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TERRAFORMING MARS AND GREENHOUSE GASES

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INTRODUCTION

Imagine walking through a forest of tall trees, with a blue sky and white clouds overhead, and one-third gravity. This is the concept behind terraforming Mars: to bring to life a planet that is now cold, dry, and very inhospitable to living organisms. The process of terraforming a planet can mostly be described as the warming of the surface and the thickening of the atmosphere so that liquid water can persist on the surface. Beyond these requirements, the desired surface temperature and composition of the atmosphere are determined by the types of organisms which are to live there. Terraforming commonly refers to creating a "second Earth" - creating conditions allowing both plants and animals to survive. An important step in the process of terraforming is ecopoiesis, where the planet is just clement enough to allow only some types of life to survive. For example, Mars would be suitable for microorganisms and plants if it was warm and wet, even if its atmospheric composition remained mostly carbon dioxide, and was not capable of supporting higher-order Earth animal life.

The initial warming of Mars (ecopoiesis) is likely to take on the order of a hundred years. Trees and grasses on Mars would produce oxygen that might naturally make a breathable oxygen-rich atmosphere, but simple energy considerations show that this would take on the order of a hundred thousand years (McKay *et al.*, 1991; McKay and Marinova, 2001).

Numerous reasons have been used to support the terraformation of Mars. The reasons can be grouped into three broad categories: (1) terraforming for scientific and practical knowledge about how planetary scale biospheres work; (2) terraforming as part of the human expansion beyond Earth; and (3) terraforming as a way to spread life - the gift from Earth to the rest of the Solar System. Terraforming Mars will be spurred by all of these motivations, and new motivations that we cannot glimpse but will become important in the future.

We can learn about how a habitable planet works by considering how to reconstruct one. The terraforming of Mars is certain to teach us about the warming processes that are currently taking place on the Earth. While there is still much controversy about why the Earth is warming up, it is certain that at least some part is due to human activities such as the release of more carbon dioxide and other super greenhouse gases (e.g. CFCs) into the atmosphere. Perhaps by warming Mars we will learn how to start the reversal of such warming, and overall how to take better care of our planet. However, scientific curiosity is generally considered an insufficient reason by itself for carrying out such a large project as terraforming, which is very demanding technologically, economically, and ethically.

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As humans advance scientifically and technologically, we are bound to step out towards other worlds. Mars is the next logical step, and terraforming the planet may be a natural part of that expansion. Terraforming Mars will certainly give humans and life from Earth a second home, and will make Mars more accessible to the broader public. A newly terraformed Mars may be the place that forward-looking people go to in search of a new start in a new land. Indeed, the human need for frontiers and the importance of expansion in invigorating human culture is often cited as a key motivation for making Mars a new home for life.

A third, new, but profound reason for terraforming Mars is to spread life beyond the Earth. Looking out into the Universe, we see many curious and interesting phenomena. But the phenomenon that is the most interesting from a scientific and human-value perspective is life: life right here on Earth; the assortment of plants and animals that we take for granted every day. While present in various forms, all life on Earth shares the very same origin. And when we look out into the Universe we have as of yet not found any signs of extraterrestrial life. In terraforming Mars, we will be spreading life to another planet, increasing the diversity of life we currently see, and watching the evolution of a new biosphere, as life adapts to its environment, and as life changes its environment. The terraforming of Mars is not incompatible with the search for life on Mars, and with the finding of life on Mars. Mars is believed to have had very much the same initial conditions as those on the Earth. Therefore, if life developed on Mars, it would have been under conditions similar to those on early Earth, that is on a warm planet with a thick CO_2 atmosphere and with liquid water present on the surface. The initial terraforming of Mars will recreate just such a place. If there are Martian organisms in the subsurface or dormant in the permafrost they would be able to expand and flourish in this recreated Martian biosphere.

It is important to dispel one impractical reason sometime given for terraforming Mars. This is making Mars habitable as a way to solve the overpopulation problem on Earth. For better or worse, Mars is not a solution to these Earthly concerns. Even advanced technology would not be capable of sending people to Mars at a rate even close to the rate of population growth, much less moving the entire population in the event of ecological collapse on Earth. It is also unpractical, and we think unethical, to think of Mars as a back-up in case we make the Earth uninhabitable, and to use that as a justification for polluting the Earth.

