Restoring Mars

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Abstract

The prospect of humans colonizing Mars has moved from the realm of science fiction to that of science. This article discusses options for reshaping the Martian environment to make it more suitable for human habitation, including a key element – a method to restore Mars' magnetic field. Although a difficult undertaking, this plan would transform the Martian environment – it would shield the surface from dangerous solar and cosmological radiation and would allow the creation of a stable high-pressure atmosphere protected from erosion by the solar wind. Once a global magnetic field was restored, by mining comets and asteroids for gases and water Martian engineers could create a permanent high-pressure atmosphere and adjust its composition to create Earth-like conditions on the Martian surface.

Contents

List of Figures

1 Colonization Stages

The human colonization of Mars will likely proceed in three phases – exploration, engineering and occupation. In the exploration phase, already underway, Mars will be measured and described in detail. In the engineering phase, brave and hardy pioneers will reshape Mars while it's still extremely hostile to human life. These pioneers will change Mars' environment, make it a suitable habitat for normal people. In the occupation phase, we will create a Martian society on a planet that's been reshaped to suit our preferences and biological requirements.

1.1 Exploration

In the present exploration phase, Mars is being studied by increasingly sophisticated robotic craft. Over time we're getting answers to certain key questions – how much water exists on Mars? Was Mars warmer and wetter in the past? Did life ever exist on Mars, and is there any life today?

With respect to questions about past and present life, those responsible for designing and launching robotic craft are exercising great care to avoid contaminating the Martian environment with earthly life forms. In a program called Planetary Protection[1], spacecraft are prepared and tested for compliance with strict guidelines for cleanliness. Whether these measures will be effective is unknown at present, but the discovery of extremophiles[2] here on Earth, organisms able to survive hostile environments, provides two messages – one, in spite of its apparent hostility to lifeforms familiar to us, present-day Mars might be able to harbor life, and two, we may be naive in thinking we can sterilize our spacecraft to the degree that we don't transport viable lifeforms into the Martian environment.

The issue of planetary protection is controversial. In the initial phases of exploration it would seem foolish to allow contamination because a key research goal is to locate any native lifeforms that may exist. Indeed, the question of life on Mars[*] and elsewhere has enormous philosophical significance – if we find that lifeforms are or were present on Mars, such a finding would suggest that life may be common in the universe, that Earth doesn't have a monopoly on life. The significance of such a discovery can't be overestimated.

But after an initial scientific exploration phase, pressure will increase to allow more intrusive kinds of exploration, with larger spacecraft, longer stays, and less discipline about biological contamination. These pressures mean there is a window of opportunity to settle the question of Martian indigenous life, but that window will eventually close, replaced by activities focused more on engineering than scientific research.

1.2 Engineering

In this phase, scientists and engineers will reshape the Martian environment to make it more suitable for human habitation. This activity, sometimes called "terraforming"[3], will have several phases. A key goal in this phase will be to raise Mars' atmospheric pressure to levels more like Earth, as well as increase oxygen levels.

During this pioneering phase, engineers and workers will need to live either in caves or surface habitats shielded by magnetic fields [†] to survive the high radiation levels of present-day Mars. Nevertheless, because much of the engineering activity must be carried out on the surface away from protected environments, those who consider taking part in this phase will have to be properly educated about the risks they're taking – about the certain prospect of higher cancer rates and shortened lives – and they would have to give informed consent as a precondition for acceptance.

Some may imagine that the risky engineering/terraforming phase might be performed by robots, but it seems improbable that robotic technology can evolve quickly enough to pose a meaningful alternative to human boots on the ground. And because of the great distance to Mars, the telepresence[4] alternative (i.e. direct remote control) isn't a practical idea – the time delays are too long for this to be practical.

Unfortunately, once Mars' atmosphere has been engineered to our liking, we may face the prospect of losing what we've just created – after all, present-day Mars has nearly no atmospheric pressure[5] for a reason. The more technical

[*] As well as the question of whether such life is based on DNA or some other encoding principle.

[†] Explained below in the "Colony magnetic field" section.

sections of this article will explain how and why Mars lost its original atmosphere and what steps we might take to prevent a recurrence.

If this phase succeeds, in many ways Martian surface conditions will resemble those on Earth – normal atmospheric pressure, reasonable temperatures in most regions, low levels of surface radiation, adequate oxygen, liquid water at the surface, and seasons much like those on Earth. In other ways Mars will never be like Earth – its surface gravity is only 38% that of Earth, and solar brightness is only 43% that of Earth[5]. These differences can't be engineered away, and Mars' future inhabitants will have to adjust.

