Icarus 206 (2010) 174–181

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Comparison study of magnetic flux ropes in the ionospheres of Venus, Mars and Titan

H.Y. Wei [a,*], C.T. Russell [a], T.L. Zhang [b], M.K. Dougherty [c]

[a] Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA 90095-1567, USA
[b] Space Research Institute, Graz A-8042, Austria
[c] Imperial College, The Blackett Laboratory, Dept. of Physics, London SW7 2BZ, UK

ARTICLE INFO

Article history:
Received 10 October 2008
Revised 5 March 2009
Accepted 9 March 2009
Available online 18 March 2009

Keywords:
Venus
Mars
Titan
Magnetic fields

ABSTRACT

Magnetic flux ropes are created in the ionosphere of Venus and Mars during the interaction of the solar wind with their ionospheres and also at Titan during the interaction of the Saturnian magnetospheric plasma flow with Titan's ionosphere. The flux ropes at Venus and Mars were extensively studied from Pioneer Venus Orbiter and Mars Global Surveyor observations respectively during solar maximum. Based on the statistical properties of the observed flux ropes at Venus and Mars, the formation of a flux rope in the ionosphere is thought first to arise near the boundary between the magnetic barrier and the ionosphere and later to sink into the lower ionosphere. Venus flux ropes are also observed during solar minimum by Venus Express and the observations of developing and mature flux ropes are consistent with the proposed mechanism. With the knowledge of flux rope structure in the Venus ionosphere, the twisted fields in the lower ionosphere of Titan from Cassini observations are studied and are found to resemble the Venus flux ropes.

1. Introduction

A magnetic flux rope has a structure like a bundle of twisted field lines. Flux ropes are believed to be created in the ionospheres of Venus and Mars by their interactions with the solar wind and possibly in Titan's ionosphere during its interaction with Saturn's magnetized plasma flow. The first observation of ionospheric flux ropes was made at Venus by the Pioneer Venus Orbiter (PVO) mission (Russell and Elphic, 1979). As shown in the left panel of Fig. 1 from Russell (1990), the Venus ionosphere is mostly field-free below the ionopause, but threaded with flux ropes which have strong fields near the center. Thus they look like discrete peaks in an altitude profile of the magnetic field. The magnetic structure inside a flux rope is illustrated in Fig. 2a: the field is strong and axial near the center and becomes more azimuthal and much weaker with increasing distance from the center. When a spacecraft flies through a flux rope, the observed magnetic vectors rotate along the trajectory and in the principal axis coordinate system (in which B_i, B_j, and B_k components refer to the maximum, intermediate and minimum variance directions, respectively) as illustrated in Fig. 2b. In the cylindrical coordinates in the illustration, the rope fields have components only in the axial direction ($\hat{z}$) and the azimuthal direction ($\hat{\varphi}$) (i.e. no radial component) and both components only vary with radial distance (ρ) from the axis (Russell and Elphic, 1979; Elphic et al., 1980). If the trajectory passes through the center of the rope, the observed fields would rotate in a plane containing the rope axial direction which is the symmetric axis of the observed field rotation, but if the trajectory has a large impact parameter relative to the rope axis, the observed fields vary in three dimensions and the rope axial direction needs to be found by inversion.

In this paper, we first review some of the earlier studies of flux ropes in the ionospheres of Venus and Mars during solar maximum observations and discuss the formation of a flux rope. Then we study the flux ropes during solar minimum from Venus Express observations and show that their properties agree with the proposed rope-formation mechanism. Finally, the twisted fields in the lower ionosphere of Titan from Cassini observations are studied and compared with the Venus ropes.

2. The Venus and Mars flux ropes during solar maximum observations

The Venus flux ropes from PVO observations have been extensively studied (Elphic and Russell, 1983a,b,c; Russell, 1990; Ledvina et al., 2002, etc.). Similarly Mars flux ropes using MGS observations have been examined (Cloutier et al., 1999; Vignes et al., 2004; etc.). The statistical study of Venus flux ropes shows that flux ropes were observed over 70% of the PVO orbits passing through the dayside

* Corresponding author. Address: 6862 Slichter Hall, University of California, Los Angeles, 595 Charles E. Young Drive East, Los Angeles, CA 90095-1567, USA.
E-mail address: hwei@igpp.ucla.edu (H.Y. Wei).

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doi:10.1016/j.icarus.2009.03.014

