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INITIAL VENUS EXPRESS MAGNETIC FIELD OBSERVATIONS OF THE MAGNETIC BARRIER AT SOLAR MINIMUM

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Abstract

Although there is no intrinsic magnetic field at Venus, the convected interplanetary magnetic field piles up to form a magnetic barrier in the dayside inner magnetosheath. In analogy to the Earth's magnetosphere, the magnetic barrier acts as an induced magnetosphere on the dayside and hence as the obstacle to the solar wind. It consists of regions near the planet and its wake for which the magnetic pressure dominates all other pressure contributions. The initial survey performed with the Venus Express magnetic field data indicates a well-defined boundary at top of the magnetic barrier region. It is clearly identified by a sudden drop in magnetosheath wave activity and an abrupt and pronounced field draping. It marks the outer boundary of the induced magnetosphere at Venus, and we adopt the name "magnetopause" to address it. The magnitude of the draped field in the inner magnetosheath gradually increases and the magnetopause appears to show no signature in the field strength. This is consistent with PVO observations at solar maximum. A preliminary survey of the 2006 magnetic field data confirms the early PVO radio occultation observations that the ionopause stands at ~ 250 km altitude across the entire dayside at solar minimum. The altitude of the magnetopause is much lower than at solar maximum, due to the reduced altitude of the ionopause at large solar zenith angles and the magnetization of the ionosphere. The position of the magnetopause at solar minimum is coincident with the ionopause in the subsolar region. This indicates a sinking of the magnetic barrier into the ionosphere. Nevertheless, it appears that the thickness of the magnetic barrier remains the same at both solar minimum and maximum. We have found that the ionosphere is magnetized ~95% of the time at solar minimum, compared with 15% at solar maximum. For

the 5% when the ionosphere is un-magnetized at solar minimum, the ionopause occurs at a higher location typical only seen during solar maximum conditions. These have all occurred during extreme solar conditions.

Introduction

Venus Express launched on November 9, 2005, is the first European mission to Venus and entered into orbit around Venus on April 11, 2006 (Titov et al, 2006). One of the main scientific objectives of the Venus Express mission is to study the interaction of the solar wind with Venus (Zhang et al., 2006). Unlike the interaction with magnetized bodies whose large intrinsic magnetic field acts to stand off the solar wind flow, the solar wind interacts directly with the upper atmosphere of Venus. This does not mean that the Venusian atmosphere absorbs the solar wind (Zhang et al., 2007). The highly electrically conducting ionosphere acts as an obstacle and deflects the oncoming supersonic solar wind around the planet. The Venusian ionosphere is formed due to various processes such as extreme ultraviolet (EUV) solar radiation, charge exchange and electron impact. These ionization processes are highly solar activity dependent. At solar maximum, most of the time the ionospheric thermal pressure is higher than the solar wind dynamic pressure, about 85% (Luhmann, 1986). Thus, the ionosphere is mostly field-free except for the fine magnetic field structure of flux ropes. At the times when the solar wind dynamic pressure is higher than the peak ionosphere thermal pressure, the ionosphere is found to be magnetized. The interaction of the post-shock solar wind flow with the ionosphere results in a distinct boundary. This is the so-called ionopause which confines the thermal plasma of the ionosphere and marks the top boundary of the ionosphere (cf., Phillips and McComas, 1991).

Taking a closer examination of the solar wind interaction with the ionosphere, one realizes that the effective obstacle is not the ionopause, but some region above it in the inner magnetosheath (Zhang et al, 1991). According to the MHD treatment, as the solar wind slows down in the magnetosheath along the streamlines, the magnetic field piles up and a magnetic barrier forms in the inner magnetosheath. The magnetic barrier transfers the solar wind momentum flux to the obstacle via enhanced magnetic pressure. Associated with the field enhancement is the depletion of solar wind particles. Thus in analogy to the Earth's magnetosphere, the magnetic barrier is an induced magnetosphere on the dayside and acts as the obstacle to the solar wind (Luhmann et al., 2004; Kallio et al., 2007).

