Boletim da Sociedade Astronômica Brasileira, **33**, no. 1, 100-103

Influence on the Earth due to Sun's entry into a dark cloud

J. Leão[1,3], T. Bentes[2,3], J. W. Vilas Boas[3], & C. A. Wuensche[3]

[1] Instituto Federal de São Paulo, SP
e-mail: jurandi.leao@gmail.com
[2] Universidade do Vale do Paraíba, SP
e-mail: bentesthays@gmail.com
[3] Instituto Nacional de Pesquisas Espaciais, SP
e-mail: jwboas@gmail.com
e-mail: ca.wuensche@inpe.br

Abstract. In this work we considered the possibility of the Solar System (SS), along its trajectory in the local Interstellar Medium (IM), to enter in a dark molecular cloud (NM), because there is observational evidence that isolated clouds exist around hundreds of parsecs of the SS. Assuming the typical characteristics of NM and some hypotheses, we explored the time and how the SS would enter in one of these clouds. We concluded that, in an event like this, the Earth would come to exist in an environment with characteristics of the IM, causing catastrophic consequences for the planet's climate.

Resumo. Neste trabalho consideramos a possibilidade do Sistema Solar (SS), ao longo de sua trajetória no Meio Interestelar local (MI), entrar em uma nuvem molecular escura (NM), uma vez que há evidencias observacionais de que existem nuvens isoladas em torno de centenas de parsecs do SS. Assumindo as características típicas das NM e algumas hipóteses, exploramos o tempo e como se daria a entrada do SS em uma dessas nuvens. Concluímos que, em um evento como esse, a Terra passaria a existir em um ambiente com características do MI, acarretando consequência catastróficas para o clima do planeta.

Keywords. first keyword – second keyword – third keyword

1. Introduction

Study of the distribution of NaI absorption lines towards stars in the solar neighborhood, show that the Solar System (SS) lies in a bubble of hot ionized gas of low density and surrounded by neutral and cold gas clouds, that meet at the distances of hundreds parsecs from the Sun (Lallemant et al., 2008). Observational evidence indicates the existence of isolated clouds closer to the SS, located less than 60 pc, as shown in Fig. 1. Most of these neutral molecular clouds lie more than 80 pc away; this region around the Sun is called the local interstellar medium (LIM) (Linsky et al., 2018).

The LIM environment suggests that there is a high chance for SS to enter in a dark molecular cloud of the solar neighborhood, performing speed of up to 25 km/s, in the next 1 million years. Even though the time for this phenomenon to occur is very long, we analyzed, in this work, the possibility for SS to enter in one of these molecular clouds and evaluated the consequences for the Earth (Frisch et al., 2009).

For our analysis, we considered some initial hypotheses, presented below, and assumed the typical parameters of molecular clouds in the solar neighborhood: densities from 10^2 to 10^8 cm^{-3}; temperatures ranging from 10 to 100 K and extinctions ranging from 0.5 mag (at the borders) to several tens of magnitudes (at the cloud cores).

In our study, we concluded that, in an event like this, the Earth could occupy an environment with a low degree of ionization, typical physical characteristics of a dark molecular cloud in the solar neighborhood. In this situation, there would be a total absence of UV radiation on Earth. Following the same idea, considering the movement of the SS in relation to the molecular clouds, there would be a deformation of the ionized region, which would no longer be spherical and would assume, in two dimensions, a cometary shape. In this case, in its translation movement, the Earth would be most of its orbit in LIM. In all cases analyzed, the consequences for the planet's climate would be catastrophic.

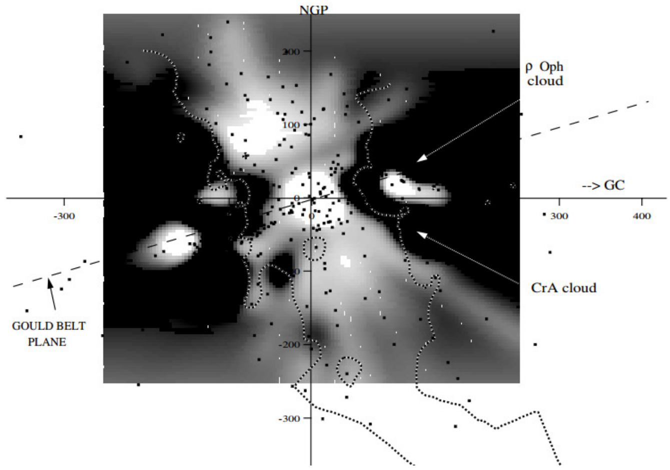

Figure 1. Neutral gas distribution (dark tones) observed in LIM from the observation of NaI lines in the direction of stars in the local neighborhood. CG refers to the direction of the Galactic center, the axes indicate the distances in parsec and the point (0,0) indicates the position of the Sun. The distribution is shown perpendicular to the plane. Adapted from (Lallemant et al., 2008).

