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LOW RAM PRESSURE OF THE SOLAR WIND AND THE HELIOSPHERE: COMPARISON OF GLOBAL MODELING RESULTS WITH VOYAGER AND IBEX OBSERVATIONS

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Abstract

We discuss results of global modeling of the heliosphere for low ram pressure of the solar wind. A quasi-stationary approach is used to simulate interaction of the solar wind and the interstellar medium for exceptionally deep recent solar minimum. It is shown that the global model may potentially explain the heliopause position strongly shifted towards the Sun. A comparison of the model results with available observations of the Voyager and IBEX spacecraft is presented.
Keywords: solar wind, interstellar medium, ram pressure, mhd modeling.

1. INTRODUCTION

Plasma streams blowing out from the solar corona produce the solar wind (SW) filling a region around the Sun including the interplanetary space. Since the Sun remains in relative motion with respect to the ambient interstellar medium, the cavity filled by the expanding plasma of the solar origin is asymmetric bubble-like structure called the heliosphere. The solar wind plasma and the interstellar medium are separated by some boundaries, where they interact in a complicated manner. The separatrix between the expanding solar wind and the counterflowing interstellar medium known as the heliopause (HP) is a pressure equilibrium surface. The supersonic solar wind has to slow down through the heliospheric termination shock (HTS) to reach the HP (see, e.g., Parker 1961; Axford 1972; Baranov 1990; Ratkiewicz et al. 1998). The region inside the heliosphere between the HTS and HP is called the inner heliosheath (IHS). Outside the HP, the nearby interstellar medium flow is likely to be affected by the presence of the heliosphere and the HP-adjacent region in the interstellar medium is called the outer heliosheath (OHS). It is still a subject of debate whether the interstellar medium velocity is supersonic and an external bow shock wave do exist. During the last decade, a great progress has been made in understanding of the physical processes in the heliosphere due to theoretical modelling attempts and measurement data that have been provided by spacecraft missions, including the Voyager 1 (V1) and Voyager 2 (V2) spacecraft and the IBEX mission (for broader review see, e. g. Zank 1999; Fahr 2004; Baranov, 2009; McComas et al. 2014). The V1 and V2 data and related modelling attempts show that both the HTS and the HP may change their locations due to the solar wind pressure variations (Webber 2005; Webber et al. 2007, 2009; Webber & Intriligator 2011; Richardson et al. 2006; Washimi et al. 2007, 2011). In a recent paper Webber & Intriligator (2011) discuss the case of low ram pressure of the solar wind in the period from 2006 to 2011 using a very simple model. They find that, in response to the decreasing solar wind ram pressure, the HTS moves inward after about mid-2008, reaching a minimum distance of ~80 AU in the direction of V1 and ~74 AU in the direction of V2 in early 2011. Then the HTS distance starts to increase early in 2011 as a result of the increasing solar activity and solar wind pressure (observed by OMNI). They argue that the low solar wind ram pressure may cause the HP to move as close as ~120 AU from the Sun along the V1 direction.