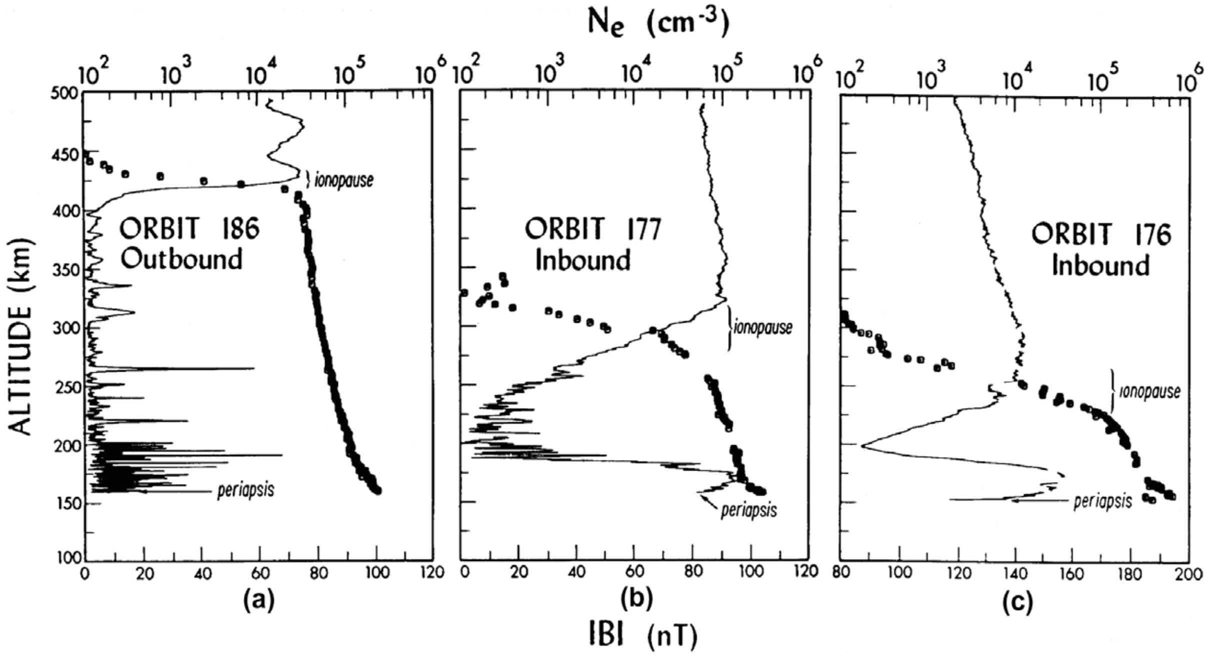

Fig. 1. Altitude profiles for the electron densities (points) and magnetic fields (solid lines) observed by Pioneer Venus Orbiter (PVO), as solar wind pressure increases from left panel to right one. Ionopause thickens and moves to lower altitudes as solar wind pressure increases, and lower ionosphere changes from field-free to magnetized (from Russell, 1990).

ionosphere. The rope occurrence frequency increases with decreasing altitude, peaking near 170 km, and then decreases markedly at even lower altitudes. The rope width is between 6 and 12 km near the subsolar region and between 7.5 and 16 km near the terminator plane. The maximum field strength within the flux rope is about 20 nT at high altitudes and increases to about 70 nT at low altitudes. At low solar zenith angles (less than 45°) the rope axial orientations are quasi-horizontal above 200 km altitude and quasi-perpendicular below 200 km. Near the terminator (solar zenith angle greater than 45°), the ropes are nearly horizontal above 300 km and randomly oriented below 300 km. Mars flux ropes were observed less frequently, on only 5% of the MGS orbits in the Mars ionosphere. The Mars ropes have a width of the order of a few tens kilometers, and their axial orientation appears to be random in the ionosphere. The Mars ropes are found to have similar global characteristics of those of Venus by (Vignes et al., 2004) although there are less flux ropes overall at Mars.

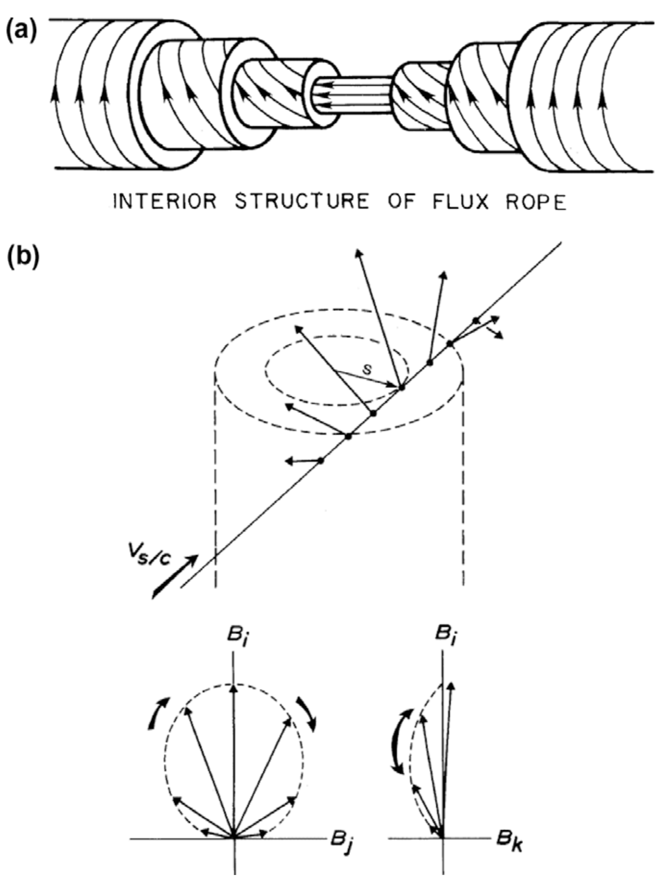

Fig. 2. (a) Illustration of the magnetic structure of an ionospheric flux rope. The field is weak and azimuthal in the outer regions, becoming much stronger and more axial near the center of the structure (from Russell and Elphic, 1979). (b) Schematic of a flux-rope traversal by spacecraft (from Elphic et al., 1980).

When the solar wind pressure is high, the Venus ionosphere could be magnetized by the penetrating upstream fields as shown in the middle and right panels of Fig. 1. The Venus ionosphere is mostly field-free during solar maximum but is often magnetized during solar minimum because of the generally weaker ionosphere during solar minimum (Zhang et al., 2007). Flux ropes were rarely observed in the solar minimum magnetized ionosphere which suggests that large-scale fields inhibit the formation of flux ropes. This could also explain the fewer occurrences of Mars ropes than Venus ropes, since the Mars ionosphere is magnetized more often and more completely than that of Venus. In the southern hemisphere where strong crustal fields exist, there are no flux ropes observed in the magnetized ionosphere.