MAGIC VERSUS CURRENT TECHNOLOGY IN TERRAFORMING MARS

Numerous papers have discussed various methods for terraforming Mars (Fig. 1). Some of these methods fall within the bounds of current technology, while others are much further into the future. Unfortunately, proposals based on futuristic technology outnumber those based on current or foreseeable technology. One proposal calls for the placing of giant mirrors in orbit around Mars, thereby increasing the average solar insulation. One reason why Mars cooled much more drastically than the Earth, since the forming of the Solar System, is that it is further from the Sun than the Earth and therefore receives 2.3 times less solar energy, causing it to be cooler. By increasing the average amount of energy hitting the surface of the planet, the surface temperature will increase. However, the making of large mirrors in space is currently beyond our technological capability, and in order to increase the solar insulation by even 2% (equivalent to a temperature increase of about 1^{o}C (2^{o}F)) would require a mirror the size of Texas (McKay, 1999).

The temperature resulting from a certain solar insulation depends on the albedo of the planet (how dark the planet is and therefore how much of the incident energy is absorbed). The polar caps, covering a significant portion of the planet (~ 1%; Kieffer *et al.*, 1992) have a very high albedo, thereby reflecting a substantial fraction of solar energy rather than absorbing it. It has been proposed (Fogg, 1992) to sprinkle dark dust over the poles, thereby decreasing their albedo and warming them. This will serve a two-fold purpose of both warming the planet directly, but perhaps more importantly the warming will cause the targeted release of carbon dioxide and water, which will significantly help in further warming Mars. While this method seems rather attractive, it has as drawbacks the difficulty of aerial platforms (as dust sprinklers) due to Mars' thin atmosphere, as well as the sinking of the warmed dust into the ice which would lead to the need for frequent dust replenishing.

A method to increase both the volatile inventory of Mars, and also warm up the planet is through the impacting of icy (comet) objects into Mars. This type of impact will most notably cause a local increase in temperature, creating a small oasis. This method is again out of our reach since we do not have the capability of moving, much less accurately aiming, very large objects through large distances. Furthermore, the impact may impact erode more volatiles than are imported, if the impact velocity is not sufficiently small (Fogg, 1992). As well, the lack of precision in targeting the impact site may be unsettling to the Martian settlers.

The most viable technique for warming Mars, so far, appears to be the use of super greenhouse gases. The technology has been proven - it is currently being demonstrated on the Earth. Since the gases can be manufactured on Mars and do not need to be brought from the Earth, it is a viable near-term method.

THE INSIDE WORKINGS OF SUPER GREENHOUSE GASES

The most commonly known greenhouse gases are carbon dioxide, water vapour, ammonia vapour, and CFCs (chloroflourocarbons). Of these, CO_2 and H_2O vapour are responsible for keeping the Earth at a comfortable average temperature of 15^{o}C (59^{o}F), which is ~30^{o}C (54^{o}F) above what it would be otherwise. While greenhouse gases on the Earth are crucial in keeping the Earth habitable, too many greenhouse gases (in conjunction with a close proximity to a star) can also render a planet uninhabitable, as exemplified by Venus. *Super* greenhouse gases derive their name from being more efficient than the more common greenhouse gases; in particular compared to CO_2.

Greenhouse gases are transparent to visible light. Sunlight passes virtually unobstructed through the atmosphere, and is absorbed by the ground, which is then warmed up. The warm ground radiates out in the infrared (IR) spectrum. Greenhouse gases are very effective at absorbing light in the IR, thus they block it form escaping into space and instead warm the atmosphere, which in turn warms the ground. Greenhouse gases can be thought of as a blanket around the planet; the thicker the blanket the warmer the surface.

