Characteristics of Ionospheric Flux Rope at the Terminator Observed by Venus Express

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Abstract

We investigate the characteristics of the magnetic flux rope in the Venusian ionosphere near the terminator observed by the Venus Express while previous works about flux rope by PVO are mainly in the subsolar region. The probability to observe the flux rope becomes larger as solar activity strengthens. A statistical work during solar maximum presents the following characteristics. (1) The flux ropes in the terminator region have a lower spatial occurrence compared with those in the subsolar region and the spatial occurrence of the flux ropes is also getting smaller when altitude increases. (2) The scale size of the flux rope is larger in the terminator region than that in the subsolar region and becomes larger when altitude increases. (3) In the terminator region, the flux rope appears to have a quasi-horizontal orientation but with some cases which can be vertical at low altitude. (4) The flux ropes in high solar zenith angle regions are confirmed to have a lower helicity compared with those in low solar zenith angle regions.
1. Introduction

Venus has no significant intrinsic magnetic field [Russell et al., 1979], which results in a direct interaction between the solar wind and the ionosphere of Venus [Luhmann and Cravens, 1991]. Under this interaction, a structure named ionopause is formed on the upper boundary of the ionosphere, carrying shielding currents and keeping the solar wind impenetrable. The ionopause can be defined as the place where the solar wind ram pressure is balanced by the thermal pressure in the ionosphere [Elphic et al., 1980a]. At solar maximum, the mean altitude of the ionopause is roughly 300 km near the subsolar region, increasing to almost 900 km near the terminator [Phillips et al., 1988]. And at solar minimum, the ionopause is found to be depressed with an altitude of approximate 250 km everywhere in the dayside, but with sometimes observed at much higher altitude [Zhang et al., 1990; Zhang et al., 2008].

Thus, depending on the conditions in the solar wind and the ionosphere of Venus, i.e. the ram pressure of the solar wind and the thermal pressure in the ionosphere, there are two basic states in the ionosphere of Venus [Luhmann and Cravens, 1991]. One is “magnetized”, in which large-scale magnetic fields are presented, and this is the major situation at solar minimum [Zhang et al., 2008; Angsmann et al., 2011]. The other is “unmagnetized”, which is the major situation during solar maximum [Luhmann et al., 1980], and in this state, the inner side of the ionosphere is almost field-free, but with many small-scale (~10 km diameter) magnetic structures being observed [Russell and Elphic, 1979]. And this small-scale structure is known as flux rope [Russell and Elphic, 1979].

The flux rope is used to describe the magnetic topology with relatively strong axial fields in the center and weaker, more azimuthal fields towards outer edge. It can be observed in many different physical situations, such as the solar atmosphere, interstellar nebulae, laboratory [Elphic and Russell, 1983a], Martian atmosphere [Vignes et al., 2004], geomagnetic tail [Elphic et al., 1986], and the Venustian ionosphere [Russell and Elphic, 1979]. The flux rope is an attractive finding in early observation by PVO, and is observed as many brief, discrete excursions of magnetic field, each lasting several seconds at most and rising from a background of few nT to tens of nT, within the unmagnetized ionosphere where the magnetic field is generally low [Russell and Elphic, 1979]. Previous works about the flux rope had revealed some characteristics of them in the subsolar region and part of the
terminator regions by using the data from PVO [Elphic and Russell, 1983a, 1983b; Ledvina et al., 2002], mainly at solar maximum.

The PVO spacecraft was inserted into Venus orbit in December 1978 and remained in orbit for 14 years investigating the solar wind interaction with Venus. While the Venus Express, known as the first mission to Venus of Europe, was inserted into Venus orbit in April 2006 [Svedhem et al., 2007]. The orbit of Venus Express is similar to that of PVO with an elliptical polar orbit of 24h period and a 12 RV (RV is the Venus radius, i.e. 6052 km) apoapsis. But the periapsis of Venus Express were initially maintained in 250-350 km range with periapsis latitude at 78°N [Zhang et al., 2006]. Thus, the sampling geometry of VEX is much different from that of PVO, covering two important regions which were not covered by the PVO measurement: the low altitude terminator region and mid-magnetotail about 4 RV. After the first few years of observation, the periapsis of the spacecraft can approach to a lower altitude than initially [Dubinin et al., 2014], i.e. 180 km or lower later, which can provide us more information about the ionosphere at low altitude.

