Instability of the Heliopause

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Abstract. The heliopause (HP) separates the tenuous hot heliosheath plasma from the relatively dense cool magnetized plasma of the local interstellar medium (LISM). Fluid acceleration in the HP region can therefore drive Rayleigh-Taylor-like and Kelvin-Helmholtz-like instabilities. Charge exchange coupling of plasma ions and primary interstellar neutral atoms provides an effective gravity, suggesting the possibility of Rayleigh Taylor-like (RT-like) instabilities. Shear flow due to the velocity difference between the heliosheath and the interstellar flows drives Kelvin Helmholtz-like (KH-like) modes on the heliopause. Magnetic fields damp the classical KH instability. However, we show that energetic neutral atoms (ENAs) destabilize KH-modes, even in the presence of interplanetary and interstellar magnetic fields. We consider a model that includes a number of effects that are important in the heliosphere such as resonant change exchange between the primary neutrals and the solar wind plasma, ENAs from the inner heliosheath, plasma flows along the heliopause and magnetic fields in the inner and outer heliosheath. We find that the nose region is unstable to RT-like modes for HP parameters, while the shoulder region is unstable to a new instability that has the characteristics of a mixed RT-KH-like mode. These instabilities are not stabilized by typical values of the magnetic fields in the inner and outer heliosheath close to the nose and shoulder regions. Whereas ENAs have a stabilizing influence on the RT instability in the vicinity of the nose region (due to counter streaming), they have a destabilizing influence on the KH instability in the vicinity of the flanks. We find that even in the presence of interplanetary and interstellar magnetic fields, ENAs can drive a new form of KH-like instability on the flanks. An analysis of the collisional and anomalous magnetic field diffusion time scales shows that ideal MHD is an appropriate model at the HP. The interstellar magnetic field therefore drapes over the HP and does not diffuse into the inner heliosheath (IHS). However, RT-like, RT-KH-like, and KH-like instabilities serve to drag outer heliosheath (OHS)/interstellar magnetic field into the IHS, allowing for local reconnection of interplanetary and interstellar magnetic field. Such reconnection may 1) enhance the mixing of plasmas across the heliopause, and 2) provide open magnetic field lines that allow easy ingress of galactic cosmic rays into the heliosphere and easy loss of anomalous cosmic rays.

1. Introduction
The Heliopause (HP), a tangential discontinuity within a magnetohydrodynamic (MHD) description, separates the high temperature, tenuous solar wind (SW) plasma in the inner heliosheath (IHS) from the relatively dense, cooler, plasma of the local interstellar medium (LISM) in the outer heliosheath (OHS). Across the HP the pressure of the plasma within the heliosphere balances the pressure of the surrounding interstellar medium [1]. The HP has been
crossed by Voyager 1 [2,3] at \( \sim 125 \) AU and the magnetic fields on either side are approximately parallel along the surface of the HP.

Neutral interstellar hydrogen drifts through the HP, coupled weakly via resonant charge exchange with the plasma. The energetic neutrals in the IHS created through charge exchange are called secondary neutrals or energetic neutral atoms (ENAs) [4,5] and propagate upstream into the OHS across the HP. These secondary neutrals or ENAs experience charge exchange with ions in the OHS leading to significant heating of the OHS plasma [6,7,8].

