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Possible Effects of Space Weather on Mars Colonies

INTRODUCTION: ON THE THRESHOLD OF A NEW EXPLORATION PERIOD FOR MANKIND

We are at the beginning of a new era of human discovery, an era that we could only encounter on the pages of science fiction literature a few decades ago: we are preparing to colonise other planets. To achieve that, we must prepare for a long interplanetary journey and an environment that is completely different from what we already know and what we are already used to on planet Earth. The new environment is expected to be hostile and unforgiving, therefore we must be prepared extremely well. In the age of previous great discoveries, when they set off for the unknown on sailing ships, at least one could know that wherever they arrived, there would be breathable air, drinkable water, and a temperature that would help them to stay alive. In the age of space exploration and colonisation, this is not the case: the air, water and temperature that are needed for maintaining life have to be also provided, which is making everyday life far more complex. So far, we have only talked about the environment that can be expected on the surface of a foreign planet. In addition to that the colonies will also have to face the dangers of various space weather effects. Under terrestrial conditions, we know that space weather can be considered a constant threat to modern technology and critical infrastructure including communication (surface-to-surface or communication using satellites), safe operation of the electrical network (power lines), positioning, and the secure

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operation of digital devices and networks. Furthermore, there is the radiation hazard that we have to take into consideration. As we can see, space weather is a non-negligible risk factor in terrestrial conditions as well. This becomes interesting when we consider that the Earth has a very effective and extensive protective shield, as it has a strong and extensive magnetic field of its own. The focus of our study is the planet Mars. Mars does not have its own magnetic field, at least not as strong and extensive as Earth's. As a result, space weather phenomena will appear with completely different effects than what we are used to under terrestrial conditions.

We will analyse the possible space weather effects on Mars colonies and we thoroughly examine the possibilities and methods of defence against them by taking into consideration the special Martian conditions and environment. It is important to mention that we lack the necessary measurement data related to space weather effects on the surface of Mars and in the near vicinity of the red planet, therefore in our study we are forced to rely on the available data we have, on theoretical assumptions and on the knowledge acquired in the near-Earth environment.

SPACE WEATHER EFFECTS

Generally speaking, the source of all space weather events is the Sun, more precisely the physical processes that take place on the surface of the Sun. The strongest space weather events are caused by eruptions from a sunspot region. It is well known that solar activity has an approximately 11-year time period cycle during which the Sun activity can change substantially. The period of high solar activity is usually called Solar Max, during which time the number of sunspots is represented in the highest number. The time of lower solar activity is referred to as the Solar Minimum, during which period the number of sunspots is low or close to zero. This also means that strong space weather events can have a substantially higher probability during high solar activity.

We basically have to reckon with four types of space weather phenomena: bursts, radio bursts, SEPs (solar energetic protons) and CMEs (coronal mass ejection). In many cases, these events occur together, but there are also cases where they can be observed separately. X-ray bursts are emitted by solar flares, and they can be characterised by intensive, high-energy X-ray packages travelling with the speed of light. Radio bursts also travel with the speed of light, and they are a high intensity, bright bursts of electromagnetic (EM) radiation packages, that can be detected in radio wave frequencies. SEP events are high-energy particle (proton, electron and heavy ion) clouds that travel with high speed through the interplanetary space: the particle energies range from a few tens of keV to GeV, and the fastest particles can reach about 80% of the speed of light. CMEs are plasma eruptions or ejections emitted by the Sun into the interplanetary space with significant plasma mass and the accompanying magnetic field. A CME can reach a speed of 3,000 km/sec in certain cases, so the time required from the moment of the eruption to the arrival on Mars can vary between 21 hours and 5 days. It is obvious that in case of X-ray bursts and radio bursts, we cannot detect the phenomenon before arriving at the planet, since they propagate at the speed of light. In case of SEP events, it is possible to detect the event a few hours before arrival to the planet. On the other hand, a CME can be detected even days before arrival on the planet and thus can be predicted. Therefore, the situation on Mars is very similar in terms of forecasting to Earth, but there is a catch. In case of Earth, we have spacecraft that are located in the vicinity of the L1 point (ACE, SOHO, etc.), so in principle, we can constantly take measurements and detect if there is any change in the interplanetary space. With this, SEP and CME events can be well predicted, and even the expected time of arrival can be determined with great accuracy. In contrast, in case of Mars, we do not have such spacecraft at least not yet. To be able to provide any kind of space weather forecast for the Martian colonies, it will be necessary to build a spacecraft–space-based observation system, as in case of Earth. In the absence of this, it is not possible to give a reliably accurate forecast. This means that – at least in the early days – preparing for and defending against space weather events will be carried out without a forecast service, which greatly narrows the options and possible solutions. It is worth mentioning that serious efforts are currently underway to predict flares and solar flares from the observation of sunspots and the dynamics of their development. If this venture succeeds, it would greatly facilitate space weather forecasts. However, even in this case, there is still uncertainty about the direction in which a possible flare or CME will spread, that is, whether it will hit Mars at all.