1.3 Occupation

Once the engineering phase is complete, true colonization can begin, somewhat like migrations in human history but with important differences. One difference is that, unlike many deplorable chapters in our history, we wouldn't be pushing aside an indigenous species of intelligent creatures (unless the real Martians cower in ice caves and never wander the surface). Another difference will arise from the high cost of transport – only the most qualified people will be accepted for emigration to the new Mars. One can only hope universally admired human qualities will decide this issue, not political, economic, ethnic or racial distinctions.

Because of Martian conditions we can't change[*], over time the citizens of Mars may evolve traits more suitable to their environment. In the long term Martians might become taller and will certainly become thinner than Earthlings. They will likely have larger eyes to accommodate the reduced solar brightness. If technological advances make space travel much less expensive than it is now, Earthlings and Martians will likely remain the same species, but if for some reason we fail to advance beyond our crude present-day chemical-fueled rockets, the two populations will likely drift apart in a permanent, biological sense.

2 Mars Past and Present

This section describes Mars and explains why it has evolved to a state so different from Earth.

2.1 Origins

According to prevailing theory, both Mars and Earth formed by gravitational collapse within a primordial solar nebula of dust and gas[6]. It is thought that Mars and Earth acquired a great deal of water only after the early formation phase – both planets are inside the so-called Frost Line[7], a radius in the early solar system roughly equal to the radius of Jupiter's orbit, inside which temperatures were too high to permit water ice and other ices to exist.

It is thought that Earth and Mars acquired their water only after the solar system cooled enough for comets and other bodies to transport water inside the primordial frost line. There is increasing evidence that Mars once had a great deal of water[8], but much of it appears to have been lost, along with Mars' early atmosphere, and the remainder exists in the form of ice.

2.2 Stable atmosphere requirements

A superficial look at the sun and inner planets might lead one to the conclusion that the solar wind[9] (a powerful stream of charged particles emanating from the sun) should over time erode a planet's atmosphere by blowing gas molecules away. The only reason this hasn't yet happened to Earth is because we have a relatively strong magnetic field that shields our atmosphere from the solar wind.

[*]Examples include a different gravitational force and sunlight level.