Recently published observations of the V1 spacecraft at ~122 AU from the Sun resulted in controversy concerning their interpretation as a possible HP crossing. In August 2012 the V1 spacecraft measured sudden enhancements in the magnetic pressure and small change of the direction of the magnetic field vector with respect to the Parker spiral model predictions (Burlaga et al. 2013). At the same time V1 observed depletions in anomalous cosmic ray (ACR) fluxes, followed by a decrease to the instrumental background (Krimigis et al. 2013), while the galactic cosmic ray (GCR) fluxes significantly increased (Krimigis et al. 2013; Stone et al. 2013). This set of observations suggested possible HP crossing, but the small deviation of the direction of the magnetic field from the Parker spiral (only over a dozen of degrees) refrained final conclusions about transition of V1 to the interstellar medium. Such small change of the direction of the magnetic field related to HP crossing was rather surprising, though predictions by numerical global models of the heliosphere show large dispersion of the expected jump of the magnetic field direction across the HP along V1 trajectory. The measurements of the magnetic field vector variations by the V1 spacecraft are conventionally presented in the RTN frame, (see, e.g., Burlaga & Ness 2012 and references therein). The orientation of the magnetic field vector can be determined by two angles λ and δ defined with respect to the RTN coordinates, where R-axis is along the radial direction from the Sun, T-axis represents the direction of the solar rotation and N-axis completes a right-handed system. The λ angle describes deviation of the magnetic field vector from the radial direction in the radial–tangential (R–T) plane, while the δ angle specifies the deviation of the magnetic field vector from the R–T plane. As concerns the elevation angle δ for MHD simulation by Swisdak et al. (2013) the predicted jump is 14°. The interstellar magnetic field (ISMF) for this simulation was chosen to match V1 and V2 HTS crossing distances without any attempt of fitting the Interstellar Boundary Explorer (IBEX) data, similarly as Opher & Drake (2013), where δ is ~10°-20°. Other MHD simulations based on fitting the IBEX ribbon yield δ ~30°-35° (Borovikov & Pogorelov 2014). Numerical studies of local effects associated with the magnetic reconnection at the HP indicated that the V1 observations can be explained if the HP is layered by magnetic reconnection (Swisdak et al. 2013; Strumik et al. 2013). The above doubts were finally dispelled by measurements of local plasma oscillations obtained from the V1 plasma wave instrument. The estimated value of the plasma number density showed clearly that V1 has entered the interstellar medium (Gurnett et al. 2013). Strumik et al. (2014) have also shown that local magnetic field variations observed by V1 in August 2012 can be well fitted by numerical simulations of dynamical interaction of the magnetic islands initiated by magnetic reconnection occuring on the HP.

Recent V1 observations suggest that the spacecraft has been measuring the interstellar magnetic field for more than two years beginning ~2012/209, when a tangential discontinuity (labeled as „CS0" by Burlaga & Ness (2014)) in the form of a current sheet was observed to have an inclination consistent with an interstellar magnetic field draped on a blunt-shaped heliopause (Burlaga & Ness 2014). The angles defining the direction of the magnetic field vector have increased their deviation from the Parker spiral during this interval. The reported difference for the azimuthal angle λ was $\lambda - \lambda_P = 22° \pm 3°$ and the corresponding difference of the elevation angle δ was $\delta - \delta_P = 23° \pm 8°$ (Burlaga & Ness 2014).

It is not clear at present why V1 crossed the HP at relatively small distance (~122 AU) from the Sun. The low solar wind ram pressure during the recent solar minimum can be invoked as a possible explanation as discussed by Webber & Intriligator (2011). Another concept refers to LISM material penetrating the heliosphere due to the Rayleigh-Taylor-type instabilities (Borovikov & Pogorelov 2014). It is also possible that a HP leakage caused by magnetic reconnection enables transport of the LISM plasma closer to the Sun than predicted by global models, where the reconnection effects are not included (Strumik et al. 2014). In this paper we rediscuss Webber & Intriligator (2011) idea and confront their results obtained from a simplified model with our MHD global simulations, focusing on the HP distance from the Sun and the jump of the azimuthal and elevation angles across the HP. For this purpose we examine the heliosphere for different SW ram pressures. We focus on the following questions: if we keep all simulation parameters constant except for only the solar wind ram pressure variable, is it possible to obtain MHD solutions that: a) fit approximately the observed V1 and V2 HTS crossings for the SW ram pressure taken from OMNI data with appropriate (~1 year) time shift, b) fit the HP location at ~120 AU for the very low SW ram pressure measured at 1 AU in 2009, c) fit the IBEX ribbon observed position modeled as $\boldsymbol{B} \cdot \boldsymbol{r} = 0$, where $\boldsymbol{B}$ is the unit vector along the local magnetic field vector and $\boldsymbol{r}$ is the unit vector from the Sun to a given point in space, d) fit the jump of the λ and δ angles across the HP along the V1 direction for the low SW ram pressure in agreement with data?