The effectiveness of a greenhouse gas is dependent both on what fraction of the IR energy it absorbs for a certain gas amount at a specified wavelength, and by where the absorption bands are placed in the IR spectrum. Every object radiates at various wavelengths depending on its temperature (Fig. 2). The placement of the absorption bands is crucial - if they are placed at where the body radiates most of its energy then that gas will have a very strong warming effect. If the bands are placed on the outskirts of the blackbody curve, the gas will not be as effective. Super greenhouse gases have been very efficient partly because their absorption bands fall in the "window region" - the area between 8 - 12 μm (1250 - 830 cm^{-1}) where CO_2 and H_2O vapour are not effective absorbers and the thermal radiation is still strong.

Since different gases absorb at different wavelengths (Fig. 3), if only one greenhouse gas is used, large transmission holes become apparent in the IR spectrum and the planet is not warmed efficiently. Furthermore, the warming due to a particular gas increases with diminishing return with the amount of gas. Therefore, in order to warm a planet efficiently, a cocktail of various carefully chosen super greenhouse gases should be used, keeping all the gases at low concentrations. Going back to the blanket analogy, this is a very similar effect to that of wearing many layers, rather than one very thick layer - that is using small amounts of many different gases rather than a large amount of one gas.

Super greenhouse gases have earned a bad reputation on the Earth, where the increase in temperature is undesirable. The most common artificial super greenhouse gases on the Earth are CFCs, which are also very effective at destroying the ozone layer, further harming the environment on the Earth. However, on Mars the increase in temperature will be desirable! In addition, if PFCs (perfluorocarbons, very similar to CFCs but do not contain chlorine or bromine) are used, then the ozone layer will not be harmed. PFCs have no harmful effects to living organisms, especially at low concentrations.

CRITERIA FOR GREENHOUSE GASES

When deciding on greenhouse gases to be used in terraforming Mars, factors such as efficiency, easiness of manufacturing, long lifetime against destruction by solar UV light, presence of all necessary elements on Mars, no harmful effects to life, and ability to be incorporated into biological cycles must be considered.

The efficiency of a greenhouse gas is measured by the increase in temperature for a given amount of gas produced. The higher the increase in temperature, the more desirable the gas. As stronger greenhouse gases are discovered, the terraforming of Mars becomes increasingly more viable since the energy requirements for the process decrease with the decrease in the amount of gas that needs to be manufactured.

It is not practical for greenhouse gases to be carried to Mars from the Earth. Even though super greenhouse gases are to represent only a very small fraction of the atmosphere (about 0.1 to 1 part per million), this is still a very significant mass to be carried across space. Therefore, the gases will need to be manufactured on Mars. This should not be exceedingly difficult since the gases are commonly made on the Earth, and similar processes are likely to be applicable to Mars. In order to manufacture the gases on Mars, all the required elements must be available in significant quantities in the soil or atmosphere.

Since the goal of terraforming Mars is to make the planet more habitable to life, using gases that have negative effects on life would be counter-productive. Most super greenhouse gases are not toxic. However, gases that contain chlorine or bromine, such as CFCs, are very destructive to the stratospheric ozone layer, and therefore are harmful to life. Ideal gases would not contain chlorine and bromine and would be inert in the atmosphere. Candidates include PFCs (perfluorocarbons; which are made up only of carbon and fluorine) and some sulfur containing compounds such as SF_6.

An ideal situation in the terraforming of Mars would be to make the emerging biosphere capable of keeping its own environment warm and comfortable. In terms of the use of super greenhouse gases, this translates into bioengineering microorganisms which themselves produce the super greenhouse gases until the temperature reaches a certain threshold. Organisms have been found which do produce halogenated compounds (Tokarczyk and Moore, 1994; van Pee, 1996; Wackett, *et al.*, 1994); it is likely within the near-term capability of biotechnology to transform the organisms so that they stop producing the greenhouse gases when a certain temperature is reached. Thus, it is desirable to use super greenhouse gases, which can be incorporated into biological cycles.