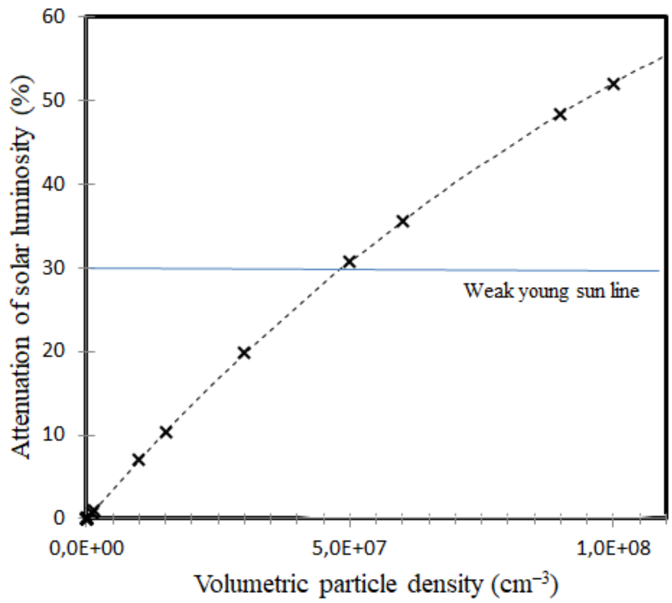

Figure 2. Variation of the Sun's luminosity as a function of the volumetric density of particles in MI, considering that the SS is uniformly filled by gas from a molecular cloud. The attenuation of solar luminosity is 30% for a medium volume density of $\approx 5 \times 10^7$ cm^{-3}.

2. Passage of the Solar System through a molecular cloud

2.1. Hypothesis 1

Our first hypothesis assumes that the SS, upon entering a dark cloud of gas and dust, is completely filled with the cloud's neutral gas, which is evenly distributed along its all extension. Thus, we can assume that the average density of LIM is equal to that of clouds, i.e., the density ranging from 10^2 to 10^8 cm^{-3}.

From our analysis, it was possible to calculate how much of the solar luminosity is attenuated in relation to the Earth. The results of this first analysis are shown in Fig. 2.

The figure corresponds to the situation of the SS uniformly filled by an interstellar cloud with an average density of the order of 10^7 cm^{-3}. In it, we highlighted the line corresponding to an attenuation of 30% in solar luminosity; this creates a variation in the luminosity received by the Earth equivalent to that received when the Sun was only 1 Bys and its luminosity was 70% of the current (Sagan & Mullen, 1972). Variations of this magnitude would have serious consequences for the Earth's climate (Meehl et al., 2009).

2.2. Hypothesis 2

As a second hypothesis, we considered the interaction between the Solar radiation and its wind with the environment where the Sun is located. Since the Sun has both an ultraviolet (UV) radiation field and a solar wind, they should be considered to explore the consequences of the SS passing through a molecular cloud.

In the beginning, the interaction is completely dominated by the propagation of the UV radiation field in the medium. As the radiation front propagates, a shock wave forms behind it, driven by the expansion of the ionized medium in the form of a solar wind. We determined the distance from the Sun that this ionization front weakens until it can no longer ionize the medium (the "heliopause").

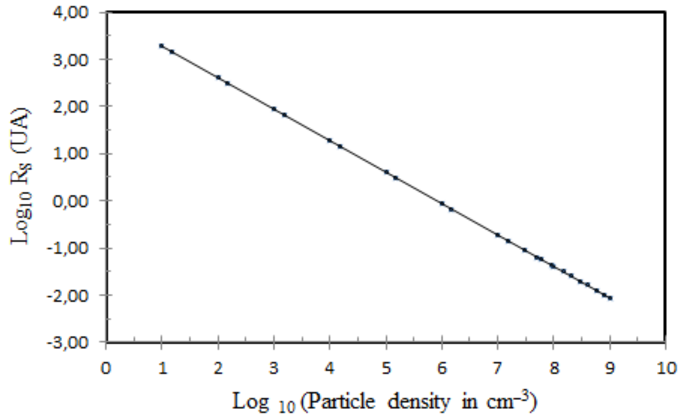

Figure 3. Logarithm of the Sun's ionized region radius as a function of the volumetric density of H atoms assuming the molecular cloud as a medium of uniform density, composed of neutral hydrogen and considering the UV luminosity of the 4.5 Gyr old Sun.

