PROTON HEATING BY PICK-UP ION DRIVEN CYCLOTRON WAVES IN THE OUTER HELIOSPHERE: HYBRID EXPANDING BOX SIMULATIONS

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ABSTRACT

Using a one-dimensional hybrid expanding box model, we investigate properties of the solar wind in the outer heliosphere. We assume a proton–electron plasma with a strictly transverse ambient magnetic field and, aside from the expansion, we take into account the influence of a continuous injection of cold pick-up protons through the charge-exchange process between the solar wind protons and hydrogen of interstellar origin. The injected cold pick-up protons form a ring distribution function, which rapidly becomes unstable, and generate Alfvén cyclotron waves. The Alfvén cyclotron waves scatter pick-up protons to a spherical shell distribution function that thickens over that time owing to the expansion-driven cooling. The Alfvén cyclotron waves heat solar wind protons in the perpendicular direction (with respect to the ambient magnetic field) through cyclotron resonance. At later times, the Alfvén cyclotron waves become parametrically unstable and the generated ion-acoustic waves heat protons in the parallel direction through Landau resonance. The resulting heating of the solar wind protons is efficient on the expansion timescale.

Key words: solar wind – instabilities – plasmas

1. INTRODUCTION

Properties of the solar wind plasma in the outer heliosphere are much influenced by inelastic collisions between ions and neutrals of interstellar origin (Burlaga et al. 1996; Richardson & Stone 2009; Zank et al. 2009). The solar wind ions and interstellar neutrals interact through the charge-exchange process. The neutrals (mostly hydrogen) become ionized, and the interaction between the newly created pick-up ions and the ambient solar wind plasma leads to a deceleration of the solar wind and likely has an important effect on ion thermal energetics (Richardson et al. 1995; Wang et al. 2000; Richardson et al. 2008). The nonthermal pick-up ions play likely an important role at the termination shock (Burlaga et al. 2008; Decker et al. 2008). The actual form of the pick-up ion distribution function just upstream from the termination shock highly influences the shock properties and ion acceleration (Giacalone & Decker 2010; Matsukiyo & Scholer 2014; Yang et al. 2015).

A pick-up ion dominated distant solar wind can be to some extent described using a macroscopic multi-fluid approach (Zank et al. 2014). Global multi-fluid simulations show that the interaction between the solar wind and interstellar neutrals has an important effect on the global properties of the outer heliosphere (e.g., Usmanov et al. 2012). However, the highly nonthermal newly born pick-up ion population leads naturally to plasma instabilities where strongly kinetic processes such as the cyclotron and Landau resonances are expected (Gary 1993). Depending on the orientation of the background magnetic field, the pick-up ions have different distribution functions (Zank & Cairns 2000). A ring distribution function is generated by injection perpendicular to the ambient solar wind. Such a distribution has an effective perpendicular temperature anisotropy and may generate Alfvén cyclotron waves (or mirror instabilities, etc.); the generated waves scatter the ring pick-up protons to a spherical shell-like velocity distribution function (Lee & Ip 1987; Williams & Zank 1994) and may directly heat the solar wind protons through the cyclotron instability (Gray et al. 1996; Richardson et al. 1996). Injection parallel to the ambient magnetic field leads to several beam-type instabilities (Daughton & Gary 1998). For a general orientation of the ambient magnetic field, a ring-beam distribution function is generated and both the temperature anisotropy and the differential velocity could be a source of free energy for kinetic instabilities (Vandas & Hellinger 2015). The pick-up ion driven instabilities are active in the solar wind as indicated by in situ observation of the generated waves (Joyce et al. 2010; Cannon et al. 2014a, 2014b; Aggarwal et al. 2016).