Putting together all the requirements for super greenhouse gases and the resources that could be reasonably devoted to terraforming Mars, the project remains a practical possibility. Several super greenhouse gases satisfy all of the above requirements. Furthermore, because of their strong greenhouse potential, these gases need to be manufactured to low concentrations in order to produce a very strong greenhouse effect. Because of their long lifetimes, several thousand years (Fogg, 1995), the rate of production remains reasonable. Still, it must be realized that the energy requirements for manufacturing the gases are not trivial. On the order of 4×10^{20} Jules, equivalent to about 75 minutes of Martian sunlight, will be required to produce enough PFCs to raise the temperature of Mars by about $5^{o}C$ ($9^{o}F$) (McKay and Marinova, 2001). This is equivalent to 250 facilities consuming 500 MW (the size of a small nuclear reactor) working for 100 years. While these energy requirements are large, they are certainly not unachievable. In addition, the predicted temperature increase is likely low since it does not take into consideration various feedback effects, as well as optimizing the mixture of greenhouse gases.

ANALYZING THE GREENHOUSE POTENTIAL OF SUPER GREENHOUSE GASES

The greenhouse potential of gases can, at first look, be compared by their transmission spectra; the more absorption bands that the gas has (the less energy it transmits), the more efficient it will be. The placing of the bands is also important, specifically covering the 8 - 12 μm (1250 - 830 cm^{-1}) region. Figure 3 (a) and (b) compare the transmission spectra of CO_2 and C_3F_8 for the same concentration of gas.

In order to be able to use the transmission data in numerical analysis, the change of transmission with increasing gas concentration should be described by an exponential sum fit. Figure 4 shows the transmission for a strong C_3F_8 absorption band, fitted using a 3-term exponential fit.

Once the exponential term fits are obtained, they are incorporated into a model calculating the downward flux generated by the presence of a gas amount in the atmosphere, as described in Marinova *et al.*, 2000. The results of this analysis for current Mars are shown in Table 1; only gases which are good candidates for terraforming Mars are shown. While the results look very promising, it is important to note that the real-life warming will likely be somewhat higher.

As the planet warms up, CO_2 will be released from the melting polar caps and from the regolith. Once the planet warms up above about 0°C, water vapour too will become an important part of the atmospheric gases. With time, CO_2 and water vapour will become the dominant greenhouse gases, with artificially or biologically produced super greenhouse gases providing a warming effect primarily in the window region. In present models, the source of CO_2 is regolith outgassing or melting of the polar caps (McKay *et al.*, 1991; Zubrin and McKay, 1994; Fogg, 1995).

The temperature increases shown in Table 1 corresponds to individual gases. Using only one gas is not efficient since the warming effect is not linearly related to gas amount; the absorption bands become saturated and are no longer effective. In order to plug up all parts of the spectrum and avoid the saturation of bands, a carefully chosen mixture of gases should be used. Currently the model does not calculate the warming due to a mixture of gases.

Current work is focused on making a radiative-convective model of the Martian atmosphere, thereby providing a more accurate calculation of the warming due to greenhouse gases. Taking into account the CO_2 released from the polar caps and the regolith as the planet warms will add another dimension of realism to the calculations.

USING A SYNERGETIC APPROACH

Results from the analysis of greenhouse gases have shown that they are a viable method for the warming and terraforming of Mars. However, the energy requirements are not trivial. Like the nonlinear warming due to greenhouse gases discussed above, other methods for warming the planet are also more effective when conducted in a limited, but targeted, manner. Therefore, the use of a synergetic approach to terraforming is likely to be the most effective and efficient (Fogg, 1992). Super greenhouse gases are likely to lead such an effort, but the use of various other techniques should not be underestimated.

THE ETHICS OF TERRAFORMING MARS

No discussion of terraforming Mars would be complete without consideration of the ethical and social questions raised. Foremost of these is the question of indigenous life. If Mars had an early Earth-like epoch then it is likely that life arose during this early period and it is possible that there are still subsurface ecosystems or frozen dormant organisms in the ancient permafrost. The ethical issues are reduced or even eliminated if the Martian life is the same as Earth life, indicating that both planets share a common biological history – the Martians are our cousins. However, if Martian life does indeed represent a second genesis of life, then the ethical issues are profound. There are three possible approaches to dealing with alien Martian life. First, we could capture a sample for scientific study and preservation and proceed to introduce life from Earth. Second, we could decide to leave it alone – neither helping nor hurting it. Third, we could study the life and alter the Martian environment so as to allow that life to create a global biosphere – a Mars full of Martians. These three approaches touch on deep ethical questions. We suggest that the best approach is the third one, which maximizes the richness and diversity of life in the solar system (McKay, 1990; 2001); this approach is consistent with the terraforming of Mars. If there is no viable life on Mars, it is probable that if there was ever life on Mars its genetic information is still preserved in the frozen ground. Even if over time this Martian genome has become fragmented and non-viable, with future biotechnology it may be possible to reconstruct it from the pieces. Thus, humans might play a role not just in restoring the Martian environment but also restoring the Martian genome.