3. The formation mechanism of ionospheric flux ropes

Based on the statistical properties of the observed flux ropes at Venus, Russell (1990) proposed that the ropes were created at the boundary between the ionosphere and the magnetic barrier. The source region of flux ropes is believed to be at high altitudes because the ropes were frequently observed when the ionosphere was able to shield the upstream fields and only the high altitude region could provide a source of magnetic field. The rope orienta-

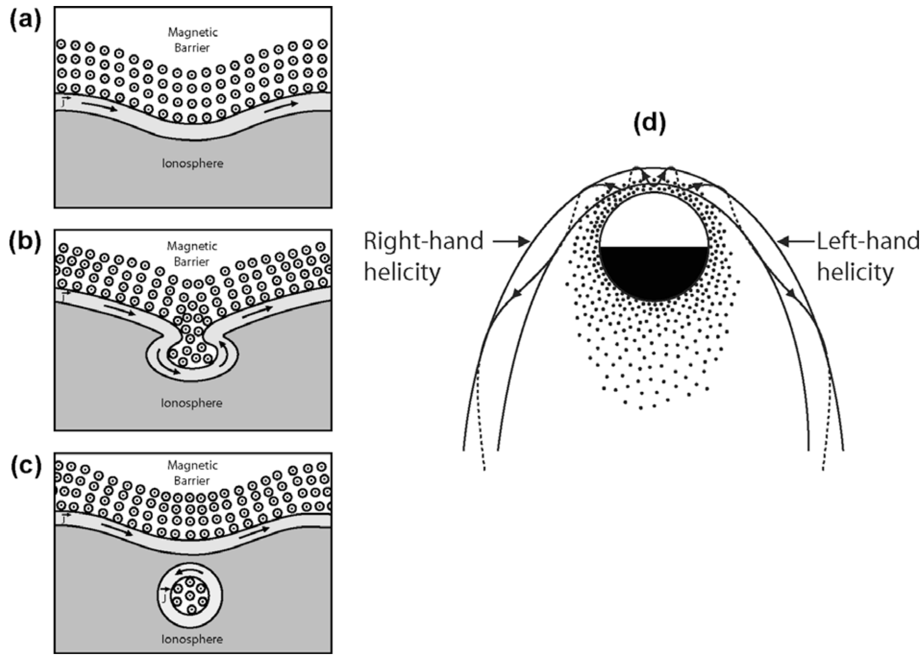

Fig. 3. Schematic diagram of the formation of a flux rope at the interface between the magnetic barrier and the ionopause (adapted from Russell, 1990): a flux tube above the ionopause starts to twist and form a helical structure near the boundary between the magnetic barrier and the ionosphere; in the meanwhile it sinks into the field-free ionosphere and becomes further twisted. In a global picture in (d), such twisted flux tube should have opposite helicity on either side of the Sun–Mars line and the helicity decreases with distance from the middle part of the flux tube where the helicity reverses.

tions were statistically more horizontal at high altitudes and more vertical at lower altitudes indicating that they were "younger" at high altitudes and evolved to become more twisted and even helical kink unstable when they sank into lower altitudes. The large number of flux ropes observed during solar maximum near the subsolar region indicates that they were possibly generated locally but unlikely to be caused by Kelvin–Helmholtz instability which is more effective near the terminator. In Russell (1990), Fig. 15 showed magnetic field fluctuations near the subsolar region ionopause which could evolve into a flux rope. Fig. 3 (adapted from Fig. 16 of Russell, 1990) illustrates a flux rope forming near the ionopause and sinking to low altitudes, and the expected helicity along this flux rope.

As shown in Fig. 3a, the piled-up magnetic fields of the magnetic barrier balance the thermal pressure in the ionosphere with a current layer between them called the ionopause. Right at this boundary, whether a flux tube can be pulled into the lower ionosphere depends on two forces, i.e. the downward curvature force to pull it to lower altitudes, and the upward buoyancy force due to different mass densities inside the flux tube and the ambient ionosphere. If the curvature force is stronger than the buoyancy force, the flux tube is dragged into the lower ionosphere (Fig. 3b) and the velocity shear across this tube twists it when it is pulled downward. If the curvature force is not stronger, the flux tube will float above the ionosphere gradually becoming heavier due to photoionization of exospheric neutrals within the tube. As the tube descends, it loses some of its buoyancy by further photoionization of the exospheric neutrals through which the rope is passing (Fig. 3c). In a global picture as shown in Fig. 3d, such twisted flux tube should have opposite helicity on either side of the flow line, and velocity shear along this flux tube is strongest near the ionopause and nearly zero in the two ends in the solar wind so that the helicity decreases with distance from the middle part of the flux tube where the helicity reverses.

In this scenario, it is important to examine the curvature force and the buoyancy force near the ionopause and in the ionosphere. For a flux tube containing magnetosheath plasma, the plasma number density is much smaller than that of the ionosphere plasma (over two orders of magnitude smaller), and it contains lighter ion species (i.e. proton) compared with the major ion species in the ionosphere (i.e. oxygen). Thus the plasma density is much smaller than that of the ionosphere. In the extreme case, a flux tube containing only magnetosheath plasma can be approximately considered as a vacuum when we estimate the buoyancy force on it in the ionosphere. In this situation, if we assume the magnetic field strength is 50–100 nT and the radius of the field line curvature can be approximated by the distance from the center of Venus to the location of the field line (i.e. the Venus radius 6051 km plus the ionopause altitude 400 km), the curvature force at altitude 400 km is about 3.08×10^{-16}–1.23×10^{-15} N/m^3. The plasma density in the ionosphere below the ionopause is about 10^5–10^6 amu/cm^3, thus the buoyancy force is 1.49×10^{-14}–1.49×10^{-15} N/m^3 by assuming no plasma inside the flux tube. The estimated buoyancy force is larger than the curvature force. Thus, an empty flux tube hung up at the ionopause boundary is more likely to float above the ionosphere than to sink to low altitudes. However, this flux tube could become denser and heavier due to photoionization of the exospheric neutrals inside the tube, thus with time it would lose some of it buoyancy and the slightly larger buoyancy force calculated above may decrease to become comparable to or smaller than the curvature force.