The solar wind interacts directly with the induced magnetosphere and only indirectly with the atmosphere or ionosphere of Venus. The induced magnetosphere of Venus consists of regions near the planet and its wake in which magnetic pressure dominates all other pressure contributions. Present knowledge of the solar winds interaction with Venus comes principally from the long-lived Pioneer Venus Orbiter (PVO) mission (cf., Russell and Vaisberg, 1983; Luhmann, 1986; Phillips and McComas, 1991). Although PVO gave us a wealth of data over a complete solar cycle, during solar minimum the PVO periapsis was too high (more than 2000 km) to sample the near Venus plasma environment. The orbit of Venus Express allows it to spend its nominal mission near solar minimum with a periapsis altitude maintained at 250-350 km. Therefore, with Venus Express we can investigate the magnetic barrier at solar minimum for the first time. In this paper, we examine the Venus Express magnetic field measurements to investigate the magnetic barrier at solar minimum.

Observations

Figure 1 illustrates an example of the magnetic barrier as seen in the time series magnetometer data. The data at 1 Hz resolution is displayed in Venus Solar Orbital (VSO) coordinates where the X-axis points from Venus to the Sun, the Y-axis is opposite to the orbital motion of Venus and the Z-axis is northward. The spacecraft moves across the terminator from dusk (-Y) to dawn (+Y) and enters the magnetosheath at about 0128 UT at a radial distance of 1.84 Rv (1 Rv = 6052 km) and 86˚ solar zenith angle (SZA). The magnitude of the field initially builds up slowly and then increases rapidly as the planet is approached. The abrupt increase in field strength marks the entry into the magnetic barrier. After periapsis at 0153 UT (altitude: 302 km; SZA 88.8˚), the field decreases gradually at first and then abruptly at the bow shock. As expected for solar minimum conditions, no ionopause is observed for this periapsis passage. The amount of wave activity is enhanced across the shock. These waves might originate in the upstream solar wind and are convected into the magnetosheath. They could also be produced locally in the magnetosheath, such as mirror waves, which are common in the Earth's magnetosheath. Figure 1 shows a clear boundary around 0146 UT where the magnetosheath waves are suddenly suppressed. Since the magnetosheath waves are embedded in the solar wind, the sudden decrease implies the end of the solar wind, i.e., crossing the effective boundary of the obstacle stopping the solar wind. Coincident with the end of the waves across this boundary, the field direction exhibits an abrupt change such as to be stronger in the X component. Examining the IMF direction before and after the bow shock crossings, we see that the IMF is mainly in the By direction. A sudden switch to the Bx direction, in the location near the terminator, indicates a pronounced draping of field. Thus from the June 27 time series field data, a distinct boundary, i.e., the magnetopause (the name convention is addressed in the discussion) can be identified by suppressed wave activity and pronounced field draping in the inner magnetosheath where the field magnitude is enhanced.

Figure 2 shows additional examples of field data. In each example, the magnetopause can be identified by variations in wave activity and draping in the region where the field magnitude enhances. However, it should be noted that not every orbit displays both identification properties. It appears that the wave activity suppression is the better indicator in identifying magnetopause. In this study, we also took full advantage of the high resolution 32 Hz data by using the dynamic power spectra (not shown here) in identifying the magnetopause (Zhang et al., 2007).