The linear and nonlinear studies of pick-up ion driven instabilities usually assume a homogeneous plasma that is at odds with the ubiquitous turbulent fluctuations observed in the distant solar wind (Fraternale et al. 2016). In situ observations of enhanced wave activity (Joyce et al. 2010; Cannon et al. 2014a, 2014b; Aggarwal et al. 2016) indicate that the pick-up ion driven instabilities are active in the solar wind. This is supported by direct hybrid simulations of Hellinger et al. (2015) showing that kinetic instabilities may coexist with turbulence. The wave activity generated by pick-up ions may be a local source of turbulence as assumed in phenomenological transport models of turbulence (Zank et al. 1996; Matthaeus et al. 1999; Isenberg et al. 2003, 2010; Smith et al. 2006; Adhikari et al. 2015); the enhanced level of turbulence leads to enhanced cascade and heating rates. However, the connection between turbulence and kinetic instabilities driven by nonthermal particle velocity distribution functions is far from understood.

In this paper we investigate the long-time evolution of the expanding solar wind plasma under the effect of a continuous injection of pick-up protons. Section 2 describes the simulation method, the hybrid expanding box (HEB) model. Section 3 presents the main simulation results. In Section 4 we discuss the simulation results.
2. EXPANDING BOX MODEL

To study the response of the plasma to a slow expansion, we use the expanding box model (Grappin et al. 1993; Liever et al. 2001) implemented with the hybrid code (Matthews 1994; Hellinger et al. 2003). In the HEB model the expansion is described as an external force where a constant solar wind radial velocity \( v_{sw} \) is assumed. The radial distance \( R \) is then

\[
R = R_0 + v_{sw} t = R_0 \left( 1 + \frac{t}{t_c} \right),
\]

where \( R_0 \) is an initial radial distance and \( t_c = R_0/v_{sw} \) is the characteristic (initial) expansion time. The initial radial distance \( R_0 \) is one of the free parameters in the model. Here we assume a strictly transverse magnetic field and \( R_0 \sim 10 \text{ au} \).

Transverse scales (with respect to the radial direction) of a small portion of plasma, co-moving with the solar wind velocity, increase with time \( \propto (1 + t/t_c) \). The expanding box uses these co-moving coordinates, replacing the spatial dependence with the temporal one (see Equation (1)). The physical transverse scales of the simulation box increase with time (see Hellinger & Trávníček 2005 for a detailed description of the code), and the standard periodic boundary conditions are used.

The kinetic model uses the hybrid approximation, i.e., electrons are considered as a massless, charge neutralizing fluid, with a constant temperature; ions are described by a particle-in-cell model and are advanced by a Boris scheme that requires the fields to be known at half time steps ahead of the particle velocities. This is achieved by advancing the current density to this time step with only one computational pass through the particle data at each time step (Matthews 1994).

The characteristic spatial and temporal units used in the model are \( c/\omega_{pi0} \) and \( 1/\omega_{pi0} \), respectively, where \( c \) is the speed of light, \( \omega_{pi0} = (n_{p0} e^2 / m_p e_0)^{1/2} \) is the initial proton plasma frequency, and \( \omega_{pi0} = eB_0/m_p \) is the initial proton gyrofrequency (where \( B_0 \) is the initial magnitude of the ambient magnetic field, \( n_{p0} \) is the initial proton density, and \( e \) and \( m_p \) are the proton electric charge and mass, respectively; finally, \( e_0 \) is the dielectric permittivity of vacuum). We use the spatial resolution \( \Delta x = 0.25c/\omega_{pi0} \) and there are initially 131,072 particles per cell for the solar wind protons. Fields and moments are defined on a 1D (periodic) grid with 8192 points. Protons are advanced using a time step \( \Delta t = 0.05/\omega_{pi0} \), while the magnetic field \( B \) is advanced with a smaller time step \( \Delta t_B = \Delta t/10 \). The initial ambient magnetic field is directed along the (transverse) \( x \) direction, parallel to the ambient magnetic field \( B_0 = (B_0, 0, 0) \), and we impose a continuous expansion in the \( x \) and \( z \) directions with the characteristic time \( t_c = 10^4/\omega_{pi0} \). The radial direction is in the \( y \) direction. The expansion leads to a decrease of the density as \((1 + t/t_c)^{-2}\) whereas the magnitude of the magnetic field decreases as \((1 + t/t_c)^{-1}\) for the strictly transverse magnetic field.

