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Reply to referee comments – angeo-2018-69

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– *The paper Can interplanetary magnetic field reach the Venus surface? provides an estimate of the interplanetary magnetic field (IMF) diffusion time across the atmosphere of Venus to be compared with previous simulation work, apparently underestimating it, and with upcoming observations by BepiColombo. The estimation is based on observed profiles of relevant quantities and numerical integration. I see the paper as a timely contribution, however, a few questions should be explained in more detail before publication.*

  – Reply: Thank you.

– *1. Convective transport of the magnetic field is completely ignored. Is this related to the impact of the IMF draping around the planet on the magnetic Reynolds number? Please comment.*

  – Reply: Yes, the convective transport of the magnetic field is an important effect in general, and the magnetic Reynolds number indeed gives an estimate of the ratio of the convective transport to the diffusion. However, our study works on a more simplified situation to give an estimate by reducing the convective-diffusive problem into a diffusive problem. The reason for this is that the convective transport does not enter the problem of the vertical diffusion (in the sense of radial direction from the planet) and the plasma flow is in the horizontal direction (tangential to the planet surface). The convective transport makes the penetration time longer, and not shorter. Therefore, our study gives an estimate of the lower limit (i.e., the shortest time) of the magnetic field penetration through the ionosphere.

  – We will add the above statement in section 1, after p. 2, L3.

– *2. I do not fully understand the reset of the magnetic field (p. 2, L5–6). Once the magnetic field enters the diffusive environment, i.e. the conductive ionosphere, the diffusive transport is local: If magnetic energy is supplied in sufficient amount to overcome ohmic losses, the IMF will make it to Venus surface. On the other hand, perhaps at that time the IMF has changed and the diffused magnetic field is no longer equal to the original IMF. Please clarify.*

  – Reply:
    We mean by the "reset" a change in the sunward or anti-sunward direction of the interplanetary magnetic field. It is true that the diffusive transport is local and linear. That is, the energy budget problem does not apply here, since the magnetic diffusion process (or the equation) is linear to the magnetic field and the diffusion time is determined by the ionospheric condition only (by the length scale and the conductivity).

  – We will add a clarification above to p. 2, L5–6.

– *3. Along the same line, the reset is discussed only in terms of the four-sector structure of the IMF. What about variability on top of this large scale pattern (which is essential e.g. for magnetic activity at Earth)? Does it matter less for Venus, in particular at solar minimum?*

  – Reply:
    We mean by the "reset" a change in the sunward or anti-sunward direction of the interplanetary magnetic field and we take the four-sector structure of the IMF for the reason of the longest time interval (as the upper time limit) of the stable IMF. There is no large-scale pattern known to the Venus induced magnetosphere, unlike the Earth substorm case. Solar minimum is more relevant to our theoretical model because the four-sector structure holds well and the CME occurrence rate (which even shortens the time length for the stable IMF) is minimum during the solar minimum.

  – We will add a clarification above to p. 2, L5–6, and around.

– *4. Please explain briefly why Pedersen conductivity transmits the magnetic field by diffusion (p.3, L4–5). Also, phrasing could be perhaps adjusted a bit, since Pedersen current actually converts the magnetic energy into heat (see also 2).*

  – Reply:
    Agreed. We will phrase like this:
    "There are three different kinds of conductivity in the plasma: (1) Pedersen conductivity, (2) Hall conductivity, and (3) field-aligned or parallel conductivity. The Pedersen conductivity (or the current, to be more precise) can transmit the magnetic field (say, in the x-direction in the horizontal plane) by the electric current flowing perpendicular to the magnetic field (in the y-direction in the horizontal plane) and generate the magnetic field in the same direction to the original magnetic field (in the x-direction) by Ampère's law

Table 1. Revised version of table 1.

magnetic field model	τ_d at solar maximum	τ_d at solar minimum
mean field case	109,068 – 114,728 s	58,811 – 59,202 s
strong field case	84,325 – 85,441 s	44,698 – 44,906 s
weak field case	194,268 – 194,343 s	92,288 – 93,536 s

on the opposite side of the current layer (on the ground or low-altitude side of the current layer). The Hall current cannot transfer the magnetic field across the current layer because the current direction is pointing vertically. The parallel current cannot transfer the field in a homogeneous fashion, either. The parallel current (in the x-direction) can generate the magnetic field across the current layer but the field rotates into the minus y-direction below the current layer. It is also worth while to note that the Pedersen conductivity also converts the magnetic energy into heat."

– We will add the explanation on p.3, L4–5 and around.