2. MODEL DESCRIPTION

We use our 3D MHD model of the SW-LISM interaction, where a set of MHD equations is solved with a source term describing charge exchange with the constant flux of hydrogen (Ratkiewicz et al. 2008). Parameters for SW and LISM are taken approximately the same as in Strumik et al. (2011), Ben-Jaffel & Ratkiewicz (2012), Ben-Jaffel et al. (2013), i.e. the velocities and temperatures of ionized and neutral components in the distant LISM are equal to V_{is}=26.4 km/s and T_{is}=6400 K; the number density of the ionized and neutral components are equal to n_{is}=0.095 cm^{-3} and n_H=0.11 cm^{-3}, respectively. The interstellar magnetic field strength is B_{is}=2.4 μG, and the direction is expressed by α=145° and β=180°, where α is an angle between $\mathbf{V}_{is}$ and $\mathbf{B}_{is}$, β is a deviation angle from the hydrogen deflection plane (Lallement et al. 2005, 2010). Densities at 1 AU for the slow/fast solar wind are assumed to be n_{SW}=5.2/2.74 cm^{-3} (see, e.g. Strumik et al. (2011); Ben-Jaffel & Ratkiewicz (2012) for details). We study three simulation cases with different slow solar wind velocities: C1 - 340, C2 - 420, and C3 - 440 km/s, while the fast wind velocities in high-heliographic-latitude sectors are set up to have 1.9-fold larger values: 646, 798, 836 km/s, correspondingly. The first case C1 represents very low solar wind ram pressure conditions, the two cases C2 and C3 have more typical slow wind ram pressure but they are different as regards to the treatment of boundary between slow and fast streams. The latitudinal asymmetry of the solar wind flow is included using slow and fast wind sectors separated at the heliospheric latitude ±lat0 (in the heliographic inertial coordinate system) with a smooth transition/mixing region (of latitudinal width ± 6°) between the slow and fast sectors. For the cases C1 and C2 lat0=36° and for C3 lat0=56°. The Sun spin axis is tilted 7.25° with respect to the normal to the ecliptic plane. The interplanetary magnetic field (IMF) has the shape of the Parker's spiral at the inner boundary located at 30 AU and the radial component of the IMF at 1 AU is assumed to be equal to 35.5 μG in the ecliptic plane.

As we discussed above the effects of variable SW ram pressure are studied in this paper by changes in the solar wind speed V_{SW}. Since our work is intended as a preliminary attempt of estimation of the influence of very low solar wind ram pressure on HP location, we use an approach that can be described as „quasi-static". We simply use three stationary solutions with different solar wind conditions to find the influence of the conditions on HP location. Referring to strictly correct physical picture, one may argue that the delays that we estimated below (especially the time delay for the HP) are not small in comparison with the time scale (~11 years) of solar cycle variations and some inertial effects will appear. Therefore our analysis gives a sort of upper limit on variations of the HP location due to SW ram pressure changes.

3. RESULTS AND DISCUSSION

First, to estimate possible values of ram pressures of SW at 1 AU related to HTS crossings by V1 (2004.96) and V2 (2007.66) and HP crossing by V1 (2012.65) we must estimate the time delay between 1 AU and distant heliosphere. V1 crossed the HTS at ~94 AU and the SW speed at the crossing was ~505 km/s as suggested by indirect estimation based on convective anisotropies of angular distributions of low-energy ions (LECP experiment on Voyager

