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P4_9 Stealing Our Atmosphere

M. Szczykulska, J. J. Watson, L. Garratt-Smithson, A. W. Muir

Department of Physics and Astronomy, University of Leicester, Leicester, LE1 7RH.

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Abstract

This paper investigates two scenarios; the first is the solar wind velocity required to compress Earth's magnetopause to an altitude of 1500km and an unrealistic value of 1.6×10^{8}ms^{-1} is found. The second scenario is the time it would take the solar wind to erode all of the oxygen in the atmosphere if the Earth did not have a magnetic field and an approximate value of 1.97×10^{9} years is calculated.

Introduction and Theory

On November 18th 2013, NASA launched its MAVEN mission, set to go into orbit around Mars on November 22nd 2014 [1]. The primary objective of this mission is to study the erosion of the Martian atmosphere due to the solar wind (SW) [1]. This erosion is prevented on Earth via the formation of the magnetosphere – rendered possible by Earth's magnetic field.

The underlying principle behind the formation of a boundary, or 'magnetopause', between the SW and Earth's magnetic field is the 'frozen-in-flux' plasma approximation. This approximation relies on the gradient in the magnetic field changing very slowly in time and space with respect to the gyroradii and gyroperiods of the plasma. It states the plasma and magnetic field lines are 'frozen' together. Since the plasma cannot cross from one field to another, the SW plasma region cannot mix with Earth's plasma region, resulting in the formation of a boundary.

However, on weakly magnetised planets, such as Mars, the SW is able to reach altitudes as low as 1000m, transferring energy and momentum to the planetary particles in the atmosphere [2]. If the energy transferred to the atmospheric particles is equal to or greater than the energy associated with the escape velocity at that altitude, they are lost to the SW [2].

The ionosphere of Mars and Earth share certain similarities, such as the predominant ion species: oxygen [3]. This suggests, without a magnetic field Earth's atmosphere would share a similar fate to the Martian atmosphere.

A Pressure 'Stand-Off'

This paper will first calculate the SW velocity required to compress Earth's magnetic field so that the magnetopause lies at the altitude of the upper ionosphere. An expression for the position of the magnetopause can be found by equating the pressure of the SW and interplanetary magnetic field (IMF) with the pressure of the magnetospheric field and plasma [4]. The position of the magnetopause is calculated at the point where the SW pressure is at a maximum and no angular components need to be considered. Furthermore, the pressure on the SW side of the magnetopause can be approximated to that associated with the SW,

$$P_{SW} = 2n(m_p + m_e){v_{sw}}^2 . \qquad (1)$$

Here P_{SW} is the solar wind pressure; n is the solar wind number density (approximately 5 particles cm^{-3} [5]), m_p and m_e are the mass of a proton and an electron respectively; while v_{sw} is the SW velocity. This approximation is valid since the IMF pressure is relatively negligible [4].

The pressure associated with Earth's magnetospheric plasma is also neglected since the pressure associated with the magnetic field is far greater [4]. An expression for the pressure associated with the magnetospheric field is

$$P_{MP} = \frac{2B_{eq}^2}{\mu_0}\left(\frac{R_P}{R_{MP}}\right)^6 , \quad (2)$$

where P_{MP} is the pressure at the magnetopause, B_{eq} is the magnetic field at the equator (approximately 3.1×10^{-5}T [6]), μ_0 is the permeability of free space (1.26×10^{-6} mkgs^{-2} A^{-2}), R_P is the planetary radius (6371km) and R_{MP} is the radius of the magnetopause. We will take

R_{MP} to be 1500km (the altitude associated with the top of the ionosphere [7]) + 6371km. Equating expressions (1) and (2), v_{sw}

$$v_{sw} = \left(\frac{B_{eq}^2}{\mu_0 n (m_p + m_e)} \left(\frac{R_P}{R_{MP}} \right)^6 \right)^{1/2}. \quad (3)$$

Substituting the correct values into (3) gives a value of $v_{sw} = 1.6\times10^{8}$ms^{-1}. This value is close to light speed, indicating the equations need to be treated relativistically for an accurate physical answer, something beyond the scope of this paper.

No magnetic field at all

We will now calculate the time it would take the SW erosion process to remove all the oxygen in our atmosphere, assuming Earth has no magnetic field. Any other loss effect is neglected. The primary SW interaction with a planet that has a conducting ionosphere is the transfer of energy and momentum from the SW plasma particles to the upper ionosphere [3].

We will concentrate on the O^+ ion species, which is the predominant species in our ionosphere [3]. As such, for the purpose of our calculation we will assume every incoming SW particle hits an O^+ ion and all the momentum is transferred in one collision. These assumptions imply the flux of O^+ ions out of the ionosphere, Φ_O, is directly proportional to the SW flux, Φ_{sw};

$$\Phi_O = \frac{v_{sw} m_{sw}}{v_O m_O} \Phi_{sw}. \quad (4)[5]$$

Here, m_{sw} and m_o are the masses of the SW particles and O^+ ion respectively and v_o is the escape velocity of the O^+ ions (corresponding to after the collision). It is apparent (4) represents the maximum possible flux of oxygen out of the atmosphere [5].

In order to calculate the time it would take the oxygen in our atmosphere to deplete, a few more assumptions need to be made. Firstly, at Earth's orbital radius, v_{sw} is approximated as 400kms^{-1} [3] and m_{sw} is taken to equal m_p. Furthermore, since the SW has a number density of 5 particles cm^{-3} and it travels at 400kms^{-1}, Φ_{sw} can be calculated provided we find the cross sectional area of Earth. Assuming Earth is a perfect sphere, the cross sectional area is given by $\pi \times {R_P}^2$; hence Φ_{sw} is calculated to be 2.55×10^{26} protons per second. Finally, v_O for the oxygen ions at an altitude of 1500km is found to be 10.1kms^{-1} by equating gravitational potential energy with kinetic energy.

Inputting the correct values into (4) and setting m_O as 16 atomic mass units, the flux of oxygen ions out of the ionosphere is equal to 6.31×10^{26} ions per second. This is equivalent to a mass of 16.87kg lost from the atmosphere every second. Since the atmosphere has an approximate mass of 5×10^{18}kg [8], and 21% of this is oxygen, there is roughly 1.05×10^{18}kg of oxygen in the atmosphere. According to our value of Φ_O this would be lost in 6.2×10^{16}s, or 1.97×10^{9} years. This time is only approximate, due to the fact we calculated the maximum possible flux, as well as because the SW velocity will vary hugely within this time frame and other loss effects, such as those associated with the increased solar radiation, were not considered.

Conclusion

The solar wind would have to travel very close to light speed in order to compress the magnetopause to a position 1500km above the surface of the Earth. Furthermore, if Earth's magnetic field were removed altogether, the solar wind would take 1.97×10^{9} years to remove all the oxygen in the atmosphere.

References

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