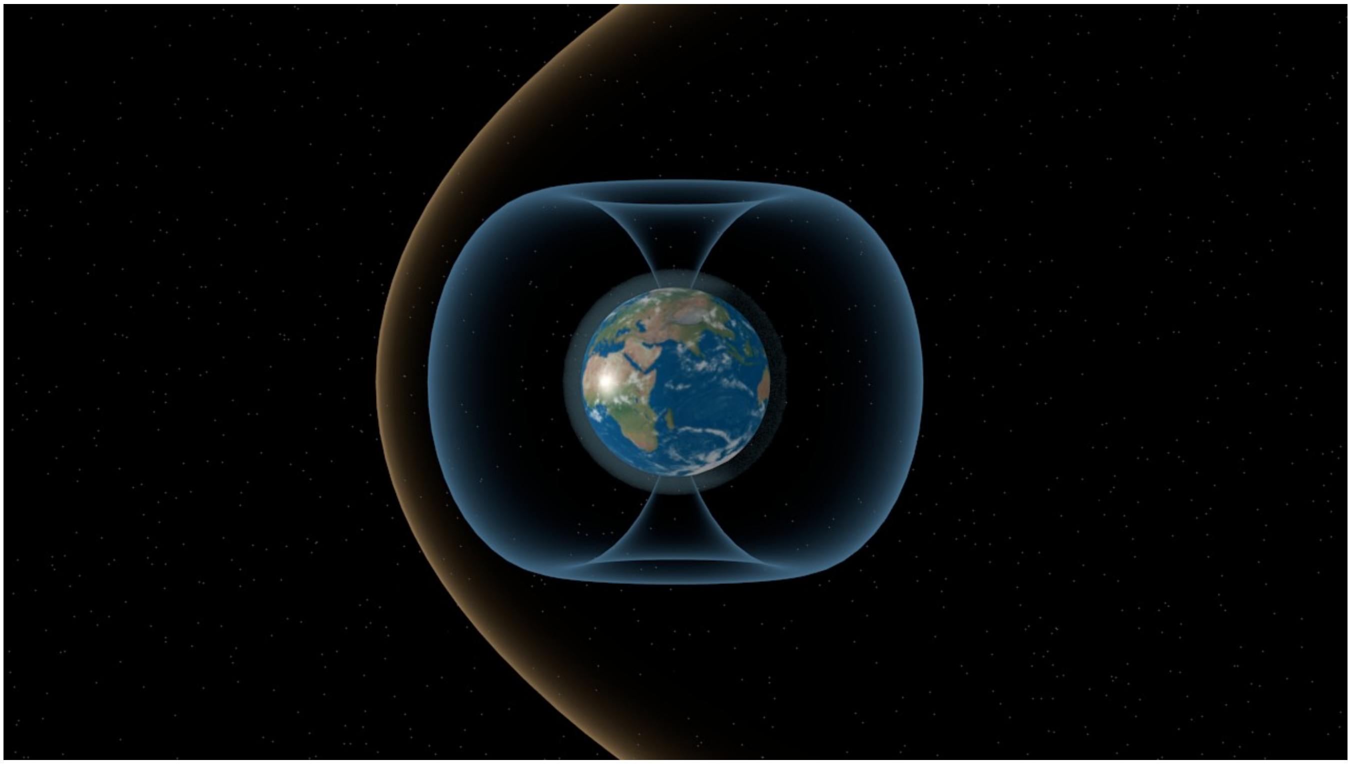

Figure 1: Solar wind deflected by Earth's magnetic field

Our magnetic field originates in a freely flowing liquid outer core of ferrous materials (primarily iron and nickel)[10] that, by moving in a particular way, creates interacting electric and magnetic fields that have the effect of protecting our atmosphere from the solar wind. Eventually Earth's outer core will cool to the point that it can no longer flow freely, this will cause our magnetic field to collapse, and we will begin to lose our atmosphere just as Mars has done.

2.3 Causes and effects

The relationship between surface conditions suitable for life, and a planet's magnetic field, can be expressed as a linked set of causes and effects:

- Earth's relatively thick atmosphere warms the surface by way of the Greenhouse Effect[11], and the atmosphere's high pressure allows liquid water to exist at the surface. High temperatures and liquid water are both conducive to life.
- Earth's atmosphere is protected from the solar wind by our magnetic field.
- The magnetic field also shields Earth's surface from solar and cosmological radiation, which, if unchecked, might have prevented the establishment of life.
- Earth's magnetic field is created by moving liquid ferrous metals in the planet's outer core[10].
- The motion of these liquid metals takes the form of convection loops that transport heat from the Earth's solid inner core to the mantle[12].
- Earth's internal heat has two primary sources[13]:
  - Energy remaining from the original gravitational collapse.
  - Heat generated by radioactive decay.
- Eventually Earth will lose enough of its heat through surface radiation and the exhaustion of radioactive isotopes that the outer core will solidify.

- When the outer core solidifies, we will lose our magnetic field.
- When we lose our magnetic field, surface radiation levels will increase and the solar wind will erode our atmosphere more efficiently than it does at present.
- As our atmosphere erodes away, Earth's surface pressure and temperature will fall and surface liquid water will no longer be possible.
- At that distant future time, Earth will come to resemble Mars – very cold and dry.

These factors show the relationship between a planet's magnetic field and its suitability for life – in essence, a planet with no magnetic field cannot easily retain an atmosphere and may have surface conditions hostile to life*.

2.4 Comparing Earth and Mars

Why does Earth still have a magnetic field – and a high-pressure atmosphere – but Mars does not? The answer can be found by comparing rates of heat loss. As it happens, assuming some basic similarities, large planets retain their heat more effectively than small planets (see the "Planetary radius and heat loss" appendix for a more detailed explanation).

It is thought that, billions of years ago, Earth and Mars began to diverge in a fundamental way. Mars, which originally had plenty of water and a thick atmosphere, lost its magnetic field, then as a consequence lost its atmosphere and much of its water. It's important to understand that, unless Mars acquires a magnetic field, efforts to restore its atmosphere must fail in the long term. It may be possible to create a replacement atmosphere by various means (see the "Mining comets and asteroids" appendix for more detail), but without a magnetic field any new atmosphere is doomed to erode away. Also, without a planetary magnetic field, Martian surface radiation levels will remain dangerously high.

This means our plans to colonize Mars must address the linked issues of atmospheric loss and surface radiation.

3 Creating Magnetic Fields

This section explores possible remedies for the absence of a Martian planetary magnetic field.

I caution my readers that some of the schemes discussed below may remain perpetually in the realm of science fiction because they rely on technologies that do not exist at the time of writing and may never exist, such as cheap fusion power and room-temperature superconductors.

*This is not to suggest that a magnetic field prevents all loss of atmospheric gases – the rate at which gases are lost is reduced but not halted[14].