We analyzed the problem analytically and calculated the radius of the ionized bubble, considering that the SS is completely immersed in a molecular cloud of gas with uniform density. Assuming characteristic values of molecular clouds in the solar neighborhood, we obtain Fig. 3.

The figure shows the radius of the ionized bubble, in astronomical units as a function of the volumetric density of medium H atoms; R_S is the radius of the fully ionized bubble, given by (Spitzer, 2006):

$$R_S = \left(\frac{3}{4\pi} \frac{S_0}{n^2 \beta_2 T_e} \right) \tag{1}$$

being n the volumetric density of H atoms, S_0 the number of UV photons produced by the Sun per unit of time, β_2 the total recombination coefficient of electrons and protons found in the ionized medium, and T_e the ionized medium kinetic temperature.

From Fig. 3, we can see that when the density of the medium is greater than 7×10^5 cm^{-3}, the R_S is less than 1 AU.

We also estimated that if the Sun completely enters in a molecular cloud with a density greater than 10^6 cm^{-3}, in less than 0.6 years, the solar UV radiation field will ionize a region with a radius equal to or less than the distance from Earth to Sun. For densities of 10^5 cm^{-3}, or smaller, the ionization front reaches 1 AU on timescales less than 20 days. For densities of 10^6 cm^{-3}, or greater, the sphere's radius does not reach Earth's orbit, ie, all solar UV radiation would be consumed in this ionized medium before reaching the planet.

If we consider this structure as stationary, the entry of the SS into a molecular cloud with a density equal to 10^6 cm^{-3} would have drastic consequences for the Earth's climate and its biomass. In reality, the ionized sphere expands even in environments with densities greater than 10^6 cm^{-3}.

3. Expansion of the ionized bubble

We evaluated how long it would take these bubbles, with radius R_S, for their surfaces to exceed the Sun-Earth distance.

The Fig. 4 shows the radius of the ionized bubble as a function of time, assuming the SS is completely filled in a homogeneous molecular cloud. The dashed line in red indicates the distance from Earth to the Sun, and the lines in green and burgundy indicate ratios between the speed of sound in the ionized

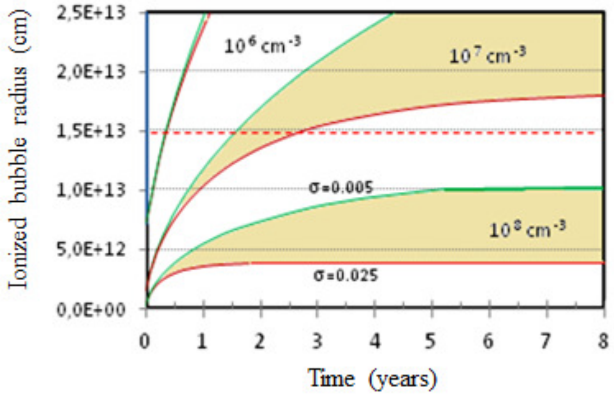

FIGURE 4. Radius of the ionized bubble created by the Sun's UV radiation field, as a function of time, for a molecular cloud with a particle volume density of 10^6 cm^{-3}, 10^7 cm^{-3} and 10^8 cm^{-3} (brown belt). The red dashed line indicates the distance from Earth-Sun and the lines in green and burgundy indicate ratios between the speed of sound in the ionized bubble and in the neutral medium of 0.005 and 0.025, respectively. In these calculations, we used speeds from 0.7 km/s to 1.5 km/s for the molecular clouds, and 10 km/s for the ionized region.

bubble and in the neutral medium, σ = 0.005 and 0.025, respectively. The brown region between these two lines represents the most characteristic conditions of molecular clouds with these densities.

We observed that, if the density of the molecular cloud is 10^6 cm^{-3}, the ionized bubble created by the solar UV field expands reaching the radius of Earth's orbit in approximately 120 days. In this case, if we consider the time for formation of the ionized region (220 days) plus the bubble expansion time, the Earth's orbit will be reached in approximately 340 days. For a cloud with a volume density equal to 10^7 cm^{-3}, the total time for the bubble to expand and reach Earth's orbit will be greater than 1.8 years. For clouds with even greater densities, the expansion of the bubble will not reach Earth's orbit.