Multi-fluid simulations by Zank et al. 1996 [6] and Liewer et al. 1996 [9] and later by Florinski et al. 2005 [10] and Borovikov et al. 2008 [11] showed that the HP was unstable to large scale modes. Zank 1999a [12] showed that frictional drag between the plasma and neutral H in the vicinity of the HP drives a Rayleigh-Taylor-like (RT-like) instability. Subsequent simulations confirmed the existence of a RT-like instability caused by charge exchange between the primary neutrals from the LISM (or OHS) and SW ions [10]. In particular, high resolution simulations by Borovikov et al. 2008 [11] identified two types of unstable modes in the vicinity of HP: a RT-like mode driven mainly by the charge exchange between neutrals and plasma ions and a RT-KH-like mixed mode, driven by a combination of charge exchange and plasma flow shear across HP. The charge exchange interaction introduces an effective gravitational force acting on the plasma in the direction of the flow of the LISM neutrals [12], which flow from the OHS to the IHS. The plasma density gradient is in the opposite direction as the LISM plasma is much denser than the SW plasmas. Hence RT-like modes are expected to be unstable in the neighborhood of the nose region of the HP, where the effective gravitational force and the plasma density gradient are nearly in the opposite direction. The plasma flows on the other hand, which are weak in the vicinity of the nose region, are strong on the flanks with significant shear across the HP. Hence the Kelvin-Helmholtz (KH) modes might be unstable on the flanks of the HP.

The charge exchange interaction introduces momentum and energy sources in the plasma dynamics and thus introduces significant changes in the dynamics of the system. Zank 1999a [12] derived a modification of the plasma incompressibility condition due to charge exchange in the heliosphere and formulated the problem of the stability of the HP in terms of the charge exchange modified plasma incompressibility condition. Later, a more detailed numerical and analytic analysis of the RT instability of HP of axisymmetric heliosphere in the vicinity of nose region, using the charge exchange modified plasma incompressibility condition was given by Florinski et al. 2005 [10].

To study the stability of modes in the vicinity of HP, we use a model that includes resonant charge exchange with primary neutrals from LISM, magnetic fields, plasma flows and ENAs. Plasma flows and flow shear are important on the flanks of HP. Magnetic fields are important since they can significantly change the stability thresholds of the RT and KH instabilities [Chandrasekhar, 1981]. There is uncertainty in the magnitude and direction of the magnetic field in the vicinity of HP. The results of Burlaga et al. 2013 [3], when interpreted as the crossing of the HP [2], suggest that the magnetic fields on either side of the HP are approximately parallel, with perhaps a change in the orientation. We present a fully, general analysis below and then consider the magnetic field parameters and densities suggested by the Voyager 1 magnetometer and wave instrument measurements. One of the main effects of the interstellar magnetic field is that it introduces a north-south asymmetry in the heliosphere as is evident by the Voyager crossings of the TS. Estimates [13] based on the numerical modeling of the IBEX observation of the enhanced energetic neutral atom flux, constrain the field to be \(< 3 \mu G\) (see also [14,8,15]). As the heliosphere is asymmetric, we carry out a stability analysis in a local reference frame located on the HP. This model is applicable to the entire HP i.e., close to the nose, flanks and the shoulder region in between. In the neighborhood of the nose where plasma flows are weak, it generalizes the earlier analyses [12,10] to include the effect of the magnetic field in the IHS and OHS.
2. Model equations

In the vicinity of the HP, the plasma and its interaction with neutral hydrogen via resonant charge exchange is described by the following equations,

\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0; \]  

\[ \rho \left( \frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} \right) + \nabla p = \frac{1}{c} \mathbf{J} \times \mathbf{B} - \nu_p \rho (\mathbf{u} - \mathbf{V}_p) - \nu_s \rho (\mathbf{u} - \mathbf{V}_s); \]

\[ \frac{\partial p}{\partial t} + \mathbf{u} \cdot \nabla p + \gamma p \nabla \cdot \mathbf{u} = \nu_p \rho \left( \frac{\gamma - 1}{2} (\mathbf{u} - \mathbf{V}_p)^2 + \frac{k T_p}{m_H} - \frac{p}{2 \rho} \right) \]

\[ + \nu_s \rho \left( \frac{\gamma - 1}{2} (\mathbf{u} - \mathbf{V}_s)^2 + \frac{k T_s}{m_H} - \frac{p}{2 \rho} \right); \]

\[ \frac{\partial N_\alpha}{\partial t} + \nabla \cdot (N_\alpha \mathbf{V}_\alpha) = -\nu_\alpha \frac{\rho}{m_H}; \]

\[ \nabla \times \mathbf{B} = \frac{4 \pi}{c} \mathbf{J}. \]

