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Quantizated variability of Earth's magnetopause distance

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Abstract- The size of the Magnetosphere is calculated during the period 1996-2011. It is discovered that the magnetopause distance D is quantized for D ≥ 8 R_E. The magnetic levels are narrow towards the Earth but widely spaced outwards. This quantization disappears in the lower magnetosphere below 7 R_E. Once the magnetopause is compressed to 8 -7 R_E, multi doors get open which we call the Geomagnetic doors, and the solar wind is injected into the inner magnetosphere then to the ionosphere inducing SID and to the troposphere where it can cause flash floods and seeds of hurricanes.

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1. INTRODUCTION

The magnetopause is the abrupt boundary between the magnetosphere and the surrounding plasma. In other words, it is the boundary between the Earth's magnetic field and the solar wind. The balance between the pressure of the dynamic magnetic field of Earth and the dynamic pressure of the solar wind determines the location of the magnetopause. As the solar wind pressure increases and decreases, the magnetopause moves inward and outward in response. Waves (ripples and flapping motion) along the magnetopause move in the direction of the solar wind flow in response to small scale variations in the solar wind pressure and to Kelvin-Helmholtz instability. If one assumes that magnetopause is just a boundary between a magnetic field in a vacuum and plasma with a weak magnetic field embedded in it, then electrons and ions penetrating one gyroradius into the magnetic field domain would define the magnetopause. Since the gyro-motion of electrons and ions is in opposite directions, an electric current flow along the boundary. The actual magnetopause is much more complex [Song et al. (1995)].

The distance from Earth to the subsolar magnetopause varies over time due to solar activity, but typical distances range from 6 - 15 R_E (radius of Earth). Empirical models [Roelof and Sibeck (1993) & Shue *et. al.* (1997)] using real-time solar wind data can provide a real-time estimate of the magnetopause location. A bow shock stands upstream from the magnetopause. It serves to decelerate and deflect the solar wind flow before it reaches the magnetopause [Pater and Lissauer (2001)].

Many authors have studied the coupling between the solar wind and the Earth's magnetosphere. [Le et al., 1999)] examined the magnetic field from Poplar's Magnetic Field Experiment (MFE) to study the magnetospheric current systems on May11, 1999. Pc3-4 magnetic pulsations (10-100 MHz) in the dayside magnetosphere are believed to have an energy source from upstream waves in the Earth's foreshock region [Troitskaya (1994)]. The upstream waves are generated by the interaction between the solar wind plasma and the streaming ion beams in the foreshock region. Then they are carried downstream to the magnetopause along the solar wind streamlines through the magnetosheath. The magnetopause responds to these pressure fluctuations and ultimately transfers the wave energy into the dayside magnetosphere and generates Pc 3-4 magnetic pulsations [Wolfe, et al., 1989)]. Thus, Pc 3-4 pulsations can be potentially a very useful diagnosis of the state of the solar wind.

The upstream waves have been studied by many scientists on low solar density events. Smith et al. [Smith *et al.* (2001)] showed that the magnetic fluctuations possess an unusual degree of anisotropy that is associated with the period of low plasma density. Moreover, fluctuations in the magnitude of the field are generally smaller than those commonly seen in the solar wind. They discussed the possibility that wave refraction is responsible for the observed depletion of magnetic fluctuation energy within the refraction interval. To explain the anomalous decrease in the magnetic fluctuations, they used the model given by Uchida [Uchida (1973)].

At close to 2345 UT on September 24, 1998, the magnetosphere was suddenly compressed by the passage of an interplanetary shock. In order to properly interpret the magnetospheric events triggered by the arrival of this shock, we calculate the orientation of the shock, its velocity, and its estimated time of arrival at the nose of the magnetosphere [Russell *et al.* (2000)]. Over the solar cycle the yearly average dynamic pressure ($P_d = N_{SW} V^2_{SW}$) change about ± 20 %, this makes ± 3 % change in the size of the magnetosphere, since the density of the solar wind and the velocity are inversely correlated as shown by [Petrinec *et al.* (1991)]. Indeed, Russell et al [Russell *et al.* (2000)] showed that extra pressure caused by powerful mass ejection hitting the Earth can reduce the magnetopause distance to half this value. On the other hand, unusual drops in the solar winds pressure can inflate the stand–off distance of the magnetosphere five or six times out further in space until it reaches the Moon's orbit.