In the simulation, pick-up protons are continuously injected (cf. Cowee et al. 2008). The injection mechanism is the charge exchange between interstellar neutrals and the solar wind protons. For the sake of simplicity we assume that the charge exchange is energy/velocity independent. For the loss rate of the incident solar wind protons with the distribution function \( f_p \) we have

\[
\left( \frac{df_p}{dt} \right)_{cx} = -\nu_{cx} f_p,
\]

where the charge-exchange frequency \( \nu_{cx} \) is taken to be \( \nu_{cx} = 10^{-6}\omega_{pi0} \). The characteristic charge-exchange time \( t_{cx} = 1/\nu_{cx} \) is 100 times longer than the expansion time \( t_c \).

The solar wind protons that are lost through the charge-exchange process are removed from the simulation (but their velocities are stored) and replaced by cold pick-up protons with the mean radial velocity \( v_R = -10v_A \). The charge-exchange process (Equation (2)), leads to the decrease of the solar wind proton number density (with respect to the electron number density) as \( n_p/v_e \propto \exp(-\nu_{cx} t) \) (note that at the same time the particle number densities decrease owing to the expansion). At the end of the simulation at \( 8t_c \), there is about 8% of pick-up protons. The injection of pick-up protons also decelerates the solar wind plasma. At the end of the simulation the solar wind protons are decelerated by about 0.75\( v_A \).

3. SIMULATION RESULTS

The chosen initial conditions are stable with respect to kinetic instabilities. The continuous injection of pick-up ions and expansion tend to change the plasma properties, creating free energy for kinetic instabilities. Let us investigate the evolution of the HEB simulation, starting with the wave activity.

Figure 1 shows an evolution of the fluctuating magnetic field (normalized to the ambient magnetic field) \( \delta B^2/B_0^2 \) as a function of time (top panel). The bottom panel shows the color scale plot of the fluctuating magnetic field as a function of time and wave vector \( k \). Figure 1 shows that \( \delta B/B_0 \) and grows exponentially for \( 0.1t_c \lesssim t \lesssim 0.2t_c \). After saturation \( \delta B \) grows secularly, i.e., about linearly in time (cf., Matteini et al. 2006; Rosin et al. 2011; Kunz et al. 2014). Between \( t_c \lesssim t \lesssim 2t_c \) there
is another change of behavior; \( \delta B/B_0 \) remains about constant. For \( t \gtrsim 2t_e \), \( \delta B/B_0 \) grows again in a secular manner. The bottom panel of Figure 1 shows that waves are initially generated with \( 0.1 \lesssim kd_p \lesssim 0.2 \). The fluctuating wave energy then shifts to smaller wave vectors (longer wavelengths) \( kd_p \sim 0.05 \). For \( t \gtrsim 2t_e \), a secondary population of wave modes with \( 0.1 \lesssim kd_p \lesssim 0.16 \) appears.

The observed wave activity is generated by the continuously injected pick-up protons that initially form a ring velocity distribution function (Vandas & Hellinger 2015). The ring velocity distribution function has a strong effective perpendicular temperature anisotropy that leads to the generation of Alfvén ion cyclotron (AIC) waves (Gray et al. 1996), which in turn diffuse the ring ions. Figure 2 shows the evolution of the pick-up proton velocity distribution functions. At \( t = 0.2t_e \), i.e., around the saturation of the initial exponential growth of the magnetic fluctuations, the pick-up proton velocity distribution function takes the shape of a partially diffused ring that is expected for the saturated level of a weak ring instability (cf., Florinski et al. 2010). The pick-up proton velocity distribution function exhibits a strong concentration of newly born ions at the injection position, \( v \sim 0 \) and \( v_\parallel \sim 10v_A \). At \( t = t_e \), the pick-up proton velocity distribution exhibits a thick spherical shell velocity distribution function as well as diffused enhancement around the injection region \( v \sim 0 \) and \( v_\parallel \sim 10v_A \). For a cold ring, a thin spherical shell is expected but the expansion leads to an anisotropic cooling that transports the diffused pick-up protons to the regions with smaller velocities. At \( t = 2t_e \), the pick-up protons exhibit a shell velocity distribution function that is further thickened owing to expansion-driven cooling. This trend continues until \( t = 8t_e \); we observe no qualitative changes between \( t = 2t_e \) and \( t = 8t_e \).