Here, \( \rho, p, J \) and \( \mathbf{J} \) are the plasma mass density, velocity, pressure and current density respectively, \( \mathbf{B} \) is the magnetic field and \( \gamma = 5/3 \) is the specific heat ratio. The charge exchange interaction introduces sources and sinks in the momentum and energy equations which appear on the RHS of Eq. (2) and (3) [16,17]. In our analysis we consider two populations of neutrals; primary neutrals from the LISM, which are relatively cooler and denser \( (T_p \sim 10^4 \text{ K}) \), and ENAs or secondary hot and rarer neutrals \( (T_s \sim 10^6 \text{ K}) \) from the IHS, created by the charge exchange of primary neutrals with the hot plasma in the IHS [6,8,18]. The density, velocity and charge exchange frequency of these two populations of neutrals is denoted by \( N_\alpha, \mathbf{V}_\alpha, \) and \( \nu_\alpha \) respectively (where \( \alpha = p, s \)). The charge exchange frequency is given by the expression \( \nu = \sigma U^* N \) where \( \sigma = 3 \times 10^{-15} \text{ cm}^2 \) is the charge exchange interaction cross section [19] and the speed \( U^* \) is the characteristic interaction speed between protons and neutrals. \( U^* \) is typically 1.5 times the thermal speed of hot neutrals [10]. The neutral velocity is taken constant since we consider scale lengths less than the charge exchange mean free path.

The relative importance of various terms on the RHS of Eq. (3) in the IHS and OHS is important in simplifying equations (1) - (5). Typically in the neighborhood of the HP, the plasma temperature varies from \( 5 \times 10^5 \text{ K} \) along the flanks to \( 10^6 \text{ K} \) at the nose in the IHS [11]. The temperature of ENAs also lies in a similar range. When hot neutrals propagate upstream into the OHS, they cause significant heating of the plasma in the OHS due to secondary charge exchange with LISM protons [6,8]. The plasma temperature is typically \( 5 \times 10^4 \text{ K} \). The primary density in the OHS is \( N_p \sim 0.2 \text{ cm}^{-3} \) while the ratio of primary to secondary hot neutral H atoms is typically \( N_s/N_p \sim 0.01 \) [6,18]. On assigning the indices \( h \) (heliospheric) and \( i \) (interstellar) for IHS and OHS variables, respectively we have in the first parenthesis on the RHS of Eq. (3), \( (p/2\rho)_h \sim 10^6 \text{ K}, T_p \sim 10^4 \text{ K} \) and \( V_p \sim 25 \text{ km/s} \), hence the third term is the largest, as first pointed out by Zank 1999a [12]. This is also bigger than all the terms in the second parenthesis as \( \nu_{sh}/\nu_{pi} < 1 \). In the OHS, the plasma term is \( 5 \times 10^4 \text{ K} \), hence it is still the largest term in the first parenthesis [10]. In the second parenthesis, the second term proportional to \( T_s \sim 5 \times 10^5 - 10^6 \text{ K} \) is the largest, but, since \( (kT_s/m_H)/(p/2\rho)_i \sim 10 \) to 20 and \( \nu_{si}/\nu_{pi} \sim 0.01 \) to 0.05, \( \nu_p (p/2\rho)_i \) is still greater than \( \nu_s (kT_s/m_H) \) and hence it is the largest term on the RHS of Eq. (3). Thus, in both the IHS and OHS, the charge exchange modified incompressibility condition becomes

\[ \nabla \cdot \mathbf{u} = -\frac{\nu_p}{2\gamma}. \]

This is consistent with the original condition suggested by Zank 1999a [12] and is different from Florinski et al. 2005 [10] and Dasgupta et al. 2006 [20] who retain the hot neutral thermal
velocity term in the OHS. The effect of ENAs is still retained in the momentum conservation equation in Eq. (2).

