Boletim da Sociedade Astronômica Brasileira, **37**, no. 1, 193-195

Impact of heliosphere reduction on the atmosphere of Mars

J. Arpiani[1] & A. Valio[2]

[1] EE-Escola de Engenharia Mackenzie e-mail: arpiani20@gmail.com
[2] Centro de Radioastronomia e Astrofísica Mackenzie (CRAAM) e-mail: adrivalio@gmail.com

Abstract. The heliosphere, formed by the solar wind and the Sun's magnetic field, functions as a protective shield for the Solar System against radiation and cosmic rays originating from the interstellar medium (ISM). Recent studies suggest that the Solar System has traversed the Local Lynx Cold Clouds (LxCC), a region of the extreme interstellar medium, leading to a substantial shrinkage of the heliosphere to within Earth's orbit. Under such conditions, planets like Mars would have been exposed to enhanced fluxes of radiation and high-energy particles, potentially contributing to atmospheric escape and modifications in its chemical composition. Geological and geochemical evidence indicates that early Mars was comparable to the primitive Earth, with a denser and more humid atmosphere and the possible presence of liquid water on its surface. The objective of this research is to quantitatively assess the impacts of a contracted heliosphere on the atmosphere of Mars. Thus, understanding this potential period of intense exposure to an extreme interstellar environment is essential for reconstructing Mars' atmospheric evolution. This study will employ simulations using the *Atmos* software, which models planetary atmospheres, and *FLUKA*, a toolkit for simulating high-energy particle interactions with matter, to quantify atmospheric mass loss and chemical alterations driven by a dense interstellar medium.

Resumo. A heliosfera é uma estrutura formada pelo vento solar e pelo campo magnético do Sol que atua como um escudo protetor do Sistema Solar contra a radiação e os raios cósmicos provenientes do meio interestelar (ISM). Estudos recentes sugerem que o Sistema Solar atravessou a Lince Local de Nuvens Frias (LxCC), regiões do meio interestelar extremo, resultando no encolhimento da heliosfera para dentro da órbita da Terra. Nesse cenário, planetas como Marte teriam ficado vulneráveis à radiação e a partículas de alta energia, o que possivelmente contribuiu para a perda de sua atmosfera e na alteração de sua composição química. Evidências apontam que Marte, em seus primórdios, era semelhante à Terra primitiva, com atmosfera mais densa e úmida, além da possível presença de água líquida. O objetivo desta pesquisa é realizar uma estimativa quantitativa dos impactos da redução da heliosfera na atmosfera do planeta Marte. Para tanto, entender essa possível exposição intensa ao meio interestelar extremo é essencial para reconstruir sua evolução atmosférica. A pesquisa utilizará simulações com o software *Atmos*, que modela atmosferas planetárias, e o *FLUKA*, utilizado para simular interações de partículas de altas energias com a matéria, a fim de quantificar a perda de massa atmosférica e as alterações químicas sob influência do meio interestelar denso.

Keywords. Sun: heliosphere – ISM: clouds – Planets and satellites: atmospheres

1. Introduction

The Sun has long been a subject of human study, and advances in our understanding of our star have progressively increased, particularly regarding its influence on the planets of the Solar System. The solar wind directly affects the planets orbiting the Sun and originates from the outermost layer of the solar atmosphere, the corona, which is the most extended region and reaches temperatures on the order of 10^6 K. The solar wind is therefore driven by the large pressure gradient between the corona and interplanetary space. Additionally, the thermal velocities of particles exceed the Sun's escape velocity, resulting in the outflow of particles, primarily ionized helium nuclei, protons, and electrons, which are accelerated to high velocities—typically hundreds of kilometers per second—and propagate throughout the Solar System.

It is now well established that a plasma originating from the supersonic expansion of the solar corona permeates the interplanetary medium between the planets of the Solar System (Oliveira 2014). This plasma consists of a flux of charged particles, known as the solar wind, which, together with the solar magnetic field, forms a structure known as the heliosphere.This magnetic bubble enclosing the Solar System delineates the region dominated by the Sun in relation to other stars. Periodic magnetic variations of the Sun, occurring over roughly 11-year cycles, directly affect the size of the heliosphere, which expands during solar maximum and contracts during solar minimum (Silva 2006).