In the present paper, the magnetopause distance is calculated during the period 1996 to 2011. This helps us to follow the size of the Earth's magnetosphere for a long period that includes a full solar cycle.

2. DATA SOURCES AND PROCEEDING

We selected the minute mean data of the solar wind velocity and density for the period 1996 - 2011 from Coordinated Data Analysis Web (Combined 1AU IP Data; Magnetic and Solar Indices). The size of the magnetosphere is determined by the distance *D* of magnetopause, along the Earth-Sun line at which the pressure of the planetary magnetic field balances the dynamic ram pressure of the solar wind. The magnetic pressure at the surface of the Earth is given by ($B_o^2/2\mu_o$), where $\mu_o=4\pi\times10^{-7}$ is the permeability of free space, $B_o=0.31\times10^{-4}\ T$ is the equatorial magnetic field strength. Since the dipole's magnetic field strength falls as the cube of the distance from the Earth, the magnetic pressure decreases as the sixth power of that distance. This means that the stand-off points where the two pressures are equal occurs when:

$$Magnetic\ Pressure = {R_E^6 \times R_o^2}\Big/{2\mu o \times D^6} = m_p\ NV^2\ = \ Solar\ wind\ pressure$$

Where the Earth's radius is R_E, the proton mass $m_p = 1.67\times10^{-27}\ kg$, *N* is the number density of the protons in the solar wind at the Earth's distance from the sun, and V is the solar-wind velocity at that distance. Solving for *D* (distance of magnetopause) we have:

$$D = \left(\frac{B_o^2}{2\mu\mu_o m_p \mathrm{N}\, V^2}\right)^{\frac{1}{6}} \qquad \text{[Lang (2001)]}$$

At the Earth's distance and under standard conditions, N=5 million protons /m³ and the solar wind velocity V= 0.4 million m/s, therefore with these numbers $D=10R_E$.

The magnetopause distance, *D*, depends on several factors, the density of the solar wind, the solar wind velocity and the Mach number (the ratio of the speed of the flow and the speed of the compressional wave that deflect the flow).

3. RESULTS AND DISCUSSIONS

3.1. *Magnetopause variation with time*

The Earth's magnetopause has been the subject of extensive observational and theoretical investigations (e.g., Fairfield (1976); Burgess (1995)]. Typically, a distance from the Earth to the subsolar point of the magnetopause is ~$14\ R_E$ but the location of the magnetopause is highly variable, depending on the speed and density of the solar wind. In general terms, the large-scale geometry of the magnetopause depends on the solar wind dynamic pressure [Fairfield, (1971)]. Figure 1 shows the variation of hour mean values of magnetopause distance with time. According to normal solar wind conditions, the mean value of magnetopause distance is ~ $5\text{-}11\ R_E$. R fluctuated during certain events to reach its maximum value during the 11th of May 1999 (the day the solar wind almost disappeared) and its minimum

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value of ~ $5R_E$ during 2006. In general, the value of distance *D* does not obey the solar activity cycle.