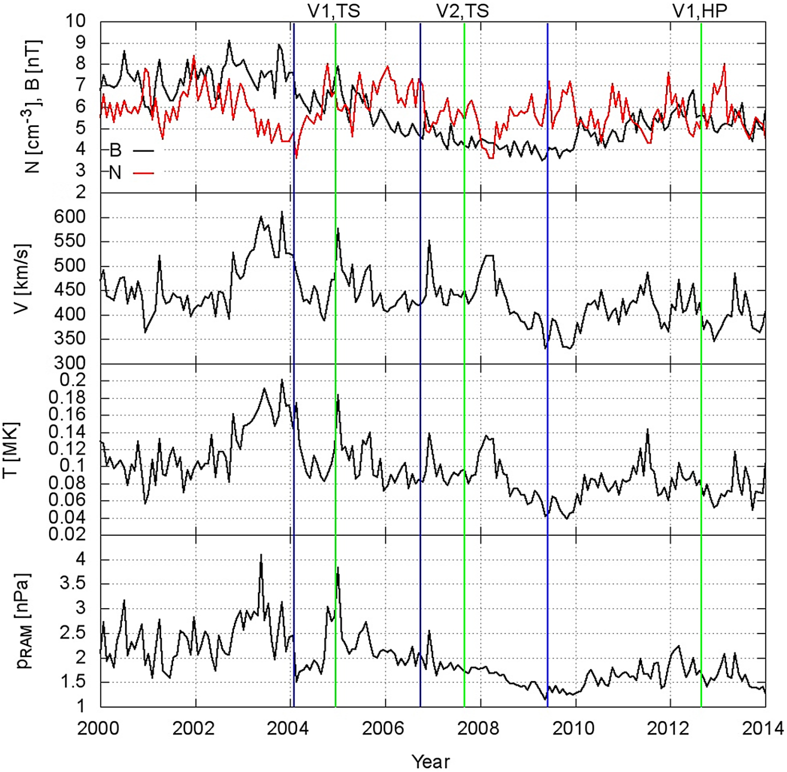

Fig. 1. Time shifts between distant heliosphere (HTS or HP) and SW conditions at 1 AU. Green bars show the time of crossing of a given discontinuity by V1, and V2, respectively, whereas blue bars show an earlier time computed from time delay needed for propagation of ram pressure changes at 1 AU to the discontinuity.

spacecraft and comparison between LECP instruments on V1 and V2 spacecraft (Richardson & Burlaga, 2013)). This velocity value gives the time interval ~0.88 year for the solar wind transport from 1 AU (OMNI data) to 94 AU (HTS crossing distance for V1). V2 crossed the HTS at ~84 AU and the measured SW speed was ~425 km/s, which gives the time interval ~0.93 year. The estimation of the time delay for HP crossing by V1 is based on the following assumptions. Since V1 crossed the HP at relatively small distance from the Sun ~122 AU, following Webber & Intriligator (2011) we assume that HTS at this time was relatively close to the Sun, i.e. at ~75 AU. Such small HTS distance must correspond to a small SW ram pressure, thus we assume 350 km/s from 1 to 75 AU. In the IHS, beyond the HTS from 75 AU to 122 AU we assume the mean speed equal to 100 km/s. This value is 1.5-fold smaller than measurements reported by Richardson & Decker (2014), because these measurements were obtained far from the HP and SW is expected to slow down significantly in the proximity of HP. Using these assumptions we get the time delay ~3.24 years between SW conditions at 1 AU and 122 AU (HP location for V1 trajectory at the time of HP crossing by V1). One should bear in mind that these estimations are very coarse and the time delay to HP should be considered as particularly uncertain. The above analysis does not take into account detailed treatment of HP-adjacent stagnation region effects that may affect the estimation significantly. However, the above estimation can be considered as one step forward with respect to Webber & Intriligator (2011) discussion, where the time delays were somewhat arbitrarily assumed as 1 year to HTS and 2 years to HP. In Figure 1 we show OMNI data and the time delays computed above between distant heliosphere (HTS or HP) and SW conditions at 1 AU. One can see that using the estimated time delays, the HP crossing by V1 (2012.65) may be tracked backward in time to very low ram pressure of SW ~1-1.5 nPa observed at 1 AU (2009.4) as a result of very deep solar minimum. Using the same procedure the HTS crossings by V1 and V2 can be tracked backward in time to ram pressure values ~2-2.5 nPa at 1 AU.

Figure 2. shows simulated HTS location for three different SW ram pressures along V1 trajectory. The shock is seen as abrupt decrease of the SW speed V with the distance R from the Sun. Due to finite resolution of the grid used in the numerical simulation the shock