Flux ropes were investigated in earlier observation of VEX at solar minimum [Wei et al., 2010]. And the magnetic field data from Venus Express including a nearly entire solar cycle enable us to make a statistical work about the characteristics of flux ropes near the terminator region. Therefore, the main purpose of this work is to investigate the characteristics of the flux ropes in the terminator regions of the ionosphere of Venus and these results could be a complement to prior works in lower solar zenith regions [Elphic and Russell, 1983a, 1983b], thus giving us an overall image of the flux rope in the dayside ionosphere, and may help us to figure out the possible origin of this structure. Firstly, we show the process how we select the flux ropes. Then, we implement a statistical work about the characteristics of the flux rope during solar maximum and make a brief comparison with previous works done by Elphic and Russell [1983b].

2. Event selection

To select the flux rope in the ionosphere near the terminator, we use the 1 Hz magnetic field data obtained from Venus Express magnetometer (MAG) [Zhang et al., 2006]. First of all, we show the two basic states observed within Venusian ionosphere in Figure 1, i.e. the magnetized and unmagnetized. The left panel shows the magnetized state, in which large-
scale field can be observed. And the right panel shows the unmagnetized state in which many brief, discrete excursions of magnetic field can be seen and those excursions could be candidates for flux rope. Therefore, we can select the candidates of the flux rope from the unmagnetized ionosphere. And Figure 2 shows one example of them, displayed in time series for 30 seconds before and after the time corresponding to its maximum magnitude of magnetic field, and this figure indicates the general profile of $B_T$ of a flux rope.

There are mainly three criteria involved to obtain the flux ropes from the magnetic field data:

1. With previous works [Elphic and Russell, 1983a, 1983b] as a reference, we define the potential flux ropes here as an individual discrete excursion of magnetic field, with its maximum $B_T$ exceeding 10 nT and a mean value of the two magnetic fields in its beginning and ending boundary less than 5 nT. The beginning boundary is where the $B_T$ starts increasing and the ending boundary is where the $B_T$ ends decreasing.

2. Since the altitude of the ionopause is high in terminator [Phillips et al., 1988] and changeable, we only focus on the magnetic field data below the altitude of 1000 km for the convenience to find the flux ropes in the ionosphere. Then we search the potential flux ropes with an automated procedure by using the magnetic field data under 1000 km altitude for all orbits of VEX from 24 April 2006 to 25 November 2014.

3. Another criterion used to visually determine the flux rope is the shape of hodograms of the three components of the magnetic field in which the components should sequentially vary like the expected magnetic signature inferred from an acceptable model applied in Elphic et al. [1980b]. This is done manually to determine the final events from the selected potential flux ropes by criterion 1 and 2.

The model in Elphic et al. [1980b] is shown below:

$$\vec{B}(\rho) = B_\phi(\rho)\hat{\phi} + B_z(\rho)\hat{z}$$

(1)

$$B_\phi = B(\rho) \sin \alpha$$

(2)

$$B_z = B(\rho) \cos \alpha$$

(3)

Here, $\rho$ is the radius, $B(\rho)$ is the magnitude of the magnetic field, $\alpha$ is the helical pitch angle and $\hat{\phi}$ and $\hat{z}$ are the azimuthal and axial direction in cylindrical coordinates, i.e. the principal axial coordinate system of the flux rope. And their expressions are presented as:
\[ B(\rho) = B_0 \exp(-\rho^2/a_2^2) \]
\[ \alpha = \alpha_s(1 - \exp(-\rho^2/a_1^2)) \quad \rho \geq a_1 \]
\[ \alpha = C\rho^2 + D\rho \quad \rho < a_1 \]

\(B_0\) is the field strength at the structure’s center, \(a_1\) and \(a_2\) represent scale lengths for pitch and field magnitude change. Figure 3a (adopted from Elphic and Russell, 1983a) shows schematically the expected magnetic signature sampled by the satellite as it passes through the flux rope, slightly off-axis.