The HP boundary has roughly three regions: The nose region where the interstellar plasma and the solar wind plasma flows each stagnate with weak plasma flows; the flanks, well separate from the nose region, with significant plasma flow and flow shear across the HP, and finally the shoulder region between the flanks and nose. From the nose region, the plasma flow on either side of HP is diverted towards the flanks. Thus the plasma flow is along the HP surface while the flow shear and the plasma density gradient are perpendicular to it. The primary neutrals from the LISM flow unhindered across the HP. In the nose region, the neutral flow is in the direction opposite to that of the solar wind plasma flow. The angle \( \theta \) between the two flows gradually decreases from 180° along the HP to nearly 0° on the flanks where both flows are nearly in the same direction. The ENAs on the other hand, which are generated in the heliosheath, propagate upstream from the IHS, in a direction roughly perpendicular to the HP everywhere.

The analysis is done in a local reference frame, assuming a planar geometry where the \( z \)-axis is perpendicular and the \( x-y \) plane is tangential to the HP surface. The solar wind flow is in the region \( z < 0 \) and the interstellar plasma flow in \( z > 0 \). The \( x \)-axis is aligned along the equilibrium plasma flow velocity \( \mathbf{u}_0 = (u, 0, 0) \) while the flow shear and plasma density gradient are along the \( z \)-axis across the HP. The primary neutrals move downstream across the HP boundary in the \( x-z \) plane with a constant speed \( \mathbf{V}_p \). Let \( \theta \) be the angle between the \( z \)-axis and \( \mathbf{V}_p \). Along the HP boundary, this angle changes, being close to 180° in the nose region and nearly 90° in the flank region. The ENAs, on the other hand, move upstream across the HP at an angle \( \Psi \) from the local \( z \)-axis, which remains close to zero everywhere along the HP boundary.

Avinash et al. 2014 [21] show that the plasma in the vicinity of the HP is nearly ideal and hence the magnetic field will not diffuse into the heliosphere but instead will drape over it. In this case, the magnetic field \( \mathbf{B} \) lies on the HP surface in the \( x-y \) plane. Since the plasma in the vicinity of HP is nearly ideal, the evolution of \( \mathbf{B} \) is governed by

\[
\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \mathbf{u} \times \mathbf{B}. \tag{7}
\]

The equation describing the zeroth-order equilibrium heliopause is given by

\[
\frac{\partial}{\partial z} \left( p + \frac{B^2}{8\pi} \right) = (\nu_p V_{pz} + \nu_s V_{sz}) \rho, \tag{8}
\]

where the zeroth-order pressure \( p \) and magnetic field \( \mathbf{B} \) depend only on the \( z \)-coordinate.

3. Stability of the Heliopause

The plasma continuity equation is given by

\[
\frac{\partial \rho}{\partial t} + \mathbf{u} \cdot \nabla \rho = \frac{\nu_p}{2\gamma} \rho, \tag{9}
\]

after eliminating the divergence of the flow velocity through Eq. (6). We use the incompressibility condition given in Eq. (6) as the equation of state to calculate the pressure.

Since the HP may be regarded as a tangential discontinuity (TD) at \( z = 0 \) in our coordinate system, the stability problem constitutes an expansion in terms of singular perturbations. The equations are solved across and away from the singular surface and the solutions are asymptotically matched to obtain the eigenvalue. For the stability analysis, we consider a simple plasma density and flow profile, which are distinct constants in the IHS and OHS i.e., \( \rho_h = \text{const.}, \ u_h = \text{const. in } z < 0 \) and \( \rho_i = \text{const.}, \ u_i = \text{const. in } z > 0 \), with a jump \( z = 0 \).
The density, pressure, magnetic field, and velocity are perturbed as $\rho + \delta \rho$, $p + \delta p$, $B + \delta B$, and $u + \delta u$ respectively. The perturbed linearized equations are then