If there was never life on Mars then the ethical issue deals simply with the choice between a rich, beautiful, scientifically interesting world devoid of life and a rich, beautiful, scientifically interesting world full of life. To us the choice is clear: life.

CONCLUSION

Planets that are good for life are hard to find. In our solar system we have only our Earth. However, Mars appears to be a world that could be made a friend for life using the unique capabilities of human technology and the powerful forces of evolutionary biology. Our present knowledge of Mars is not sufficient to be certain that we can terraform Mars or to show the final path to terraforming. However, the data collected so far and the studies done to date indicate that altering Mars to allow for a plant-based biosphere is a possibility, and one that could begin in our generation and be completed in the life-times of our great-grandchildren.

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FIGURES

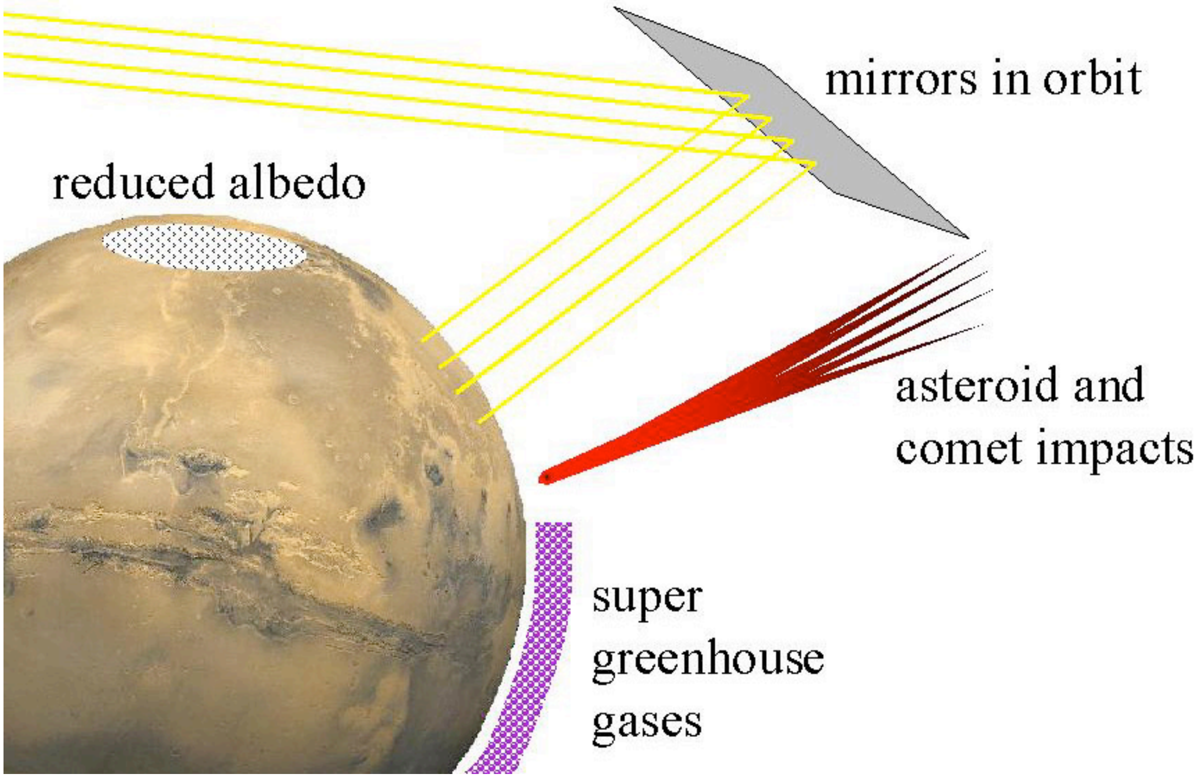

Figure 1. Several of the methods proposed for warming Mars and re-creating habitable conditions on that planet. Of the methods shown, greenhouse warming is the one approach that has already been demonstrated on Earth.