Figure 3 shows 137 clear crossings of the magnetopause from April – August 2006. Due to the Venus Express orbital geometry, most of the crossings are in the polar region with SZA from 50º to 110º. Few nightside crossings have been identified. Those that have been identified exhibit large scattering, indicating a dynamic variation of the induced magnetotail size. Since the magnetopause crossings in the dayside show much less scatter than the nightside, a typical average magnetopause location can be obtained. In the study, we adopted the second-order polynomial curve as our earlier study (Zhang et al., 1991), best fit to the magnetopause for SZA from 50º to 90º:

$$\text{altitude} = 0.087\,(\text{SZA})^2 + 0.001\,(\text{SZA}) + 299$$

for altitude in kilometres and SZA in degrees. The magnetopause obtained at solar minimum is depicted in Figure 4 as a solid line. Also displayed are the expected ionopause locations at solar minimum, based on observation from PVO radio occultation (Zhang et al, 1990). In comparison, the magnetopause and ionopause locations at solar maximum derived from PVO observations are plotted (Zhang et al., 1991). The magnetic barrier is significantly lower than that at solar maximum. In fact its upper boundary is at the same altitude as the lower boundary of the magnetic barrier at solar maximum.

Discussion

An initial survey of the Venus Express magnetic field time series data indicates a well-defined boundary located at the top of the magnetic barrier region. This boundary can be clearly identified as a sudden suppression of magnetosheath wave activity and an abrupt pronounced field draping in the inner magnetosheath where the field magnitude is enhanced. A boundary with very similar characteristics was found at Mars by the Phobos mission (Riedler et al., 1989) and was named the "Planetopause". Later, the same boundary at Mars was named the MPB (magnetic pile-up boundary) by MGS mission (cf. Bertucci et al., 2003). Various names have been given to this boundary following numerous missions and experiments (cf., Nagy et al, 2004). Here we use "magnetopause" to describe the magnetic barrier upper boundary. This term is adopted because it is the outer boundary of an induced magnetosphere consisting of regions near the planet and its wake in which the magnetic pressure dominates the other pressure contributions. This magnetopause is the boundary of the induced magnetospheric obstacle, which determines the position of bow shock and plasma flow around Venus. We note that this boundary does not exhibit a signature in the field magnitude and no abrupt jump of field has been identified across the boundary. In Figure 5, we illustrate the examples of Figure 1 and 2 as magnetic field altitude profiles. The Venus Express data are very similar to the PVO in that the magnetopause has no signature in the field magnitude and instead increases gradually and steadily in the inner magnetosheath. In addition, the draping of the magnetic field occurs in a region about 200 km in vertical extent. This is much thicker than the thickness of the ionopause, which is in the order of 50 km (Elphic et al., 1980).

At solar maximum, the location of the ionopause varies from the surface of Venus to 300 km altitude at the subsolar point, to 900 km altitude near the terminator. At solar minimum, there are no direct PVO measurements of the ionopause due to increasing orbital altitude. However, electron density profiles measured by the radio occultation experiment showed a significant decrease in the electron density from solar maximum to solar minimum. The ionopause was found to be depressed during solar minimum with an altitude of ~ 250 km everywhere in the dayside (Zhang et al, 1990). Our survey of magnetic field data confirms these observations at solar minimum, since we seldom observe the ionopause with the current Venus Express periapsis of 250 – 350 km. Our observations show that the ionosphere appears to be magnetized most of the time at solar minimum as shown in Figure 5. A preliminary survey of the field data for all 2006 orbits shows that the ionosphere is magnetized about 95 % of the time. The remaining 5 % all occur during extreme solar conditions such as ICME's and a field-free ionosphere, except for flux ropes, is observed. Figure 6 shows two examples of field altitude profiles where the ionopause, indicated by the abrupt drop in field magnitude upon entry into the field-free ionosphere, is observed at much higher altitude than at the nominal solar minimum conditions. These ionopause locations are expected only for typical solar maximum conditions. The cause of these 5% with a field free ionosphere at solar minimum is mostly ICME events (For example, see Futaana et al, 2007, for the December 2006 ICME event at Venus).

