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Solar cycle variation of the venus magnetic barrier

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ABSTRACT

Although there is no intrinsic magnetic field at Venus, the convected interplanetary magnetic field piles up to form an induced magnetosphere around the planetary ionosphere. Previous investigations show that the magnetic barrier, the part of the induced magnetosphere in the dayside inner magnetosheath, can act as an effective obstacle to the solar wind during solar maximum, and the magnetic barrier can stop the solar wind even during solar minimum. In this study, we perform a comprehensive statistical study of the magnetic barrier near the terminator during almost a complete solar cycle by using Venus Express magnetic data. The magnetic barrier configuration is located at the dayside even near the terminator and a hemispheric asymmetry exists during the whole solar cycle. We also demonstrate that the general magnetic barrier configuration is controlled by the interplanetary magnetic field orientation and solar cycle dependent. The magnetic barrier under IMF quasi-perpendicular to the solar wind flow is stronger than quasi-parallel to the solar wind flow during the solar cycle, and this difference becomes larger with the increase in solar activity.

1. Introduction

There is no global intrinsic magnetic field in Venus. The solar wind interacts directly with the highly conducting ionosphere of Venus (e.g., Zhang et al., 2008a) and the interplanetary magnetic field (IMF) is draped around the ionosphere to form an induced magnetosphere (e.g., Luhmann, 1986; Zhang et al., 2008a). The induced magnetosphere consists of regions near the planet and its wake where the magnetic pressure dominates all other pressure contributions. The magnetic barrier is formed in the inner region of the dayside magnetosheath to transfer solar wind momentum flux to the ionosphere, and characterized by a strong magnetic field in the dayside magnetosphere (e.g., Zhang et al., 1991). Previous investigations using the Pioneer Venus Orbiter (PVO) (e.g., Russell et al., 1979; Luhmann, 1986; Zhang et al., 1991) show that the magnetic barrier can act as an effective obstacle to the solar wind during solar maximum. Initial Venus Express observations (Zhang et al., 2008b) indicate that the magnetic barrier can stop the solar wind even during solar minimum. The magnetosheath waves convected from the upstream solar wind or produced locally are suddenly suppressed at the upper boundary of the magnetic barrier.

The magnetic pressure of the barrier balances the solar wind pressure at the upper boundary and the ionospheric pressure at the lower boundary. The magnetic barrier can be affected by the variation of the ionosphere. Some prior studies (e.g., Bauer and Taylor, 1981; Elphic et al., 1984; Kar et al., 1986) reported that the ionosphere responds to variations in solar EUV radiation. The solar cycle variation of the EUV flux plays an important role in the solar wind interaction with Venus. Since the Venus ionosphere is modulated highly by the solar activity, we would expect that the magnetic barrier is also solar cycle dependent. The magnetic barrier during solar minimum is significantly lower than that during solar maximum (Zhang et al., 1990, 1991; 2008b). The upper boundary of the magnetic barrier during minimum is almost at the altitude of the lower boundary during solar maximum. The altitude of the ionosphere at the terminator is ~900 km during solar maximum (Zhang et al., 1991) and ~250 km during solar minimum (Zhang et al., 1990). The altitude of the magnetopause at the terminator is ~1700 km during solar maximum (Zhang et al., 1991) and ~1000 km during solar minimum (Zhang et al., 2008b). By using the data of PVO during solar maximum, Zhang et al., (1991) found the magnetic barrier is strongest at the subsolar point and weakens with increasing solar zenith angle. Also, the magnetic barrier exists a hemispheric asymmetry, which is observed in the nightside magnetosphere (magnetotail) (Zhang et al., 2010; Xiao et al., 2016). It is interesting to investigate the solar cycle dependence of these properties. However, these results are mostly observed by PVO, with its periapsis near subsolar point. The properties of the magnetic barrier at low altitude near the terminator and their solar cycle dependence still need further investigations. In addition, the structure of the Venusian magnetosphere is highly dependent on the orientation of IMF

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(e.g., Kallio et al., 2006; Zhang et al., 2009; Vech et al., 2016). IMF dependence of the magnetic barrier during solar cycle is also an important property to investigate.

In this study, we perform a comprehensive statistical study of the magnetic barrier near the terminator during nearly a complete solar cycle by using Venus Express magnetic data. The IMF orientation control and asymmetry of the magnetic barrier near the terminator can be observed, and their solar cycle variation can also be examined.

2. Data

Venus Express (Titov et al., 2006; Svedhem et al., 2007), which is the first Venus exploration mission of the European Space Agency (ESA), launched in November 2005, arrived at Venus in April 2006 and stayed in its polar orbit around Venus until November 2014. Venus Express provides a good opportunity to explore the solar cycle dependence of the magnetic barrier of Venus.

Different from PVO, with a periapsis near subsolar point, Venus Express has its periapsis at 80°N. Thereby, Venus Express covers the low altitude terminator region, which was not covered by the PVO. That allows us to investigate the properties of the magnetic barrier near the terminator, both of day and night side, during the solar cycle by using Venus Express data.