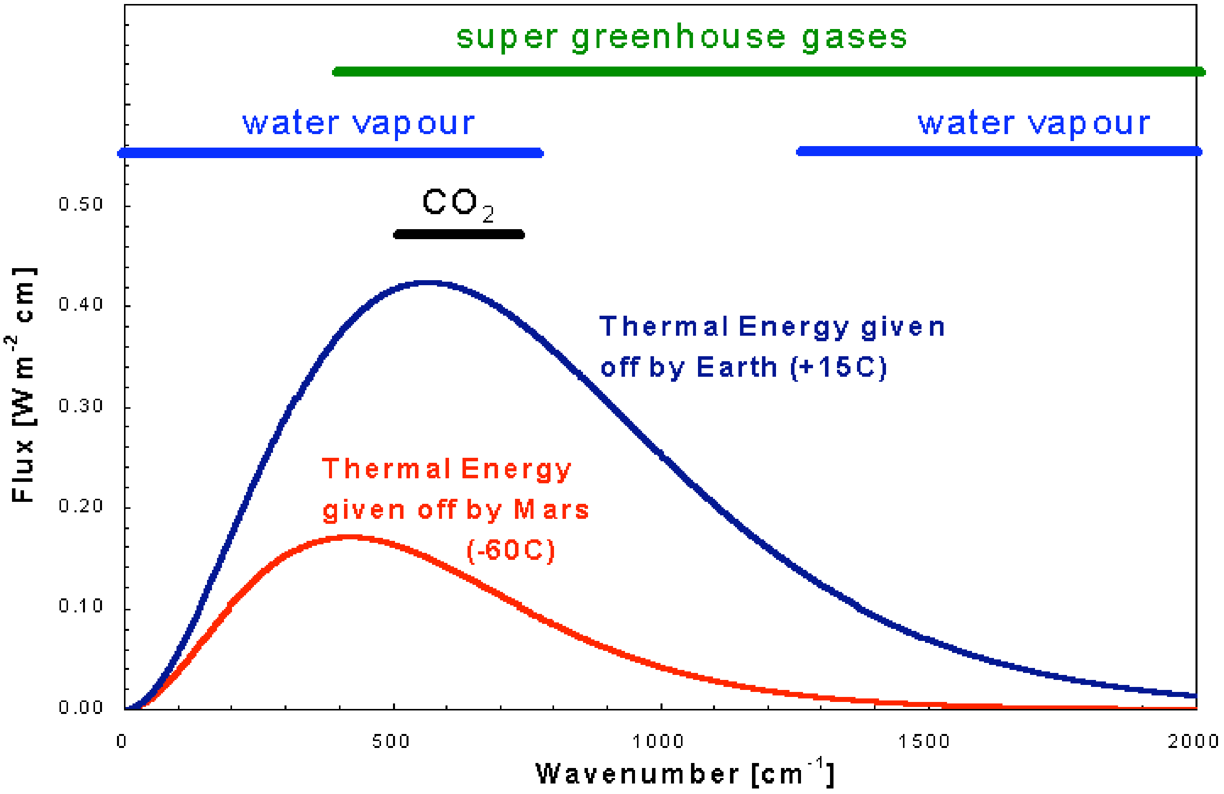

Figure 2. Thermal radiation (black body curves) from the surface of Mars and Earth corresponding to temperatures of –60°C and +15°C, respectively. Also shown are the main spectral regions for the absorption of thermal radiation by atmospheric water vapor, carbon dioxide, and super greenhouse gases. Super greenhouse gases can absorb in the “window” region where neither water vapor nor carbon dioxide absorb.