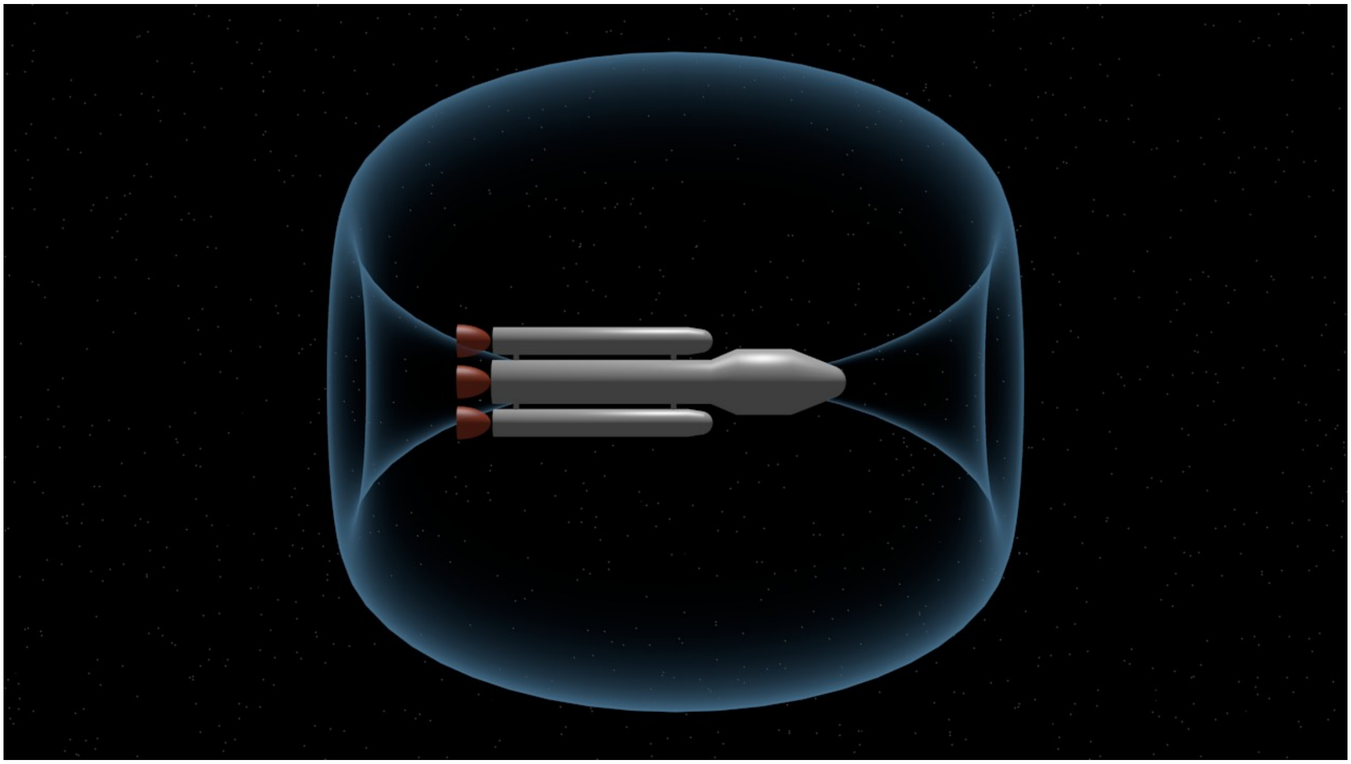

Figure 2: Spacecraft magnetic field

3.1 Spacecraft magnetic field

With respect to a problem at a smaller scale, an organization named SR2S[15] is actively studying methods to protect astronauts traveling in interplanetary space from the high radiation levels found outside Earth's protective magnetic field. This proposed scheme relies on superconducting magnets[16] for the reason that, once established, the magnetic field requires no additional power to maintain itself. Modern spacecraft have limited power available and the protective magnetic field should ideally persist for the entire flight, so a superconducting magnet is the remedy of choice. A drawback to present-day superconducting magnets is that they rely on field windings whose superconducting state requires cryogenic cooling, a complex scheme that ultimately depends on the gradual loss of cooling agents such as liquid nitrogen and liquid helium.

3.1.1 Superconductors and cryogenic cooling

A common cooling scheme uses both liquid nitrogen and helium – the less expensive liquid nitrogen, with a boiling point of 77 Kelvins[17], reduces the loss of the more expensive liquid helium, which boils at 4.2 Kelvins[18]. A newer scheme uses a mechanical compressor to eliminate the liquid nitrogen components of the earlier method while reducing the loss of liquid helium[19].