How small does the buoyancy force need to be for the flux tube to be dragged into the ionosphere? If we examine the situation showed in the left panel of Fig. 1, the curvature force is 7.89×10^{-16} N/m^3, for a magnetic field of 80 nT, and a radius of curvature of 6451 km. For a flux tube to be pulled into the ionosphere, the buoyancy force should be smaller than this value, thus the mass density difference (between the plasma inside the rope and that outside) should be less than 5.28×10^4 amu/cm^3. This value leads to a number density of 3.3×10^3 cm^{-3} (assuming oxygen as major ion species), which occurs near altitude of 420 km in the left panel of Fig. 1. At this altitude, we can see from the plasma profile that there should be a fairly large amount of exospheric neutrals which are possibly ionized within the flux tube and make it heavier. From the left panel of Fig. 1, we can see that the ionosphere plasma number density changes from 3×10^4 to 1×10^2 cm^{-3} from 400 to 450 km. Assuming the major ion species is oxygen (i.e. mass of 16 amu), on average the mass density decreases 9.6×10^3 amu/cm^3 per kilometer with increasing altitude. This density difference is about 1/6 of that needed for a flux tube buoyancy force to balance curvature force. Thus if the flux tube density is about the same as or smaller than that of the ionosphere plasma within 6 km above its location, the curvature force is stronger than the buoyancy force and it can be pulled downward into the ionosphere. Thus, as the flux tube is gradually filled by ionospheric plasma, the buoyancy force is much reduced and is likely to become smaller than the curvature force, so the curvature force can pull it into the ionosphere.

These two calculations imply that a flux tube is unlikely to be pulled into the ionosphere if it has nearly no plasma in it, however, if it loses some of its buoyancy by photoionization of the exospheric neutrals within the flux tube, the curvature force is very likely to overcome the buoyancy force and drag it to lower altitudes. This model also predicts that the sub-flow point on the ionopause is the most likely place for flux ropes to form since the exospheric density at the ionopause is greatest and their residence time there is longer, allowing the plasma density to build up to a larger value.

4. Flux ropes in the ionosphere of Venus during solar minimum

During solar minimum, Venus Express (VEX) (Svedhem et al., 2007) detects a largely magnetized ionosphere (Zhang et al., 2007) and fewer flux ropes. Because the Venus ionosphere is generally weaker than at solar maximum, the ionopause and lower regions often resemble the situation reached during high solar wind pressure during solar maximum (right panel in Fig. 1). The regions below the ionopause are often not field-free but contain large-scale field structure. Since the existence of a large-scale field tends to preclude flux rope formation because it inhibits cross-field flow shear, there are many fewer flux ropes observed by Venus Express. In the 225 orbits of the surveyed VEX data from April 24th to December 30th in 2006, there are 23 orbits (10% of the surveyed orbits) containing flux rope observations, which is much smaller than during solar maximum observations (70% of PVO orbits, Elphic and Russell, 1983b). Since the ionosphere is often magnetized during solar minimum, this small percentage is primarily because of the existence of large fields below the ionopause. In the surveyed 225 orbits, there are 39 orbits in which some unmagnetized ionosphere was observed below the ionopause, and 23 of these orbits (i.e. 59%) contained flux ropes (including either the mature ropes or the developing ropes which will be discussed below). Thus flux rope occurrence is close to the solar maximum rate if we exclude orbits when the ionosphere is magnetized.

Fig. 4 shows an example of flux ropes observed during solar minimum by VEX. In the altitude profile of the magnetic field strength, the ionopause crossing is between 400 and 450 km where the field strength decreases sharply with decreasing altitude. The region below the ionopause is nearly field-free and two flux ropes are observed around altitudes of 350 km and 310 km. The hodogram (i.e. a diagram of the maximum variance component B_i in the principal axis coordinate system versus the intermediate component B_j) of the flux rope around 350 km shows that the field lines are twisted in a helical structure inside the flux rope. This situation is similar to the unmagnetized state of Venus ionosphere shown in left panel of Fig. 1.