The appearance of a secondary population of wave modes indicates another possible secondary instability. The AIC waves are prone to parametric instabilities (Hollweg 1994); the AIC waves couple to compressible ion-acoustic modes and AIC waves with different wavelengths. Enhanced proton density fluctuations may be an indication of such a process. Figure 3 shows the (core) proton density fluctuations \( \delta n_p^2/\langle n_p^2 \rangle \) (normalized to the background density \( n_p \)) as a function of time (top panel). The bottom panel shows the color scale plot of the fluctuating magnetic field as a function of time and the wave vector \( k \). Figure 3 shows that weak density fluctuations appear during the exponential phase. This is due to the second-order effects owing to ponderomotive force. After the saturation there is an exponential-like growth of the density fluctuations until \( t \sim 1.5t_e \). The enhanced density fluctuations appear initially around \( kd_p \sim 0.1 \) at \( t = 2t_e \) and shift to smaller wave vectors as time goes on.

Figures 1 and 3 suggest that the AIC waves generated by the pick-up protons become parametrically unstable and generate the ion-acoustic waves and the secondary population of AIC waves that parametrically couple to compressible ion-acoustic modes.
waves. An additional, bi-coherence analysis (not shown here) indicates a weak phase coherence between the two AIC waves and compressible modes. The phase coherence starts for \( t > t_e \) and remains until \( t = 8t_e \); it is important to note that the situation is symmetric with respect to the background magnetic field \( B_0 \), the initial AIC waves are generated both parallel and anti-parallel to \( B_0 \), and the secondary AIC waves as well as the ion-acoustic waves also appear both parallel and anti-parallel to \( B_0 \). The presence of forward and backward propagating modes considerably complicates the phase coherence analysis. The actual nature of the parametric instability needs more work as the theoretical properties of parametric instabilities at ion kinetic scales are complicated (cf., Hollweg 1994; Vasquez 1995).

![Figure 4](image1.png)

**Figure 4.** Evolution of the (core) proton velocity distribution function (normalized to its maximum value) as a function of \( v \) and \( \nu \) at \( t = 0.2t_e, t_e, 2t_e, \) and \( 8t_e \) (from top to bottom). The color scale is shown on the top.

The ion-acoustic modes interact through Landau resonance with protons and lead to parallel acceleration/heating of the resonant particles (Araneda et al. 2008; Matteini et al. 2010). Figure 4 shows the evolution of the core proton velocity distribution functions. At \( t = t_e \), i.e., around the saturation of the initial exponential growth of the magnetic fluctuations, the solar wind protons are essentially unaffected by the AIC waves. At \( t = t_e \), the solar wind protons exhibit signatures of perpendicular heating (and parallel cooling) through cyclotron resonance with the AIC waves (for \(|v| \sim 0.3-0.6v_A\)). At \( t = 2t_e \) the solar wind proton distribution functions exhibit regions with an efficient parallel heating (for \(|v| \sim 0.3-0.7v_A\)) owing to the Landau resonance with the compressible ion-acoustic waves.

The total proton distribution function consists of both the solar wind and pick-up ions. It is interesting to look at this total distribution function. Figure 5 shows the total one-dimensional velocity distribution function \( F \) (normalized to its maximum) as a function of \( v \) at \( t = 0.2t_e, t_e, 2t_e, \) and \( 8t_e \) (from top to bottom). The one-dimensional distribution function \( F \) is obtained by integrating the three-dimensional total proton distribution function over spherical angles \( \Omega = 4\pi \). Figure 5 shows in a more quantitative way the thickening of the pick-up ion shell. At the end of the simulation (Figure 5, bottom panel) the one-dimensional distribution function \( F \) falls as \( \propto v^{-1.4} \) between 3 and \( 8v_A \). We expect that the distribution function of

![Figure 5](image2.png)

**Figure 5.** Evolution of the total (core solar wind + pick-up protons) one-dimensional distribution function as a function of \( v \) at \( t = 0.2t_e, t_e, 2t_e, \) and \( 8t_e \) (from top to bottom).
pick-up ions would eventually become power-law like with a cutoff at the injection velocity.