– *5. The Pedersen conductivity is attributed to electrons (Eq. 5), partly because electron-neutral collision frequency is much larger than ion-neutral collision frequency. However, the conductance formula can be cast as ne/B (\nu_en/f_ge/(1+\nu_en^2/f_ge^2) + similar ion term), therefore what actually matters is the ratio of the collision frequency to the respective (electron or ion) gyro-frequency. At Earth, most of the Pedersen current is carried in the E ionospheric layer by ions, while electrons, already non-collisional at E heights, carry the Hall current. Please comment the case at Venus in more detail.*

– Reply:
Yes! Thank you very much for pointing out that the ion contribution may not be negligible. Indeed, Dubinin et al. (JGR 2014) show that the ion-neutral collision frequency exceeds the ion gyrofrequency at altitudes below 220 km. In contrast, the electron-neutral collision frequency exceeds the electron gyrofrequency at altitudes below 140 km. We improved our estimate by keeping the ion term in Eq. (4) in the calculation, and we will not use the electron-term approximation (Eq. 5) any more. The conductivity (now including the ion term) is higher than our previous result. The diffusion time becomes consequently longer than our previous estimate by about 10 to 20%. The revised figure and table are attached to this reply. The range in the table represents the choice for the mean ion mass (11.6 proton mass or 23.3 proton mass, values taken from Dubinin et al. 2014).

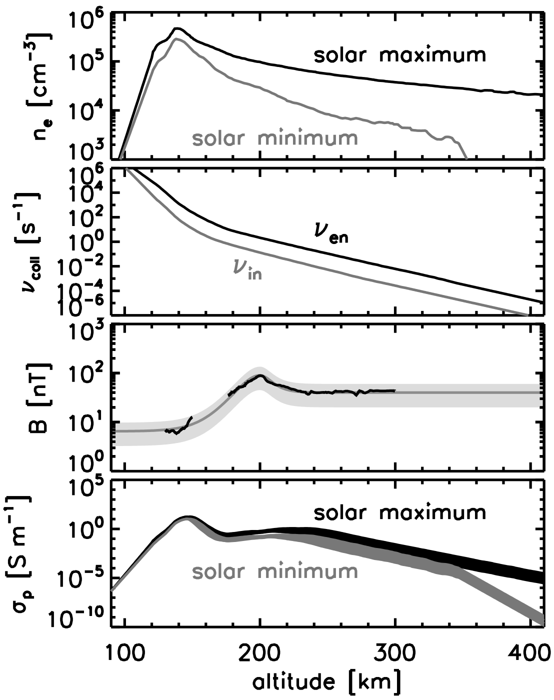

Fig. 1. Revised version of figure 1.

- We will update the item 4 (Pedersen conductivity) on page 4 and replace Fig. 1 and Tab. 1 by our new results.

- *6. The difference between the estimated diffusion time and the simulation result is larger than an order of magnitude. Please discuss this more closely. Incidentally, I was no able to find the less than one hour estimate (p. 1, L19) in the study of Martinecz et al. (2009).*

  - Reply:

    Thank you for double-checking the paper by Martinecz et al. (2009).

    Typical time scale for the magnetic field penetration is estimated from the hybrid plasma simulation by taking the total simulation time (not the computation time) as an upper limit. The total simulation time represents the time by which the magnetosphere (or induced magnetosphere) reaches a quasi-stationary state and the interplanetary magnetic field penetrates the ionosphere. The penetration time (using the total simulation as proxy) is about 1000 s at Venus (Martinecz, 2008) and about 1400 to 1800 s at Mars (Bößwetter et al., 2004, Bößwetter, 2009).

    The numerical diffusion cannot be avoided in the numerical simulation studies, and the diffusion time estimate may not be realistic in the simulation studies. Moreover, the hybrid plasma simulation code treats electrons as a massless fluid and the electron-neutral collisions are not included. Therefore, we find our theoretical calculation complementary to the numerical studies on the diffusion problem.

- We will add the above statement in section 1 (p. 1, L19–20) and also the following literatures:

  (1) Bößwetter, A., Bagdonat, T., Motschmann, U., and Sauer, K.: Plasma boundaries at Mars: a 3-D simulation study, Ann. Geophys., 22, 4363–4379, doi:10.5194/angeo-22-4363-2004, 2004.

  (2) Bößwetter, A.: Wechselwirkung des Mars mit dem Sonnenwind: Hybrid-Simulationen mit besonderem Bezug zur Wasserbilanz, p. 59, PhD thesis, Tech. Univ. Braunschweig, Braunschweig, Germany, https://publikationsserver.tu-braunschweig.de/receive/dbbs_mods_00028707, 2009.

  (3) Martinecz, C.: The Venus plasma environment: a comparison of Venus Express ASPERA-4 measurements with 3D hybrid simulations, p. 71, PhD thesis, Tech. Univ. Braunschweig, Braunschweig, Germany, https://publikationsserver.tu-braunschweig.de/receive/dbbs_mods_00024412, 2008.

- *7. The suggested test by BepiColombo relies on the stability of the IMF during the flyby (see also 2 and 3 above). Please comment.*

  - Reply:

    First of all, there is a correction in the Venus flyby plan for BepiColombo in the manuscript. Venus-Flyby 1 is planned on 12 October 2020 to an altitude down to 11,317 km, and flyby 2 on 11 August 2021 down to 1,000 km. BepiColombo's flyby at Venus is too far to measure the near-surface magnetic field. Yet, the flyby data will help us to determine or constrain the stability of IMF and the condition for the magnetic field penetration through the ionosphere. The test for the magnetic field penetration would ideally be performed during a stable IMF period, for another Venus mission in future.

