Giant flux ropes observed in the magnetized ionosphere at Venus

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[1] The Venus ionospheric response to solar and solar wind variations is most evident in its magnetic field properties. Early Pioneer Venus observations during the solar maximum revealed that the Venus ionosphere exhibits two magnetic states depending on the solar wind dynamic pressure conditions: magnetized ionosphere with large-scale horizontal magnetic field; or unmagnetized ionosphere with numerous small-scale thin structures, so-called flux ropes. Here we report yet another magnetic state of Venus' ionosphere, giant flux ropes in the magnetized ionosphere, using Venus Express magnetic field measurements during solar minimum. These giant flux ropes all have strong core fields and diameters of hundreds of kilometers, which is about the vertical dimension of the ionosphere. This finding represents the first observation of these giant flux ropes at Venus. The cause of these giant flux ropes remains unknown and speculative.
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1. Introduction

[2] Pioneer Venus orbiter (PVO), inserted into Venus orbit on December 1978, made the first in situ observation of the Venus ionosphere during its main mission phase of the first 450 days with its low periapsis altitude of 150 km [*Russell*, 1992]. The measurements of the PVO clearly indicate that the Venusian ionosphere responds not only to variations in solar extreme ultraviolet (EUV) radiation, but to changes in solar wind conditions as well [cf. *Russell and Vaisberg*, 1983; *Luhmann*, 1986]. Venus' ionosphere, particularly as evidenced by its magnetic character, responds dramatically to changing solar wind conditions [*Luhmann et al.*, 1980]. Observations by PVO revealed that for normal solar wind dynamic pressure at solar maximum, about 70% of time, the Venusian ionosphere has sufficient thermal pressure to stand off the solar wind well above the atmosphere and is basically magnetic field-free, but when the solar wind pressure becomes high, the ionosphere becomes magnetized. Thus the observed magnetic state of the ionosphere during solar maximum falls into two broad categories, unmagnetized and magnetized depending on the solar wind dynamic pressure [*Luhmann et al.*, 1980]. The magnetized ionosphere of Venus is generally found where the local ionopause has been forced to altitudes less than 250 km by the incident solar wind dynamic pressure. For an unmagnetized ionosphere state, although dayside ionosphere of Venus has very low average field strength in general, typically only ∼1 nT, however, it is often filled with filamentary magnetic fields, thin regions of very large field strength [*Russell and Elphic*, 1979]. These intense, small scale enhancements are magnetic flux ropes, bundles of twisted magnetic field lines surrounded by ionospheric plasma. Flux ropes are observed at all solar zenith angles on the dayside characterized by numerous events during one single ionospheric passage, with randomized axial orientation and a typical 10-km scale [*Elphic and Russell*, 1983], well smaller than ionospheric vertical dimensions (hundreds of kilometers).

[3] In complement to PVO, Venus Express has taken Venus plasma environment measurements during solar minimum since its orbital insertion on April 2006 [*Titov et al.*, 2006; *Svedhem et al.*, 2007]. Initially, its periapsis was at 78° latitude and 250 km altitude during the main phase of the mission. The ionosphere is found to be magnetized during solar minimum and the ionopause is about 250 km at all solar zenith angle [*Zhang et al.*, 2007, 2008]. Thus few in situ measurements of ionosphere were made during the first two years of Venus Express mission. Occasionally, flux ropes were found during extreme solar wind condition when the ionosphere behavior resembled the solar maximum situation [*Zhang et al.*, 2008; *Wei et al.*, 2010], with characteristics similar to their counterparts found at solar maximum by PVO.

[4] Since July 2008, the Venus Express spacecraft has lowered its periapsis to a height of ∼170 km and latitude around 90°. It allows us to probe the Venus ionosphere in situ at high solar zenith angle during solar minimum for the first time. Here report our finding of a new ionospheric magnetic state not seen by PVO before: giant flux ropes in the magnetized Venus ionosphere. The ropes are embedded in the magnetized ionosphere and are always observed as a single event during one spacecraft ionospheric passage. They occur quite often and have the same scale as the ionospheric vertical