To understand what space weather effects we have to expect on the surface of Mars, it is worth learning about the magnetosphere and atmosphere of Mars (including the Martian ionosphere). The Earth's magnetosphere and ionosphere serve as reference points because through this we better understand the differences and why a space weather event can have completely different consequences in the Martian environment.

THE MAGNETOSPHERE AND IONOSPHERE OF MARS

Planet Mars does not have its own extensive magnetic field like Earth does. This is because Mars does not have an internal dynamo mechanism that can create and maintain a strong, extended magnetic field like Earth's. In case of Earth, the intrinsic magnetic field (magnetosphere) extends far towards the Sun: at the subsolar point (the point along the line connecting the Sun with Earth) the position of the magnetopause (in other words: the boundary of the magnetosphere) is located at a distance between 6 and 15 Earth radii, depending on the parameters of the solar wind.

The extended magnetosphere means that Earth's magnetic field can resist the pressure of the solar wind, that is, there is a dynamic balance between the planet's magnetic field and the pressure of the solar wind. For the solar wind, the lines of force of the magnetosphere form an impenetrable barrier, so the solar wind – to put it figuratively – collides with the magnetosphere, slows down, and then changes direction and flows around the magnetosphere. The solar wind is slowed down by the so-called shock wave, which forms even before the magnetopause, as a result of which the solar wind that reaches the magnetopause already loses a lot of its kinetic energy.

For Earth, the extended magnetosphere means that the position of the magnetopause is located much further out than the Earth's atmosphere, so the solar wind cannot come into contact with the atmosphere, and there is practically no interaction between the atmosphere and the solar wind. For Mars, on the other hand, there is no internal dynamo mechanism that could create an extensive magnetic field around the planet; nevertheless, Mars does have its own magnetic field. The Mars Global Surveyor (MGS) satellite (NASA [s. a.]a) carried out measurements between 1997 and 2006 at 100 and 400 km above the surface, based on which it can be concluded that there are relatively strong magnetic fields of a few hundred nT in the Martian crust. These areas of residual magnetism suggest that Mars may once have had an extensive magnetosphere and an internal dynamo mechanism.

Crustal magnetism is typically low in the Tharsis Ridge, impact basins and northern plains. In contrast, the value of the magnetic field is much stronger in the southern areas, where these magnetic fields frozen in the rock practically create small, local magnetospheres, the value of which, according to MGS measurements, can locally reach 1,600 nT on the surface. This is very small compared to the terrestrial magnetic field, which varies between 25,000 and 65,000 nT on the surface. On the other hand, this value is already enough to withstand the pressure of the solar wind at 400 km altitude (Ma et al. 2008), and it can presumably be strong enough to ward off the major effects of a space weather event. These small, local magnetospheres act as a kind of shield because they prevent charged particles from reaching the surface of the planet in these areas (Connerney et al. 2004). Therefore, these areas will be very important in selecting colony locations.

The Martian ionosphere is the part of the planet's upper atmosphere in which ions are created under the influence of the Sun's ultraviolet radiation, and therefore it is in an ionised state. Earth's ionosphere is located deep inside the magnetosphere and is not in contact with the solar wind. For Mars it is different, the solar wind is in direct contact with the ionosphere. This is a fundamental difference between the two planets that determines the environment around Mars and how it changes. In addition to the extreme ultraviolet and X-ray radiation of the Sun, the Martian ionosphere is also affected by the local magnetic environment and the shower of charged particles. Of these, the main reason for the development and changes in the ionosphere is clearly the interaction of the material of the solar wind with the already mentioned local magnetic fields (Withers et al. 2012). The interaction of the Martian ionosphere with the material of the solar wind results in the creation of an upper boundary that separates particles (electrons) originating from the Sun from charged particles (electrons) originating from the Martian atmosphere. Although this limit can vary significantly, it is usually found at an altitude of 400 km (Withers et al. 2012).

