The structure of the Venusian current sheet


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Abstract

We investigate the current sheet (CS) of the Venusian magnetotail using the data collected by the Venus Express mission in 2006–2010. We have found that the observed profiles of the main magnetic field component $B_x$ have single-scale or double-scale structures. For single-scale CSs the $B_x$ profile is well approximated by the Harris model, $B_x \tan(\tau/T_0)$ ($T_0$ is the characteristic temporal scale, $B_0$ is the magnetic field at the CS boundary). For double-scale CSs the $B_x$ profile is better described by the double-scale model, $B_1 \tan(\tau/T_1) + B_2 \tan(\tau/T_2)$ with $B_2 > 0.38 B_0$ and $T_2 > 2T_1$. The magnetic field component perpendicular to the CS plane and the shear component are on average uniform across CSs and ten times smaller than the amplitude of $B_x$. The observed $B_x$ profiles can be described by the quasidiabatic CS model. According to our interpretation the electric current in single-scale CSs is generally carried by protons on transient orbits. In double-scale CSs the current density is provided by transient protons and oxygen ions. In this case, the inner CS scale is supported by the proton population, while the outer scale is supported by the oxygen population. We suggest that the Venusian CS thickness is likely several ion thermal gyroradii.

1. Introduction

Although Venus does not have an intrinsic magnetic field (Russell et al., 1980), the interaction between the solar wind and the planetary ionosphere results in the formation of the induced magnetosphere with a well-developed magnetotail (see the review by Phillips and McComas, 1991). The mechanism of the Venusian magnetotail formation is similar to that of the formation of cometary tails (Alfvén, 1957). Solar wind flux tubes are slowed down near the magnetic barrier at the day side. Convecting along the magnetic barrier, these flux tubes are mass-loaded by ionospheric oxygen ions ($\approx$ Cloutier et al., 1974; Taylor et al., 1980; Vaisberg and Zelenyi, 1984). The parts of flux tubes passing through the barrier move slower than their ends in the solar wind. Therefore, flux tubes get stretched in the antisunward direction. The magnetotail is formed by these stretched flux tubes at the night side.

The orientation of the Venusian magnetotail is determined by directions of the solar wind flow and the interplanetary magnetic field (IMF). It is convenient to introduce the coordinate system $(X, Y, Z)$ (Eroshenko, 1979): the $X$-axis is directed opposite to the solar wind flow, the $Y$-axis is along the cross-flow IMF component and the $Z$-axis is along the convective electric field. The Venus–Sun component of the magnetic field is $B_x$, the $XZ_y$ plane is the magnetotail neutral plane (where $B_y = 0$) and $B_y$ is the magnetic field component perpendicular to the neutral plane. The magnetotail electric current flows in the $Z_y$ direction, providing the $B_x$ reversal across the neutral plane. The fundamental magnetotail element is the region of the $B_x$ reversal, the current sheet (CS). The investigation of the Earth magnetotail have shown that the CS structure is important for the magnetotail dynamics (Baumjohann et al., 2007; Sergeev et al., 2012; Artemyev and Zelenyi, 2013). The present paper is devoted to the structure of the Venusian magnetotail CS.

The CS structure at $X \sim -10R_V$ was investigated during Pioneer Venus Orbiter (PVO) mission, McComas et al. (1986b) have shown that the average $B_x$ profile can be described by the Harris model, i.e. $B_x \sim B_0 \tan(y/L)$, where $B_0 \sim 15$ nT and the CS half-thickness $L \sim 1.3R_V$. $B_x$ is on average constant across the CS and is about 4 nT.
We point out that the positive value of $B_y$ is consistent with the mechanism of the magnetotail formation. In fact, the technique used by McComas et al. (1986b) substantially overestimates the CS thickness. Moore et al. (1990) have shown that the CS half-thickness does not exceed $0.25R_V$. They have also pointed out that the plasma temperature should be about 1 keV to keep the pressure balance across the CS. The CS structure at $X \approx -3R_V$ was investigated during Venera-9,10 mission. The plasma data have indicated that the CS plasma consists of protons and oxygen ions with temperatures in the range from $\sim 100$ eV to $\sim 1$ keV (see review by Vaisberg et al., 1994). However, observations of Venera-9,10 did not allow to study the CS structure on a statistical basis. The currently operating Venus Express (VEX) mission allows to fill this gap (Titov et al., 2006).

