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Atmospheric mass loss of telluric planets due to solar or stellar wind

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Abstract. The Sun, like other stars, exhibits a dynamic behavior, producing energetic phenomena such as flares and mass ejections that often have harmful consequences for the Earth. The continuous flow of particles from the Sun, known as the solar wind, also affects our planet. This work presents a study of the solar wind, mainly estimating the loss of atmospheric mass, over time, of the telluric planets due to the solar wind. For that, a code written in Python was created that calculates the loss of atmospheric mass due to the incident solar wind on the planets, throughout the entire lifetime of the Solar System. The solar wind velocity was estimated using the Parker equation, which depends on the coronal temperature. Solar-like stars of different ages were used to estimate the coronal temperature for the Sun in time. The range for the total loss of atmospheric mass for the planets throughout the lifetime of the Solar System is 1.1-8.3×10^{20} g. The smaller value is for Mars, whereas the larger value is for Earth, with Venus and Mercury having intermediate values.

Resumo. O Sol, assim como as outras estrelas, apresenta um comportamento dinâmico, produzindo fenômenos energéticos como explosões e ejeções de massa que têm consequências muitas vezes danosas para a Terra. O fluxo contínuo de partículas do Sol, conhecido como vento solar, também afeta o nosso planeta. Este trabalho tem como objetivo apresentar um estudo do vento solar, estimando a perda de massa atmosférica, ao longo do tempo, dos planetas telúricos devido ao vento solar. Para tanto, foi desenvolvido um código escrito em Python que calcula a perda de massa atmosférica devido ao vento solar incidente nos planetas, ao longo de todo o tempo de vida do Sistema Solar. A velocidade do vento solar foi estimada usando a equação de Parker, a qual depende da temperatura coronal. Estrelas do tipo solar de diferentes idades foram utilizadas para estimar a temperatura coronal do Sol ao longo do tempo. O intervalo dos valores de perda de massa atmosférica dos planetas ao longo da vida do Sistema Solar foi de 1.1-8.3×10^{20} g. O menor valor é para Marte, enquanto o maior valor refere-se à Terra, com Vênus e Mercúrio tendo valores intermediários.

Keywords. Atmospheric effects – Stars: mass-loss – Solar wind

1. Introduction

Parker (1958) was the first to predict that there was a mechanism capable of releasing mass from the solar corona due to the large pressure difference existing between the Sun and the interplanetary medium. Such theoretical model was based on discrete variations in the Earth's magnetic field, which were attributed to solar activity and the pressure difference mentioned above.

Therefore, the solar wind was defined as a flow of ionized plasma, which material originates from the solar corona. This flux of ionized plasma continuously flows into the interplanetary medium traveling through locally open lines in the solar magnetic field. The solar wind has different interactions with the planets of the Solar System (Figure 1), depending on whether or not the planet has a magnetic field and therefore a magnetosphere (Kivelson & Russell 1995).

A stable atmosphere is needed to regulate the Earth's surface temperature, however, in some planets of the Solar System, the atmosphere may have been eroded by a sufficiently strong young solar wind to make the planet uninhabitable. It is believed that Earth retained its secondary atmosphere thanks to the shielding provided by its magnetosphere. Mars and Venus, for example, do not have a magnetic field similar to the terrestrial one (Vidotto & et al. 2011). Thus, significant atmospheric losses from Mars, for example, resulted in a much thinner atmosphere due to the solar wind (Wood 2011). Venus's atmosphere is much denser and hotter than Earth's atmosphere, with the planet's surface temperature being approximately 740 K (Wood 2011). Even though Venus does not have a magnetic field, its ionosphere separates the atmosphere from the interplanetary medium and the incidence of the solar wind.

The main agent of solar activity on Earth are the giant ejections of matter from the solar corona (Bisikalo & Cherenkov 2016). A mass ejection differs from the solar wind being sporadic events with higher densities and velocities of the ejected plasma than the steady and continuous flow of plasma of the solar wind. The frequency of occurrence of coronal mass ejections varies from 0.5 to 2.5 times a day during periods of maximum activity of the solar 11 year cycle. While during periods of minimum activity, no ejection will occur at all. The Earth's atmosphere is important for the maintenance of life due to the greenhouse effect, in addition to filtering X and ultraviolet radiation, which are harmful to life. Fortunately, Earth was able to retain its atmosphere due to the protection provided by its magnetosphere.