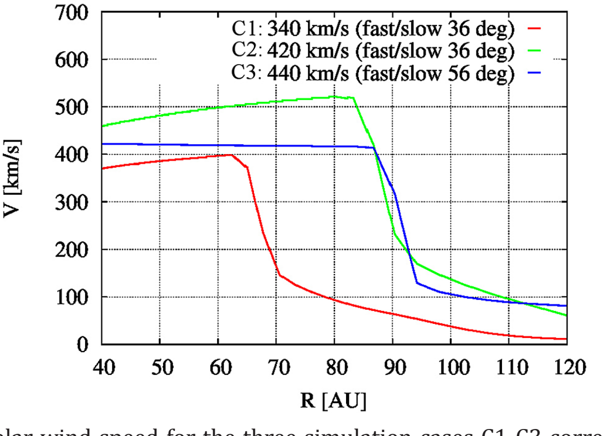

Fig. 2. Profiles of the solar wind speed for the three simulation cases C1-C3 corresponding to different solar wind pressures at the inner boundary condition located at 10 AU in the simulation. The profiles are computed along the V1 trajectory in the simulation box. The termination shock can be identified as an abrupt decrease of the SW speed V with the distance R from the Sun at ~67 AU for the case C1(red line), ~88 AU for the case C2 (green line), ~92 AU for the case C3 (blue line). See the model description in Sec. 2 and discussion of the plot in Sec. 3 for details.

transition is extended and for purposes of the paper we define the HTS position as the middle of the abrupt jump of V(R). For the case C1 (slow wind speed 340 km/s - red line, low ram pressure, p_{RAM} ~ 1 nPa) the HTS position can be as close as ~67 AU. For the cases C2 (420 km/s – green line) and C3 (440km/s – blue line) the ram pressure is larger and HTS is shifted outward from the Sun to distances ~88 AU and ~92 AU, respectively. Focusing on the V1 trajectory we show that the very low SW ram pressure in our simulation gives the position of the HTS at ~67 AU, which is much lower value than the distances ~88 AU and ~92 AU obtained in our simulations for the cases of higher ram pressure. Note, that the latter values are comparable to V1 and V2 measurements (which are 84 AU and 94 AU, respectively) as they differ only a few AU from the spacecraft measurements, whereas the low-ram-pressure simulation case C1 gives the difference of order of 20-25 AU with respect to the measurements. For the cases C1 and C2 (red and green line) the boundary between the slow and fast sectors is at lat0=36° with transition/mixing region of latitudinal width ± 6°, which is close to the latitude of V1 for large distances from the Sun. For this reason for the cases C1 and C2 we can see apparent increase of SW velocity, that in fact is related to transition from slow to fast wind sector in the simulation. For the case C3 lat0=56° and this effect is not seen.

In Figures 3-5 we present the HP position and magnetic field orientation near the HP for different V_{SW}. The magnetic field vector jump across the HP in the numerical model is extended in the simulation domain due to numerical dissipation of the code. The HP position is found by backward-in-time tracking along streamlines as the position along V1 trajectory separating in the simulation box streamlines connected to the Sun from those connected to the interstellar medium. The orientation of the magnetic field is described by two angles λ and δ defined in Section 1.

For the case C2 V_{SW}=420 km/s (Figure 3.) our model predicts HP located at ~140 AU along the V1 direction. Note that numerical smearing of the numerical code leads to a gradual transition through the HP for the angles λ and δ. However, since the max value of δ is 23° in the

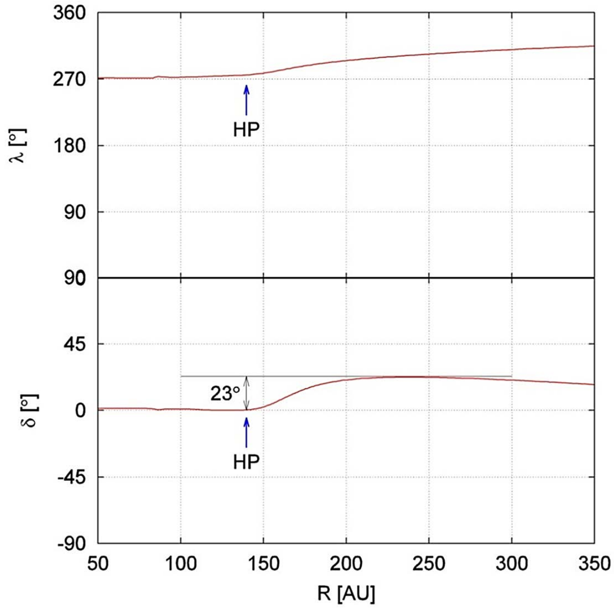

Fig. 3. HP position and magnetic field orientation near the HP for the case C2 V_{SW}=420 km/s along V1 direction