  - We will add the above statement in the conclusion section (p. 5, L8–10).

- 8. Minors:

  - *p. 1, L9: about ⇒ around?*
  - *L12: Orbiter*
  - *L14: studied ⇒ observed?*
  - *L16-17: The field magnitude becomes diminished ⇒ Further down, the field magnitude decreases*
  - *L21: as a proof ⇒ as very accurate?*

  - *p. 2, L3: becomes reset when the external field (in the induced magnetic field) reverses its orientation ⇒ please rephrase (see also 2).*
  - *L8: report our study ⇒ find?*
  - *L10: delete by permeability. For the substance of the message, see also 2, 3.*
  - *L17: L is,..., \mu_0 ... is, and \sigma is...*
  - *L20: strictly ⇒ exactly*
  - *L25: I think (or diffusion speed) should be deleted.*
  - *p. 3, L3: zˆ2 ⇒ \Delta zˆ2 (i.e. z_maxˆ2 – z_minˆ2); ⟨\sigma⟩ ⇒ \sigma (no brackets); diffusivity ⇒ conductivity.*
  - *L4-5: Please rephrase Since the Pedersen conductivity transmits the magnetic field by diffusion (see also 4).*
  - *L20: from Venus Express*
  - *L31: referred ⇒ inferred*

  - Reply:
    Thank you for the suggestions. We will add changes in the revision.

- **Editor's note** (4 Oct. 2018)

  The only recommendation from my side is to investigate whether there are more recent global simulations of Venus-solar wind interaction, that may include another estimation for the diffusion time of the magnetic field, in addition to what Martinecz et al. (2009) provides. From a short bibliographic search, I came up e.g. with the study by Dimmock et al. (Dimmock, A. P., Alho, M., Kallio, E., Pope, S. A., Zhang, T. L., Kilpua, E., et al. (2018). The response of the Venusian plasma environment to the passage of an ICME: Hybrid simulation results and Venus Express observations. Journal of Geophysical Research: Space Physics, 123, 35803601. https://doi.org/10.1029/2017JA024852) which may be of relevance, although I have not explicitly checked whether that paper contains any relevant information about magnetic field diffusion.

  - Reply:
    To the authors' knowledge, the magnetic diffusion problem at Venus has not yet been studied qualitatively or quantitatively. For example, the global hybrid simulation by Dimmock et al. (2018) indicates the possibility of ionosphere magnetization during the ICME (interplanetary coronal mass ejection) event, but the diffusion time estimate is not given and the simulation deals with a time-dependent phenomenon of ICME.
  - We will add Dimmock et al. (2018) to the reference list.

Changes in the revised manuscript

Ref.01.01
page 2, line 31 to page 3, line 2
"It is worth mentioning that ... ionosphere."

Ref.01.02
page 2, line 15--17
"Here, we mean by the... ionosphere"

Ref.01.03
page 2, line 22--26
"We take ...solar minimum."

Ref.01.04
page 3, line 9--18
"There are...into heat."

Ref.01.05
page 1, line 3
"between 12 hours and 54 hours"

page 5, Eq. (4)
Only Equation (4) is shown, and Equation (5) in the original manuscript has been deleted.

page 5, line 8--17
"The ion term ....at about 10 S m^-1."

page 5
Table 1 has been updated.

page 6
Figure 1 has been updated.

page 6, line 2--7
"Diffusion time... days"

Ref.01.06
page 1, line 19 to page 2, line 2
"Hybrid code simulations....Bößwetter 2009)."

page 8, line 5--9, line 22--24
Reference to Bößwetter et al. (2004), Bößwetter (2009), and Martinecz (2008).

page 2, line 4--8

"Numerical diffusion... problem."

Ref.01.07
page 7, line 3--10
"Third, the upcoming missions...future."

page 8, line 2--4, line 17--19, line 29--30
Reference to Benkhoff et al. (2010), Fox et al. (2016), and Müller et al. (2013).

Ref.01.08
page 1, line 9, "around"
page 1, line 12, "Orbiter"
page 1, line 14, "observed"
page 1, line 16--17, "Further down, the field magnitude decreases"
page 2, line 4, "as very accurate"
page 2, line 15--17, (We keep the term "reset" and add an explanation in the text.)
page 2, line 27, "find"
page 2, line 29, "by permeability" has been deleted. "Venus interior for a long time period"
page 3, line 7, "is" (three times)
page 3, line 21, "exactly"
page 3, line 26, "(or diffusion speed)" has been deleted. "differential diffusion time"
page 4, line 3, $L^2 \mu_0 \sigma$,
page 4, line 3, "conductivity"
page 4, line 4--5, "Since we work on the Pedersen conductivity
for the magnetic diffusion problem"
page 4, line 20, "from Venus Express"
page 4, line 31, "inferred"

Others
page 7, line 13--14
"YN thanks... plan."

Editor's note
page 2, line 8--9
"A more recent... (Dimmock et al., 2018)."

page 8, line 10--12
Reference to Dimmock et al. (2018)