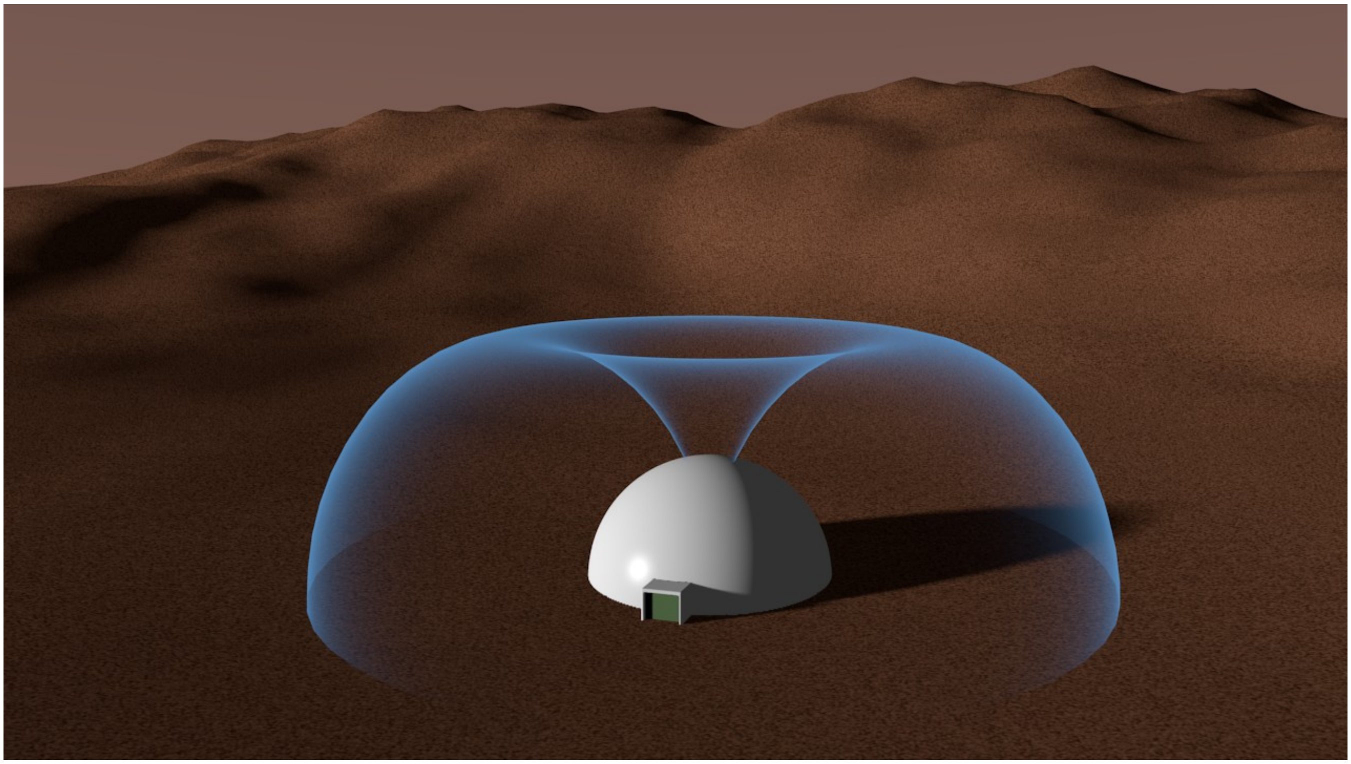

Figure 3: Colony magnetic field

3.2 Colony magnetic field

This proposal enlarges the method described above and is feasible in principle with present-day technology. It should be possible to create a magnetic field around each Martian surface settlement. The field would surround a pressurized habitation structure, protecting its inhabitants from dangerous surface radiation levels. For this method, colonists would be warned to avoid wandering too far, or for too long, beyond the magnetic field's boundaries. Once put in place, this method would allow colonists to abandon caves as a method for dealing with surface radiation[20]. Because of its comparatively small scale, this solution addresses the surface radiation issue but not the loss of atmospheric gases over time.

As with the planetary magnetic field methods to be discussed next, the colony magnetic field could take the form of either a powered superconducting magnet or a permanent magnet. The latter would have the advantage that, once created, it would require no electrical power or cryogenic cooling.