Macroscopic evolution of the simulated system is given in Figure 6, which compares the evolution of the solar wind proton temperatures (parallel, perpendicular, and total ones) with the double adiabatic/CGL prediction (Chew et al. 1956)

\[ T_p|_{\text{CGL}} \propto \frac{n^2}{B^2} \quad \text{and} \quad T_{p\perp}|_{\text{CGL}} \propto B \]

(and the adiabatic one \( T_{p\text{adiab}} \propto n^{2/3} \) for the total temperature). During the initial exponential growth of the magnetic fluctuations, protons are cooled in the parallel direction and heated in the perpendicular direction as expected from the cyclotron resonance between protons and AIC waves (cf., Hollweg & Isenberg 2002); this cooling is also apparent in Figure 4 (at \( t = t_c \)). An efficient parallel heating appears later, \( t \gtrsim t_c \), during the generation of enhanced density fluctuations due to the parametric instability, in agreement with the microscopic properties of the proton velocity distribution function.

Finally, the numerical code keeps information about the velocities of the neutralized solar wind protons. Figure 7 shows the velocity distribution function \( f_n \) of the accumulated hot neutrals of solar wind origin at the end of the simulation: the left panel displays \( f_n \) as a function of the radial component of the velocity \( v_R \) and the component parallel to the ambient magnetic field \( v \). The right panel shows \( f_n \) as a function of \( v_{\perp} \) and \( v_R \) and the component of the velocity perpendicular both the radial direction and the ambient magnetic field \( v_{\perp,1} \). The two 2D projections indicate that the 3D velocity distribution function of hot neutrals is rather complex. The distribution is elongated along the radial direction owing to the overall deceleration of the solar wind plasma due to the injection of pick-up protons. The different profiles of the distribution in \( v \) and \( v_{\perp,1} \) are a result of generally anisotropic proton velocity distribution function evolving differently in the direction parallel and perpendicular to the ambient magnetic field.

4. DISCUSSION

We investigated the effects of continuous injection of pick-up protons in the distant solar wind using a 1D HEB model. We assumed an ideal 1D homogeneous system parallel to the ambient magnetic field directed along the transverse direction with respect to the radial direction. We assumed slow expansion \( (t_c = 10^4 \omega_{cpl}^{-1}) \) in the two transverse directions and a slow continuous injection of cold pick-up protons due to the charge-exchange process with the solar wind protons \( (t_c = 100t_c) \). The injection of pick-up protons leads to the formation of a ring velocity distribution distribution. This distribution becomes rapidly unstable and generates AIC waves that scatter the pick-up protons through the cyclotron resonance, which consequently form a shell velocity distribution distribution. The AIC waves also scatter the solar wind protons and heat them in the perpendicular direction and cool them in the parallel one. The continuous injection of pick-up protons keep the instability active, and, at later times, the AIC waves grow slowly (secularly, about linearly in time). The AIC waves eventually become unstable with respect to a parametric instability that leads to formation of a secondary, shorter wavelength population of AIC waves and compressible ion-acoustic waves. The ion-acoustic waves interact with solar wind protons through the Landau resonance. The combined effect of the AIC and ion-acoustic waves lead to an efficient proton parallel and perpendicular heating. The pick-up proton shell distribution thickens during the evolution due to diffusion.
owing to the AIC waves and due to the expansion-driven cooling; eventually, a power-law distribution is expected with a cutoff near the injection velocity. The pick-up proton generated AIC waves and the ion-acoustic waves generated by the parametric instabilities may be partly responsible for the enhanced level of density fluctuations observed in the outer heliosphere (Bellamy et al. 2005; Zank et al. 2012).