At typical solar maximum conditions, lower boundary of the magnetic barrier is the ionopause and the magnetopause is its upper boundary. The thickness of the magnetic barrier is found to be about 200 km for the subsolar point and 800 km at the terminator (Zhang et al., 1991). However, when the solar wind dynamic pressure is stronger than the ionosphere thermal pressure, the ionosphere is magnetized. The magnetic barrier is partially merged with the ionosphere, while the position of the ionopause remains at about 250 km altitude. Since PVO observed large field values down to the periapsis at 150 km which is deep inside the subsolar ionopshere, it is reasonable to infer that the lower boundary of the magnetic barrier in the subsolar region could be as low as 80 - 100 km. At solar minimum, we have determined the magnetopause location to be at an altitude of 1013 km at the terminator and 300 km at the subsolar point (Figure 4). If we take an ionopause altitude of 250 km as the lower boundary of the magnetic barrier at the terminator, we get a barrier thickness of about 800 km. If we take the lower ionosphere altitude of 100 km as the lower boundary of the magnetic barrier in the subsolar region, we get a subsolar barrier thickness of about 200 km. Thus our observations reveal that the thickness of the magnetic barrier remains the same for both solar maximum and minimum conditions. At solar maximum, the magnetic barrier sits above the ionopause, which varies from 300 km altitude at the subsolar point to 900 km altitude near the terminator. At solar minimum, the ionopause is lowered to about 250 km over the whole dayside. Thus, the magnetic barrier lowers its position accordingly whilst maintaining the same thickness. In the subsolar region, the magnetic barrier merges with ionosphere to withstand the solar wind. Finally, we note that the poor understanding of the nature of the upper boundary of the magnetic barrier, i.e., the magnetopause of the induced magnetosphere, is by part because of the insufficient temporal resolution of the PVO plasma instrument. It is clear that future studies with a fully integrated Venus Express magnetometer and plasma dataset will provide a deeper understanding of the Venusian induced magnetosphere and its boundaries.

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Figure Captions:

Figure 1 : Magnetic field measurements around periapsis (0153 UT; altitude: 302 km; SZA 88.8˚) on June 27th, 2006 displaying the major plasma boundaries. The missing data is due to the data cleaning processes (Zhang et al, 2007). The solid lines indicate the crossing of magnetopause, and the shadowed area is the induce magnetosphere.

Figure 2: Typical inbound time series of the magnitude and the x-component of the magnetic field observed along the Venus Express orbit 30 minutes before periapsis. The solid line indicates the crossing of magnetopause, and the shadowed area is the induce magnetosphere.

Figure 3: Magnetopause crossings during April – August 2006.

Figure 4: Best fit for the magnetopause boundary as a function of SZA. The expected ionopause at solar minimum is also shown. In comparison, the altitudes of the boundary of the magnetic barrier at solar maximum are shown.

Figure 5: Altitude profiles of magnetic field magnitude and x-component from Figure 1 and Figure 2.

Figure 6: Examples of the altitude profiles of the magnetic field magnitude during solar extreme conditions.