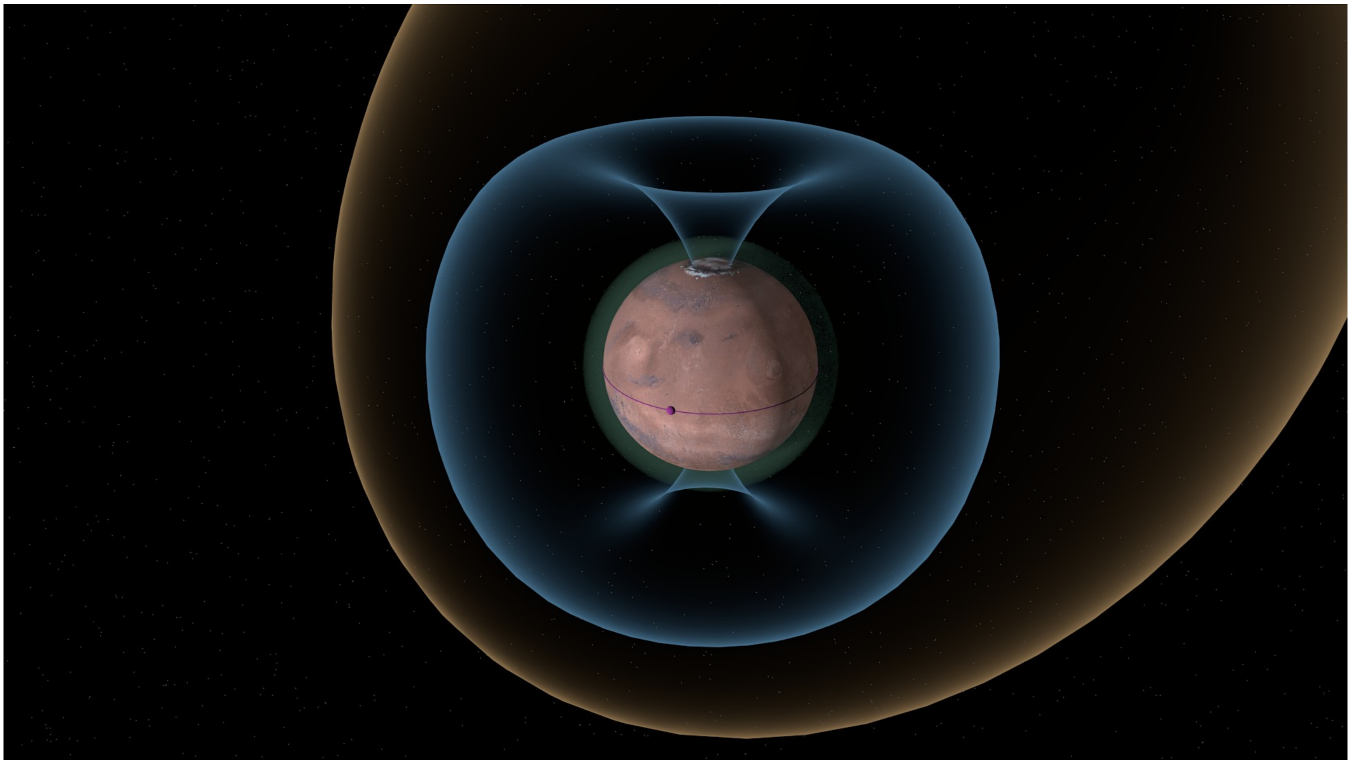

Figure 4: Solar wind deflected by induced magnetic field (some elements not to scale)

3.3 Planetary induced magnetic field

This method greatly expands on the methods described above and is speculative because, although technically sound, it relies on a scale of engineering that has never been attempted. It involves encircling Mars with an electrical conductor, either conventional or superconducting, with the aim of creating an artificial planetary magnetic field. The method has two alternative forms:

1. Generate a protective field by means of a continuously powered planet-scale electromagnet.
2. Permanently magnetize ferrous materials in Mars' mantle by means of a briefly energized, very powerful planet-scale electromagnet.

3.3.1 Powered field

The advantage of method (1) above is that it relies on well-established electromagnetic principles and could be put in place with little insight into Martian geology. Its drawback is that it must be supplied with a constant flow of electrical power and, unless constructed using hypothetical future room-temperature superconductors, its power budget would be quite beyond imagining from a modern perspective.

3.3.2 Permanent field

The advantage of method (2) above is that it permanently magnetizes Martian ferrous minerals located in the planet's mantle, after which the electromagnet can be switched off. One problem with this idea is that the power level required to magnetize the Martian mantle is much higher than the power required to create a steady-state field as in method (1)[21]. A related problem is that Martian mantle ferrous materials that are above their Curie temperature[22] (1043K for Iron, 627K for nickel) by definition cannot retain an imposed field, and the proportion of present-day Martian mantle ferrous materials that are below their Curie temperature (therefore useful in this scenario) isn't known.

It must be emphasized about method (2) that it can only work by magnetizing ferrous materials located in the mantle. Martian inner and outer core materials are certainly above their Curie temperatures and therefore cannot retain an imposed magnetic field.