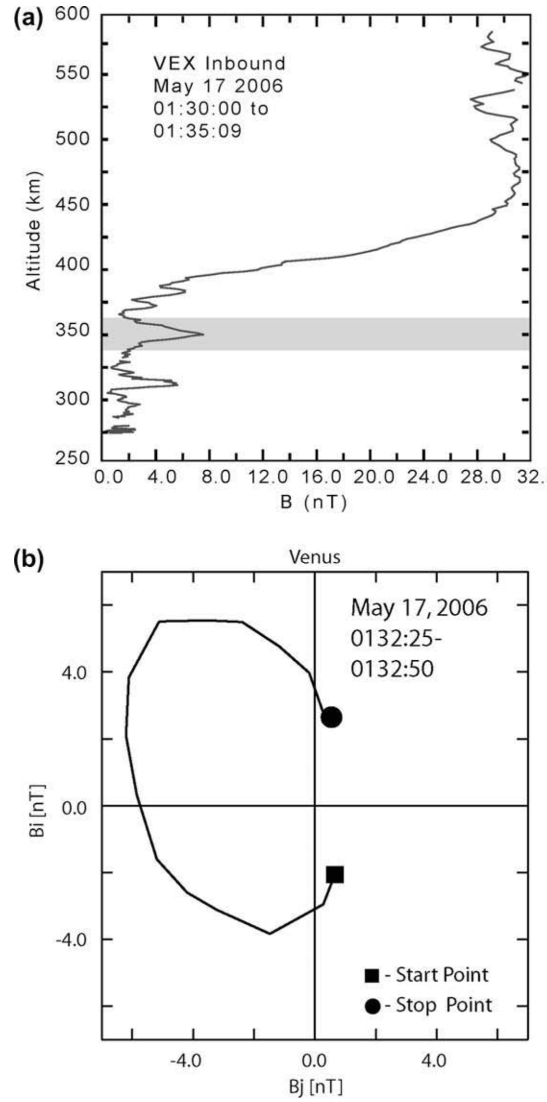

Fig. 4. (a) Altitude profile of magnetic fields in Venus ionosphere observed by Venus Express during solar minimum. (b) Hodogram of flux rope in the field-free region of the Venus ionosphere during solar minimum, at altitude about 350 km in (a).

In the VEX observations, there are some cases with twisted fields near the lower boundary of the ionopause which appear to start forming a flux rope. As shown in Fig. 5, the shaded part in the altitude profile is a twisted flux tube and its hodogram is shown in Fig. 5b. This flux tube probably starts to form a flux rope (as in the middle panel of the Fig. 3) so that the field inside this flux tube is less twisted than the flux rope observed in the field-free ionosphere. We use a simple Bessel function model to fit the data and find the rope's axial and azimuthal components, that is $Bz = b_0 \times J_0(\rho) + B_0$, and $B\varphi = b_0 \times J_1(\rho)$, where J_0 and J_1 are zero-th and first order Bessel functions and ρ is the radial distance in cylindrical coordinates. The model fittings of flux ropes in Figs. 4 and 5 are shown in Fig. 6a and b. The axial orientation of the flux rope so obtained is compared with the field orientation right above the ionopause. The axial direction of the developing rope in Fig. 5 is nearly parallel to the fields above the ionopause boundary, with an angle of 25° between the two directions. While the axial direction of the mature rope in Fig. 4 largely deviates from the field orientation above the ionopause, with an angle of 82°. These results are consistent with the rope-formation mechanism illustrated in Fig. 3. Because when the rope starts to form near the ionopause

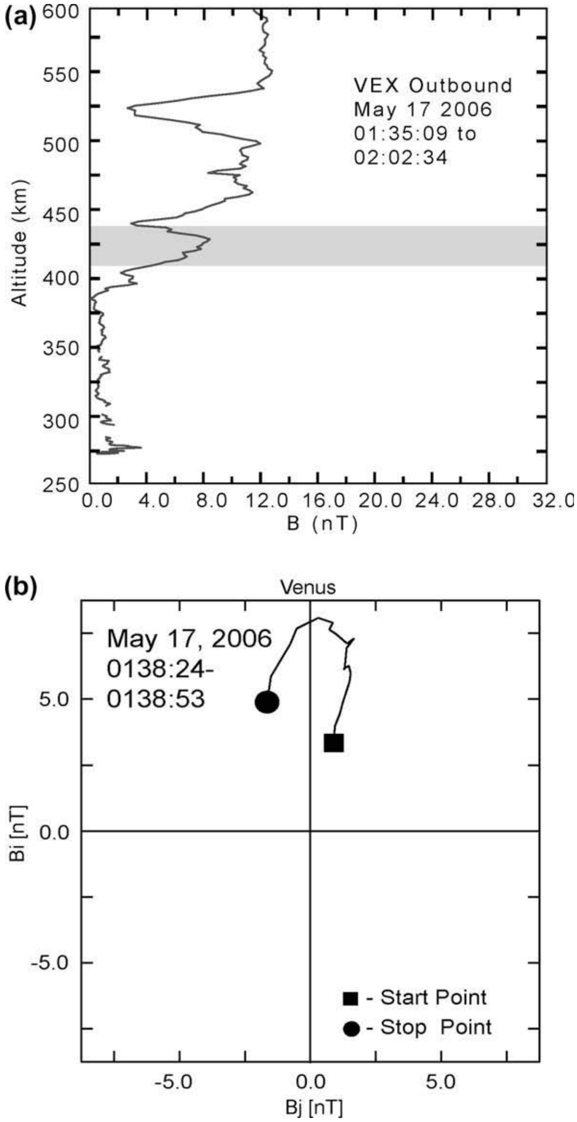

Fig. 5. (a) Altitude profile of magnetic fields in Venus ionosphere observed by Venus Express during solar minimum. (b) Hodogram of a flux rope which is at the lower edge of the ionopause, at altitude about 420 km in (a). This rope is considered to be starting to form and later it will sink into the lower field-free ionosphere and get further twisted.