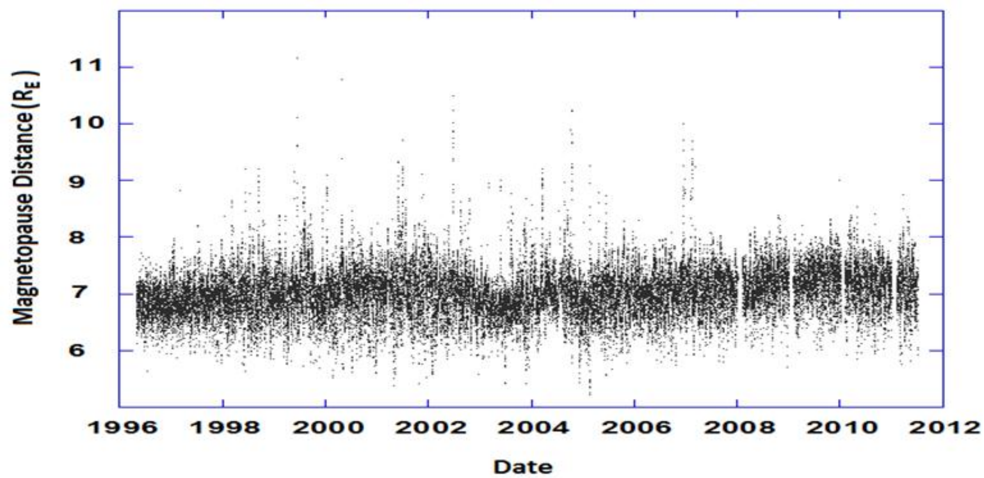

Fig. 1: Long-term variation of the magnetopause distance.

Fig. 2: Quantization of magnetic lines of force of an ordinary magnet.

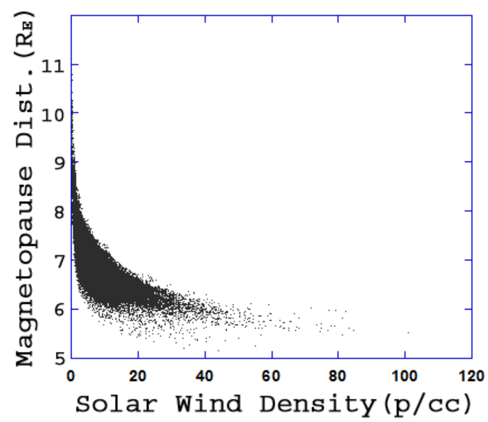

Fig. 3: The dependence of the magnetopause distance on solar wind density.

The magnetopause distance *D* shows quantized levels above the Earth's surface according to the density and velocity of the incoming solar wind. It seems that quantization is a universal law. The atomic levels, the orbits of planets, degeneracy in the dense cores of white dwarfs. In our case, it is the Earth's magnetic field which is quantized. It is obvious from elementary tracings of magnetic lines of force by magnetic fillings that these lines are quantized. In the case of the Earth's magnetic field, it is the solar wind which traces the magnetic lines of force like the iron fillings.

The Earth's magnetic lines of force are crowded nearer to the Earth and more spaced further out. These spaces clearly indicate the quantization of the earth's magnetic field as manifested by the magnetopause distance. A system with angular momentum *J* makes in magnetic field which is rotating about an axis inclined with respect to the field have been calculated by Rabi [Rabi (1937)] in his paper space quantization in a gyrating magnetic field. He applied his method of gyrating magnetic moment of the neutron, the rotational moment of molecules, and the nuclear moment of atoms with no extra-nuclear angular momentum. In principle this idea can be extended to the gyrating magnetic field of the Earth.

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Figure 3 illustrates the dependence of the magnetopause distance on the solar wind density.

The following conclusions can be deduced from Fig 4:

(1) There is a quantization in magnetic levels defining the extension of the magnetosphere as is evident from magnetopause- solar wind velocity curves.

(2) Those magnetic levels are narrow towards the Earth but widely spaced outwards.

(3) The quantization of the magnetopause distance can be interpreted as a reflection of quantization of Earth's magnetic field lines of force in analogy to magnetic bar lines of force.

(4) We can divide the magnetosphere into the inner and outer magnetosphere. Quantization is only evident in the outer magnetosphere above 8 R_E.

(5) Between magnetopause distance of 7 and 8 R_E, there are open magnetic doors through which solar wind particles can be injected from the outer magnetosphere into the inner magnetosphere. We call these doors the Geomagnetic doors.