The field components within a flux rope should sequentially vary. However, the magnetic field data are displayed in Venus Solar Orbital (VSO) coordinates, where the X-axis points from Venus to the sun, the Z-axis is northward and the Y-axis completes the right-hand system. Thus, we chose the minimum variance analysis (MVA) [Sonnerup et al., 1998] to reorder the data of each potential flux rope in VSO coordinate to its principal axis coordinate system in which the three components would show some order [Elphic and Russell, 1983a]. From the MVA technique, three eigenvalues representing the three variance \((\sigma_i^2, \sigma_j^2, \sigma_k^2)\) of the field component can be derived and also the three corresponding eigenvectors. And then field components in three directions \((B_i, B_j, B_k)\) in the principal axis coordinate system can be obtained \((i, j, k)\) corresponds to \((z, \Phi, \rho)\) in the cylindrical coordinates, respectively). Here, \(i, j, k\) represent the directions of maximum, intermediate, and minimum variance of the field components correspondingly. And by applying the MVA technique, field data between the beginning time and the ending time of each potential flux rope selected by the first criteria are reordered into its principal axis coordinate and then the hodograms of \(B_i, B_j,\) and \(B_k\) are obtained. The example illustrated in Figure 3b presents some similarities to the model results presented in Figure 3a. And only those events whose components vary orderly in hodograms, similar to the model results, will we take as flux ropes.

The numbers of the flux ropes displayed in Table 1 show a connection to the solar cycle, as illustrated in Figure 4, in which a simple comparison is made, between the number of events within each Venus year and the smoothed monthly sunspot number, which indicates the strength of solar activity. More flux ropes can be observed at solar maximum than at solar minimum, that is, the events at solar maximum exceed more than 50 times of that at solar minimum, though bias may exist since the observation time the spacecraft spent in the
ionosphere may vary in different Venus year. A recent statistical work about magnetic states in the Venusian ionosphere observed by VEX showed that almost 58% of the time at solar minimum the ionosphere is magnetized, which is sufficiently higher than that at solar maximum [Angsmann et al., 2011]. The radiation from sun could be responsible for this variation since the EUV radiation could vary significantly between solar maximum and solar minimum, and then affects the ionization in the Venusian ionosphere [Zhang et al., 1990]. So the reason that many flux ropes are observed at solar maximum may be the high solar radiation and typical unmagnetized situation with structures of flux ropes in the ionosphere of Venus [Lumann et al., 1986; Elphic and Russell, 1983b]. And that flux ropes can be observed, though less, at solar minimum may also due to the strong EUV radiation, which could enhance the ionization in the ionosphere, on some extreme solar conditions, such as ICME’s [Futaana et al., 2008, Zhang et al., 2008; Wei et al., 2010].

3. Statistical results

3.1 Spatial Occurrence of Flux Ropes

Flux ropes observed by VEX are near the terminator region as opposed to the subsolar point by PVO. And since the flux ropes are mainly observed at solar maximum and the PVO’s results about the flux ropes are also mainly at solar maximum, we focus on investigating the flux ropes at solar maximum and make a comparison with the characteristics of the flux ropes observed by PVO. This section shows the statistical results of characteristics of the flux ropes selected from the process mentioned above from 10 November 2011 to 27 April 2014 during solar maximum. A total of 3899 events are observed within these 4 Venus years.

Flux ropes are assumed to be stationary since the speed of the spacecraft, roughly 10 km/s near the periapsis, is generally larger than the motion of the ropes [Elphic and Russell, 1983b; Knudsen et al., 1980]. One of the characteristics of the flux rope is its spatial occurrence, and as shown in Figure 5, flux ropes are more frequently found at low altitude. The relative occurrence is the ratio of the time the spacecraft spent within flux ropes to the total time the spacecraft spent in each altitude bin [see, Elphic and Russell, 1983b]. At altitude of 250 km, approximately, a sudden fall in relative occurrence can be seen and the occurrence is more even at least between the altitude of 250 and 400 km, same for both regions with solar zenith angle (SZA) greater or less than 90°. The error bars in Figure 5 represent the standard
deviation associated with orbit-to-orbit variations within each altitude bin and the large bars show the occurrence changes a lot for different day.

3.2 Flux Rope Scale Size

The full width at half-maximum (FWHM) of the variation in the magnetic field strength is used to measure apparent flux rope diameter. FWHM corresponds to the time required to pass from half the observed maximum value, through the maximum and back down to the half-maximum point again. The result of the apparent average diameter of the flux ropes is shown in Figure 6.