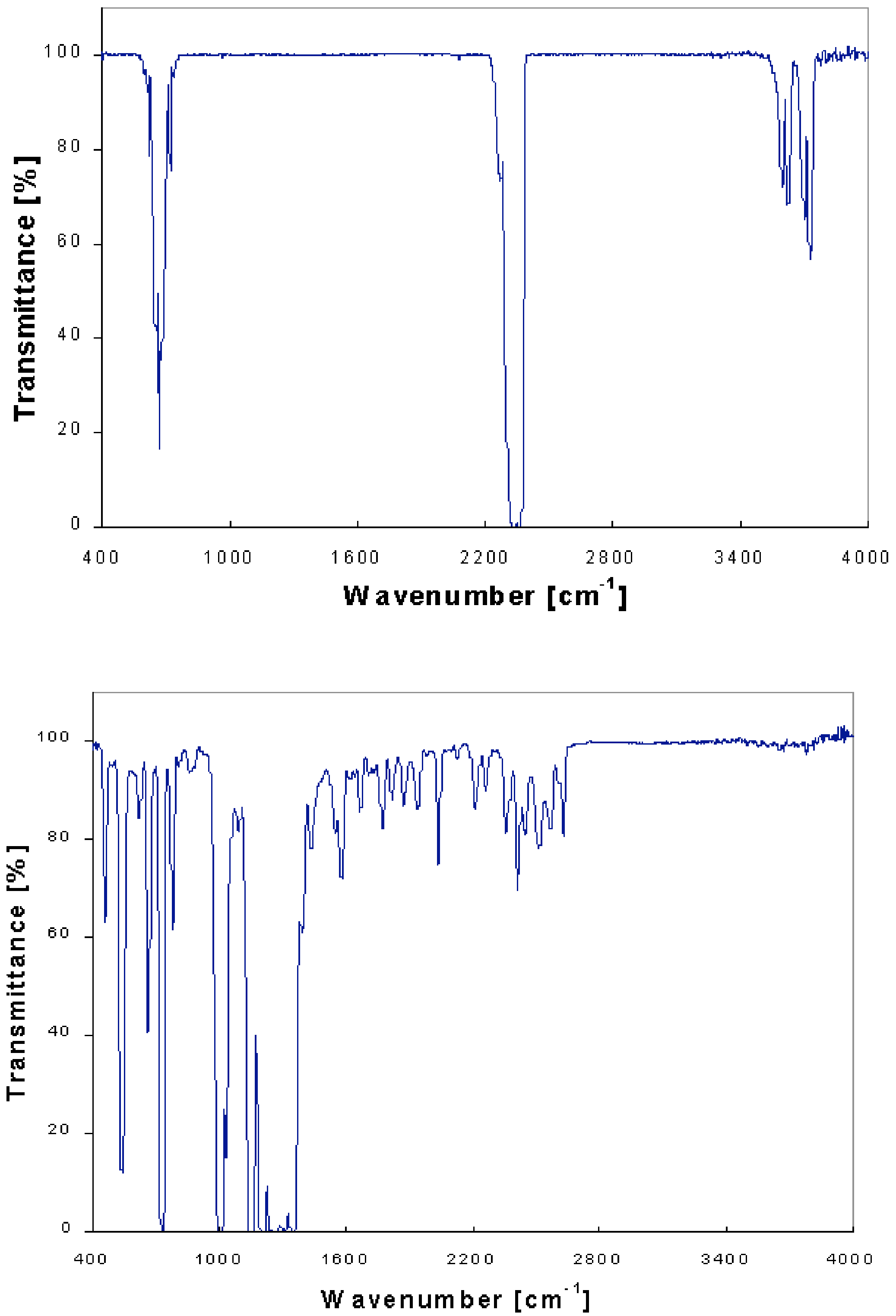

Figure 3. Transmission spectra for (a) CO_2 and (b) C_3F_8, at a concentration of 10% in Argon (P_{tot}=101.3kPa).