2. Results

The loss of Earth's atmospheric mass due to the solar wind ($\dot{M}$) for different ages of our star, including its current age of 4.6 Gyr, can be estimated by equation below:

$$\dot{M} = \alpha \, 4\pi \, R_p^2 \, \rho(r) \, u(r), \tag{1}$$

where R_p is the radius of the planet Earth, $\rho(r)$ the density of the solar wind (g cm^{-3}) and $u(r)$ is the speed (cm s^{-1}) as a function of the distance r from the star (Ribas & et al. 2005). In this case the distance considered was 1 AU, or the average distance between the Earth and the Sun. The entrainment parameter α (coefficient of drag) was measured in laboratory and varies between 0.01 and 0.3. In this work, $\alpha = 0.3$ was used in the calculations.

The density of the solar wind $\rho(r,t)$ in g cm^{-3}, as a function of the distance and solar age of the wind, for each age considered, was calculated from Vidotto & Cleary (2020):

$$\rho(r,t) = \frac{n(r) \, m_H}{2} \left(\frac{4.56}{t}\right)^{0.3}, \tag{2}$$

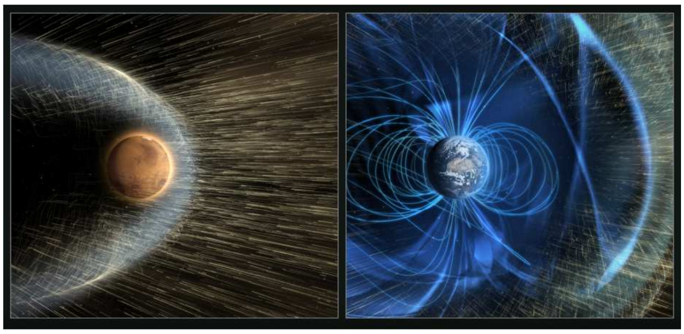

Figure 1. Artistic conception of the solar wind on Mars (left), a planet without a magnetic field, and on Earth (right) with its magnetosphere [http://lasp.colorado.edu/home/maven/the-solar-wind-at-mars-and-earth].

where $n(r)$ is the particle density in cm^{-3}, at a distance r from the Sun, m_H is the proton mass and t is the solar age in Gyr (10^9 years). The density of the solar wind $n(r)$ can be calculated from Leblanc et al. (1998):

$$n(r) = 7 \times 10^4\ r^{-1.67} + 4.1 \times 10^6\ r^{-4} + 2.6 \times 10^7 r^{-6}. \qquad (3)$$

Once the radius of the planet is known, and the speed and density of the wind in the planet's orbit are calculated, for a given age, t, as a function of distance, r, the value of the loss of atmospheric mass $\dot{M}$, in g s^{-1} can be estimated.

The calculation of solar wind speed, $u(r)$ is based on Parker's equations Parker (1958). In the 1950s, Parker described the solar corona's mass release mechanisms due to the pressure difference between the Sun and interstellar space. This model was based on discrete variations in the terrestrial magnetic field. The existence of ionized plasma flux in the interplanetary medium was confirmed by space probes around 1960 and later studies led to the conclusion of the existence of the solar wind (Kivelson & Russell 1995).

The Parker's equation was stated in such a way that the left side of the equation is entirely a function of u (wind speed) and the right side is a function of r. The solution of the velocity as a function of the distance from the Sun is obtained by solving the transcendental equation:

$$u^2 - \frac{2KT}{m_H}\ \ln\left(\frac{m_H\, u^2}{2KT}\right) = \frac{2KT}{m_H} + 8\ \frac{KT}{m_H}\ \ln\left(\frac{r}{r_c}\right) + 2GM_\odot\left(\frac{1}{r} - \frac{1}{r_c}\right). \qquad (4)$$

where u is the speed of the solar wind, K is the Boltzmann constant, T is the absolute temperature of the solar corona, m_H is the mass of the proton, G the universal gravitational constant, $M_\odot$ the mass of the Sun, r the distance from the Sun and r_c the critical radius, which is given by:

$$r_c = \frac{G\, M_\odot\, m_H}{4KT}. \qquad (5)$$

To obtain Parker's solution for the solar wind, it is necessary to estimate the temperature of the solar corona, T, over the billion-year lifetime of the Sun. Currently, the temperature of the Sun's corona is known to be around a few million degrees. However, to obtain the coronal temperature throughout the life of the Sun, we use solar-type stars with different ages (Ribas & et al. 2005). The coronal temperature, in MK, can be obtained from the values of the measured X-ray flux (F_x) of these stars of different ages using Equation 6 of Johnstone & Güdel (2015):

$$T = 0.11\ F_x^{0.26}. \qquad (6)$$

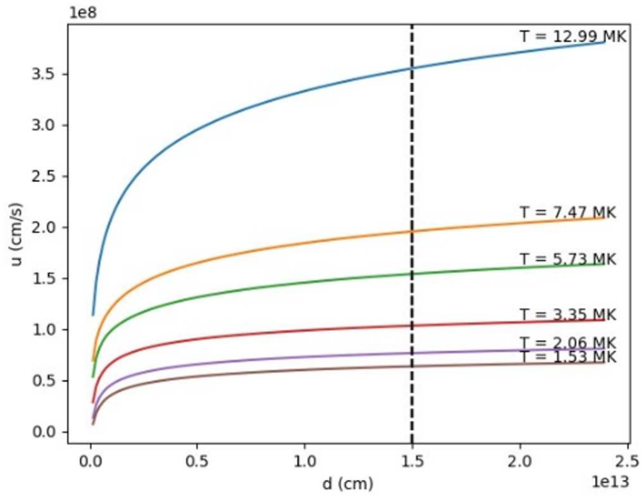

Figure 2. Solar wind speed u (cm s^{-1}) as a function of distance d (cm) for different coronal temperature representing different solar ages. The vertical dashed line corresponds to 1 AU.

Age (Gy)	Total mass loss (g) to Mercury	Total mass loss (g) to Venus	Total mass loss (g) to Earth	Total mass loss (g) to Mars
0.10	5,1.10^19	1,1.10^20	7,2.10^19	9,8.10^18
0.30	7,1.10^19	1,5.10^20	9,9.10^19	1,3.10^19
0.65	1,6.10^20	3,5.10^20	2,3.10^20	3,1.10^19
1.60	3,4.10^20	7,3.10^20	4,7.10^20	6,4.10^19
4.56	6,0.10^20	1,3.10^21	8,3.10^20	1,1.10^20
6.70	6,5.10^20	1,4.10^21	9,1.10^20	1,2.10^20

Figure 3. Table with total mass loss, in grams, for each terrestrial planet.

In Figure 2, are shown the calculated behavior of the solar wind speed at different distances and for different coronal temperatures, or for different solar ages. The highest temperature of almost 13 MK refers to the youngest star with the smaller age of 0.1 Gyr, whereas the smallest temperature of 1.53 MK is for the oldest star of 6.7 Gyr. The vertical dashed line in the graph in the figure represents the distance from the Earth to the Sun, that is, 1 AU.

In Figure 3 we present the results obtained for the telluric planets of our Solar System. The first column shows the ages of the Sun, while the second to fifth columns show the result of the total mass loss, in grams, for each planet. The value calculated here for the loss of total atmospheric mass for the Earth at its current age was 8.3×10^{20} g, which is larger than that obtained by Sekyia & et al. (1981) of 1.3×10^{20} g. In this work, we used the maximum value of 0.3 for α, had we used $\alpha = 0.047$, which is still within the limits measured in the laboratory, our results would agree.

Venus is the planet with the most mass loss of its atmosphere due to the solar wind, thus a very efficient mechanism for replenishing its atmosphere must have been at work in the past, probably volcanic outgassing. In second place comes Earth, followed by Mercury, and last is Mars with the least atmospheric mass loss, mainly due to its larger distance from the Sun.

The results obtained in this work show that as the Sun ages, its coronal temperature decreases, and, therefore, the speed of the solar wind also decreases, as well as its density. Therefore, there is a lower rate of loss of atmospheric mass for the terrestrial planets as time goes by.

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