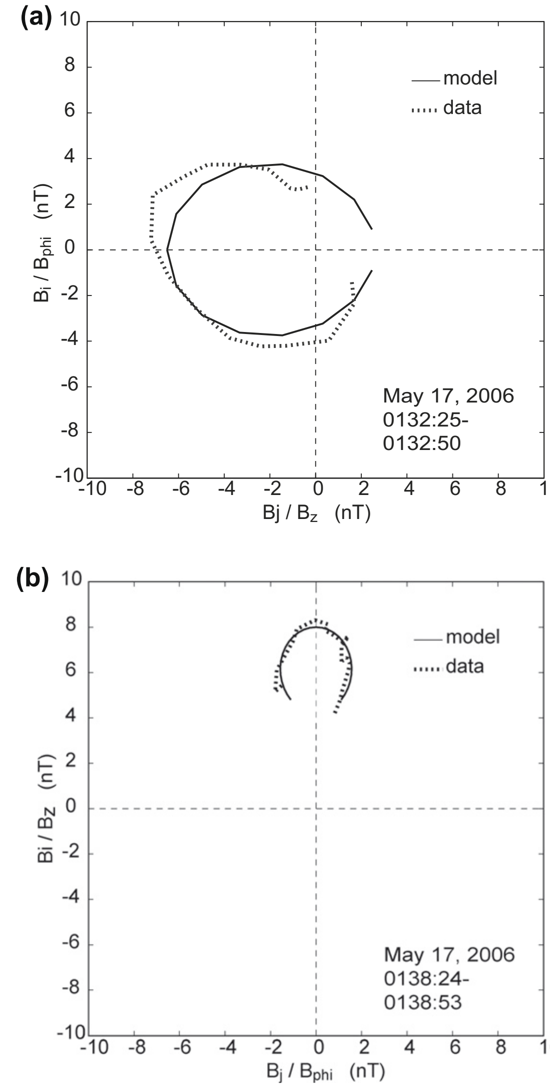

Fig. 6. (a) Model fit of the flux rope in Fig. 4b, with $B_0 = 0$ nT, and $b_0 = 7.0$ nT. (b) Model fit of the flux rope in Fig. 5b, with $B_0 = 5.3$ nT, and $b_0 = 2.7$ nT.

the flux tube hung up right above the ionopause starts to be twisted by velocity shear to form an azimuthal field around the axial field which is in the direction of the untwisted flux tube field, the developing rope should have an axial field nearly parallel to the fields above the ionopause. When the flux rope is sinking into the ionosphere it gets further twisted and also may be subject to helical kink instability (Elphic and Russell, 1983c), so the rope axial direction twists further from the direction of its axis when it was starting to form, i.e. the direction of fields above the ionopause (in the magnetic barrier). Such developing ropes are observed in 13 orbits, i.e. 6% of the total surveyed orbit and 33% of the orbits which observed unmagnetized ionosphere.

These solar-minimum flux rope studies complement the earlier studies of flux ropes at solar maximum. The greatly reduced flux rope occurrence at solar minimum can be simply explained by the ionosphere magnetization state. The observations of mature and developing flux ropes are consistent with the formation mechanism in Fig. 3.

5. Comparisons of flux ropes at Venus with twisted flux tubes in lower ionosphere of Titan

The Titan interaction with the corotating Saturnian magnetospheric plasma is similar to the Venus and Mars interaction with the solar wind in many ways (Kivelson and Russell, 1983; Verigin et al., 1984; Luhmann et al., 1991). Since the magnetospheric corotating flow is sub-magnetosonic at Titan, a fast mode shock like that in front of Venus and Mars does not rise at Titan. However, the plasma flow slows down and deflects around Titan while the upstream magnetic fields pile up and drape around, forming a magnetotail downstream. Cassini observations reveal that the lower ionosphere of Titan is often magnetized, resembling the situation at Venus during solar minimum or under high solar wind pressure (right panel in Fig. 1). At low altitudes in Titan's ionosphere, the observed magnetic fields change directions and magnitude with a length-scale much smaller than the length-scale of the expected draping field lines. From the observations, the flux tubes in the lower ionosphere of Titan seem to be slightly twisted, resembling the developing flux ropes in the ionosphere of Venus.

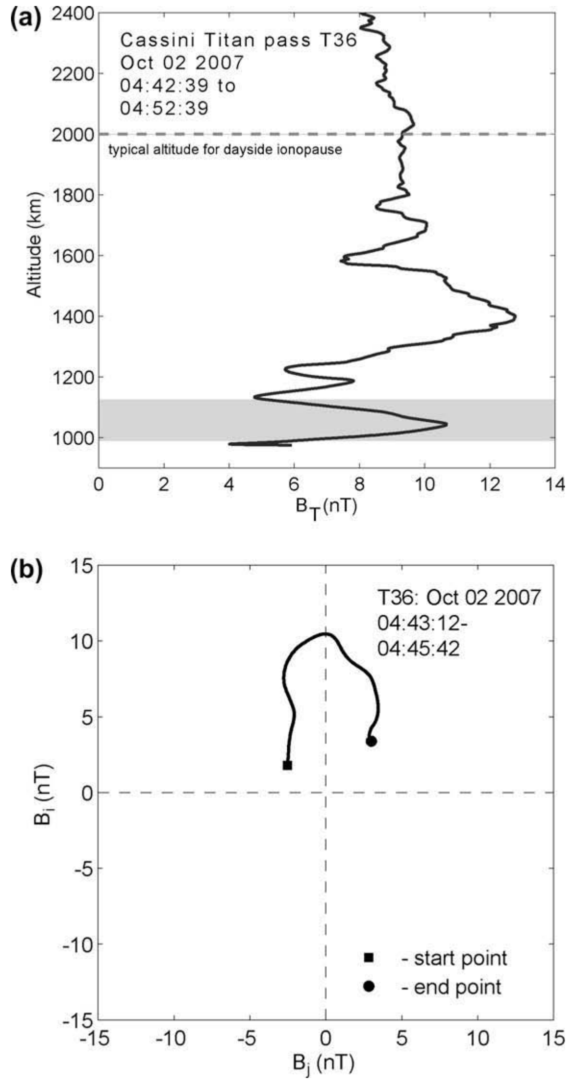

Fig. 7. (a) Altitude profiles of magnetic fields at Titan on the outbound of pass T36. Ionosphere is strongly magnetized and resembles the situation at Venus during solar minimum or under high solar wind pressure. The typical altitude of dayside ionopause defined by sharp gradient of plasma density is about 2000 km (marked as dashed line). (b) Hodogram of the field near CA at about 1100 km in (a). The field line is twisted like a developing flux rope in the Venus ionosphere.