$$\frac{\partial \delta \rho}{\partial t} + u \cdot \nabla \delta \rho + \delta w \frac{d\rho}{dz} = \frac{\nu_p}{2\gamma} \delta \rho; \hspace{1cm} (10)$$

$$\rho \frac{\partial \delta u}{\partial t} + \rho \delta u \cdot \nabla u + \delta \rho u \cdot \nabla u + \rho u \cdot \nabla \delta u + \nabla \left( \delta p + \frac{\delta B \cdot B}{4\pi} \right) = \frac{B \cdot \nabla \delta B}{4\pi} - \nu_p (u - V_p) \delta \rho - \nu_p \rho \delta u - \nu_s (u - V_s) \delta \rho - \nu_s \rho \delta u; \hspace{1cm} (11)$$

$$\nabla \cdot \delta u = 0 = \nabla \cdot \delta B; \hspace{1cm} (12)$$

$$\frac{\partial \delta B}{\partial t} = \nabla \times \delta u \times B + \nabla \times u \times \delta B, \hspace{1cm} (13)$$

where $\delta w$ is the $z$ component of the perturbed plasma velocity. The eigenfunction $f(z) \exp[nt + ik \cdot r]$ is used to describe the perturbed quantities, and represents waves propagating on the singular surface in the $x$-$y$ plane $k = (k_x, k_y)$. Matching the solution across the singular surface with the solution away from the singular surface finally gives the dispersion relation (DR) as [21]

$$\rho_i (n + \nu_{ph} + \nu_{sh} + ik \cdot u_h) (n + ik \cdot u_h) + \frac{(k \cdot B_h)^2}{4\pi}$$

$$+ \rho_i (n + \nu_{pi} + \nu_{si} + ik \cdot u_i) (n + ik \cdot u_i) + \frac{(k \cdot B_i)^2}{4\pi}$$

$$= \frac{(\rho_i - \rho_h) k}{2} \left[ \frac{(-\nu_{pi} V_p \cos \theta - \nu_{si} V_s \cos \Psi) (n + ik \cdot u_i)}{n - \nu_{pi}/2\gamma + ik \cdot u_i} \right.$$

$$\left. + \frac{(-\nu_{ph} V_p \cos \theta - \nu_{sh} V_s \cos \Psi) (n + ik \cdot u_h)}{n - \nu_{ph}/2\gamma + ik \cdot u_h} \right]. \hspace{1cm} (14)$$

The dispersion relation Eq. (14) takes into account charge exchange interactions with primary neutrals from the LISM and ENAs from the heliosheath, as well as plasma flows and magnetic fields in the IHS and OHS. Eq. (14) is quartic in $n$ and possesses either four real roots or two pairs of complex roots. Instability occurs if the roots have positive real parts.

We use (14) to study the stability of a particular region of the HP by appropriately choosing the value of $\theta$ and $\Psi$. Typical values of the plasma density and temperature in the IHS and OHS and neutral density in the nose and flanks region have been given above. Typical values of the neutral flow velocity, charge exchange frequencies, and magnetic fields and ratio of plasma densities in the OHS and IHS are $V_p \simeq 20 \text{ km/s}$, $V_s \simeq 100 \text{ km/s}$, $\nu_{pi} \simeq 10^{-9} \text{ s}^{-1}$, $\nu_{ph} \simeq 10 \nu_{pi} \simeq 10^{-8} \text{ s}^{-1}$, $\nu_{si} = 10^{-11} \simeq \nu_{sh}$, $B_i \simeq 3 \mu G$, $B_h \simeq 5 \mu G$ and $\alpha \simeq 20 \ [11,8]$.