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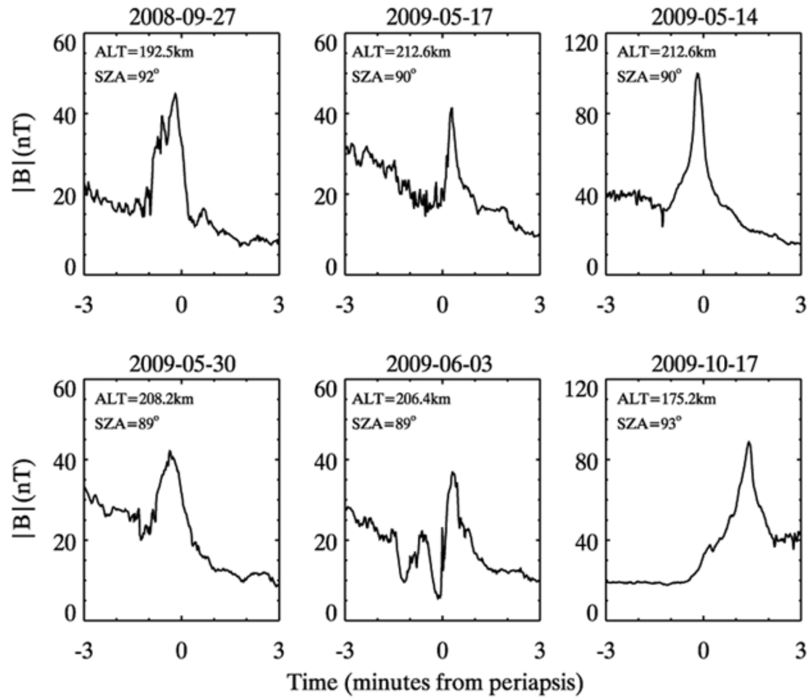

Figure 1. Examples of giant flux ropes observed in the magnetized ionosphere at Venus. The ALT and SZA are the altitude and solar zenith angle at periapsis. Note the scales of the right two panels are different than the others.

dimension. In this paper, we present the first result of our ongoing investigation.

2. Observations

[5] Figure 1 shows several examples of the magnetic field strength observed near periapsis by Venus Express magnetometer from a selected set of passes. The magnetic field data [*Zhang et al.*, 2006] have 1-sec resolution and the time series are displayed as time around periapsis. The altitude and solar zenith angle at periapsis are indicated on the plots. As the examples in Figure 1 illustrate, the magnetic field has an extraordinary enhancement near the periapsis at these times, well above the background magnetized ionospheric magnetic field. In each orbit, the field enhancement occurs as an isolated single event, unlike the field enhancements in the unmagnetized ionosphere during solar maximum observed by PVO [*Elphic and Russell*, 1983]. Table 1 lists the maximum field strength, altitude, and solar zenith angle (SZA) of each field enhancement event. It is clear that all field enhancements occur in the ionosphere well below the ionopause/the photo-electron boundary [*Martinecz et al.*, 2009; *Angsmann et al.*, 2011]. The duration of the field enhancement is of the order of one minute. Consider the orbital speed of the spacecraft near periapsis is ~10 km/s, and assuming that the spacecraft is travelling faster than the magnetic structure, we obtain that it has a scale of several hundred kilometers.

[6] Figure 2 shows the three components of the magnetic field and the total field near the periapsis on May 14, 2009 in Venus Solar Orbital (VSO) coordinates where the x axis points from Venus to the Sun, the Y axis is opposite to the Venus orbital motion and Z axis is northward. The solar zenith angle of periapsis here is 90° and periapsis is in the 212.6 km altitude. A strong field enhancement with peak field at 100 nT is clearly seen around the periapsis. The structure exhibits well-defined flux rope properties such as a bipolar like rotation of the field in B_Z component and magnetic core field in B_Y. Here a By core field suggests that the axial orientation of the flux rope is along Y, i.e., in the horizontal direction relative to the planet surface considering that the observation is made at SZA 90°. In Figure 3, we show the same interval of data in LMN coordinates obtained from minimum variance analyses, a traditional treatment to study the flux rope in an attempt to the field variation to two dimensions [e.g., *Russell and Elphic*, 1979; *Elphic and*

Table 1. Maximum Field Strength, Altitude, and Solar Zenith Angle (SZA) of Each Field Enhancement Event

Date	Time (UT)	Bmax (nT)	Alt (km)	SZA (deg)	R[a]	Rope Axis (VSO)	IMF (nT) (VSO)
2008-09-27	7:32:02	45	193	91	3.2	0.43, 0.86, −0.28	1.20, −4.01, −1.09
2009-05-14	1:58:19	100	213	89	3.6	−0.10, 0.98, −0.16	6.67, 5.66, 4.03
2009-05-17	1:55:32	42	214	91	2.2	−0.38, 0,90, −0.22	2.14, −6.88, 8.93
2009-05-30	1:40:32	42	210	87	2.0	0.46, 0.86, 0.25	8.53, −4.34, 0.68
2009-06-03	1:36:44	37	208	91	2.1	−0.15, 0.98, 0.11	−5.86, 0.25, 7.88
2009-10-17	3:36:40	89	199	87	2.7	0.47, 0.84, 0.28	4.43, 2.72, −4.77

[a]Ratio of Bmax and background field strength.

