including H_2O, CO_2, N, HCN, NH_4, etc. This is evidenced by comets arriving from the peripheral parts of the solar system. Comet 67P/Churyumov–Gerasimenko has a density of 470 kg m^{-3}, which indicates a high content of volatile substances. The mass of this comet is: 9.98×10^{12} kg [2] .

An overview of the solar system shows three places where we have many bodies large enough to bring them to Mars: the asteroid belt (AB) between the orbits of Mars and Jupiter, the Kuiper Belt (KB) beyond the orbit of Neptune), and Oort Cloud (OC) [3]. The bodies used for terraforming will eventually collide with Mars. That's why we will call them here: impactors.

The closest collection of these bodies to Mars is the asteroid belt. Its mass is 2.39×10^{21} kg. This mass is several hundred times greater than needed for terraforming. However, MB bodies are significantly depleted in light elements and their compounds, as evidenced by their high density. For Ceres it is 2162 kg m^{-3} [3]. Therefore, the MB is not a source of material to recreate the atmosphere and hydrosphere of Mars.

Jupiter's Trojan asteroids constitute 20% of the mass of the AB [3], but the composition and stability of their orbits may be obstacles to their use for terraforming.

The Kuiper belt (KB) extends from about 30 to 55 a.u. from the Sun. Its shape resembles a torus. It is believed to contain over 70,000 objects over 100 km in diameter. The mass of KB is approximately 1/30 of the mass of the Earth [3, 4], enough to regenerate the atmosphere and hydrosphere of Mars. In fact, one body with a diameter of over 100 km would be enough - Table **1.**

The Oort Cloud OC is still a hypothetical object (not directly observed), but the effects of its existence (comets) are observed. It contains, among others, billions of bodies with a diameter of over 20 km. The total mass is ~3×10^{25} kg [5]. The chemical composition meets our goals, but the problem is the large distance of OC from the Sun. In Table **2** we have given the approximate distance of the inner edge of the OC (2000 a.u. from the Sun).

Tab. 2. Selected Parameters

1	2	3	4	5	6	7	8	9
Objects	**Initial distance [a.u.]**	**Time of falling [yr]**	**v_{orb} [km/s]**	**v_{fall} [km/s]**	**$Dv=v_{fal}-v_{orb\ Mars}$**	**Chemical engine (NH_4+O_2) 380 s**	**Nerva (thermal nuclear) 841 s**	**Ionic engine 10000 s**
MB inner limit	2,2	3,86E-01	20,07	18,92	-5,18	0,052410	0,024031	0,002044
Jupiter (trojan)	5,2	1,94E+00	13,05	28,68	4,58	0,034410	0,015697	0,001330
Kuiper B. inner l.	30	2,90E+01	5,43	33,23	9,13	0,014472	0,006565	0,000554
Kuiper B. outer l.	50	6,25E+01	4,21	33,59	9,49	0,011229	0,005089	0,000429
Oort C. inner limit	2000	1,58E+04	0,67	34,10	10,00	0,001784	0,000806	0,000068

(1) Source of the matter. (2) semi-major axis w [a.u.], 1 a.u.=~150 mln km, (3) Time of falling [yr] from (1) to Mars' orbit. (4) orbital velocity v_{orb} for given semimajor axis [km/s]. (5) final velocity of falling v_{fall} from distance (1) to Mars' orbit [km/s]. (6) $v=v_{fall} - v_{orb\ Mars}$ [km/s]. (7, 8, 9) mass of propellant used to reducing v_{orb} to 0,99 v_{orb} for specific impuls [s] for: (6) chemical engine (NH_4+O_2), (7) for Nerva (thermal nuclear), (8) for ionic engine.

Transport of bodies

The above reasoning shows that, due to its composition, it is worth considering transport from two places: from KB and from OC. Table **2** shows the basic quantities: including the distance from the Sun and the orbital velocity of bodies located at a given distance (in a circular orbit).