(6) Fast solar wind streams pass through these doors via the inner magnetosphere to ionosphere causing sudden ionospheric disturbances SID.

Continuing their journey to the troposphere, such solar wind beams can cause flash floods on striking narrow seas like the Red Sea [see Yousef et al, 2015a in this volume] or seeds for cyclones as they strike Oceans [See Yousef 2015b this volume].

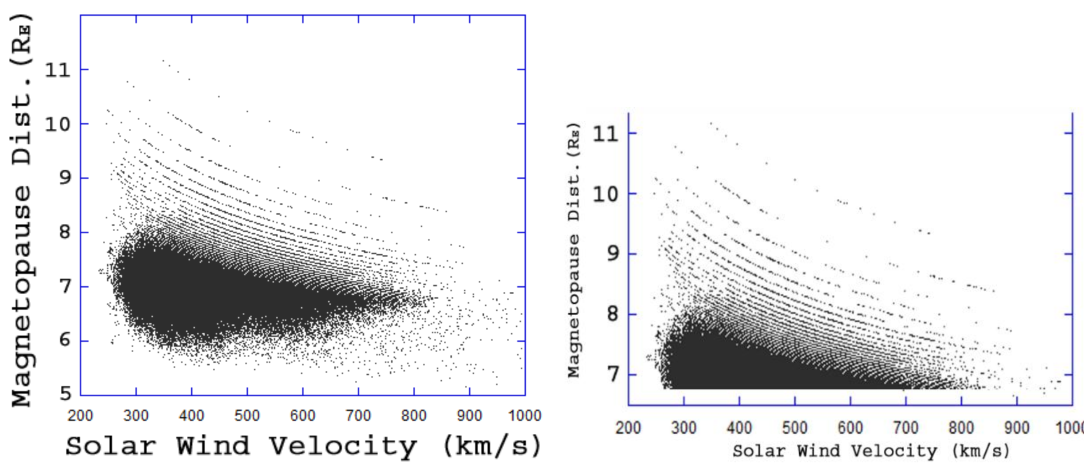

Fig. 4: The dependence of the magnetopause distance on the solar wind velocity. The right panel is a magnification of left panel.

3.2. *Effect of solar activity on magnetopause distance and solar wind relation*

As shown from figure 5, the correlation coefficient R of the magnetopause distance and the solar wind density relation during the minimum of the solar cycles 23 on 1996 (R=0.78) is less than its 2000 maximum value of (R=0.86). Similar results are found for solar cycle 24. The correlation coefficients are R=0.62 and R=0.76 for the 2008 minimum and the 2011 maximum respectively. This result means that the relation between magnetopause distance and the solar wind density is improved with high solar activity levels. The interpretation of that result is that the magnetopause distance - solar wind density relation is more scattered during the periods of low solar activity (1996 and 2008) than its behavior

during the periods of high solar activity (2000 and 2011).