However, the heliosphere is influenced not only by solar activity but also by the surrounding interstellar environment. The Solar System has been inside the Local Bubble for at least 3 million years, a low-density, X-ray–emitting cavity located in the Orion Arm of the Milky Way (Fuchs et al. 2006). Nevertheless, the surroundings of the Sun are not homogeneous; numerous partially ionized interstellar clouds exist, and the Solar System has likely traversed multiple regions of the local interstellar medium (Opher et al. 2024). Among these regions are cold dense clouds, and an encounter between one of these clouds and the Solar System could drastically alter the structure of the heliosphere, potentially shrinking it to about 0.22 AU—smaller than Earth's orbital radius (Opher et al. 2024).

A contracted heliosphere would have significant impacts on the planets of the Solar System, as this structure shields the system from cosmic radiation and blocks approximately 75% of incoming cosmic rays from the interstellar medium (Opher 2012). Mars is particularly vulnerable to cosmic radiation because it lacks a global magnetic field capable of protecting its atmosphere from direct interaction with the interstellar environment, making its atmosphere more susceptible to loss and chemical modification.

Thus, the objective of this study is to investigate the effects of heliospheric contraction occurring millions of years ago on the atmosphere of Mars, examining how a reduction in heliospheric shielding may have influenced the loss and chemical evolution of the planetary atmosphere. To achieve this, computational simulations will be performed using the *Atmos* and *FLUKA* software packages. The *Atmos* model will be used to simulate the evolution of the Martian atmosphere and its interaction with ultraviolet radiation from the interplanetary medium, while *FLUKA* will be employed to simulate the interaction of cosmic radiation with the planet's surface and atmosphere.

2. Theoretical Framework

2.1. Heliosphere and its Possible Contraction

The interactions between the interstellar medium (ISM) and the heliosphere can influence both its characteristics and its overall size. The Solar System moves through the ISM at a velocity of approximately 18 pc per million years, encountering environments with different physical properties that directly affect the structure of the heliosphere. Recent studies (Opher et al. 2024) indicate that about 2 Myr ago, the Solar System crossed a dense interstellar cloud, one of the most extreme environments of the ISM, comparable to molecular clouds.

The dense cloud crossed by the Solar System is the Local Lynx Cold Cloud (LxCC), which forms the tail of the Local Ribbon of Cold Clouds (LRCC). According to the model proposed in the study, this cloud had a sufficiently high density ($\sim 3000\,\mathrm{cm^{-3}}$) to compress the heliosphere inside Earth's orbit (1 au), exposing both Earth and Mars to the dense interstellar medium. Another similar event may have occurred 6.8 Myr ago, when the Solar System crossed the boundary of the Local Bubble (density $\approx 900\,\mathrm{cm^{-3}}$) (Miller et al. 2024).

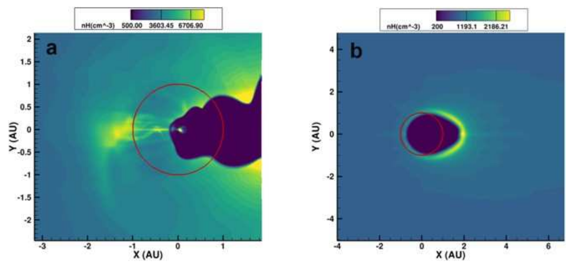

Figure 1. Equatorial slices from MHD simulations (Opher et al. 2024) showing heliospheric compression by interstellar clouds with densities of (a) $3{,}000\,\mathrm{cm^{-3}}$ and (b) $900\,\mathrm{cm^{-3}}$ at 2 and 7 million years ago. The red circle denotes Earth's orbit (1 au).

According to Miller et al. (2024), one of the most significant impacts of exposure to the interstellar medium on the terrestrial mesosphere is mesospheric ozone depletion. Yeghikyan & Fahr (2005) reports a 50–80% reduction in ozone near 80 km altitude. Ozone destruction occurs through catalytic reactions involving HOx particles, in which O_3 is converted into O_2. Therefore, ozone depletion increases proportionally with HOx abundance. The high concentration of interstellar hydrogen in dense cold clouds is supported by the model presented in their study.