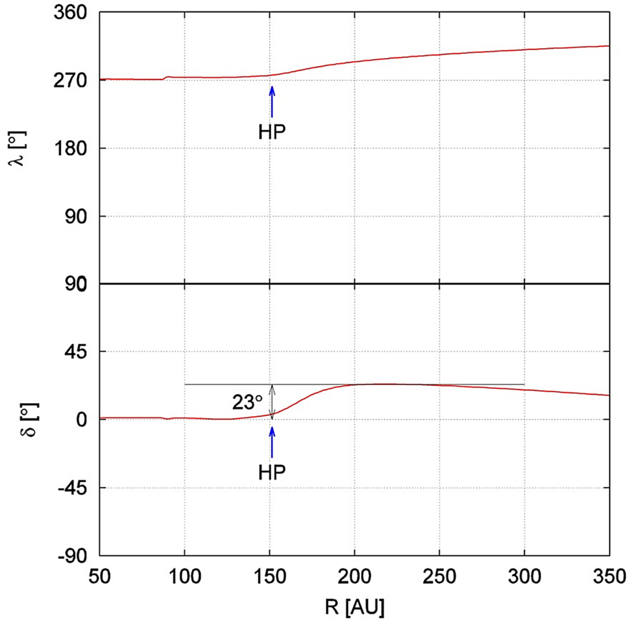

Fig. 4. The same as in Fig. 3 but for the case C3 V_{SW}=440 km/s

OHS region we may expect that jump of δ across the HP is ~ 23°. For the case C3 V_{SW}=440 km/s (Figure 4.) our model predicts the HP located at ~151 AU along the V1 direction. The jump of the δ angle across the HP predicted by our model is ~23°. For the case C1 V_{SW}=340 km/s (Figure 5.) our model predicts the HP located much closer: at ~110 AU along the V1 direction.

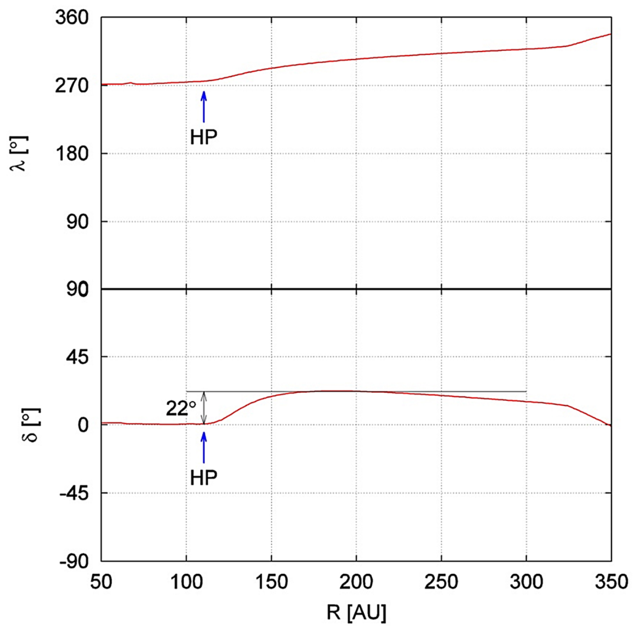

Fig. 5. The same as in Fig. 3 but for the case C1 V_{SW}=340 km/s

In fully time dependent approach we may presumably expect a slightly larger distance from the Sun due to inertial effects that are not properly included in the quasistatic approach used in our paper. The jump of the δ angle across the HP predicted by our model is ~ 22°. This case corresponds to deep solar minimum conditions (p_{RAM} ~ 1 nPa).

The inner heliosheath thickness is presented in Table 1 as a function of the SW speed (and consequently also the SW ram pressure). The inner heliosheath thickness decreases with the SW ram pressure, but even for the lowest values of the ram pressure the inner heliosheath remains rather thick.