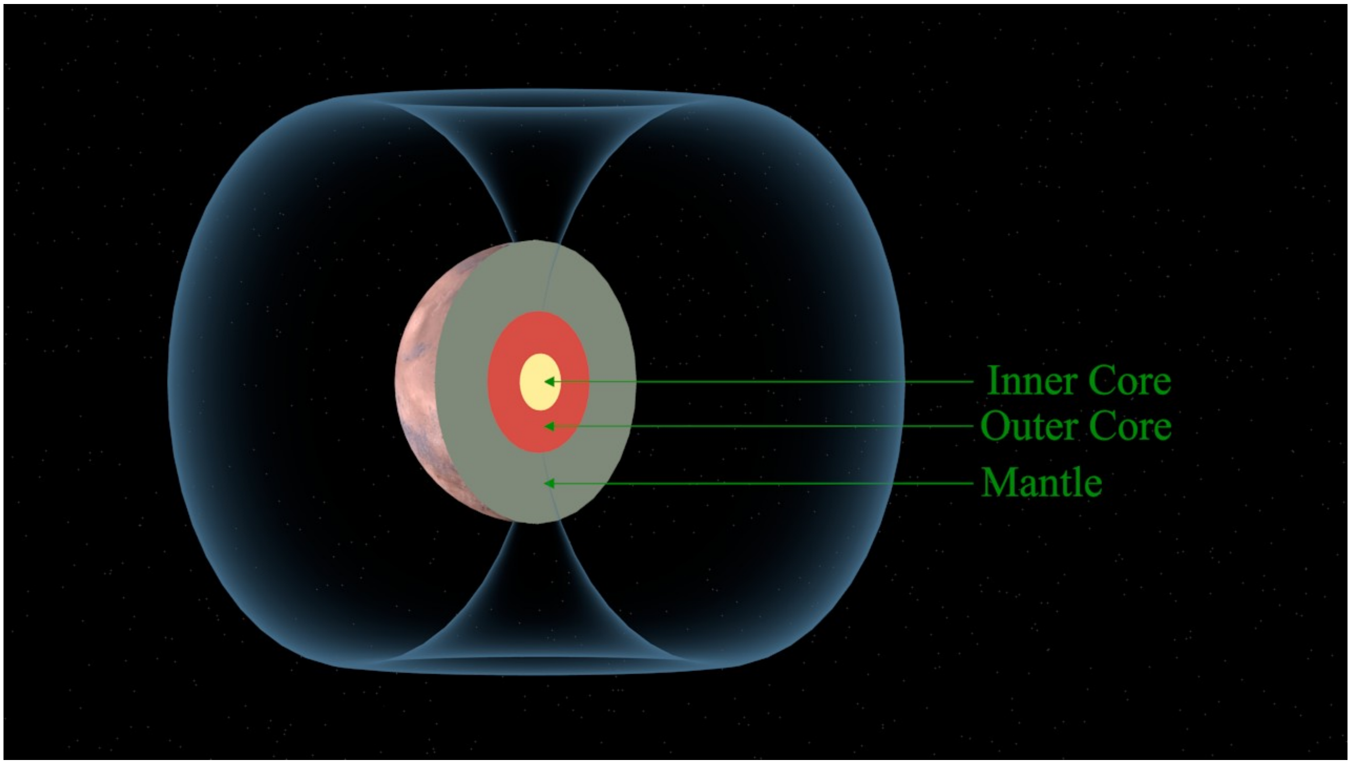

Figure 5: Mars cross-section diagram

3.3.3 Magnetic Properties

For both methods described above, remanence[23], the ability of Martian mantle ferrous materials to respond to and retain an imposed magnetic field, is a central issue. It would decide how much power would be required to create a protective magnetic field in method (1), and it would determine the much higher transient current level required to create a permanent magnetic field in method (2). Unfortunately, at the time of writing these properties aren't known to any degree of precision.

4 Conclusion

From today's perspective, in which we have only begun to explore Mars, the above suggestions may sound extreme and impractical, but once we establish ourselves on Mars in significant numbers, once we begin to think of Earth and Mars as sister planets occupied by humans, the idea of a planetary civil engineering project to save lives and preserve the Martian environment, notwithstanding its enormous scale, may seem to be a practical investment as well as a moral imperative.

5 Appendices

5.1 Planetary radius and heat loss

The rate at which an object radiates heat depends on the relationship between the object's mass and its surface area. For a given temperature an object possesses an amount of heat energy proportional to its mass, and radiates that energy at a rate proportional to its surface area. Assuming a material density d (expressed in $\frac{\text{kg}}{m^3}$, a scale in which water has a density of 998[24] at STP[25]), for a given planetary radius r, a planet's mass m is given by:

$$m = d\frac{4}{3}\pi r^3 \tag{5.1}$$

While a planet's surface area is given by:

$$a = 4\pi r^2 \tag{5.2}$$

Based on this, a first-order approximation* of the efficiency q at which a planet loses heat energy is given by:

$$q = \frac{4\pi r^2}{d\frac{4}{3}\pi r^3} = \frac{3}{dr} \tag{5.3}$$

Taking into account the radii and densities of Earth and Mars[5] and assuming equal specific heats, we can compare Mars' rate of heat loss to that of Earth:

$$\frac{r_e d_e}{r_m d_m} = \frac{6378 \cdot 10^3 \cdot 5514}{3396 \cdot 10^3 \cdot 3933} = 2.6 \tag{5.4}$$

On this basis, Mars loses heat 2.6 times faster than Earth. This is the principal reason Mars has almost no atmosphere and is cold and dry – it lost too much of its internal heat energy early in its life, then its protective magnetic field collapsed, then the solar wind stripped away most of its atmosphere and much of its water.