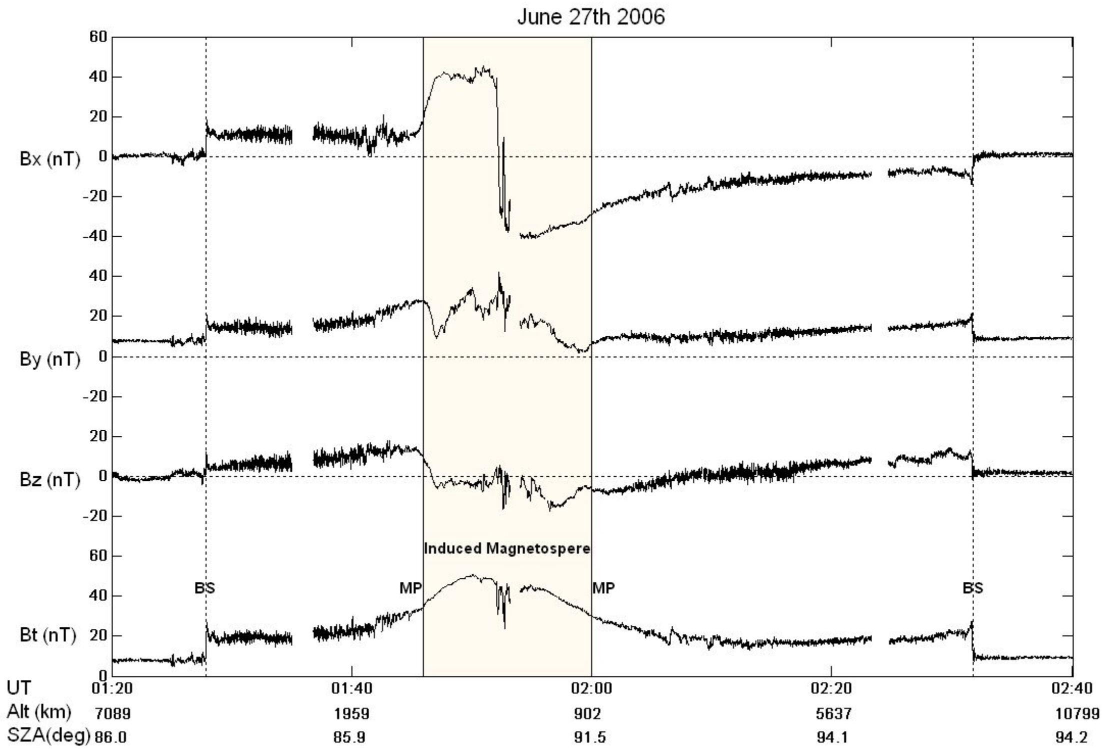

June 27th 2006
Bx (nT)
By (nT)
Bz (nT)
Bt (nT)
Induced Magnetospere
BS
MP
MP
BS
UT 01:20 01:40 02:00 02:20 02:40
Alt (km) 7089 1959 902 5637 10799
SZA(deg) 86.0 85.9 91.5 94.1 94.2