In the presented simulation we initialized the solar wind protons with $\beta_p = 0.2$. To test the sensitivity of the simulation results with respect to $\beta_p$ we performed additional simulations with $\beta_p = 0.1$ and 1. For higher solar wind proton beta the cyclotron perpendicular heating becomes less efficient but overall behavior remains the same. For higher $\beta_p$ one expects that the mirror instability would become important (Gary et al. 1997) and, also, the properties of the parametric instabilities depend on $\beta_p$ (Hollweg 1994). Therefore, the present results are relevant for $\beta_p \lesssim 1$.

The present model is in many respects simplified: only one dimension is considered, the solar wind velocity is assumed to be constant and is about ten time faster than in the reality. Also, the system is assumed homogeneous, no pre-existing fluctuations/turbulence is assumed, Coulomb collisions and electron impact ionization are neglected, etc. However, the model self-consistently describes the kinetic plasma behavior in the expanding solar wind where pick-up protons are continuously injected.

The one-dimensional geometry strongly reduces the available physics: only parallel propagating modes are allowed. In a low-beta plasma the ring is expected to generate cyclotron waves primarily along the magnetic field, which justifies the 1D geometry but other instabilities (such as the mirror instability) may appear at oblique angles and may modify the nonlinear behavior. Also the 1D geometry tends to lead to larger amplitude fluctuations, which are prone to parametric instabilities. At 2D and 3D the effect of parametric instabilities will be likely reduced.

The numerical resolution of the code could be the source of other problems; our choice of the spatial grid, the box size, and the time step guarantees a good resolution of the AIC waves. While the used number of particles per cell is substantial (note that at $t = t_r$ there are about $10^3$ particles per cell for pickup protons) the resulting numerical noise may lead to enhanced scattering of the ring pick-up protons (Florinski et al. 2016). This is likely a minor problem since the continuous injection of pickup ions tends to keep the system unstable and rapidly generates fluctuations well above the numerical noise level.

The presence of large-scale fluctuations/turbulence will modify the initial local pick-up ion distribution function and the resulting instabilities (Zank & Cairns 2000). For injection at nearly parallel angles with respect to the magnetic field beam-type instabilities are expected (Gary 1993). These instabilities have different nonlinear properties but quite generally one expects formation of partial spherical shells (cf., Williams & Zank 1994; Matteini et al. 2015).

Coulomb collisions are expected to be weak in the solar wind but may lead at the expansion timescale to scattering of pick-up ions (via interaction with the solar wind ions, cf., Tracy et al. 2015; Hellinger 2016) reducing thus the source of free energy for instabilities. Electron impact ionization is expected to generally have a subdominant effect with respect to the charge-exchange process in the solar wind (but it is likely important in the heliosheath, cf., Decker et al. 2008). This process would have a similar effect as the charge exchange (i.e., generation of pick-up ions) but without the reduction of the solar wind ion density. We expect the overall effect of electron impact ionization would be comparable to that of charge exchange.

The connection between instabilities driven by the pick-up ions and turbulence remains an important open question. The turbulent fluctuations (or another wave activity) already present in the solar wind would scatter the pick-up ions and possibly reduce the source of free energy for instabilities. On the other hand, instabilities driven by pick-up ion ring-beam velocity distribution function generate typically waves at short, ion scales, often at nearly parallel angles with respect to the ambient magnetic field. Coupling between the strongly oblique turbulent fluctuations and quasi-parallel waves at ion scales is likely weak (while waves generated at strongly oblique angles seem to participate in the cascade, cf., Hellinger et al. 2015). There are many open problems that will be subject of future work.

In conclusion, the present work shows that (i) collisionless plasma with an energetically important population of pick-up ions generally needs a fully kinetic treatment, (ii) pick-up ion generated waves are able to directly quite efficiently heat the solar wind protons, (iii) the distribution function of pick-up ions at later times/larger distances has a wide spread of velocities/energies owing to scattering of the initial distribution on the generated waves and to the expansion-driven cooling, (iv) the hot neutrals of solar wind origin have a complex velocity distribution function since they are neutralized at different distances and the solar wind ion temperature and the bulk velocity vary substantially over time/distance.

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