5.2 Mining comets and asteroids

Once Mars has a magnetic field that can protect its atmosphere, creating such an atmosphere and acquiring more water will become a practical and important objective. The simplest way to do this is to survey the so-called "asteroid belt[27]" for likely candidate asteroids – asteroids with a high percentage of volatiles[28]. Also, with sufficient astronomical and orbital mechanics resources, celestial mining engineers could capture and/or exploit passing comets for their gases and water.

In asteroid mining, the key principle is to locate suitable asteroids that have an orbital energy similar to the destination planet (in order to minimize the energy required to bring the asteroid or its contents to the planet). Total orbital energy ϵ is the sum of kinetic and potential orbital energies[29]:

$$\epsilon = \epsilon_k + \epsilon_p \tag{5.5}$$

$$\epsilon = \frac{v^2}{2} - \frac{\mu}{r} = \frac{1}{2}\frac{\mu^2}{h^2}(1 - e^2) = -\frac{\mu}{2a} \tag{5.6}$$

Where:

- v is the relative orbital speed.
- μ is equal to $G(m_1 + m_2)$
- G is the Universal gravitational constant[30].
- m_1 and m_2 are the masses of the two orbiting bodies.
- r is the orbital distance between m_1 and m_2.
- h is the specific relative angular momentum[31].
- e is the orbital eccentricity[32].
- a is the semi-major axis[33].

In the above equations, ϵ has units of Joules per kilogram. Unfortunately equation 5.6 is only a first step in choosing between possible mining targets – one must also take position into account. A suitable asteroid might have nearly the same orbital energy as Mars but be located 180° away in its orbit.

In practical asteroid mining where economics plays a part, target asteroids would be evaluated both with respect to what they contain, and the energy required to:

- Change the orbit of the body to bring it closer to the destination planet, and/or
- Minimize the travel time and energy required to transport material from the asteroid to the destination planet.

*Disregarding the issue of specific heat[26].

In the case of a body consisting of nearly all volatiles[28] and from economic considerations, it might sometimes be better to expend the energy required to create a converging orbit, then instead of transporting materials from the body to Mars, allow the body to collide with an unoccupied region of Mars, releasing its volatiles as it collides. Such a strategy will make more sense in the early phases of Martian colonization while there are still large unoccupied regions, and while the need to raise the planet's atmospheric pressure still has a high priority.

References

[1] Planetary Protection – methods to prevent biological contamination of other planets.
[2] Extremophile – a class of organism able to survive extreme environmental conditions.
[3] Terraforming – an activity that reshapes a planet's environment to make it suitable for human occupation.
[4] Telepresence – a technology that allows a human to control a robot from a distance.
[5] Planetary Fact Sheet - Metric
[6] Formation and evolution of the Solar System
[7] Frost line – in the early solar system, a radius inside which temperatures were too high to allow ices to exist.
[8] Water on Mars
[9] Solar wind
[10] Outer core (Earth)
[11] Greenhouse effect
[12] Dynamo theory – the theory behind Earth's magnetic field.
[13] Earth's internal heat budget
[14] Atmospheric escape – a discussion of the various mechanisms by which planetary gases are lost.
[15] About Sr2S – an organization studying ways to use magnetic fields to protect astronauts from interplanetary radiation.
[16] Superconducting magnet – an electromagnet whose energizing coil has zero electrical resistance.
[17] Liquid nitrogen
[18] Liquid helium
[19] Cryocooler – a mechanical method to produce cryogenic temperatures.
[20] Candidate cave entrances on Mars – Glen E. Cushing
[21] Magnetization – a measure of the density of magnetic dipole moments in a given material.
[22] Curie temperature – the temperature above which a material cannot retain an imposed magnetic field.
[23] Remanence – the measure of a material's ability to retain an imposed magnetic field.
[24] Density : Water
[25] Standard conditions for temperature and pressure
[26] Specific Heat – a measure of the amount of heat energy required to change the temperature of a material.
[27] Asteroid belt
[28] Volatiles – gases and ices
[29] Specific orbital energy
[30] Gravitational constant
[31] Specific relative angular momentum
[32] Orbital eccentricity
[33] Semi-major axis