The ionosphere of Mars has a layered structure, typically with two important layers. The first layer is located approximately 120 km above the surface, this is the so-called M1 layer. The M1 layer is basically excited and created by the Sun's low-energy X-ray radiation.

The M2 layer is created by the Sun's extreme ultraviolet radiation, where the highest electron density is typically found at an altitude of 140 km. Above this layer, the electron density decreases exponentially with height (Withers et al. 2012).

The Martian ionosphere therefore is capable of absorbing a significant part of the Sun's low-energy X-ray and extreme UV radiation, thus it can have a protective effect against these radiations during quiet times. On the other hand, during a space weather event most probably the Martian ionosphere will not be able to provide a substantial shielding effect, especially against high-energy X-ray radiation and high-energy particles, like the ones expected during SEP events and CMEs.

Another characteristic of the Martian ionosphere is that the height of the upper part of the ionosphere can vary significantly, as evidenced by the Mars Express (MEX) measurements. According to the MEX data, in 1% of the detections, this height was located at 650 km, while in 25% of the detections, this limit (ionopause) was below 250 km height. Based on the analyses, it seems that the unusually high ionopause occurs above areas where there is a locally stronger (crust-derived) magnetic field. These local spaces can keep the solar wind away from the planet by "acting" as a local magnetosphere (WITHERS et al. 2012). Lower-than-average ionopause heights occur during intense solar activity, which indicates that lower-than-average or much lower ionopause heights should also be expected during space weather events, which can significantly increase the risks caused by radiation on the surface. Another characteristic is that the composition of the ionosphere can vary according to geographical location. The reason for this is that molecular oxygen is more common in the lower parts of the Martian atmosphere (i.e. closer to the planet's surface), while atomic oxygen is dominant at higher altitudes.

The ionosphere does not only depend on the local conditions, as we presented above but also depends to a large extent on the time of day. In the absence of the Sun's radiation, the structure of the ionosphere changes completely on the night side, and the electron density is greatly reduced (WITHERS et al. 2012).

Based on all of this, it can be said that we are dealing with a very variable Martian ionosphere, dependent on many factors, even during quiet periods from the point of view of space weather. During a space weather event, the structure of the ionosphere is expected to become even more complicated and diverse, and this will be important for the colonies from the point of view of communication, which we will return to later.

THE MAGNETIC ENVIRONMENT STRUCTURE ON MARS

After learning about the magnetic properties of the planet Mars and the structure and processes of the ionosphere, the global structure and its consequences become understandable, but for this, we still need to examine the interaction with the solar wind, which completes the picture.

In the flow of the solar wind, Mars appears as an obstacle, therefore a shock wave forms in front of Mars, where the flow of plasma of the solar wind slows down to subsonic speed. As a result of the Sun's ultraviolet radiation, the upper atmosphere of Mars is ionised, thereby turning it into an electrically charged medium. The magnetic field of the solar wind does not penetrate this medium, so the solar wind flows around the planet. As a result, it interacts with the planet's ionosphere and creates a so-called induced magnetosphere (Szegő 2016). For this reason, the magnetic environment of the planet Mars is special in that it consists of a superposition of the induced magnetosphere and the local crustal magnetic fields.

Based on MGS measurements, the bow shock is located at a distance of approximately 2.33 Mars radii from the planet, which in case of Earth – as mentioned earlier – is much further away. At the shock wave, the magnetic field strength increases suddenly, and due to the acceleration processes taking place here, high-energy electrons also appear (Acuña et al. 1998). Moving towards the planet, the next interface is the so-called Magnetic Pileup Boundary (MPB), which separates the Magnetic Pileup Region (MPR) from the magnetic sheath (Martian magnetosheath or simply sheath). The MPR is the region dominated by the ions of the planet's atmosphere and characterised by a stronger magnetic field (Nagy et al. 2004).

The innermost boundary is the Photo Electron Boundary (PEB), which separates the ionosphere from the outer plasma environment (Wang et al. 2022). As already mentioned, the height of the PEB depends to a great extent on the crustal magnetism of the areas below it: where crustal magnetism is present, this limit is pushed up, as can be seen in *Figure 1*. This is typically observed in the southern hemisphere (Bertucci et al. 2005).