The relationship between the mean value of FWHM ($<\text{FWHM}>$) and the model scale length ‘a’ (i.e. $a_2$ in the model presented in fore section) can be simply written here as $<a> = <\text{FWHM}>V/2.61$, [see, Elphic and Russell, 1983b], in which V represents the average velocity of spacecraft and here 9.6 km/s. Also presented in Figure 6 upper scale is this mean scale size $<a>$ distributed along altitude based on the values of $<\text{FWHM}>$. This relationship is based on the assumption that the spacecraft sample all impact parameters (distance between the rope axis and the spacecraft traversal) and all impact angles (rope axis-spacecraft trajectory angles) for a large ensemble of rope traversals. This may involve some bias due to the difference between assumption and reality which could have been reflected by the error bars. The scale size of the flux rope becomes larger at high altitude, ranging from about 9 to 20 km in regions SZA less than 90° and from about 15 to 25 km in regions SZA greater than 90° as the altitude starts from 150 km to 500 km, and it seems slightly larger in regions SZA greater than 90° at the same altitude. There is no result presented above 600 km for regions SZA>90° because the flux ropes in that altitude bin are less than 10. The error bars in Figure 6 denote the standard deviation.

3.3 Flux Rope Orientation

The cases used to determine the inner characteristics of the flux ropes should be those that the spacecraft pass through, or close to, the center of the structure, which were described as the small parameter subset in Elphic and Russell [1983a]. A brief description of the selection criteria for the small impact parameter subset should be presented here. First, we chose the cases with $\sigma^2_\phi/\sigma^2_\theta > 100$, and the maximum field strength of those cases would fall into two
categories, one peak at high magnitudes and another peak at low magnitudes; Second, we chose the category with high magnitudes which corresponds to the small parameter subset (for detailed description see Elphic and Russell, 1983a). And by using the selection criteria for the small impact parameter cases, we finally get 251 cases belong to the small impact parameter subset from those 3899 events in 4 Venus years.

The small impact parameter subset can be used to investigate the orientation of the flux rope, so the estimate of the rope axial direction could be reliable. The angle \( \theta \) at which a rope is inclined to the horizontal, the local surface of the planet, can be obtained from the dot product of the axis direction, represented by the maximum magnetic field vector \( \vec{B}_{max} \) for these cases, and the radius vector from the center of the planet (local vertical) [Elphic and Russell, 1983b]:

\[
\sin \theta = \frac{\vec{r} \cdot \vec{B}_{max}}{|\vec{r}| \|\vec{B}_{max}\|}
\]  

(7)

Then the angle \( \theta \) can be derived from the value of \( \sin \theta \). And the small value of angle \( \theta \) indicates that the cases should be horizontal, while the large value means that the cases are vertical. The results of \( \theta \) of these small impact parameter cases are illustrated in Figure 7, plotted as a function of altitude for regions SZA greater or less than 90°.

Most of the cases investigated in SZA less than 90° possess a small value of \( \theta \), i.e. \( \theta < 30° \), which means the flux ropes are almost horizontal. And, attention should also be paid to that the value of \( \theta \) of some cases is getting larger as altitude decreases, i.e. below 300 km, and that means flux ropes at low altitude can be vertical or have a tendency to be vertical. Cases in regions SZA >90° show a quasi-horizontal orientation, but it may not be reliable since there are only 5 cases in these regions.

3.4 Flux Rope Helicity

Helicity measures how twisted a flux rope is. A higher helicity means the flux rope is more twisted, and this attribute is basically determined by two characteristic length scales: the scale length \( (a_2) \) over which the field magnitude decreases and the scale length \( (a_1) \) over which the helical pitch increases. If \( a_2 < a_1 \), the field magnitude decreases faster than the helical pitch increases, then the rope is not tightly wound with a peak azimuthal component not comparable to the peak axial field; however, if \( a_2 > a_1 \), the field magnitude decreases slower
than the helical pitch increases, then the rope is tightly wound with a peak azimuthal component comparable to the peak axial field [Elphic and Russell, 1983b].

The ratio of the maximum variance $\sigma_i^2$ to the intermediate variance $\sigma_j^2$, derived from MVA technique, for the flux ropes in the small impact parameter subset, i.e. $\sqrt{\sigma_i^2/\sigma_j^2}$, provides some measure of the axial field $B_z$ (which contributes to $\sigma_i^2$) in comparison with the azimuthal field $B_\Phi$ (which contributes to $\sigma_j^2$). The larger this quantity is, the smaller helicity is; the closer this quantity is to unity, the greater helicity is. The distribution of this quantity as a function of altitude is illustrated in Figure 8. The values of $\sqrt{\sigma_i^2/\sigma_j^2}$ of most of the cases are less than 8, and their distribution almost center near 3. Draw attention to that in some cases, their values are greater than 8, which means a very low helicity.