The magnetic field data of VEX (Zhang et al., 2006) has already advanced our knowledge of the Venusian CS structure at $X \approx -3R_V$. Zhang et al. (2010) have confirmed that negative $B_y$ is frequently observed in accordance with the previous case studies (Marubashi et al., 1985). Observations of negative $B_y$ are prescribed either to the tight flux tubes draping (Marubashi et al., 1985) or to the reconnection in the magnetotail CS (Zhang et al., 2012).

Zhang (2013) has recently determined the average $B_y$ profile across the CS. In contrast to the distant tail CS (Moore et al., 1990), this average $B_y$ profile has a double-scale structure and cannot be described by the Harris model. The nature of the double-scale CS structure has not been explained yet. Moreover, the averaging technique used by Zhang (2013) smooths out the peculiarities inherent to particular CS crossings, so that the actual CS structure may be more complex.

In the present paper we investigate the CS structure based on separate CS crossings by VEX and suggest the mechanism for the formation of the double-scale CS structure. We point out that measurements at one spacecraft do not allow to distinguish spatial and temporal variations of the measured magnetic field. We assume that the variation of the magnetic field observed during the CS crossing is due to the relative motion of the spacecraft and the CS, while the CS is quasi-stationary in its rest frame.

### 2. Data and methods

We have analyzed magnetic field data (with 4 s time resolution, Zhang et al., 2006) obtained in 2006–2010. The ion data of ASPERA-4 (with 192 s time resolution, Barabash et al., 2007) are used to determine the direction of the solar wind (SW) flow.

#### 2.1. Selection criteria of CS crossings

The rotation of the cross-flow IMF component $B_z$ causes the rotation of the CS neutral plane. On the other hand, the variation of the IMF component directed along the SW flow results in CS flapping motions (McComas et al., 1986b; Dubinin et al., 2012). The stationary structure of the Venusian CS can be studied if $B_z$ does not substantially rotate during VEX observes within the tail. We determine average directions of undisturbed SW flow and IMF observed for 20 min before the inbound and for 20 min after the outbound bow shock (BS) crossings. Then we calculate the average cross-flow IMF component observed before the inbound ($B_z^{\text{pre}}$) and after the outbound ($B_z^{\text{post}}$) BS crossings. We have required that: (1) the angle between $B_z^{\text{pre}}$ and $B_z^{\text{post}}$ is smaller than $30^\circ$ (Zhang et al., 2010); (2) the IMF direction is quite steady, i.e. the root mean square deviation from the average IMF direction is smaller than $20^\circ$.

The criterion (1) does not actually ensure that the CS neutral plane is steady. Indeed $B_z$ can strongly deviate from $B_z^{\text{post}}$ during the tail crossing, while returns to $B_z^{\text{pre}}$ (i.e. close to $B_z^{\text{pre}}$) just prior the outbound BS crossing. This scenario can be recognized, when $B_z$ changes direction several times, the spacecraft then observes multiple CS crossings due to the neutral plane rotation. To exclude CS crossings observed due to this scenario, we have chosen events without multiple CS crossings. The other problem is that $B_z$ could change just after the inbound BS crossing and remain steady during the tail crossing. The spacecraft observes then a single CS crossing, but $B_z^{\text{post}}$ (or $B_z^{\text{pre}}$) cannot be used to determine the CS orientation. This problem can be overcome only by means of statistical studies (Zhang et al., 2010). We have assumed that the CS orientation is determined by $B_z^{\text{post}}$ (or equiv. $B_z^{\text{pre}}$). We show in Section 3 that this assumption leads to results consistent with the statistical study by Zhang et al. (2010). The criterion (2) ensures that one can reliably determine the average direction of the IMF observed before and after the BS crossing.

We select CS crossings observed at $X < -1.2R_V$, and within the tail, $\sqrt{Y_{\text{sc}}^2 + Z_{\text{sc}}^2} < 1.3R_V$ (Zhang et al., 2010). This criterion ensures that VEX crosses the magnetotail CS rather than some CS-type structure associated with “holes” at the night side ionosphere (Brace et al., 1982). We have selected 13 CSs presented in Table 1. The locations of CS crossings and the angles between $B_z^{\text{pre}}$ and $B_z^{\text{post}}$ are given in Table 1.