2.2. Mars

Mars has long been a central topic in planetary science due to its drastic climatic evolution. Hiscox (1999) discusses the possibilities and evidence of a potentially habitable environment in Mars's past, suggesting that the planet may once have been suitable for life. The study highlights early similarities between Earth and Mars, supported by evidence of past liquid water, such as deep channels and dry riverbeds. Another important similarity is the presence of a denser early Martian atmosphere, according to theories proposing a CO_2-rich layer (1–5 bar), which would have generated a significant greenhouse effect and maintained average temperatures above the freezing point of water. Thus, Mars may have been a less hostile planet in the past, with environmental conditions favorable to liquid water. Over time, however, the planet underwent substantial changes leading to its current cold and tenuous state, making the study of Mars's atmospheric and climatic evolution essential.

3. Preliminary Results and Discussion

We used the *Atmos* code, which is capable of simulating atmospheres with detailed chemical and climate profiles, to investigate the modern Earth and the potential mesospheric ozone depletion associated with heliospheric compression. The initial studies focused on Earth due to the availability of literature that enables validation and comparison of the results. Subsequently, the goal is to extend the application of the model to the Martian atmosphere.

We analyzed the ozone profile of Modern Earth and Mars using the photochemical–climate model *Atmos*. The simulated ozone profiles for both scenarios are shown in Figure 2.

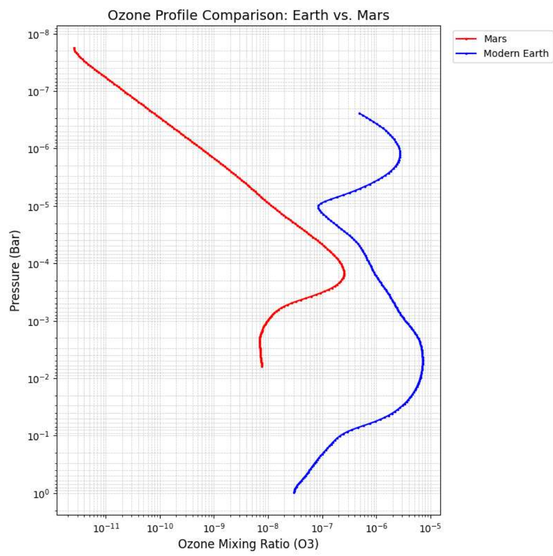

Figure 2. Ozone profile of Mars and Modern Earth, obtained through simulation using the *Atmos* code.

The ozone profiles obtained for both planets are presented in Figure 2. The ozone concentration is higher on Modern Earth, with a peak between 10^{-2} and 10^{-3} bar, characteristic of the terrestrial stratospheric ozone layer. For Mars, the simulation resulted in a lower ozone concentration, shifted toward lower pressures (higher altitudes). These preliminary results are important because they establish a baseline for future comparison with the heliospheric compression scenario.

4. Next Steps

The next steps involve using *FLUKA*, a particle-transport and radiation–matter interaction simulation code, to investigate the interaction of cosmic rays with the Martian atmosphere, as well as to further advance the study of the impacts of heliosphere reduction on Mars' climate and atmospheric composition.

References

Fuchs, B., Breitschwerdt, D., de Avillez, M., Dettbarn, C. & Flynn, C., 2006, Monthly Notices of the Royal Astronomical Society, 373(3), 993–1003.
Hiscox, J. A., 1999, Earth, Moon, and Planets, 87, 191–212.
Izzo de Oliveira, M. N., Rockenbach, M. e Pacini, A.A. 2014, Revista Brasileira de Ensino de Física, 36(2), 2316-1–2316-13.
Miller, J. A., et al., 2024, Geophysical Research Letters, 51(17), id. e2024GL110174.
Opher, M., 2012, Astronomical Review, 7(1), 68–78.
Opher, M., Loeb, A. & Peek, J. E. G., 2024, Nature Astronomy, 8, 983-990.
Silva, A. V. R., 2006, Nossa Estrela: o Sol, São Paulo: Ed. Livraria da Física, 166 p.
Yeghikyan, A. & Fahr, H., 2005, Astronomy & Astrophysics, 430, 875–884.