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Some problems of gravity assist and terraforming of Mars

Comparisons of atmospheres of Mars and Earth

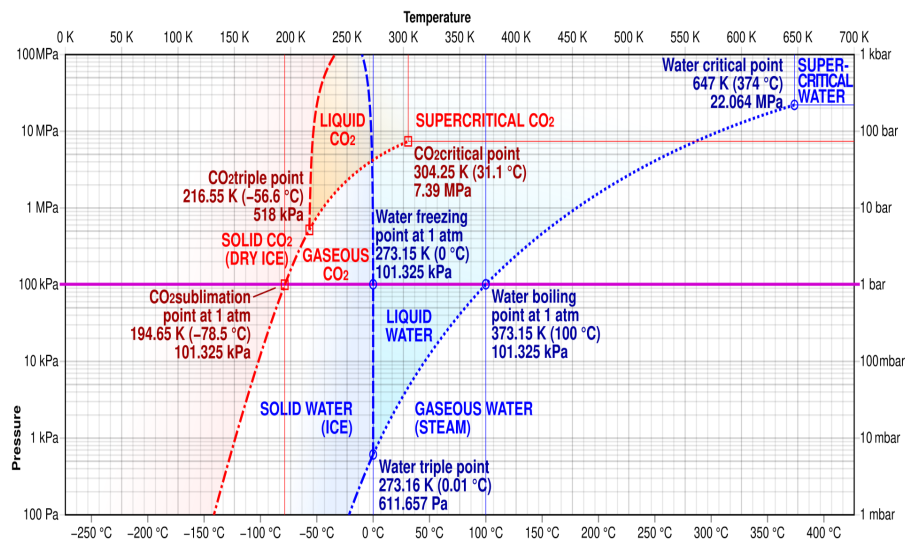
Atmospheric pressure on the surface of Mars ranges from 72 Pa at the top of Olympus Mons (Mars' highest mountain) to 1.16 kPa at the bottom of Hellas Planitia (Mars' lowest lowland). For the adopted reference level on Mars, the average value is 610 Pa [1]. At the top of Mount Everest on Earth, the pressure 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 2.5x10^{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.

Table 1
Variants of terraforming considered in the paper [2,3]

Variant	Opis	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 far from the Sun contain large amounts of volatile substances (e.g., N, HCN, NH_4, H_2O, CO_2). 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 main belt (MB) 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 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.

Table 2

1	2	3	4	5	6	7	8
Objects	**Time of f alling [yr]**	**v_{orb} km/s**	**v_{fall} km/s**	**Dv= $v_{fal} - v_{orb}$ Mars**	**chemical 380**	**thermal nuclear 841**	**ionic 10000**
MB inner limit	3,86E-01	20,07	18,92	-5,18	0,052410	0,024031	0,002044
Vesta	4,56E-01	19,38	20,31	-3,79	0,050649	0,023212	0,001973
Ceres	6,41E-01	17,88	22,89	-1,21	0,046843	0,021444	0,001821
MB outer limit	8,45E-01	16,64	24,69	0,59	0,043655	0,019967	0,001695
Jupiter	1,94E+00	13,05	28,68	4,58	0,034410	0,015697	0,001330
Kuiper B. inner	2,90E+01	5,43	33,23	9,13	0,014472	0,006565	0,000554
Kuiper B. outer	6,25E+01	4,21	33,59	9,49	0,011229	0,005089	0,000429
Oort C. inner	1,58E+04	0,67	34,10	10,00	0,001784	0,000806	0,000068
Oort C. outer	1,98E+06	0,13	34,11	10,01	0,000357	0,000161	0,000014

(1) Source of the matter; (2) Time of falling [yr] from (1) to Mars' orbit. (3) orbital velocity v_{orb} for given semimajor axis [km/s]. (4) final velocity of falling v_{fall} from distance (1) to Mars' orbit [km/s]. (5) $v=v_{fall} - v_{orb}$ Mars [km/s]. (6) - (8) mass of propellant used to reducing v_{orb} to 0,99 vorb, for given specific impuls [s] for: chemical engine (NH_4+O_2), (7) for thermal nuclear (e.g. Nerva), (8) for ionic FEEP Liquid caesium.

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. 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.

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].

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