#### 2.2. Local coordinate system and CS flapping motion

We study each CS crossing in the local coordinate system $(l, m, n)$. The maximum variance direction $l$ is determined by the

<table>
<thead>
<tr>
<th>$N$</th>
<th>Date</th>
<th>$B_y$</th>
<th>$B_n$</th>
<th>$n$</th>
<th>$\gamma$</th>
<th>$v_{sw}$</th>
<th>$(X, Y, Z)_V$</th>
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<tr>
<td>1</td>
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<td>-0.4</td>
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<td>−0.6</td>
<td>(0.05,−0.996, −0.07)</td>
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<tr>
<td>3</td>
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<td>2.5</td>
<td>(−0.05,−0.95,−0.13)</td>
<td>12</td>
<td>1.8</td>
<td>(−2, 0.9, 0.9)</td>
</tr>
<tr>
<td>4</td>
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<td>−1.3</td>
<td>1.9</td>
<td>(−0.07,−0.66,0.75)</td>
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<td>5</td>
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<td>2.5</td>
<td>(−15, 0.0, 5)</td>
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<td>16</td>
<td>3.4</td>
<td>(−16, −0.1, 0.4)</td>
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</table>
minimum variance analysis, MVA (Sonnerup and Cahill, 1968). In our dataset vector \( l \) is determined reliably and its direction differs from that of the SW flow (the X-axis) within only 25°. The minimum and intermediate eigenvalues calculated by MVA are comparable, their ratio is within the range from 0.3 to 0.9. Thus, vectors \( n \) and \( m \) cannot be accurately determined by MVA. We assume that normal vector \( n \) is along the IMF component perpendicular to \( l \), i.e. \( n \) is almost along \( B_{\text{pre}} \) (or the YB-axis). Vector \( m \) completes the system to the right-handed, \( m = [l, n] \).

Table 1 presents normal vectors (in VSO coordinate system analogous to GSE). In the local coordinate system we have the magnetic field \( B = (B_l, B_m, B_n) \).

We have calculated the spacecraft velocity \( v_{\text{sc}} \) along the CS normal vector \( n \) for each CS crossing. The typical duration of the CS crossings is smaller than 100 s. Table 1 shows that the upper estimate \( |v_{\text{sc}}| \times 100 \text{ s} \) of the CS thickness can be rather small, ~200 km (see e.g. CS#1, 2, 3, 5, 6, 10). Thus, the CS crossing is due to the spacecraft motion as well as the CS flapping motion (McComas et al., 1986b), as in the Earth magnetotail (McComas et al., 1986a).  

2.3. Magnetic field approximation

During Venus CS crossings variations of \( B_n \) and \( B_m \) are substantially smaller than the variation of \( B_l \) (see Section 3). This property corresponds to the locally one-dimensional CS structure

\[
B = B_l(r_\text{c})\hat{l} + B_m\hat{m} + B_n\hat{n}
\]
where $r_n$ is the distance from the neutral plane along the normal vector $\mathbf{n}$. The relation between the observed (i.e. temporal) profile $B(t)$ and the spatial profile $B(r_n)$ is determined by the velocity of the CS flapping motion. If this velocity is constant during the CS crossing, temporal and spatial profiles coincide. Otherwise these profiles can substantially differ.

We discuss the methods of magnetic field approximation using CSs#1, 8. Panels 1 and 8 in Fig. 1 show that profiles $B(t)$ are almost symmetric with respect to the neutral plane $B(t_0) = 0$. For simplicity one can analyze the part of the profile observed at $t > t_0$ or $t < t_0$, where $t_0$ is the moment of the neutral plane crossing ($B(t_0) = 0$). We use both parts to determine the averaged profile as $\langle B(t) \rangle = \frac{1}{t - t_0} \int_{t_0}^{t} B(t) \, dt$. Panels 1 and 8 in Fig. 2 present averaged profiles for CSs#1, 8.

The profile $\langle B(t) \rangle$ can be characterized by the magnetic field $B_0$ at the CS boundary and the characteristic temporal scale $T_0$. 

**Fig. 2.** Profiles of averaged magnetic field $\langle B(t) \rangle$ (gray line) and the profiles of Harris model (dotted curve) and double-scale model (full curve). The blue dotted line corresponds to $\langle B(t) \rangle = 0.95B_0$. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)
(equivalently, spatial scale) of the CS crossing. The fitting of \( B(t) \) by
the Harris model \( B(t) \) tanh\( (t/\tau_0) \) (further we assume that \( \tau_0 = 0 \))
allows to determine \( B_0 \) and \( \tau_0 \) so that the mean square deviation \( \sigma^2 \) of
the temporal profile from the model one reaches minimum. For CS\#1 we obtain \( B_0 = 25.9 \) nT, \( \tau_0 = 8.7 \) s and \( \sigma^2 = 0.95 \) nT\(^2\). Fig. 2 shows that there is a rather good correspondence between
temporal and model profiles for CS\#1. We have also fitted the
profile \( B(t) \) for CS\#1 by the double-scale model, \( B(t) = B(t/T_1) + B_2 \) tanh\( (t/T_2) \), where \( T_2 > T_1 \). We have found that \( B_2 < 10^{-4} \) nT, i.e. the magnetic field amplitude corresponding to
the second scale is very small.