Figure 1

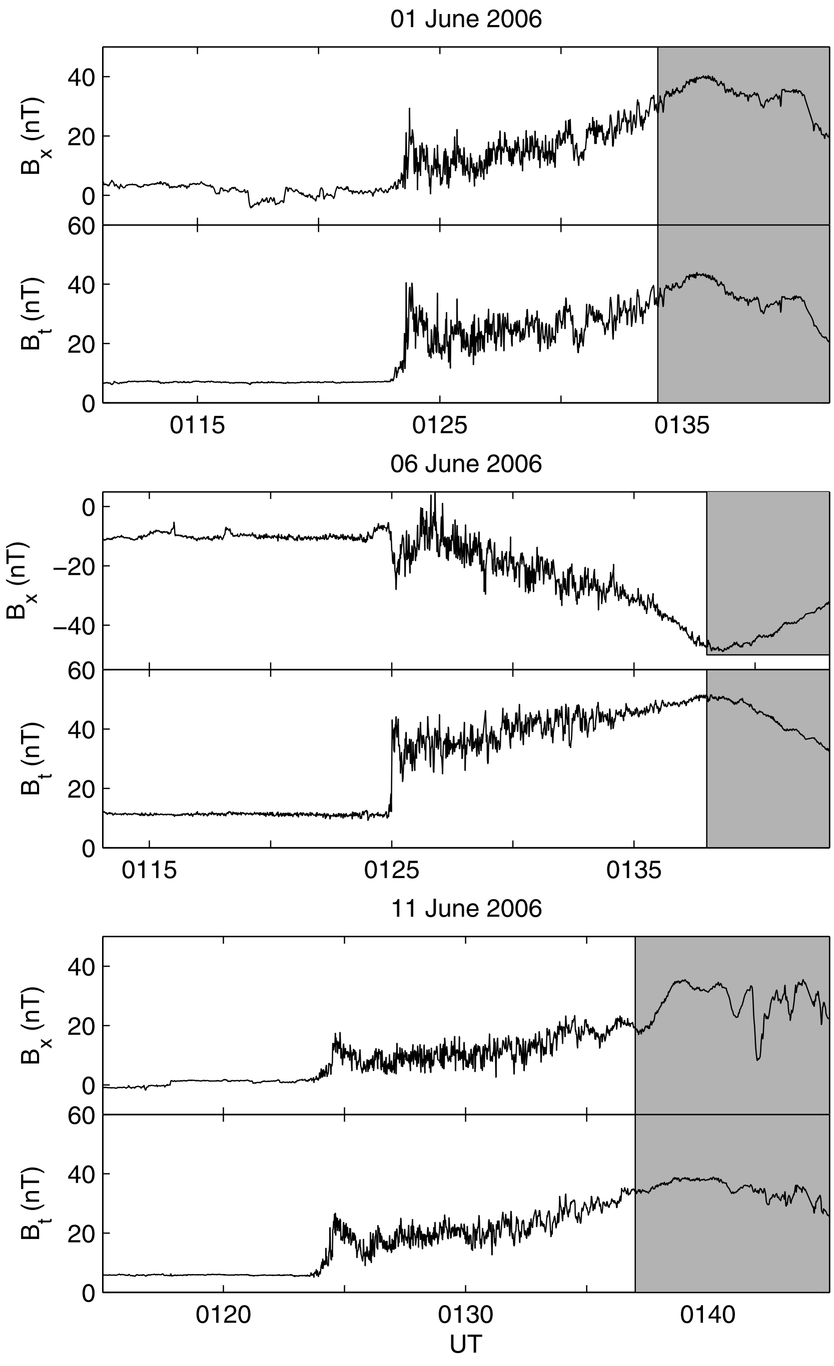

01 June 2006
B_x (nT)
40
20
0
60
B_t (nT)
40
20
0
0115
0125
0135
06 June 2006
B_x (nT)
0
−20
−40
60
B_t (nT)
40
20
0
0115
0125
0135
11 June 2006
B_x (nT)
40
20
0
60
B_t (nT)
40
20
0
0120
0130
0140
UT