The atmosphere of Mars is constantly eroding due to the interaction with the solar wind and has already lost a significant part of its atmosphere in the past. According to analysis, the erosion of the atmosphere began after the planet's internal magnetic field ceased.

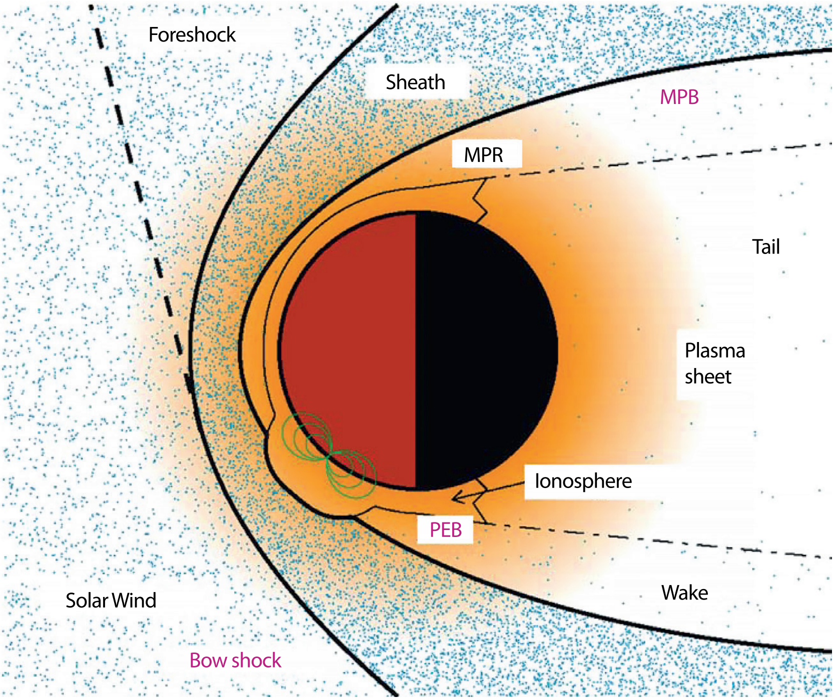

Figure 1
Structure of the magnetic environment on Mars
Source: Brain 2006: 79.

RADIATION

If we want to create settlements on Mars, settlements where people stay and work for a longer or shorter period of time, we must examine the issue of radiation as a condition. As we have already mentioned, Mars does not have a protective magnetosphere like the Earth, so ionising, high-energy radiation can reach the surface practically unhindered. Furthermore, the solar wind is constantly eroding the rare atmosphere that still remains on Mars, so the atmosphere is not an appreciable protection against radiation either. To be precise, the Martian atmosphere can provide some protection against cosmic radiation and moderate protection against radiation from the Sun.

Therefore, it can be said that a much higher radiation exposure than the terrestrial environment must be expected on Mars, and to this we must also add the occasional space weather effects, which can carry even lethal amounts of radiation, and that is in a very short time. The risk posed by space weather events is of course even more pronounced during the solar maximum.

To be more specific, let us discuss specific events and specific numbers. Most particles from most SEP events are likely to be intercepted by the Martian atmosphere. At the same time, these particles interact with the particles of the atmosphere, and neutrons can be created from this interaction, and these neutrons can reach the surface. In other words, it can be said that although the direct risk posed by SEP particles can be greatly reduced by the presence of the atmosphere, it does not completely eliminate the health risk.

The protective effect of the Martian atmosphere also depends to a large extent on where on the planet we are, i.e. near the equator or rather near the poles. In other words, because of the angle of inclination, radiation coming from near the horizon has to travel a much longer distance through the atmosphere than radiation coming from near the zenith. For the settlement to be established on the surface of Mars, this aspect should also be taken into account as much as possible. On the other hand, it has to be taken also into consideration that the temperature conditions are not very favourable for colonies in the vicinity of the poles.

If we want to talk about specific numbers, we should know that there are various, sometimes different, estimates in the literature about the expected radiation on the surface of Mars. The average radiation dose on Earth's surface, which comes from cosmic rays, is about 0.26 mSv/year. This value naturally increases with altitude and corresponds roughly to 10% of the total annual radiation exposure. The dose caused by cosmic radiation on the surface of Mars is about 230mSv/year, taking into account the data measured by the Curiosity Mars rover. As estimated by other models, the annual radiation dose on the surface of Mars varies between 156.4 mSv/year and 273.8 mSv/year; the former value is expected at the time of solar maximum, and the latter at the time of solar minimum.