Fitting the profile \( B(t) \) for CS\#8 by the Harris model we obtain \( B_0 = 14.9 \) nT, \( \tau_0 = 18 \) s and \( \sigma^2 = 0.23 \) nT\(^2\). The fitting by the double-scale model results in \( B_1 = 10.5 \) nT, \( B_2 = 4.6 \) nT, \( T_1 = 10.9 \) s, \( T_2 = 51 \) s and \( \sigma^2 = 0.03 \) nT\(^2\). Thus, the magnetic field amplitude corresponding to
the second scale is a substantial part of the magnetic field at the CS boundary, \( B_2 = 0.3B_0 \). Fig. 2 shows that for CS\#8 the double-scale model fits the observed profile much better than the
single-scale model.

We introduce quantitative criteria to separate profiles \( B(t) \) into
single-scale and double-scale. For this purpose we use ratios \( B_2/B_0 \) and \( T_2/T_1 \). The parameter \( B_2/B_0 \) represents the fraction of the
current (i.e. current density integrated across the CS) corresponding
to the second scale in \( B(t) \). If \( B_2/B_0 \) is smaller than 0.3 the CS is assumed to be single-scale. In the opposite case, \( B_2/B_0 > 0.3 \), the CS is assumed to be double-scale, if there is a clear separation between two temporal scales, i.e. \( T_2 > 2T_1 \).

3. Magnetic field data

3.1. Observations

Fig. 1 presents magnetic field profiles in the local coordinate system for all 13 CSs. The magnetic field \( B(t) \) has the strongest variation across the CS and changes sign in the neutral plane. The variations of magnetic fields \( B_0 \) and \( B_m \) are substantially smaller (except for CSs\#6, 7, 9). We determine averaged profiles \( \langle B(t) \rangle \) and fit these profiles by single-scale and double-scale models. The averaged and model profiles are presented in Fig. 2. The fitting parameters of the models are presented in Table 2. We have found that for CSs\#2, 5, 8, 10–13 the magnetic field amplitude \( B_2 \) is larger than \( 0.3B_0 \) and the temporal scales are well separated, i.e. \( T_2/T_1 \) is within the range from 3.5 to about 15. Therefore, these CSs are
assumed to be double-scale. For other six CSs we have \( B_2 < 0.3B_0 \), so that these CSs are single-scale.

The profiles \( \langle B(t) \rangle \) of single-scale CSs are well described by the
Harris model. Therefore, at \( t = T_0 \) and \( t = 2T_0 \) we have \( \langle B(t) \rangle \approx 0.7B_0 \) and \( \langle B(t) \rangle \approx 0.95B_0 \), respectively. We conclude that for single-scale CSs \( T_0 \) can be considered as the half-duration of the CS crossing. Table 2 shows that \( T_0 \) is within the range from 10 s to 90 s. For double-scale CSs the half-duration of the CS crossing is determined by the moment as the magnetic field of the corresponding double-scale becomes equal to 0.95\( B_0 \). Fig. 2 shows (blue lines correspond to \( B_j = 0.95B_0 \) that half-durations for CSs\#2, 5, 8 are within the range from 55 s to 80 s, while for CSs\#10–13 half-durations are within the range from 125 s to 300 s. Thus, on average double-scale CSs are crossed longer than single-scale CSs.

We consider now the structure of magnetic field components
\( B_0 \) and \( B_m \). We calculate their averaged values across the CS central region, \( |B_j| < 5 \) nT. These averaged values \( B_0 \) and \( B_m \) (we keep previous notations) are presented in Table 1. Fig. 3 presents distributions of \( |B_j|/B_0 \) and \( |B_m|/B_0 \). On average \( B_0 \) and \( B_m \) are substantially smaller than \( B_0 \). Fig. 3c shows that for particular CS crossings \( B_m \) can be more than three times larger than \( B_0 \).