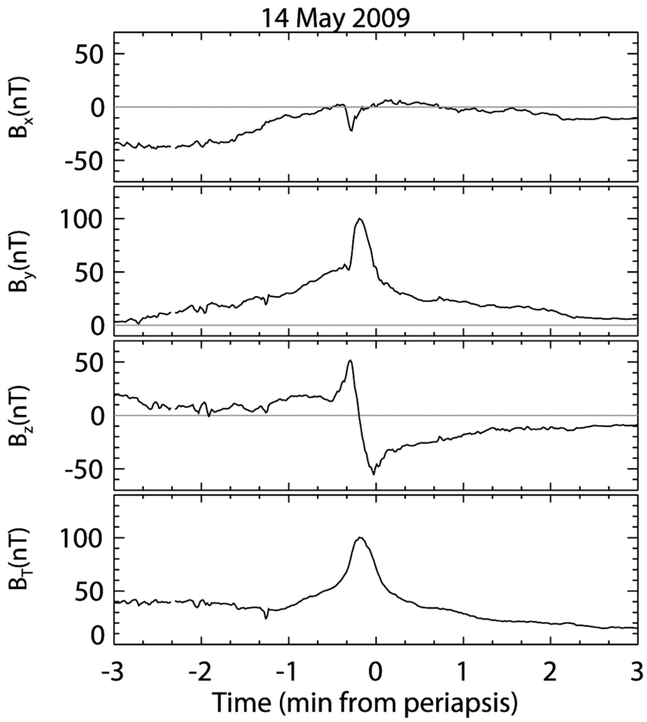

Figure 2. Magnetic field measurements on May 14, 2009, in VSO coordinates. The spacecraft positions at −3, 0, 3 minutes from the periapsis are (1655, 993, 6093) km, (85, 237, 6260) km, (−1488, −528, 6162) km in VSO coordinates respectively. The flux rope has a core field in the Y direction.

Russell, 1983]. The LMN components, here L = (−0.133, 0.144, 0.981), M = (−0.101, 0.982, −0.158), and N = (0.986, 0.120, 0.117), refer to the maximum, intermediate and minimum variance directions respectively. The time interval used for the analysis is between 01:57:49 and 01:58:49 UT. The method is well defined with the eigenvalue ratio (intermediate/minimum variance) of 25. In this coordinate system the bipolar signature is in the B_L component and core field in the B_M component.

[7] We can reconstruct the magnetic field configuration of the related magnetic island structure seen by the Venus Express on May 14, 2009, by use of the steady, 2-D magnetohydrostatic reconstruction technique [*Hau and Sonnerup*, 1999]. Since we do not have the plasma pressure measurements, we assume $\boldsymbol{j} \times \boldsymbol{B} = 0$ and then spatially integrate the equation by use of the magnetic field data from the spacecraft as initial values [e.g., *Teh et al.*, 2010]. Figure 4 is the reconstructed magnetic field map with the axial magnetic field in color, showing a magnetic flux rope with a strong core field at the island center. The reconstruction axes are in VSO: $\boldsymbol{x}'$ = (−0.999, −0.038, −0.027), $\boldsymbol{y}'$ = (−0.031, 0.110, 0.993), and $\boldsymbol{z}'$ = (−0.035, 0.993, −0.111), where the z' axis is the invariant axis along which the variation is negligible. Since we do not have the available plasma velocity measurements, we assume that the island is stationary and is sampled by the moving spacecraft as it moves at $\boldsymbol{V}_{SC}$, where $\boldsymbol{V}_{SC}$ = (−8.8, −4.3, 0.2) km/s. In the field map, the region between the two peaks of the bipolar signature is surrounded by the magenta line. Within this region, the total axial magnetic flux and the total axial current are estimated, being 1.2×10^3 Wb and 1.8×10^4 A, respectively.