The Mars Odyssey probe (NASA [s. a.]b) was equipped with an instrument specifically designed to measure the radiation environment around Mars. The name of the instrument is MARIE (Martian Radiation Experiment), and the radiation value measured by it corresponds approximately to what is expected on the surface due to the rare atmosphere of Mars. During 18 months, the instrument measured an average value of 22 millirads per day, which corresponds to 8 rads or about 80 mSv/year (1 mSv = 100 millirads). As can be seen, the expected radiation value (from cosmic rays) on the surface of Mars on average is about 300–1,000 times higher compared to radiation values on the Earth's surface.

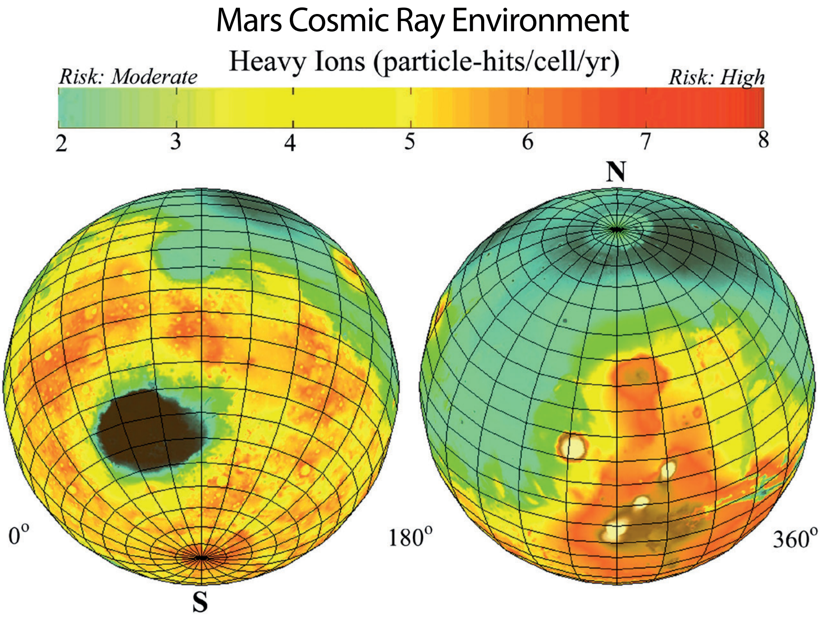

Figure 2
Estimate of the high energy cosmic radiation reaching the surface of Mars
Source: NASA/Jet Propulsion Laboratory/JSC 2002

THE STRUCTURE AND CONDITIONS OF THE MARTIAN COLONY

When examining the possible effects of space weather on a Martian colony, it is worth mapping out the vital elements of such a colony, so what are the things that are absolutely necessary for such an establishment. The list is obviously incomplete and rough, its main purpose is to list the elements that can be directly affected by space weather events. These are the following:

- the complex systems controlled by computers that ensure life support
- growing plants that provide food
- communication between stations and units on Mars
- communication with satellites (including positioning)
- satellites orbiting Mars and performing various tasks
- the larger structural units and facilities of the colony (electrical network, possibly railway and water supply network, etc.)
- the structures providing radiation protection

When compiling the list, it is necessary to start from the assumption that the operation and security of a colony cannot be imagined without space technology applications; therefore, the presence and use of satellites are absolutely necessary. The space station (which ensures the transportation of people and useful materials), industrial facilities and mining sites were not specifically mentioned, because the latter can be integrated into the above list.

Effects on plants and crop production

The primary condition for the existence of colonies is the provision of food. This is obviously not possible with transport supplies from Earth, which is why it is necessary to start growing crops on Mars as early as possible. In this section, we examine the potential consequences of radiation and space weather events for plant development. We have never tried to grow plants outside of Earth, so this is an interesting task and challenge in itself. Note: there were valuable plant growing experiments onboard the ISS, but since the space station orbits between 370 and 460 kilometres above the Earth's surface, these experiments were conducted still in the protective Earth's environment, deep inside the Earth's magnetosphere.

Fortunately, there has already been an experiment (Tack et al. 2021) that specifically examined the development of cultivated plants, exposing them to approximately the amount of radiation expected on the surface of Mars, according to calculations and measurements. The radiation was simulated or more precisely replaced by the gamma radiation of cobalt-60. In the test, the germination and development of rye and garden cress were investigated after being exposed to radiation. The experiment ended with some interesting results.