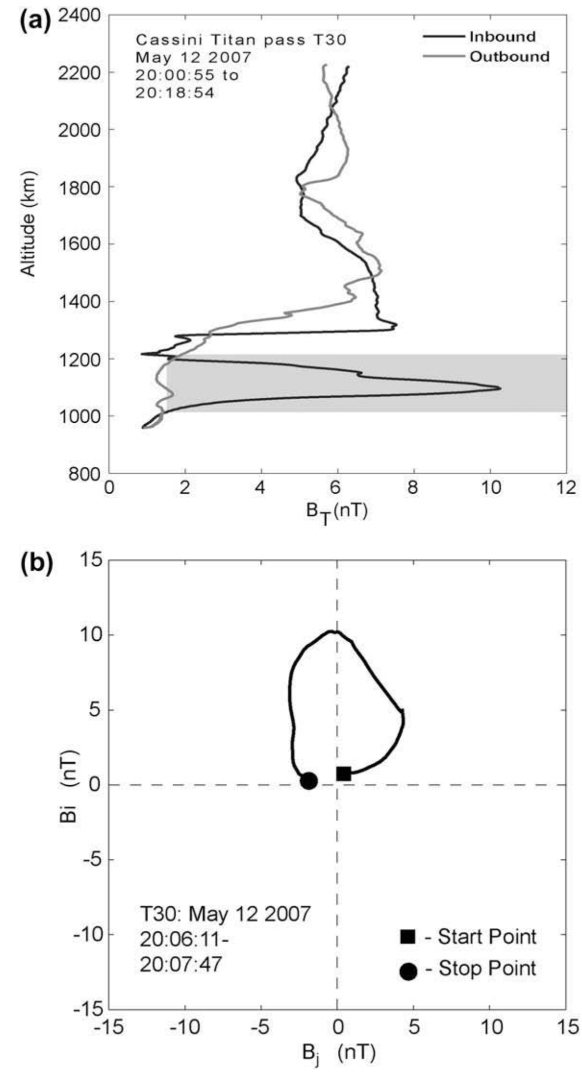

Fig. 8. (a) Altitude profiles of magnetic fields at Titan on the outbound of pass T30. Both inbound and outbound observations show that the magnetic upstream fields sharply decrease near 1300 km and the region below has very small magnetic fields except the shaded part of inbound. (b) Hodogram of the fields in the shaded region of inbound in (a). This strong flux tube is twisted like flux ropes in the Venus ionosphere.

In Fig. 7, the altitude profile of magnetic field shows that the upstream fields could penetrate far below the typical ionopause altitude (i.e. 2000 km from the Langmuir probe observation of a sharp gradient in the ionospheric plasma density; J.-E. Wahlund, personal communication). In the shaded region, the fields change directions and strength very rapidly and the field variation in the hodogram (Fig. 7b) shows that this flux tube is twisted, similar to the Venus flux rope in Fig. 5. In Fig. 8, the altitude profile and hodogram show a twisted flux tube isolated in the lower ionosphere surrounded by a very small ambient field (less than 2 nT). Its structure is quite similar to that of the flux ropes in the Venus ionosphere in Fig. 4. We use the Bessel function model to fit the two ropes (shown in Fig. 9) and obtain their axial orientations. When comparing the rope axial direction with the field direction right above them in the magnetic barrier, the rope in Fig. 7 has its axis about 25° from the magnetic barrier fields above it (near 1400 km) and the one in Fig. 8 has its axis about 109° from the fields at the higher altitudes (around 1300 km). The helical structures of the two twisted flux tubes in Titan's lower ionosphere are quite similar to developing and mature flux ropes in the Venus ionosphere. The rope in Fig. 8 is mature so its axial field orientation is nearly vertical and its axis significantly deviates from the field direction in the magnetic barrier above. The rope in Fig. 7 is still developing, so it is less twisted and its axial orientation is nearly horizontal and nearly parallel to the field above it. The closest approach for this pass is at altitude of 976 km so that we cannot tell the magnetization state at lower altitudes. In the surveyed 38 Titan flybys (from October 26th 2004 to December 20th 2007), the developing flux ropes are observed in 12 passes but there is just one case of a mature rope (shown in Fig. 8) because the Titan ionosphere is always magnetized at the observed altitudes.