4. Discussion

A lot of works about Venus had been conducted by PVO, including the investigations done mainly by Russell and Elphic [1983a, b] about the flux ropes within the Venusian ionosphere. We will discuss the results obtained above together with the relevant results obtained by PVO [Elphic and Russell, 1983b].

PVO found that the spatial occurrence of the flux rope increases as altitude decreases and reach a maximum value at altitude of 170 km in the subsolar region. This work also finds that the spatial occurrence of the flux ropes decreases as altitude increases, but the occurrence is relatively lower in the terminator than that in the subsolar region. The maximum occurrence can exceed more than 50% in the subsolar ($SZA < 45^\circ$) region at low altitude, while it is only nearly 33% in the terminator ($SZA < 90^\circ$) and becomes more less at larger solar zenith angle. The differentia of occurrence could be caused by that the magnetic flux penetrated into the ionosphere are different along SZA.

The scale size is larger at high altitude than at low altitude, with a magnitude of tens kilometers. PVO found that the characteristic radii of the flux ropes vary between about 6 km at altitude of 160 km and 15 km at altitude of 500 km. This work finds that the rope size is slightly larger in the terminator than in the subsolar region, which starts from approximately
9 to 20 km in regions SZA <90° and 15 to 25 km in regions SZA >90° as the altitude varies between 150 and 500 km. The pressure variation in the ionosphere, which is higher in the subsolar region and lower in the terminator [Zhang et al., 1992], could be responsible for this scale size variation of the flux rope.

PVO results showed a quasi-horizontal orientation of the flux ropes above 200 km altitude and a quasi-vertical orientation below 200 km altitude in the subsolar region (SZA<45°), and near the terminator, the flux ropes are quasi-horizontal at high altitude (above 300 km) and randomly orientated at low altitude (below 300 km). In this work, most of the flux ropes are quasi-horizontal at the terminator, but at low altitude, some cases also have a vertical orientation. We could conclude that there is a tendency that the flux rope becomes vertical when altitude decreases though it is not obvious in the terminator. These different orientation preferences could indicate the different formation mechanism of the flux rope at high and low altitude but need further investigation.

PVO found that the mean value of the root variance ratio \(\sqrt{\sigma_f^2/\sigma_i^2}\) (representing the helicity of flux rope) is about 1.78±0.89 (means a large helicity) in the subsolar region, and the value is about 3.25±1.85 above 300 km, and 2.84±0.96 below 300 km near the terminator. The statistical results in this work also demonstrate that the helicity of the flux rope is lower in the terminator region than in the subsolar region since we find the value of the root variance ratio is about 2.94±1.3 above 300 km and 2.86±0.79 below 300 km in SZA<90°. And the helicity is probably even lower because some cases have a higher value than 8, which is not included in Elphic and Russell [1983b]. In SZA>90°, the value also becomes larger though only several cases are included. We infer that the lower electron density in the ionosphere in the high SZA regions [Miller et al., 1980], which could result in a weaker current thus a weaker azimuthal component of magnetic field, may contribute to the lower helicity there.

Those characteristics of the flux rope in the dayside ionosphere of Venus may uncover some mysteries of the flux rope’s formation mechanism. The variation of the occurrence of the flux rope along SZA indicates that the flux rope may form at high altitude, i.e. near the ionopause. And as the mechanism presented by Wei et al. [2010] suggested, which shows force unbalance between buoyancy and curvature force can form a flux rope, the change of
the magnetic field in the dayside Venus near the ionopause may cause the variation of the occurrence. That mechanism also predicts the helicity change of the flux rope as we observed. The flux ropes show a different orientation preference between the high and low altitude. That the flux ropes at low altitude could be vertical may due to the helical kink instability of flux ropes and could partially explain the different spatial occurrence of the flux rope because the quasi-vertical orientation of flux rope at low altitude and low SZA regions indicates a larger occurrence [Elphic and Russell, 1983c]. And this difference may also indicate that other formation mechanism could exist at low altitude, such as the internal gravity waves as Cole [1994] suggested. Since the current systems in the ionosphere can well explain the formation of the large-scale magnetic field [Dubinin et al., 2014] we shall also value their role in the flux rope formation process though these two kinds of magnetic field are different such as that the scale size of the flux rope is at a magnitude of tens kilometers while that of the large-scale magnetic field is hundreds kilometers.