The results showed that radiation had no detectable effect on germination, however, biomass development was significantly reduced in the first four weeks. The decrease was 48% for rye and 32% for cress. The article notes that, in principle, the not exactly identical environment, possible changes in temperature and humidity can explain some of the difference, however, the difference measured in the experiment is such that it can clearly be attributed to the effect of radiation. In addition, discolouration, necrosis and browning of the leaves were also observed. It is also described that the short-term, but higher-intensity radiation (with which they tried to simulate solar SEP events) that reached the plants in their various development phases did not significantly affect the amount of the crop.

Knowing this, it is clear that plants should be protected from radiation, e.g. considering that the cultivation could take place deep underground, but in this case, we obviously lose what would be the most important from the point of view of plant cultivation: natural light.

Overall, based on the results of the experiment, it can be said that in order to ensure the appropriate amount of the planned crop, the production area must be increased at least twice as compared to the conditions on earth.

SEU–SEE

Under Martian conditions, we must definitely discuss the effects of various ionising radiations on electrical devices, which may occur more frequently during space weather events. Here we are not thinking of events that, for example, cause permanent damage to electronics as a result of strong radiation, because space vehicles normally are built in such a way that they are resistant to (expected) radiation. This is called the "rad-hard" requirement, and as a result, devices built in this way usually operate safely in environments with significant radiation.

However, there is also an event when a single ionising particle, be it an ion, an electron or even a photon, which has sufficient energy, hits a sensitive point (node) in microelectronics and causes a state change in it. The change of state is the result of the ionising particle creating a free charge that changes the value of a bit in a memory cell or the processor, for example. This obviously causes an error in the output signal, the consequence of which is an operational error (program error), which can also cause a complete interruption in the operation of the system.

This is called single event upset (SEU) or single event error (SEE). It is important to emphasise that this does not cause permanent damage to the system, but rather an operational error or shutdown which typically occurs after the incomprehensible program instruction. This error usually disappears after restarting the program or the process. It is also worth noting that this error typically occurs during operation, and not when it is turned off. The first article (Binder et al. 1975) describing the SEU event was published in 1975.

It is clear that during space weather events, especially SEP events, SEU failures can be expected more frequently, not only for satellites orbiting Mars but also on the surface of Mars. The reason is obvious: due to the lack of an extensive magnetosphere and the rare atmosphere, ionising radiation reaches the surface much more easily, posing a serious threat to electronic devices. Taking into account the fact that the living conditions for the colony on the surface of Mars are provided by well-functioning devices controlled by complicated electronics, even a temporary malfunction cannot be allowed because it can have fatal consequences.

For this reason, it is clear that when designing and building systems using microelectronics, maximum consideration must be given to failures caused by SEU and adequate redundancy must be ensured. Without it, the protection and proper functioning of the colonies cannot be ensured.

Data protection must also be mentioned here: malfunctions caused by space weather events can seriously threaten the integrity of the data stored in the databases. For this reason, duplicated redundant data protection will probably not be enough, but it may also be necessary to make the units storing important data geographically redundant. According to this, all data will have to be stored on servers that must have at least one (or even more) copies at a location as far away from the primary data server as possible, possibly deep below the surface, which is maximally protected from all kinds of space weather events.

In the case of satellites orbiting Mars, we can expect even more SEU events, because the satellites will be located outside the atmosphere, so even the minimum protection that the rare atmosphere might mean for the satellites will not be provided.

Magnetic storm on Mars and its expected consequences

A CME under terrestrial conditions (if it hits the Earth) causes a geomagnetic storm. The Earth's magnetosphere is compressed, which causes a significant and rapid change in the magnitude of the local magnetic field that can also be measured on the Earth's surface. We know that a rapidly changing magnetic field induces an electric field, which generates currents in the ionosphere and the Earth's crust. These are the so-called geomagnetically induced currents or GIC. Mars does not have an extensive magnetic field, but it does have some remanent and induced magnetic fields, as has been discussed previously.

If a CME hits Mars, we can expect similar consequences, that is, a rapid change in the magnetic field that can also be felt on the surface. It is important to note that the consequences of a CME on Mars have not yet been measured; therefore, we do not have reliable measurement data for such an event. Here we can only refer to analogy and physical laws, but this is enough to be able to predict the expected consequences. The rapidly changing magnetic field creates an induced electric field on the surface of Mars, this is certain.