Tab. 1. Inner heliosheath thickness

V_SW km/s	**V1 direction**	**V2 direction**
340	~41 AU	~44 AU
420	~49 AU	~56 AU
440	~59 AU	~65 AU

In Figure 6-8 we show the IBEX ribbon in the sky map for the three cases C1-C3 corresponding to different V_{SW} speeds. The modeled ribbon is computed as $\boldsymbol{B} \cdot \boldsymbol{r} < 0.05$ where $\boldsymbol{B}$ and $\boldsymbol{r}$ are the unit vectors. The condition is averaged over a layer of width ~100 AU outwards of the HP. The modeled IBEX ribbon position in the sky map appears to be generally weakly sensitive to variations of the SW ram pressure. For decreasing SW ram pressure and latitudinal extent of the slow wind the southernmost part of the ribbon moves equatorward. The shift is very small (of order of few degrees), which may potentially explain observations reported by McComas et al. (2010). Based on all-sky maps of energetic neutral atom fluxes obtained from the IBEX mission measurements separated in time by 6 months, McComas et al. (2010) discussed possible evolution of the southernmost portion of the IBEX ribbon moving approximately 6 degrees equatorward over the 6 month timeframe, which closely corresponds to our simulation.

4. CONCLUSIONS

OMNI data suggest very low solar wind ram pressure (~1 nPa) at 1 AU in 2009. After appropriate time delay (~1 year for the HTS and ~3 years for the HP according to our coarse estimations) this low SW pressure should affect the HTS and HP locations. For the lowest values of the solar wind ram pressure our model gives the HP located very close to the Sun ~110 AU along the V1 direction. This is even less than ~122 AU observed by V1, probably due to the quasistatic approach that we use in our study. This quasistatic approach does not include inertial effects and thus the response of the HTS and HP positions to ram pressure changes is likely to be overestimated in the model. This question requires further studies.

The HTS position for the low SW ram pressure case in our simulations is ~67 AU along the V1 direction. For appropriately higher values of the ram pressure the model provides a reasonable fit for the HTS crossings by V1 and V2 observed at larger distances. For the low ram pressure values the HP is located at ~110 AU from the Sun in our model whereas for larger ram pressures it moves to ~140-150 AU. This clearly confirms that HTS and HP positions appear to be strongly dependent on the SW ram pressure. The inner heliosheath thickness decreases with the SW ram pressure, but even for the lowest values of the ram pressure the inner heliosheath remains rather thick (~40 AU).

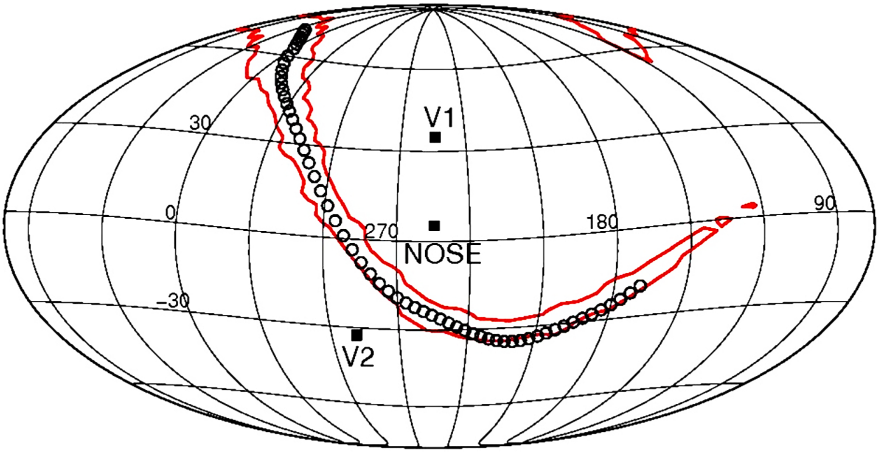

Fig. 6. IBEX ribbon in the sky map (Mollweide projection) for the case C1 V_{sw}=340 km/s. Black circles show observed ribbon position and the red contour shows the modeled ribbon.