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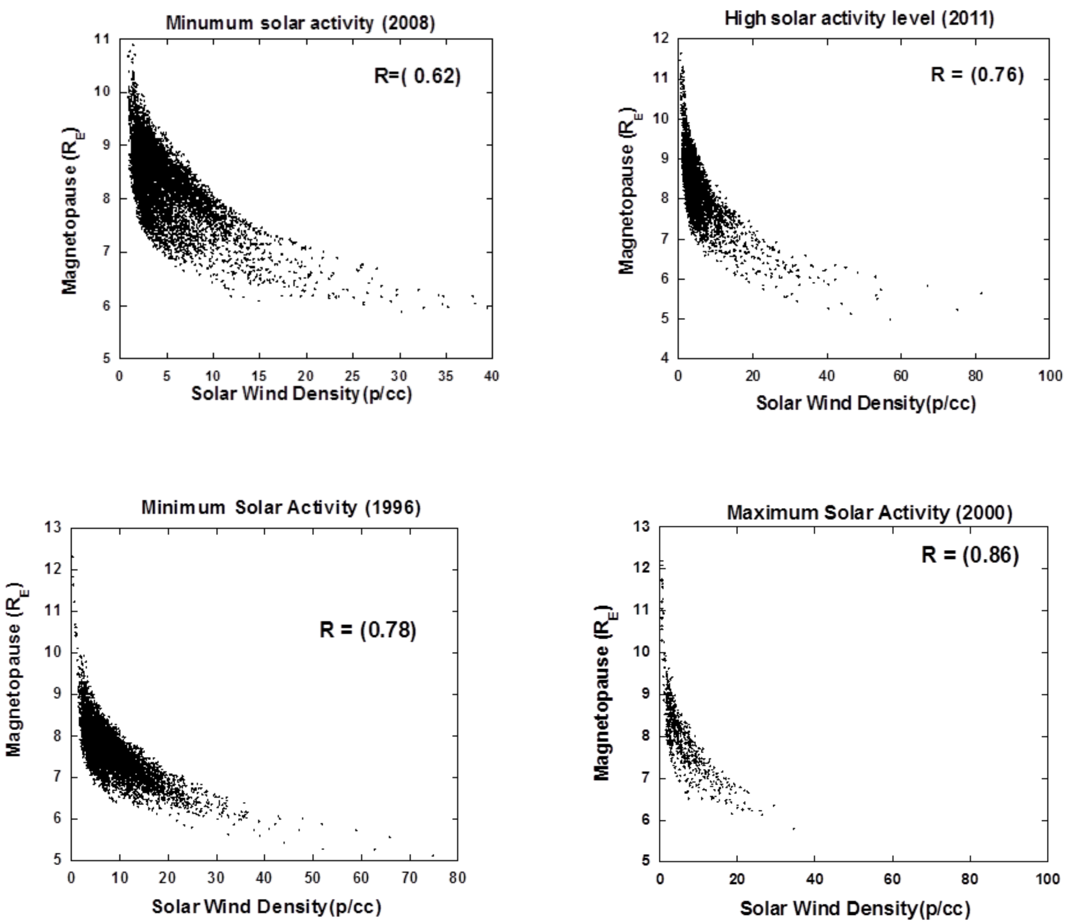

Fig. 5: Comparison of the effect of solar wind density during minimum and maximum solar activity of cycles 23 and 24 on the extension of the magnetopause. Note the values of the correlation coefficients

4. CONCLUSIONS

The magnetopause distance shows quantized levels above the Earth's surface according to the density and velocity of the incoming solar wind. It seems that quantization is a universal law. The Earth's magnetic lines of force are crowded near the earth and more spaced further out. These spaces clearly indicate the quantization of the earth's magnetic field as manifested by the magnetopause distance. Once the magnetopause is compressed to 8 - 7 R_E the quantization disappears and the magnetic lines of force get open allowing the solar wind to enter the inner magnetosphere and from it to the ionosphere and troposphere.

We found that the mean value of magnetopause distance is ~ $7R_E$. Magnetopause distance fluctuated during certain events to reach its maximum value of ~ $11\ R_E$ during 2002 and its minimum value of ~ $5\ R_E$ during 2003. The mean value of magnetopause distance is $11\ R_E$ for the slow solar wind, while for the fast-solar wind the mean value of magnetopause distance decreased to less than $5\ R_E$. The size of the magnetosphere is controlled principally by the solar wind density and velocity fluctuations. The quantization of the magnetopause distance can be interpreted in terms of quantization of Earth's magnetic field. In the case of low solar wind density, the magnetic levels are crowded and because most of the solar wind lies in this range of density. However, space quantization is more distinct in the case of high-density solar wind which represents abnormal solar wind events. The relation between magnetopause distance and the solar wind density is improved at high solar activity levels. The interpretation of this result is that the magnetopause distance and solar wind density relation is more scattered during the periods of low solar activity (1996 and 2008) than it is during periods of high solar activity (2000 and 2011).

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