Compared to the effects that can be observed on Earth, this will not cause a global effect, but rather we can expect local, quite specific effects, which are more characteristic of the given areas and can be very different in different areas of Mars. For this reason, it is difficult to predict the changes in the magnetic field perceptible in specific areas. If, however, these are significant changes, the appearance of an excited electric field and, as a consequence, crustal currents in the soil of Mars can be expected. We can call these Martian Magnetically Induced Currents, or MMIC.

These induced currents seek a path and flow where the resistance is least, so they tend to attach to man-made metal structures that span over great distances. In terrestrial conditions, such are, for example, railways, petroleum pipelines and high-voltage lines. In case of a Martian settlement, similar structures can be expected: electric lines, pipe systems, etc., which are absolutely necessary for the operation of the settlement.

MMIC can attach to these structures and devices and due to that can cause failures. As has been said, sensitive electronics can be potentially endangered by these stray currents, which can be in some cases very high-intensity currents. How to defend against MMIC? Fortunately, a magnetic storm is a space weather event that can be predicted before it happens with sufficient certainty. A CME (depending on the propagation speed of the plasma cloud) needs 1–4 days to reach Mars.

The CME can be detected immediately after its ejection if a satellite is available at the appropriate observation point. And here is a problem: in case of Earth, several satellites are available to observe CMEs (SOHO, ACE, etc.), but they can only be used to predict geomagnetic storms that are expected on

Earth. We do not (at least for now) have such an option for Mars. The existing satellites are of limited use to detect the plasma cloud spreading towards Mars, if the position of the Earth and Mars and their relative positions make this possible. However, if Earth and Mars are at two very different points in their orbits, then obviously no prediction or observation is possible.

Communication on Mars

For radio communication on Earth, the presence of the terrestrial ionosphere is of primary importance. Since Mars does not have an ionosphere comparable to Earth's, it can be clearly stated that radio communication will be realised with a completely different technology than on Earth. On Earth (especially in case of radio broadcasting on the HF band), communication over long distances (to targets beyond the horizon) is possible in such a way that the radio wave can travel between the ionosphere and the Earth's crust like a waveguide.

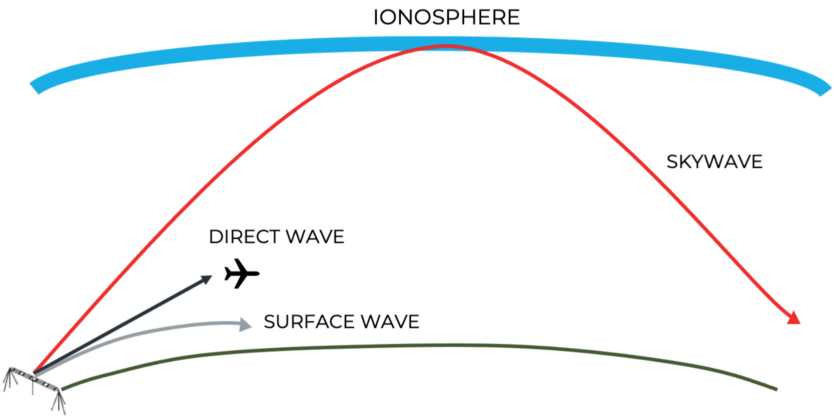

Figure 3
The path of the HF radio wave in the terrestrial environment
Note: Most probably it will not be possible to use the skywave in radio communication on Mars due to the dynamic nature of the Martian ionosphere.
Source: Daly 2021

HF is popular even today, when communication via satellites is already widespread because it is a very reliable method in normal conditions.

On HF frequencies we communicate with aircraft, the frequency is used by government agencies and by the military, just to name a few. In terrestrial conditions, problems in HF band radio communication usually arise when the structure of the ionosphere changes due to a space weather event. In this case, partial or complete data loss may occur.

On Mars, radio communication will probably be achieved by using a direct wave (when the receiver "sees" the transmitter), or through communication satellites orbiting in stationary position. The reason for this is obviously the lack of a "stable" ionosphere similar to Earth's, which enables reliable radio communication. In principle, it might be possible to communicate on Mars by using the presence of the Martian ionosphere, but due to its dynamically changing nature, it is unlikely that this can be realised.

According to our current knowledge, the use of direct waves and communication via satellites seems to be possible on Mars. On the other hand, both can have serious problems, especially during space weather events. During radio burst events serious interruptions can occur even when the direct wave is used.