Figure 2

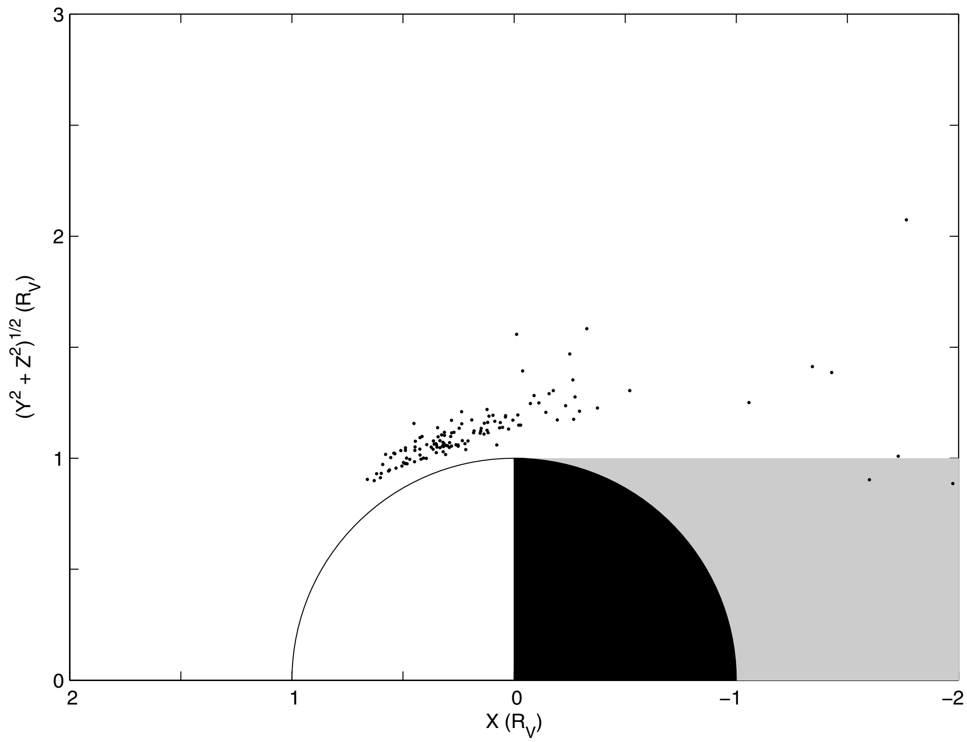


Figure 3

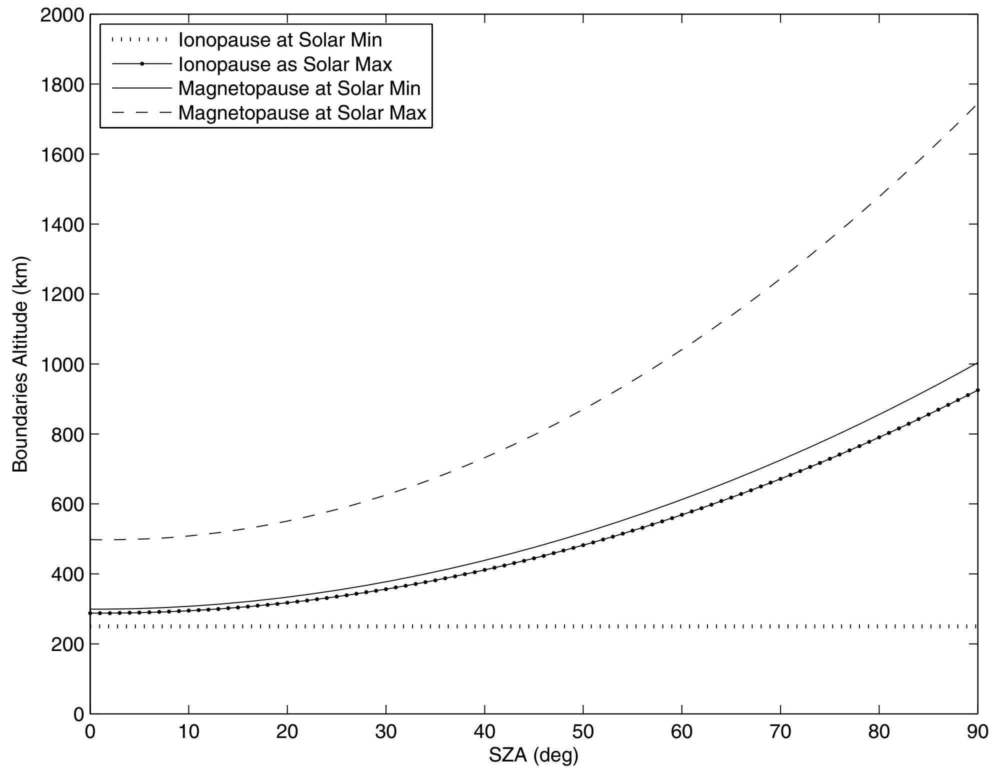
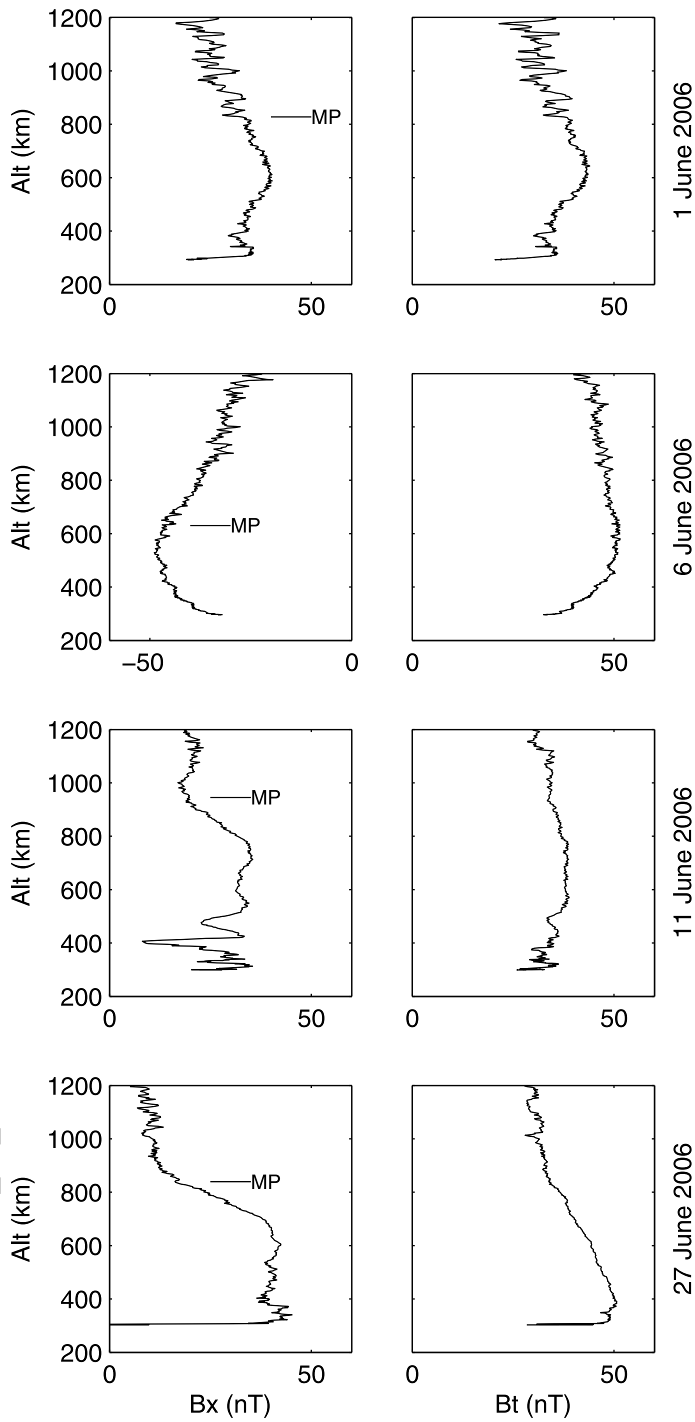