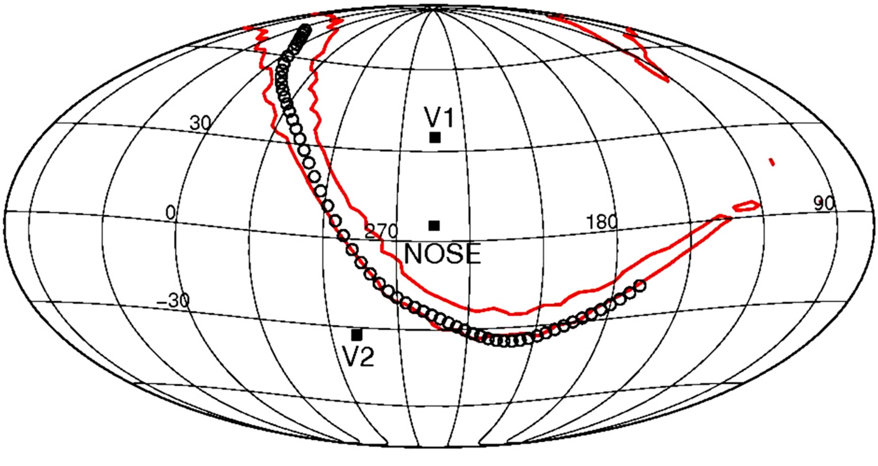

Fig. 7. The same as in Fig. 4a but for the case C2 V_{sw}=420 km/s

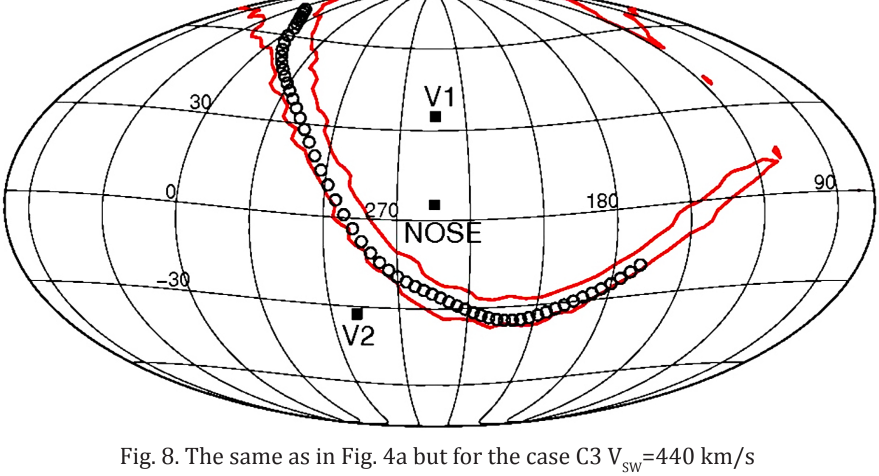

Fig. 8. The same as in Fig. 4a but for the case C3 V_{sw}=440 km/s

The jump of the elevation angle δ across the HP estimated by our model is ~ 22° for the low ram pressure conditions. This is consistent with V1 observations in 2012 and 2013 (Burlaga & Ness 2014). At the same time our model reproduces approximately the IBEX ribbon position in the sky map and the small distance of the HP from the Sun.

The IBEX ribbon position in the sky map appears to be generally weakly sensitive to variations of the SW ram pressure. For decreasing SW ram pressure and latitudinal extent of the slow wind the southernmost part of the ribbon moves equatorward. The shift is very small (of order of a few degrees), which may potentially explain observations reported by McComas et al. (2010).

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NISKIE CIŚNIENIE DYNAMICZNE WIATRU SŁONECZNEGO I HELIOSFERA: PORÓWNANIE WYNIKÓW GLOBALNEGO MODELOWANIA Z OBSERWACJAMI MISJI VOYAGER I IBEX

Streszczenie

Dyskutujemy wyniki globalnego modelowania heliosfery dla przypadku niskiego ciśnienia dynamicznego wiatru słonecznego. W celu przeprowadzenia symulacji oddziaływania wiatru słonecznego z materią miedzygwiazdową dla wyjątkowo głębokiego ostatniego minimum słonecznego stosujemy quasi-stacjonarne podejście. Pokazujemy, że model globalny może potencjalnie wyjaśnić mocno przesuniętą w stronę Słońca heliopauzę. Wyniki modelu są porównane z dostępnymi obserwacjami misji Voyager i IBEX.

Słowa kluczowe: wiatr słoneczny, materia międzygwiazdowa, ciśnienie dynamiczne, magnetohydrodynamiczne modelowanie.