(i) Nose region of the HP: This region is characterized by weak plasma flows $U \equiv |v_i - v_h| \simeq 0 \text{ km/s}$, LISM neutral flow along $z \ (\cos \theta \sim -1)$ and ENAs that are counter streaming along $-z$, hence $\cos \Psi \simeq 1$. In this case, the dispersion relation is fourth order in $n$. Because the plasma density gradient and the effective gravity due to primary LISM neutrals are in opposite directions, the RT mode dominates. The counter streaming ENAs, magnetic field, and the ion-neutral collisions provide a stabilizing influence on the RT instability. In the absence of a magnetic field and ENAs, the dispersion relation Eq. (14) reduces to the cubic dispersion relation obtained originally by Zank 1999a [12] and later by Florinski et al. 2005 [10].

Fig. 1 shows the four roots for the dispersion equation in the presence of magnetic fields in the IHS and OHS. Compared to the no magnetic field case (not shown), the plot shows a marginal reduction of the growth rate even when the unstable mode is propagating in the
The roots of the dispersion relation near the nose with magnetic field. With a non-zero magnetic field, there are four roots instead of three. The stabilization of the unstable roots due to the magnetic field is marginal. Here the label axes are normalized as $\lambda \equiv n/\nu_{pi}$ and $\mu \equiv kV_p/\nu_{pi}$.

This region is characterized by the simultaneous presence of a KH-like instability due to flow shear and the RT-like instability, though the latter is somewhat weakened as compared to the nose region because $|\cos \theta| < 1$. For our calculation we choose $\theta = 135^\circ$, $\cos \theta = -0.7$ and $\cos \Phi \approx 1$. A typical value for the flow shear across HP is $U \equiv |v_i - v_h| \approx 2$. Values for the other parameters are the same as given above. The dispersion relation has four roots for these parameters, which are shown in Fig. 2. Two roots have positive direction of the magnetic field, which is when stabilization by a magnetic field is expected to be strongest. Stabilization by the magnetic field for other angles is weaker and zero for perpendicular propagation. Most importantly, we find that stabilization by the magnetic field is not complete even for very large values of the field. Typical values of the growth rates are $\lambda \equiv n/\nu_{pi} \approx 1 - 3$, which for heliospheric parameters corresponds to a growth time of 50 to 100 years. This time scale agrees with that of quasi-periodic oscillations of the nose seen in numerical simulations of the HP [10]. Our results thus show that the nose region of the HP is unstable to RT-like modes with a growth time of roughly 50-100 years with wavelengths ranging from 100 to 500 AU. The stabilizing influence of magnetic fields in the IHS and OHS and of ENAs is weak in the nose region.

(ii) Shoulder region of the HP: This region is characterized by the simultaneous presence of a KH-like instability due to flow shear and the RT-like instability, though the latter is somewhat weakened as compared to the nose region because $|\cos \theta| < 1$. For our calculation we choose $\theta = 135^\circ$, $\cos \theta = -0.7$ and $\cos \Phi \approx 1$. A typical value for the flow shear across HP is $U \equiv |v_i - v_h| \approx 2$. Values for the other parameters are the same as given above. The dispersion relation has four roots for these parameters, which are shown in Fig. 2. Two roots have positive
Figure 2. The roots of the dispersion relation in the shoulder region. The unstable roots correspond to mixed RT-KH modes. The dotted lines identify the imaginary part of the solution to the dispersion relation. The imaginary part of the solution shows that these are propagating modes. The axes are described in the caption of Fig. 1.