The easiest method to calculate for transporting a body from distant US regions, such as KB and OC, is to reduce its speed to almost zero (in the calculations we assume reduction to zero). The body will then start falling towards the Sun. The fall time is shown in column 3, and column 5 shows the velocity of the body (impactor) when it reaches the orbit of Mars. Column 6 shows the difference of the speed of the body and Mars, i.e. the relative speed at which the collision would occur (assuming that Mars and the impactor are moving in the same direction).

The important result is the fall time. This time for KB bodies ranges from 29 to 63 years, and for OC bodies it is over 15,000 years. The time scale for planning and implementing investments of several dozen years is acceptable in today's society, e.g. the time scale of forest management. However, the time of 15,000 years exceeds possible scales. So, we should use KB bodies for terraforming.

To change the velocity, it is necessary to use rocket engines. The three columns of Table **2** show the consumption of the propellant (as the ratio of the mass of matter thrown out by the engine to the mass of the entire body) necessary to change the speed by 0.01 v_{orb}. Three engines were considered: a chemical one (with a specific impulse of 380 s), a Nerva-class thermal nuclear engine (841 s) and an ion engine (10,000 s). Of course, a chemical engine requires huge amounts of fuel and oxidant. A Nerva-class engine could use the volatile substances contained in KB bodies, but a nuclear reactor is required as a heat source. An ion engine would require a much smaller amount of working fluid, but a power plant would be needed to power it.

Gravity assist

The small velocity change of $0.01v_{orb}$ introduced above, assumes that the main energy for the orbit change will be provided by the gravity assist mechanism. It is the maneuvering of a body so that it passes close to another body of large mass. With the right approach, with the right direction, we can get the desired change of velocity. This maneuver is now widely used in astronautics. It is quite difficult and requires very precise maneuvering. The maneuver can be used whenever impactor approaches a large celestial body. There are a number of bodies of considerable size in KB, and on the way to Mars the gravitational field of large planets can be used. Table **3** gives the ratio of the energy needed to reduce the impactor's speed by 50 m/s to the energy currently consumed by humanity in 1 year: E1yrE [6]. It can be seen that for the poorest variant v1 the energy required is approximately 21% of E1yrE, but for the most ambitious variant v6 it exceeds E1yrE by almost 8 times.

However, gravity assist in our case is fraught with significant danger. KB bodies can be quite unstable, especially when they get close to the sun and volatile substances will escape, creating a natural rocket engine with thrust that is difficult to control.

It is also worth using gravity assistance to reduce the relative velocity of Mars and the impactor at the moment of impact. This is important because a strong heating of the atmosphere will lead to the escape of gases from the atmosphere. Moreover, a powerful impact on the surface of Mars may lead to cracks in the lithosphere, earthquakes and volcanism [7].

Tab. 3. Energy required for a given terraforming variant

Energy required for a given terraforming variant					
Variant	**Description**		**Required mass [kg]**	**E_{50} [J]** **Energy for** Δv=50 m/s	**E_{50} / E_{1yrE}**
v1	Armstrong l. at Hellas		1,096E+017	1,371E+20	2,12E-01
v2	p_{50} at Hellas		1,905E+017	2,381E+20	3,68E-01
33	Armstrong l. at h=0		2,311+017	2,889E+20	4,46E-01
v4	p_{50} at h=0		3,848E+017	4,810E+20	7,42E-01
v5	Pressure 101,3 at Hellas		2,1581E+018	2,698E+21	4,16E+00
v6	Pressure 101,3 at h=0		4,1266E+018	5,158E+21	7,96E+00

E_{1yrE} energy consumed by humanity during 1 year: assumed here: 6.48e20 J/yr [6]**.**

Summary

Creating an atmosphere on Mars that would allow human life on its surface is possible by importing matter from other celestial bodies. The required amount of energy required for implementation is comparable to the current energy consumption of humanity within a few months to several years, depending on the selected terraforming variant. Due to the huge amounts of energy needed, a power plant based on a thermonuclear reactor (operating on local hydrogen) and an ion engine seems to be the most appropriate. There may also be difficulties in using gravity assist.

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