Our dataset includes four CSs with negative \( B_m \). The observation of \( B_m < 0 \) in a particular CS crossing could be related to the improper choice of the local coordinate system. However, the observation of CSs with \( B_m < 0 \) have been confirmed in the statistical study by Zhang et al. (2010). Moreover, Zhang et al. (2010) have found that CSs with \( B_m < 0 \) are generally observed at \( Z_l < 0 \). Fig. 3d shows that even for our relatively small dataset of CS crossings the CSs with \( B_m < 0 \) are observed at different \( Z_l \). CSs with \( B_m < 0 \) are observed at small \( Z_l \), while CSs with \( B_m > 0 \) are observed at \( Z_l > 0 \) (except for one CS). This distribution is qualitatively consistent with the one reported by Zhang et al. (2010). We conclude that local coordinate system for each of our 13 CSs is determined properly.

The set of double-scale CSs includes a particularly interesting
CS\#13. In this CS \( B_0 \) profile has characteristic dips observed symmetrically on both sides of the CS (see Fig. 1). These symmetric dips can be related either to the oscillatory CS flapping motion or to the CS structure. Similar dips are observed in other crossings at one side of the CS (CSs\#6, 11, 12). These asymmetric dips are more likely due to the non-uniform CS motion.

3.2. The double-scale CS structure

Zhang (2013) have found that the average \( B_0 \) profile has the double-scale structure. However, the average profile does not resolve peculiarities of particular CS crossings. Based on our 13 CS crossings we have shown that the observed profiles \( B(t) \) can be single-scale and double-scale. Thus, the double-scale structure of the average profile is due to the superposition of single-scale and double-scale CSs. Let us discuss mechanisms, which could be responsible for the observation of double-scale profiles \( B(t) \).

One can suppose that the spatial profile \( B_0(t_0) \) has actually single-scale structure, while the non-uniform CS flapping motion results in the double-scale temporal profile \( B(t) \). Unfortunately, measurements at one spacecraft do not allow to determine the velocity of the CS motion to verify this hypothesis. On the other hand, Cluster observations in the Earth magnetotail show that quite often the velocity of the CS flapping motion weakly varies during the CS crossing (Vasko et al., 2014). Assuming that the velocity of the CS motion in the Venus magnetotail does not significantly vary during the crossing we can propose the alternative scenario for the formation of double-scale CSs. Ion population of the Venusian CS consists generally of solar wind (SW) protons and oxygen ions picked up by SW flux tubes during their
convection around Venus (see e.g. review by Vaisberg et al., 1994). The double-scale CS structure could correspond to the multi species ion population of the CS (Zelenyi et al., 2006, 2011). This hypothesis is supported by observations in the Earth magnetotail. Zelenyi et al. (2011) have shown that the presence of oxygen ions in the Earth magnetotail during disturbed periods results in the double-scale current density profile and larger CS thickness. The double-scale structure has been interpreted in the frame of the thin CS (TCS) model developed by Sitnov et al. (2000) and Zelenyi et al. (2000). In TCS model the main current carriers are transient (or ‘Speiser’) particles (Speiser, 1965). The double-scale CS structure is explained as follows: the first (or inner) scale is provided by transient protons, while the second (or outer) scale is provided by transient oxygen ions (Zelenyi et al., 2006). The thicknesses of inner and outer scales are about several proton and oxygen thermal gyroradii, respectively. Further, we show that the magnetic field profiles presented in Fig. 1 can be described by TCS model.

4. Observations and TCS model

4.1. TCS model

TCS model developed by Sitnov et al. (2000) and Zelenyi et al. (2000) takes into account only one ion specie. This model has been generalized to explain various properties of the Earth magnetotail CS (see for details the review by Zelenyi et al., 2011 and paper by Sitnov et al., 2000). We outline here the modification of TCS model, which takes into account several ion species (Zelenyi et al., 2006). We do not consider the electron current and a shear component of the magnetic field, since they do not substantially influence B1 profile (Zelenyi et al., 2004; Malova et al., 2012).

The magnetic field has two components B = B0(t0) + Bα n. CS is symmetric relative to the neutral plane, B1(−r0) = −B1(r0). The magnetic field is uniform far from the neutral plane, B1(r→∞) = B0. Ion population consists of protons (α = h) and oxygen ions (α = o). Protons and oxygen ions are assumed to be unmagnetized near the CS neutral plane due to the smallness of the perpendicular field component, B0 ≪ B0. The ion distribution functions at the CS boundary are taken in the form of the Maxwellian function:

\[ f_{0,a}(v) = \frac{n_a}{\pi^{3/2}v_{T,a}^3} \exp\left(-\frac{(v - v_{T,a})^2 + v_0^2}{v_{T,a}^2}\right) \]  (2)

where \( v_0 = (vB)/B_0 \), \( v_{T,a} = (v - v_B)/B_0 \), \( n_a \) determine ion densities, \( v_{T,a} = (2T_a/m_a)^{1/2} \) are thermal velocities and \( v_{0,a} \) are ion velocities along the magnetic field at the CS boundary. In the CS with \( B_0/B_0 < 1 \) the ion motion can be described using the approximate integral of motion, the quasi-adiabatic invariant \( I_{a,\alpha} = (2\pi)^{-1} \int f_{m,a}(v_B) \, dv_B \) (Büchner and Zelenyi, 1989).