Ionopause at Solar Min
Ionopause as Solar Max
Magnetopause at Solar Min
Magnetopause at Solar Max
Boundaries Altitude (km)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
0
10
20
30
40
50
60
70
80
90
SZA (deg)

Figure 4



1200
1000
800
600
400
200
Alt (km)
MP
0
50
1 June 2006
–50
6 June 2006
11 June 2006
27 June 2006
Bx (nT)
Bt (nT)

Figure 5

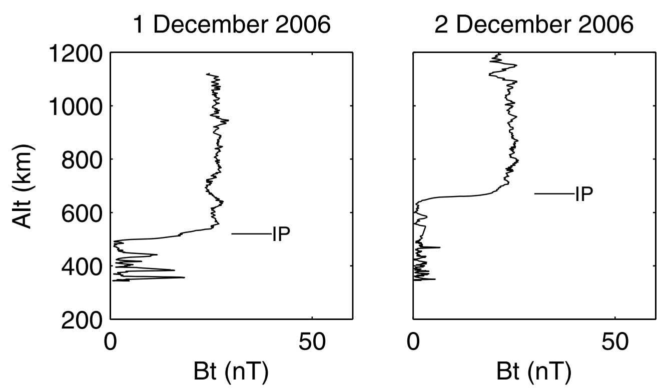

1 December 2006
2 December 2006
1200
1000
800
600
400
200
Alt (km)
IP
IP
0
50
0
50
Bt (nT)
Bt (nT)

Figure 6