(iii) Flank region of the HP: In the flanks, the LISM neutral flow (as well as the plasma flow) is along the $x$ direction, hence $\cos \theta = 0$. Since the plasma density gradient is along $z$, the RT mode is absent and LISM neutrals play no role in destabilizing the flanks (and in fact can act to damp a KH instability [12]). However, ENAs now play an important role. The ENAs travel upstream nearly along $z$, hence $\cos \Psi \approx 1$. Consequently, energetic neutrals influence the KH instability on the flanks, which is caused by flow shear along $z$. In the absence of ENAs, the dispersion relation for modes propagating parallel to the magnetic field is a quadratic equation with two roots, both of which are stable. This is the KH instability that is stabilized by magnetic fields. However, when ENAs are retained, the dispersion relation now admits roots with positive real parts, i.e., unstable roots, which show that ENAs revive the instability on the flanks. Thus, in the presence of a magnetic field, ENAs are essential for driving an instability of the HP flanks.

4. Conclusions
With the crossing of the HP by Voyager 1, its structure and stability have assumed great interest. In an idealized view, the HP is a tangential discontinuity that separates the tenuous and hot
heliosheath plasma from the relatively dense and cool plasma of the local interstellar medium. We have explored the effects of resonant change exchange between primary interstellar neutrals atoms and the solar wind plasma, ENAs, interstellar and heliosheath magnetic fields, and plasma flows on the stability of the HP. We use Zank’s charge exchange modified incompressibility condition [12] as the equation of state in our model. Under typical conditions, the plasma resistivity due to electron-neutral collisions, electron-ion collisions, or turbulence (anomalous) is found to be small hence the interstellar magnetic field drapes around the heliopause causing a north-south asymmetry. The stability analysis is performed in a local reference frame located on the HP, and we consider three regions. The nose region where plasma flows are weak is unstable to RT-like modes; the shoulder region is unstable to mixed RT-KH-like modes, and the flank region (with strong flow and flow shear) is unstable to a KH-like instability. The dispersion relation shows that, in the relevant parameter space, magnetic fields cannot stabilize any of the instabilities. However, ENAs are found to be essential for destabilizing the flanks when magnetic fields are included.

Let us consider what the effect might be of an instability on the HP that drags a loop of interstellar magnetic field (colored blue) into the inner heliosheath (IHS) – Figures 4 A and B. At the nose and shoulder regions of the HP, the latter being the current location of Voyager 1,