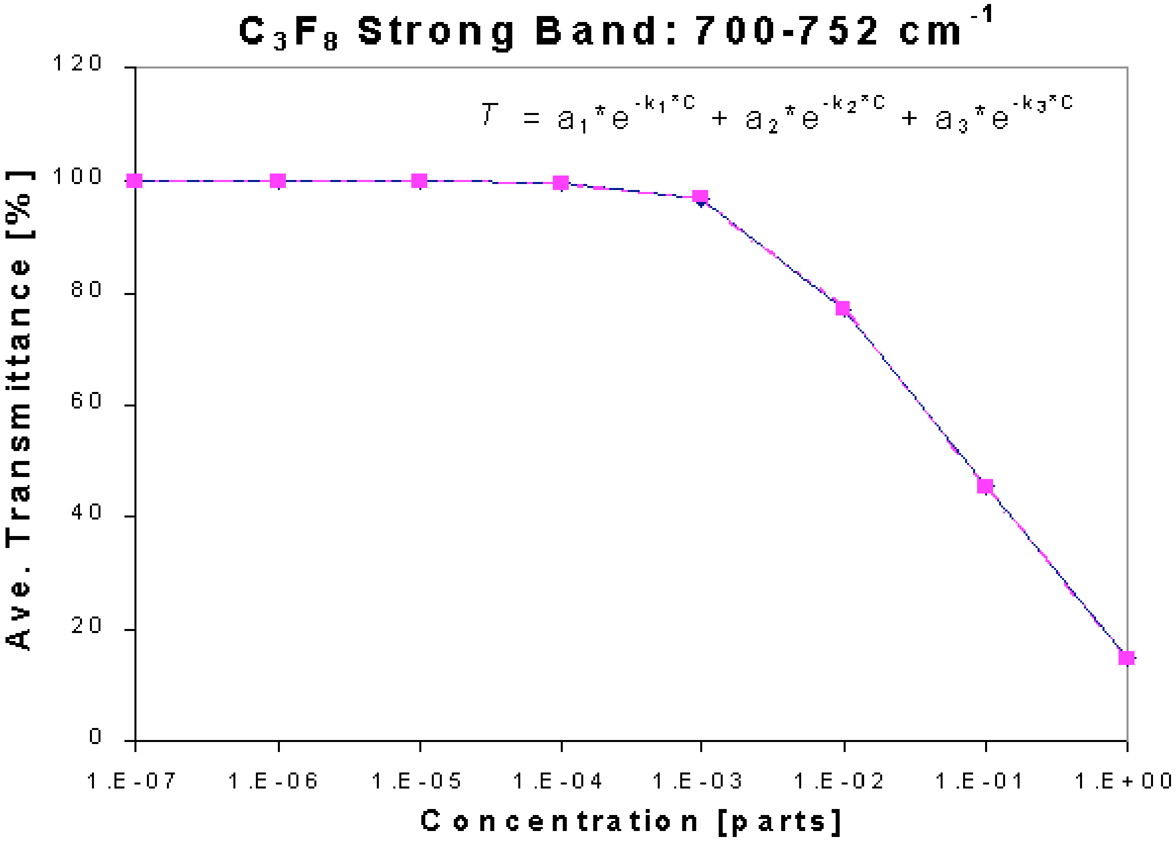

Figure 4. Exponential sum fit for a C_3F_8 strong band: 700-752 cm^{-1}. The values in the fit are: $a_1=0.456$, $k_1=2.43 \times 10^{-23}$ m^2 molecule^{-1}, $a_2=0.342$, $k_2=3.31 \times 10^{-25}$ m^2 molecule^{-1}, $a_3=0.2$, $k_3=1.27 \times 10^{-24}$ m^2 molecule^{-1}; *C* is the column concentration of the gas in units of molecules m^{-2}. A three term exponential sum is a convenient way of expressing the transmission in a band as a function of increasing concentration of the gas molecules that contribute to the band.

TABLE

Table 1. Warming of Mars due to greenhouse gases. Only gases suitable for terraforming Mars (no Cl or Br) are shown (atmosphere on Earth = 101,300 Pa).

Table 1. Temperature increase from greenhouse gases on Mars.

	Partial Pressure			
Gas	0.001 Pa	0.01 Pa	0.1 Pa	1 Pa
SF_6	0.33°C	1.36°C	2.50°C	4.87°C
CF_4	0.11°C	0.38°C	1.35°C	3.05°C
C_2F_6	0.28°C	1.24°C	3.29°C	6.96°C
C_3F_8	0.46°C	1.94°C	6.01°C	14.5°C