3. Discussion

[8] Lowering the Venus Express spacecraft periapsis altitude into the ionosphere during solar minimum since 2008 has brought a surprising discovery on the magnetic state of Venus' ionosphere. Looking through magnetic field measurements from July 2008 to October 2009, about two Venus years, we found about one hundred cases with the enhanced magnetic strength structures near the periapsis in the ionosphere. Thus the giant flux rope revealed in this report occurs quite often and it represents a basic magnetic state of the Venusian polar ionosphere.

[9] Our finding of the giant flux rope in the magnetized ionosphere is quite different from the earlier PVO observation of flux ropes in the unmagnetized ionosphere in many aspects. Firstly, our flux rope has a scale of 10^2 km, which is about the same scale as the vertical ionospheric dimension (less than 200 km). The magnetic flux contained in the rope is on the order of 1000 Webers. In contrast, the PVO flux ropes are tiny filamentary 10 km scale structures with a magnetic flux of 2 to 3 Webers [e.g., *Russell*, 1990]. Secondly, the Venus Express rope is an isolated single event for each periapsis passage of the spacecraft with orientation in the horizontal direction, while the PVO flux ropes are numerous for each orbital passage of ionosphere and their orientations are random [*Russell and Elphic*, 1979]. Thirdly, the giant rope occurs in the magnetized ionosphere, while

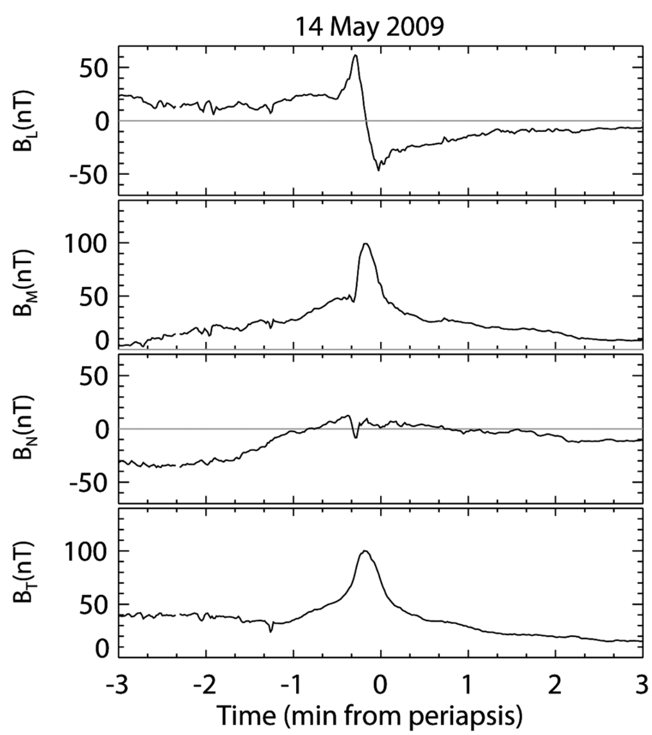

Figure 3. Time-series plots of the magnetic field data in LMN coordinates, with the field strength shown in the bottom panel. The time interval used for the minimum variance analysis is between 01:57:49 and 01:58:49 UT. The bipolar signature is shown in the B_L component.

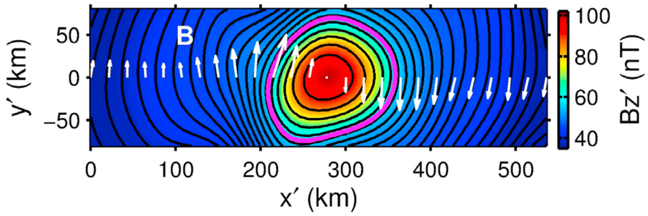

Figure 4. Magnetic field map of the island structure on May 14, 2009 obtained from the magnetohydrostatic reconstruction for force-free conditions. The color code represents the axial magnetic field component. The reconstruction time interval is between 01:57:49 and 01:58:49 UT. The white arrows are the measured magnetic field vectors projected on the reconstruction plane. The region between the two peaks of the bipolar signature is surrounded by the magenta line.

the PVO flux ropes are found in the unmagnetized ionosphere with nearly zero ambient fields. Finally, we observe the giant flux rope at solar minimum only near 90° latitude due to the Venus Express spacecraft orbital geometry, while the PVO flux ropes were observed at solar maximum throughout the sampled dayside ionosphere [cf. *Russell*, 1990]. Thus the flux ropes at Venus can be divided into two distinguished categories: giant flux ropes as report in this study and small-scale flux ropes observed by PVO.