For the situation in Fig. 8, the upstream fields seem to be shielded above 1300 km, resembling the ionopause boundary at Venus in the left panel of Fig. 1. We can estimate the curvature force and buoyancy force at Titan in this situation and see if it is possible for the flux tube to be dragged into the lower ionosphere. The curvature force is 2.06×10^{-17} N/m^3, for magnetic field of 10 nT and curvature radius of 3875 km (i.e. the radius of Titan

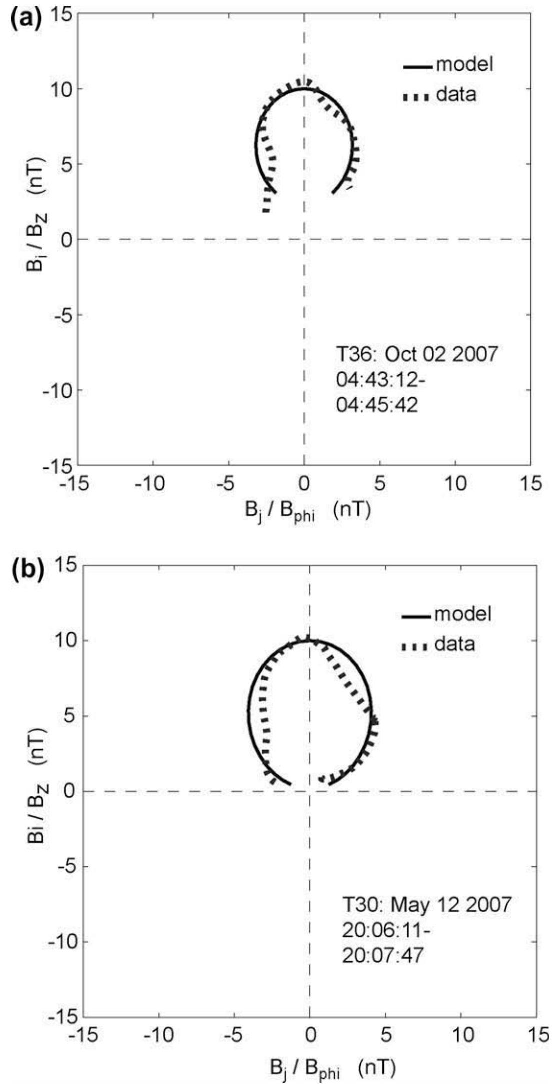

Fig. 9. (a) Model fit of the flux rope in Fig. 7b, with B_0 = 4.5 nT, and b_0 = 5.5 nT. (b) Model fit of the flux rope in Fig. 8b, with B_0 = 3.5 nT, and b_0 = 7.0 nT.

2575 plus an altitude of 1300 km). The buoyancy force is 9.96×10^{-18}–9.96×10^{-17} N/m^3, assuming the ionosphere density is 10^4–10^5 amu/cm^3 and the plasma density inside the flux tube is negligible. The curvature and buoyancy forces are comparable so it is quite possible for a flux tube near this boundary to be pulled into lower altitudes and form a flux rope.

6. Discussion

The comparison of flux ropes in the Venus ionosphere and the twisted fields at low altitudes of Titan's ionosphere shows that they have similar helical structures and are consistent with the flux rope-formation mechanism discussed in Section 3. Further comparisons are needed to understand the differences between the Titan ropes and the Venus ropes. We see that the maximum field in the Titan rope shown in Fig. 8 is stronger than the field strength in the magnetic barrier above but the Venus ropes generally have their maximum field weaker than the fields in the magnetic barrier. Moreover, if we assume the flux rope has round cross-section the calculated diameter of this Titan rope is about 100 km, while the diameter of the Venus rope (in Fig. 4) is about 20 km. The Mars rope is about similar size as Venus rope (Vignes et al., 2004), thus it is also much smaller than the Titan rope. Further study is needed to understand these differences.

The global characteristics of the Venus rope during solar minimum and solar maximum should be further studied with a larger group of events. In the surveyed 2006 data, the flux ropes were observed between 302 and 605 km and with solar zenith angle of 60–88°, because the spacecraft trajectories generally have periapsis above 300 km and near the terminator. The so-far observed flux ropes have their maximum field strength and occurrence rate increasing as getting to lower altitudes, in consistent with the solar maximum observations by PVO. The spacecraft periapsis gets lower in the 2007 and 2008 data, so we expect more ropes to be found and a better statistical study will be performed by including them.

In Fig. 3, the flux rope-formation mechanism shows that the flux rope should have opposite helicity on either side of the Sun–Mars/Venus line along the flux tube and the rope helicity decreases with distance away from the middle. This behavior could be tested using the rope events not far from the ionopause. But it may not be observed for the ropes at low altitudes, because the kink instability could turn the originally straight (but twisted) flux tubes into corkscrew-shaped structure as they convect to lower altitudes (Elphic and Russell, 1983c).

7. Concluding remarks

Magnetic flux ropes can be created in the ionospheres of Venus, Mars and Titan during their interactions with their encountering plasma flows. A flux rope is thought to first form near the boundary between the magnetic barrier and the ionosphere and be twisted by velocity shear across the flux tube. Later it is pulled into the lower ionosphere and gets further twisted. The curvature force must overcome the buoyancy force to pull it downward. At Venus the buoyancy force is slightly larger than the curvature force if the flux tube contains no plasma, but photoionization of exosphere neutrals within the flux tube would reduce the buoyancy force so that the flux tube could be dragged to lower altitudes by the curvature force. At Titan the buoyancy force and curvature force are comparable even for an empty flux tube so it can be readily pulled into lower regions.

At Venus during solar minimum, observations of developing and mature ropes are analyzed and their axial orientations agree with the proposed formation mechanism. In the ionosphere of Titan, the twisted fields at low altitudes can resemble both types of Venus flux ropes (either developing or mature ones). The axial orientations of the Titan ropes also agree with the formation mechanism. To understand the differences in rope size and field strength at Venus and Titan and their statistical characteristics, further study is required with a larger group of events.

Acknowledgment

This work was supported by the National Aeronautics and Space Administration under NNG06GC62G.

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