5. Summary

In this paper, we study the flux ropes in the ionosphere of Venus based on VEX data. Our results find or confirm that flux ropes within the unmagnetized ionosphere can be more often observed at solar maximum. The flux rope is more often found at low altitude and low solar zenith angle. The scale size of the flux rope is found to be larger at high altitude and high SZA with a magnitude of tens of kilometers. The orientation of the flux rope is quasi-horizontal at high altitude, with a tendency to be vertical when altitude decreases but a little different along SZA. The flux rope is more tightly twisted at low altitude and low SZA. Flux ropes can also be observed in regions SZA greater than 90°. The results in this work are consistent with the results of PVO, which indicates that the formation mechanism could be similar in the subsolar region and in the terminator region. But the different properties between the flux ropes at high and low altitude, such as the occurrence and scale size, indicate that the mechanism forming the flux rope at low altitude could be different from that at high altitude. The air motion and the current systems in the ionosphere should be considered in seeking the origin of the flux rope.
Acknowledgements

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Figure 1. Magnetic field data displayed in time series for orbit 2009-08-20 and orbit 2012-05-16 near the periapsis. This shows the situations of the magnetized (left) and unmagnetized (right). Dash line in each panel indicates the periapsis and the altitude of periapsis is about 189 km for the orbit 2009-08-20 and 351 km for the orbit 2012-05-16. Figures in lower panels show the detailed magnetic field and altitudinal track of the spacecraft in the ionosphere.
Figure 2. Profile of the total magnetic field strength $B_T$ (left) and corresponding field components in VSO coordinates (right). The field was presented in time series with “0” corresponding to the time of maximum magnetic field (presented in figure). Excursion in shadow region is assumed to be a flux rope.
Figure 3. (a) Schematic of a flux rope traversal. The rope axis is vertical, the spacecraft trajectory horizontal and slightly off the rope axis. The arrows at points along the trajectory represent sampled field vectors. The lower panel shows how these vectors, when cast into principal axis coordinates, trace out hodograms. $B_i$, $B_j$, and $B_k$ refer to field components in the directions of maximum, intermediate, and minimum magnetic variation [From Elphic et al., 1983a]. (b) Hodograms of three components $B_i$, $B_j$ and $B_k$ of the flux rope, with time from 04:52:36 to 04:52:45. The hodograms are consistent with what is expected from the model.
Figure 4. Comparison between sunspot numbers and the flux rope events. Numbers of the flux rope events in each Venus year are displayed in time series, along with smoothed monthly sunspot numbers. Time range is from April 24, 2006 to November 25, 2014. Smoothed monthly sunspot numbers are from WDC-SILSO, Royal Observatory of Belgium, Brussels.
Figure 5. Relative occurrence of flux ropes as a function of altitude for regions that solar zenith angle (SZA) is greater (red line) or less (black line) than 90°. The relative occurrence is defined to be the ratio of the amount of time spent within flux ropes for a given altitude interval to the total amount of time spent within that interval. This quantity is proportional to the fractional volume occupied by flux ropes in a given region. A total of 3097 cases were used for SZA less than 90°, and 802 cases for SZA greater than 90°. Error bars denote the standard deviation.
Figure 6. Average full width at half-maximum (FWHM) of flux ropes as a function of altitude for regions with SZA greater than 90° (red line) and SZA less than 90° (black line). Upper axis converts \( <\text{FWHM}> \) to the average rope scale radius \( <a> \) in km. A total of 3097 cases were used for SZA less than 90°, and 802 cases for SZA greater than 90°. Error bars denote the standard deviation.
Figure 7. Flux rope inclination $\theta$ with respect to local horizontal, distributed along with altitude, for the small impact parameter cases in regions SZA less and greater than 90°. Here use the small impact parameter cases, 246 cases (black “o”) for SZA<90° and 5 cases (red “x”) for SZA>90°.
Figure 8. Distribution of helicity of flux ropes in an altitude profile, and the helicity is represented by the root variance ratio $\sqrt{\sigma_i^2/\sigma_j^2}$. A root variance ratio near unity implies high twist (large helicity), while larger values imply less twist. Here also use the small impact parameter cases, 246 cases (black “o”) for SZA<90° and 5 cases (red “x”) for SZA>90°.
<table>
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<th>NO. of Venus year</th>
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Note: Total orbits of VEX observation are divided into 14 Venus years. One Venus year approximate to 225 days in Earth. And there is only 212 days in the 14<sup>th</sup> Venus year.