We have to prepare for such events. These events cannot be predicted or forecasted, because a radio burst arrives at the speed of light. Note: this may also partially or completely limit the operation of radars. Radio bursts do not cause permanent damage to the instruments, but they can cause temporary disturbance.

Communication via satellites is also exposed to the effects of space weather, as we have seen by satellites around Earth. Communication with satellites on Mars also takes place through the Martian ionosphere, which means that the radio wave must pass through the ionosphere. During a space weather event, the structure and density of the Martian ionosphere can change significantly, which changes the path and direction of the radio wave passing through it.

This is when the phenomenon called scintillation (Kenpankho–Suwanjan 2004) occurs, when, to put it simply, the radio signal bounces back and forth in the ionosphere, travels through several paths, and the signal arriving at the receiver (if a signal arrives at all) is formed by the interference of the original signal travelling through several paths, which was broken up. Obviously, this can result in partial or even complete data loss. The condition persists until the ionosphere returns from its disturbed state to its "normal" state.

Here, however, it is worth noting that in case of the Martian ionosphere, we are facing a highly dynamic environment, and as a result, we can expect data loss even in a period free of space weather events.

When using GPS, we can also expect scintillation during space weather events resulting in satellite-based positioning becoming unreliable. The reason for this is that the signal from the satellite arrives from a different direction due to the scintillation, so the degree of positioning will be incorrect, and if strong scintillation occurs, it might become completely unreliable.

Where should we settle on the surface of Mars?

The complete question would rather sound like this: Where can we create settlements on the surface of Mars, where the colony is as protected as possible from the effects of space weather? Obviously, it is very difficult to give a clear answer to this question, so we will take a look at the possible options.

1. The first and logical option would be for the colony to be established deep below the surface of Mars, where the thickness of the crust provides reliable and sufficient protection against all kinds of radiation and space weather effects. The creation of a functional city underground or under the soil/crust of Mars would involve incalculably high costs and technical solutions. It is necessary to ensure breathable air, suitable temperature, drinking water, food production (using artificial light!) and, of course, an acceptable living space for people (and, where appropriate, animals). Not to mention the expected psychological effects of living in such a closed and humanly oppressive environment, deep inside an actual cave. If we want to be insightful, we could imagine such a colony as the city of Zion in the Matrix movie.

2. If we start from the assumption that the effects of space weather occur mainly on the side facing the Sun, then it is possible to imagine a colony that retreats to safety during the Martian day and is only active during the night. Here it is no longer necessary to plan a city deep under the crust, the buildings can be located on the surface, assuming sufficient protection against all kinds of influences. On the other hand, the effects on technology must also be taken into account, against which protection can be provided by ensuring that devices, machines, computers, etc. on the day side switch to a "protected" or "sleep" state, ensuring that failures are minimised while the colony residents are in a safe and protected space. On the night side, one can move more freely, the technology becomes active, and it is possible to perform all the activities that are the purpose of the colony.
3. If the goal is to create a colony that is not significantly restricted in its operation, and all kinds of activities can be carried out relatively freely even on the day side with an acceptable risk, the position of the colony on the surface of the planet must be chosen extremely carefully.

The requirement is obviously the maximisation of the protection capacity of the natural environment. This means that the chosen place must be one that provides the best possible natural protection against radiation and other space weather effects. It has two important elements: the atmosphere and the magnetic field; both act as a protective shield. The atmosphere must be as thick as possible, therefore, it is necessary to look for a place that is as low as possible compared to Martian conditions.

Basins and low-lying regions can be considered. The other condition requires the strongest possible magnetic field to be present in the given area, therefore, it is worth looking for places where the crustal magnetic field is as strong as possible. If we manage to find a low-lying region where the crustal magnetic field is strong enough, then we have practically found the ideal location for the colony.

SUMMARY

It is very important to emphasise that all the topics and discussions presented in this analysis can be considered only a preliminary study due to the simple fact that at this point we do not have enough reliable data and experience from the red planet. On the other hand, the conclusions are the result of careful and deliberate use of the available scientific knowledge.

We currently do not know exactly where, when, under what conditions and future knowledge the first Martian colony will be created. We can only hope that this study can provide useful assistance in one of the greatest enterprises of mankind: the colonisation of other planets and the expansion of human civilisation beyond the borders of the cradle of life, the Earth.

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