Figure 3. The roots of the dispersion relation in the flank region with magnetic field and ENAs. The plot illustrates three unstable roots showing the destabilizing influence of ENAs on the KH modes. The axes are described in the caption of Fig. 1.
Figure 4. A. Cartoon showing the possible evolution of an OHS/VLISM magnetic field line dragged into the IHS by either a RT-like or mixed KH-RT-like instability on the HP. For convenience, we have assumed that we are in the stationary frame of the OHS flow. The red line shows the IHS magnetic field. In this example, we suppose that the IHS and OHS magnetic field lines are approximately parallel to one another on either side of the HP (sketched as the shaded block, and labeled HP). The heavy black arrow depicts the IHS plasma flow direction as measured in the frame of the OHS flow. (i) The solid blue line depicts the initial incursion of the OHS magnetic field dragged into the IHS by a RT-like instability. The dashed blue line shows the later OHS magnetic field line after being dragged northward and westward (assuming we are considering the approximate location of Voyager 1) by the IHS plasma flow. The IHS magnetic field (red line) is convected northward and westward by the IHS plasma flow. (ii) As the IHS magnetic field line is advected in the IHS plasma flow, it will eventually be forced against the intruding OHS magnetic field line, which in the OHS plasma flow frame of reference, is anchored to the HP. Because the OHS magnetic field has been dragged as illustrated in (i), there will always be a region that is anti-parallel to the impinging IHS magnetic field. In this region, as illustrated, the IHS and OHS magnetic field lines can reconnect. In so doing, the entering OHS magnetic field line is connected to an IHS magnetic field section, thereby allowing direct access of OHS plasma into the IHS. Conversely, the other segment of the IHS magnetic field is now connected to the OHS magnetic field, thereby allowing direct access of IHS plasma into the OHS. (iii) After some time, the magnetic field connecting the IHS to the OHS and vice versa will be dragged into the parallel configuration illustrated here. The dash-dotted lines, labeled A1 and A2, depict possible Voyager 1 trajectories through the magnetic field line topologies and HP. B. Same as A except that the IHS is now oriented anti-parallel to the OHS magnetic field. Four possible Voyager 1 trajectories have been sketched, B1 - B4. The net result is that again the IHS and OHS magnetic fields reconnect and allow the exchange of plasma from IHS to OHS and vice versa.
the RT element of the instability described here will drag a loop of magnetic field through the HP into the IHS. If we adopt a frame of reference that is co-moving with the interstellar flow adjacent to the local HP, then the magnetic field lines on the interstellar side of the HP are fixed. The initial loop is illustrated in Fig. 4 (i). The flow in the IHS is faster than in the very local ISM (VLISM) and has both a northward and westward component as viewed from the Sun. As the VLISM magnetic field protrudes into the IHS, it is dragged in a corresponding direction (relative to the VLISM flow) with the footpoints remaining anchored to the same relative locations on the HP. The dragged and distorted interstellar magnetic field is shown in Fig. 4A (i) by the dashed blue line. The interplanetary field (colored red) in the inner heliosheath can be oriented in one or the other direction as illustrated in Fig. 4A or B, depending on the sector boundary structure ahead of the HP. Interplanetary magnetic field that was below the interstellar loop protruding into the IHS will be pushed up against the loop as it is dragged (more slowly) by the IHS flow. As illustrated in Fig. 4A (i), part of the dragged loop of VLISM magnetic field will be anti-parallel to the IHS magnetic field that is pushing up against it. These sections of the VLISM and IHS magnetic fields can experience reconnection, with the resulting re-configured field lines (now red and blue) illustrated in Fig. 4. No island-like structures are expected to form but instead, one part of the IHS magnetic field connects to the VLISM magnetic field that returns to the VLISM. The other section of the IHS magnetic field connects to the VLISM magnetic field that is entering the IHS from the ISM. The IHS flow will tend to straighten the recently reconnected magnetic field, yielding a final configuration similar to that shown in Fig. 4 (iii). The key points are that i) one of the field lines allows direct access from the IHS to the VLISM, and thus allows direct access of energetic heliospheric particles to the ISM, and the other magnetic field line allows direct access of energetic galactic particles from the VLISM into the IHS; and ii) the magnetic field structure on either side of the HP is unlikely to be very complicated.

There is an important implication of the analysis presented here. As discussed in detail in Avinash et al. 2014 [21], the classical collisional and anomalous magnetic field diffusion time scales show that the VLISM magnetic field may be described using ideal MHD. The OHS magnetic field therefore drapes over the HP and thus should not be able to reconnect with IHS magnetic field (reconnection found in the vicinity of the HP in global numerical simulations is due to numerical diffusion and not due to the inclusion of a physical magnetic field diffusion coefficient). However, the instabilities described here, as illustrated in the cartoons of Fig. 4 (and possibly other forms of instability, e.g., [1]), provide a critical mechanism that allows IHS interplanetary and OHS interstellar magnetic field to reconnect. The form of the reconnected IHS and VLISM magnetic field described above might be an explanation for the observed galactic and anomalous cosmic ray behavior seen by Voyager 1. Furthermore, since the magnetic field configuration holds for either orientation of the IHS magnetic field, we believe that this explanation is quite robust. We note that Borovikov & Pogorelov 2014 [22] suggest that solar cycle variation might provide the perturbation to initiate the Zank instability. It is also possible that that the highly dynamical state of the IHS [23,24] will perturb the HP and thus drive instabilities, which can then lead to magnetic field reconnection. Such reconnection may 1) enhance the mixing of plasmas across the heliopause, and 2) provide open magnetic field lines that allow easy ingress of galactic cosmic rays into the heliosphere and easy loss of anomalous cosmic rays.

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