Fig. 1 displays the yearly mean total sunspot number (Sunspot data from the World Data Center SILSO, Royal Observatory of Belgium, Brussels) during the Venus Express period and a clear solar activity variation (nearly a complete solar cycle) is shown. We distinguish the data into two groups to examine the solar cycle dependence of the Venus magnetic barrier. The data from 2006 to 2010, with an average monthly sunspot number ~9.0, represent the solar minimum; the data from 2011 to 2014, with an average monthly sunspot number ~64.3, represent the solar maximum. The Venus magnetic barrier is examined in these two groups by using the magnetic field data obtained by the Venus Express magnetometer (Zhang et al., 2006) with a sampling rate of 1 Hz and a comparative study between them is also performed. The results show the solar activity dependence of the Venus magnetic barrier.

Since the Venus magnetosphere is of induced nature from the interplanetary magnetic field, the field data would be best ordered in the coordinates defined by the upstream magnetic field. In this study, only the orbits with relatively steady IMF are chosen. The bow shock crossings can be identified by the abrupt change in the magnitude of the magnetic field in each orbit, and the inbound (outbound) IMF is the mean value within 15 min window before (after) crossing bow shock. Fig. 2 shows the orbits distribution of the angle θ_R over the orbits where θ_R is defined as the IMF rotations before and after the bow shock crossings during solar minimum and solar maximum. The orbits with steady IMF are defined by the directional changes of the IMF between inbound and outbound of bow shock less than 30°. Thereby, 566 orbits during solar minimum and 369 orbits during solar maximum are selected and rotated into the aberrated IMF coordinates, where the X axis is set as anti-parallel to the average solar wind flow with the aberration angle of 5°. The Y axis is aligned with the cross-flow component of the interplanetary magnetic field, and the Z axis is aligned with the motional electric field, i.e., in the $-V \times B$ direction.

3. Observation

Fig. 3 shows the original (upper) and normalized (lower) magnetic field magnitude distribution in cylindrical coordinates, where X is anti-parallel to the average solar wind flow, during solar minimum and solar maximum with $0.1 \times 0.1\ R_V$ (Venus radius of 6052 km) bins.

As shown in Fig. 3 upper, the enhanced magnetic field envelop around Venus shows the magnetic barrier region at the dayside and the induced magnetotail at the nightside. Since the induced magnetosphere

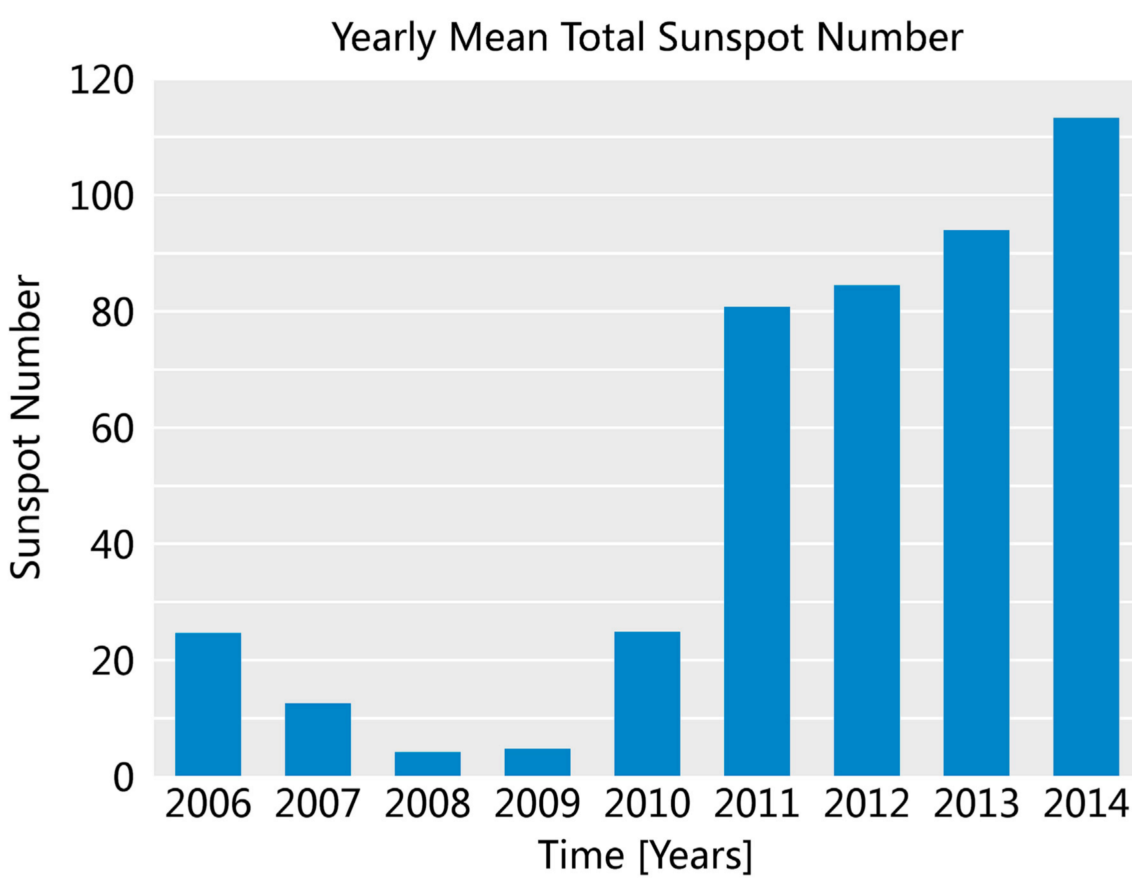

Fig. 1. The yearly sunspot number during the Venus Express period, from 2006 to 2014.