The existence of the quasi-adiabatic invariant allows to trace the distribution function \( f_{0,a} \) from the boundary over the entire CS:

\[ f_{a}(B_1, v) = \frac{n_a}{\pi^{3/2}v_{T,a}^3} \exp\left(-\sqrt{v^2 - v_{T,a}^2 - 2I_{a,\alpha} - \epsilon_a^2} - 2I_{a,\alpha}\right), \]  (3)

where \( I_{a,\alpha} = \int f_{m,a} \, dv_B \), \( \epsilon_a = v_{0,a}/v_{T,a} \). Distribution function (3) is defined only in the phase space domain, where \( I_{a,\alpha} \leq v^2/2v_{T,a}^2 \). This phase space domain corresponds to ‘Speiser’ particles (Speiser, 1965). Phase space domain, where \( I_{a,\alpha} \geq v^2/2v_{T,a}^2 \), corresponds to trapped particles. The distribution function of the trapped population can be set as

\[ f_{a}(B_1, v) = k_{a,\alpha}n_a\frac{\pi}{\pi^{3/2}v_{T,a}^3} \exp\left(-\sqrt{v^2 + v_0^2}\right) \]  (4)

where parameter \( k_{a,\alpha} \) determines the density of the trapped population (see details in Zelenyi et al., 2011).

The self-consistent profile of the magnetic field \( B_1 \) is determined by the Ampere’s equation:

\[ \frac{dB_1}{dr_n} = \frac{4\pi}{c} \sum_\alpha k_{\alpha} \int (vB)f_{a}(B_1, v) \, d^3v \]  (5)

where \( m \) is a unit vector of the local coordinate system (l, m, n). Eq. (5) is complemented by boundary conditions \( B_1(0) = 0 \) and \( B_1(\infty) = B_0 \). The numerical solution of Eq. (5) can be derived by the iterative procedure (Sitnov et al., 2000). The self-consistent \( B_1 \) profile depends on parameters \( \epsilon_h \) and \( \epsilon_o \), amounts of trapped ion populations \( k_{h,\alpha} \) and \( k_{o,\alpha} \), density ratio \( n_o/n_h \), and ratio \( \rho_o/\rho_h \). In the model with one ion specie \( B_1 \) profile depends on two parameters, \( \epsilon_a \) and \( k_{a,\alpha} \).

4.2. Interpretation of observed CS profiles

In the observed CSs the magnetic field \( B_0 \) is much smaller than \( B_0 \) as it is required by TCS model. In the present section we demonstrate that observed single-scale and double-scale profiles of the magnetic field \( B_1 \) can be described by TCS model. For this purpose we use single-scale CS#9 and double-scale CSs#12, 13.

In TCS model the magnetic field profile has a single-scale structure if the electric current is generally provided by one ion specie (denoted as \( \alpha \)). The current density is generally provided by

\[ j = \frac{4\pi}{c} \sum_\alpha k_{\alpha} \int (vB)f_{a}(B_1, v) \, d^3v \]  (6)

Fig. 3. Distributions of (a) \( B_n/B_0 \), (b) \( B_n/B_0 \) and (c) \( B_n/B_0 \). Panel (d) shows the correlation between the sign of the perpendicular component \( B_n \) and the coordinate \( Z_e \) of the CS crossing.
transient ions, while the contribution of trapped ions is substantially smaller. The CS half-thickness predicted by TCS model is \( \sim 2\rho_o \) (Sitnov et al., 2000). Fig. 4a presents the comparison between the averaged profile \( (B_i) \) for CS#9 and the theoretical profile obtained for \( \epsilon_o = 1 \) and small amount of trapped ions, \( k_{ir,o} = 1 \). The magnetic field \( (B_i) \) is normalized on \( B_0 \), while the time is normalized on the time value, where \( (B_i) \) becomes equal to \( B_0 \). The spatial scale of the theoretical profile is normalized on the distance, where the magnetic field becomes equal to the unity. One can see that theoretical and observed profiles are in good agreement.