[10] Although giant flux rope has not been reported in the Venus ionosphere, it has been indeed found in the near Venusian magnetotail recently [*Slavin et al.*, 2009; *Zhang et al.*, 2012]. Using MESSENGER Venus Flyby magnetic and plasma measurements, *Slavin et al.* [2009] found a very large flux rope embedded in the Venus magnetotail current sheet. The duration of the rope is 30 second and dimension of the rope is about 1800 km by using plasma velocity of 60 km/s. Further analysis of the principal axis of the flux rope suggests the velocity shear/ionopause K-H instability formation of the flux rope. In contrast, *Zhang et al.* [2012] found a large flux rope (3400 km) in the Venus magnetotail and it attributed to magnetic reconnection. We note that the magnetotail flux rope reported by *Slavin et al.* [2009] occurs at an altitude of 480 km and SZA of 130°, it might be related to the ionospheric giant flux rope presented in our study.

[11] Information on where and what circumstances flux ropes are found in the Venus ionosphere is crucial for understanding how they arise and evolve. In addition, rope scale size, magnetic flux, orientation, and occurrence rate all have implications of the source and evolution of the flux rope. The apparent differences from the PVO flux ropes suggest that the Venus Express flux rope has a quite different origin and evolution. Two competing processes are often suggested for flux rope formation in space plasmas: magnetic shear and velocity shear. Magnetic reconnection resulting from the magnetic shear is important in forming flux ropes at Earth's magnetopause and its magnetotail for example. Velocity shear, coupled to the Kelvin-Helmholtz instability, has been suggested to be responsible to the small-scale flux rope formation at Venus observed by PVO [cf., *Russell*, 1990]. Cassini observations of twisted field lines in the ionosphere of Titan are also attributed to large scale flux ropes generated by velocity shear [*Wei et al.*, 2010, 2011]. Since the giant flux rope described here is quite different from the PVO small flux ropes, is it caused by magnetic reconnection? Although this question remains open for future observation and analysis, below we examine another weakly magnetized terrestrial planet, Mars, for possible implications.

[12] Like Venus, Mars has an atmosphere but no global intrinsic magnetic field. Thus the solar wind interactions with these two planets are quite similar except that the existence of the remanent crustal magnetic fields at Mars makes it a more complicated situation. In addition, since the Martian ionospheric thermal pressure is weaker than the solar wind dynamic pressure, its ionosphere in regions removed from strong crustal fields is typically magnetized [*Luhmann et al.*, 1987], like the solar wind interaction with Venus at solar minimum [*Zhang et al.*, 2008]. Observation from Mars Global Surveyor magnetometer revealed two distinguishing kinds of flux ropes at Mars: small scale ropes and large scale ropes [cf. *Vignes et al.*, 2004; *Brain et al.*, 2010]. The large scale flux ropes at Mars are very similar to the giant flux rope at Venus in this study, characterized by hundreds of kilometers in scale size and strong core field. *Brain et al.* [2010] have observed hundreds of large scale flux ropes at Mars, all occurring in the southern hemisphere and near the strong crustal fields of Mars. They have attributed the formation of the large flux ropes at Mars to the magnetic reconnection process between the interplanetary magnetic field and crustal field.

[13] The observation and formation of the large flux rope at Mars might raise speculative questions related to the giant flux ropes at Venus: are they produced by magnetic shear through a reconnection process? If so, does it imply a crustal remanent magnetic field at Venus although the planet surface is at high temperature comparable with Curie temperature? Or is it evolved from the flux rope caused by the magnetic reconnection in the near Venusian magnetotail [*Zhang et al.*, 2012]? Or does it hint to a local dynamo or an induced dipole field in the ionosphere (E. Dubinin et al., Toroidal and poloidal magnetic fields at Venus, submitted to *Planetary Space Science*, 2012)? How does it change globally? At this stage, we will not be able to answer these questions. Much of the difficulty in this study is related to the fact that the global behavior of the giant flux rope in the ionosphere is not known. An investigation of the solar wind interaction with Venus depends critically on the spacecraft orbits, However, the ionospheric observations of Venus Express are quite restricted due to the periapsis around 90° latitude north. Finally, the ionospheric magnetic fields of Venus contain key information about the physics of the solar wind interaction with planetary atmospheres. Whatever the origin and evolution of the giant flux rope, it has important implications for weakly magnetized planetary bodies, and may play an important role in the solar wind interaction and ionospheric plasma transport.

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