3.1. Influence of solar wind

Our last analysis, presented in Fig. 5, was about the influence of the solar wind, considering the Sun at rest and in motion in relation to the molecular clouds. In the figure, the blue dotted circle shows the Earth's orbit of radius R_T, and the red circle, of radius R_S, represents the bubble of ionized gas around the Sun, assuming the Sun has zero velocity. If the velocity is non-zero with respect to the medium, the red circle becomes the ellipse of radius $r(\theta)$, given by (Raga et al., 2012):

$$r(\theta) = \sqrt{\left(\frac{S}{2\pi n V\star}\right)(1 - \cos\theta)} \qquad (2)$$

where S is the number of ionizing photos, $V\star$ is the speed of the Sun and θ is the angle between the direction of the Sun's motion and an arbitrary position at the edge of the ionized region. Thus, we see that the ionized bubble assumes, in the two-dimensional figure, the appearance of a cometary orbit. Therefore, the Earth remains, in its orbit, much of the time outside the ionized region, with characteristics of LIM.

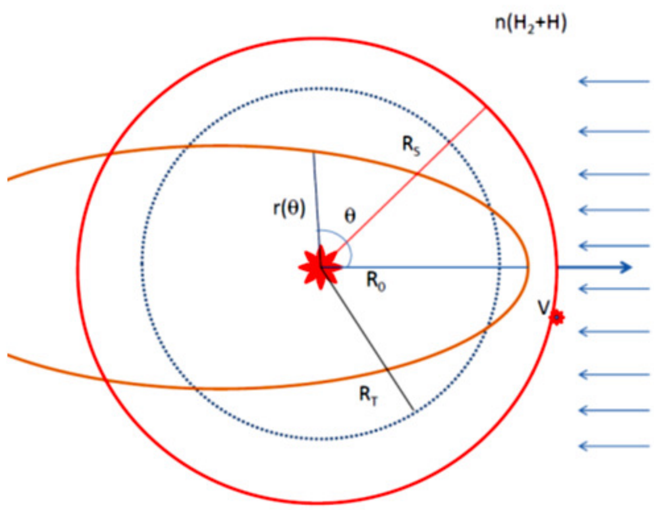

FIGURE 5. Representation of the ionized bubble created by the solar UV field considering the Sun at rest (red circle) and in motion with velocity $V_\star$ (red ellipse), in a medium of uniform density. Here, the ionized sphere has a radius greater than the Earth's orbit (dotted blue). The arrow to the right indicates the direction of movement of the SS, and the arrows to the opposite direction indicate the gas flow from the molecular cloud that interacts with the ionized region. The density of the medium considered is less than 10^6 cm^{-3}. Note that the Earth remains, in its orbit, much of the time outside the ionized region.

4. Conclusion

In this work, we reviewed the distribution of gas in the solar neighborhood to identify where molecular clouds are located. Considering the distribution of this gas and the movement of the SS in the solar neighborhood, it is likely that the Sun will dip into one of these clouds in a few million years.

Based on this premise, we explored the interaction of the solar UV radiation field with clouds of different volumetric densities and investigated the effect of the relative movement of the Sun within the molecular cloud, aiming to study whether the presence of these clouds could have any consequences about the Earth's climate.

We calculated the attenuation of the Sun's luminosity if the SS enter in a molecular cloud. For densities of 10^8 cm^{-3}, the attenuation can be up to 50%. The variations in solar radiation, over the 11-year period, are approximately 0.2% (Fröhlich & Lean, 2004), and already have consequences for the Earth's climate.

We also estimated the radius of the ionized bubble, considering the Sun fully immersed in a molecular cloud of uniform density. For a density greater than 7×10^5 cm^{-3}, with its expansion in less than 1 year, the radius of the bubble is less than 1 AU. In an event like this, the Earth would be outside the heliosphere. The planet would be in a region of temperatures in the order of 20 to 100 K, with practically no solar UV radiation flux.

All these situations evaluated would generate catastrophic variations in the Earth's climate.

References

Fröhlich, C. & Lean, J. Solar radiative output and its variability: evidence and mechanisms, The Astronomy and Astrophysics Review, 273–320, 2004.

Lallemant, S.J. et al. , Accretionary wedge growth and the limit of the seismogenic zone, AGU Fall Meeting Abstracts.

Linsky, J. et al.The Local Interstellar Medium: Comparison with IBEX Results, Sightlines to Exoplanet Host Stars, and Trajectories of the Voyager Spacecraft, IOP Publishing, 2018.
Meehl, G. A. et al. Amplifying the Pacific climate system response to a small 11-year solar cycle forcing, Science, 1114–1118, 2009.
Frisch, P. et al. The galactic environment of the Sun: Interstellar material inside and outside of the heliosphere, Space science reviews, 235–273, 2009.
Raga A. C. et al. The physics of the interstellar medium, 2012.
Sagan, C. & Mullen, G. Earth and Mars: Evolution of atmospheres and surface temperatures, American Association for the Advancement of Science, 1972.
Spitzer, L. Physics of fully ionized gases. Courier Corporation, 2006.