In TCS model the magnetic field profile has a double-scale structure if the electric current is provided by transient ions of both species (protons and oxygen ions). The inner scale is provided by transient protons, while the outer scale is provided by transient oxygen ions (Zelenyi et al., 2006). The half-thicknesses of inner and outer scales are \( \sim 2\rho_h \) and \( \sim 2\rho_o \), while the ratio of these half-thicknesses is \( \sim 4\sqrt{T_o/T_h} \). Fig. 4b presents the comparison between the averaged profile \( (B_i) \) for CS#12 and the theoretical profile. In this model the amount of trapped ion populations is small, \( k_{ir,h} = k_{ir,o} = 1 \), while \( n_h/n_o = 1.5, T_o/T_h = 2.25, \epsilon_o/\epsilon_h = 0.5 \).

The ratio of temperatures \( T_o/T_h \sim 2.25 \) is chosen so that the ratio of thicknesses of inner and outer scales \( \sim 4\sqrt{T_o/T_h} \sim 6 \) approximately coincides with the ratio \( T_2/T_1 \) observed for the profile \( (B_i) \) in CS#12. In Fig. 4b observed and theoretical profiles are normalized in the same way as in Fig. 4a. Fig. 4b shows that there is rather good correspondence between observed and theoretical profiles.

CS#13 is a typical double-scale CS and can be satisfactorily described by TCS model. However, the model cannot reproduce the dips observed in this CS. This inconsistency is not critical, since these dips can be prescribed to the non-uniform (oscillatory) CS structure. On the other hand, if these dips correspond to the CS structure, we can still explain such a CS in the frame of TCS model. The \( B_i \) profile with dips can be obtained by assuming that the current is carried by transient protons and trapped oxygen ions. Thus, contrary to the model by Zelenyi et al. (2006) the majority of oxygen ions is assumed to be trapped.

Fig. 5 presents the theoretical \( B_i \) profile and corresponding ion current densities obtained for the CS with small amount of trapped protons, \( k_{ir,o} = 1 \), large amount of trapped oxygen ions, \( k_{ir,h} = 14, n_h = n_o \) and \( T_h = T_o/h (i.e. \rho_h = 2\rho_o) \). Fig. 5 shows that dips are due to the following: (1) specific current density profile of trapped ions in TCS model, i.e. the current density is negative near the neutral plane (Zelenyi et al., 2000); (2) the negative current density of trapped oxygen ions is locally uncompensated by the positive current density of transient protons. The latter condition cannot be satisfied in the CS model with large amount of trapped protons instead of oxygen ions. The negative current of trapped protons turns out to be compensated by the positive current of transient protons. On contrary, in the CS model presented in Fig. 5 the negative current appears since the current density profile of trapped oxygen ions is wider than that of transient protons (due to larger thermal gyroradius of oxygen ions). Fig. 4c shows that \( B_i \) profile observed in CS#13 is qualitatively described by the theoretical model. Although the CS with dips can be described by TCS model, one needs to carefully tune the model parameters to reach the reasonable agreement (e.g. \( T_o/T_h \sim 4 \)). Therefore, in the further discussion we assume that the dips observed in CS#13 are due to the non-uniform CS motion. However, for future studies we keep in mind that the alternative scenario exists.

5. Discussion

We have found that temporal profiles of the magnetic field observed in the Venus CS have single-scale or double-scale structures. This property may be an artifact caused by the nonuniform CS motion during the crossing. On the other hand, it can be an intrinsic property of the spatial profile of the magnetic field. We have shown that the observed profiles can be explained in the frame of TCS model. According to TCS model in single-scale CSs the electric currents provided by protons and oxygen ions \( O^+ \) are comparable. According to TCS model the half-thickness of the Venus CS is about several ion thermal gyroradii.

Table 2 shows that the ratio \( T_2/T_1 \) for double-scale CSs is within the range from 3.5 to 15. On the other hand, according to TCS model the ratio of half-thicknesses of outer and inner scales is \( \rho_o/\rho_h \sim 4\sqrt{T_o/T_h} \). Thus, the ratio of oxygen and proton temperatures should be within the range from 1 to 14. These values seem to be realistic, since the proton energy does not exceed \( \sim 1 \) keV, while oxygen ions with energy per charge up to \( \sim 20 \) keV have been observed at the terminator (Mihalov and Barnes, 1981). At the same time we note that there are still no reliable measurements of ion temperatures within the CS. The plasma data of VEX do not possess a sufficient time resolution and sensitivity to solve this problem.

Oxygen ions are captured at the day side due to the pick-up process and are transferred into the CS. Therefore the amount of oxygen ions within the CS depends on the efficiency of the pick-up process. Observed variations of the bow shock position indicate that the efficiency of the pick-up process varies depending on the intensity of the solar ultraviolet radiation and orientation of the IMF (Alexander and Russell, 1985; Alexander et al., 1986). We can speculate that the ion population in single-scale CSs includes small
amount of oxygen ions due to the weak efficiency of the pick-up process at the day side. As a result, the electric current in single-scale CSs is generally provided by protons, while the electric current of oxygen ions is much smaller. On the other hand, there can be much more oxygen ions in double-scale CSs. Their electric current results in the formation of the outer scale in double-scale CSs. At the moment there are no reliable measurements of ion densities in the CS, so that our hypothesis cannot be immediately checked.

The $B_0$ profile obtained by Zhang (2013) is the average temporal profile. Assuming that the velocity of the CS motion is generally constant during CS crossings, this profile can be interpreted as the average spatial profile. The half-thicknesses of inner and outer scales are $\sim 0.1R_0 \sim 600$ km and $\sim 0.4R_0 \sim 2400$ km (Zhang, 2013). On the other hand, according to TCS model thicknesses of inner and outer scales are $\sim 2\rho_h$ and $\sim 2\rho_o$, so that $\rho_h$ and $\rho_o$ should be $\sim 300$ km and $\sim 1200$ km, respectively. For the characteristic magnetic field $B_0 \sim 15$ nT (Zhang et al., 2010), these thermal gyroradii correspond to proton and oxygen temperatures of about $1$ keV. We note that ion populations with the temperature of $1$ keV in the CS have been reported only by Verigin et al. (1978). Vaisberg et al. (1994) have argued that ion temperatures are generally of the order of hundreds of eV. On the other hand, the average profile obtained by Zhang (2013) have been obtained using the technique proposed by McComas et al. (1986b). Moore et al. (1990) have shown that this technique overestimates the CS thickness. Thus, thicknesses of inner and outer scales can be smaller than $0.1R_0$ and $0.4R_0$, while the required ion temperatures can be lower.

In the present paper we have investigated the CS structure based on several separate CS crossings, which have been carefully selected. The study of the average magnetic field profile requires much broader dataset of CS crossings. We note that such a dataset can be gathered using less strict selection criteria in comparison with those used in the present study. The use of a broad dataset of CS crossings allows to determine the average profile following techniques proposed by Moore et al. (1990). This study requires a separate publication.

Our interpretation suggests that the Venusian CS half-thickness is several ion thermal gyroradii. In fact, the same conclusion follows from the data presented by Moore et al. (1990) for the Venusian CS in the distant magnetotail ($X \sim -10R_0$). According to Moore et al. (1990) the CS half-thickness in the distant tail does not exceed $1500$ km, while the plasma temperature is about $1$ keV. Thermal gyroradii of protons and oxygen ions with temperatures of $1$ keV in the magnetic field $B_0 \sim 15$ nT (McComas et al., 1986b) are about $250$ km and $1000$ km, respectively. Thus, the CS thickness in the distant magnetotail is only several ion thermal gyroradii.

To prove strictly that the Venusian CS has kinetic scales, which can be described by TCS model one needs to analyze the plasma data. In the present study the plasma parameters for theoretical models discussed in Section 4 have been chosen to reach the reasonable agreement between observed and theoretical $B_0$ profiles. We have not used VEX plasma data in the present study, since (1) the plasma data resolution is quite low (192 s); (2) plasma measurements within the tail have rather low quality.

6. Conclusions

We have studied the structure of the Venusian CS. Our major findings are summarized below:

1. The profiles of magnetic field component $B_y$ have single-scale or double-scale structure. On average, double-scale CSs are crossed longer than single-scale CSs.

2. Perpendicular $B_y$ and shear $B_m$ components are about ten times smaller than the amplitude of $B_y$. On average, $B_y$ and $B_m$ are uniform across the CS.

3. The observed $B_y$ profiles can be described by TCS model. We suggest that the current density in single-scale CSs is provided by the transient proton population. In double-scale CSs the inner scale is provided by the transient proton population, while the outer scale is provided by the transient oxygen population. Our interpretation suggests that the Venusian CS half-thickness is several ion thermal gyroradii. Finally, we have pointed out the role of trapped oxygen ions in producing the $B_y$ profile with dips observed for one of the CSs.

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