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Pickup Ion–Mediated Magnetic Reconnection in the Outer Heliosphere

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Abstract

Pickup ions (PUIs) play a crucial role in the heliosphere, contributing to the mediation of large-scale structures such as the distant solar wind, the heliospheric termination shock, and the heliopause. While magnetic reconnection is thought to be a common process in the heliosphere due to the presence of heliospheric current sheets, it is poorly understood how PUIs might affect the evolution of magnetic reconnection. Although it is reasonable to suppose that PUIs decrease the reconnection rate since the plasma beta becomes much larger than 1 when PUIs are included, we show for the first time that such a supposition is invalid and that PUI-induced turbulence, heat conduction, and viscosity can preferentially boost magnetic reconnection in heliospheric current sheets in the distant solar wind. This suggests that it is critical to include the effect of the turbulence, heat conduction, and viscosity caused by PUIs to understand the dynamics of magnetic reconnection in the outer heliosphere.

Unified Astronomy Thesaurus concepts: Heliosphere (711); Solar magnetic reconnection (1504); Pickup ions (1239)

1. Introduction

It has now been established over several decades that pickup ions (PUIs) born through the interaction of interstellar neutral atoms with the solar wind play a crucial role in shaping the physics and structure of the heliosphere. The Voyager 2 and New Horizons spacecraft observed the increase of the solar wind temperature in the outer heliosphere, and this has been understood as the result of the dissipation of turbulence driven by newly born PUIs (Williams et al. 1995; Matthaeus et al. 1999; Isenberg et al. 2003) and modeled well in the upwind and downwind directions (Matthaeus et al. 1999; Zank et al. 2018; Nakanotani et al. 2020). The structure of the heliospheric termination shock (HTS) is greatly mediated by PUIs (Matsukiyo & Scholer 2014; Mostafavi et al. 2017, 2018; Kumar et al. 2018). While PUIs are preferentially reflected at the HTS and gain energy, the core-proton component transmits downstream without a strong heating (Zank et al. 1996a). This may result in a large shock thickness as observed by the Voyager spacecraft, which can be described by a PUI MHD model with PUI viscosity and heat conduction effects (Mostafavi et al. 2017). Charge exchange of neutral atoms around the heliopause causes a pseudo-gravitational force that drives a Rayleigh–Taylor–like instability in the nose region (Zank et al. 1996b; Zank 1999; Florinski et al. 2005; Opher et al. 2021) as well as a Kelvin–Helmholtz–like instability (Borovikov et al. 2008; Avinash et al. 2014). It is possible too that PUIs can modify the nature of low-frequency waves in the distant solar wind, introducing a modified sound speed and moreover, very-long-wavelength PUI-modified waves can be driven unstable by PUIs, for which there may be some evidence (Zank et al. 2005; Fujiki et al. 2014).

Although large-scale structures, waves, and discontinuities are mediated by PUIs in the heliosphere, the question of how PUIs affect magnetic reconnection in the heliosphere has not been addressed in any detail. This is because it is difficult to observationally locate where reconnection occurs, and we had/have only the Voyager and New Horizons spacecraft in the outer heliosphere. In addition, the Voyager spacecraft magnetometer did not have sufficient resolution to observe reconnection at current sheets, and unfortunately New Horizons does not have instrumentation to measure magnetic fields. However, because of the possibility that reconnection processes can yield energetic particles in the solar wind (Zank et al. 2014b; Khabarova et al. 2015; Zhao et al. 2018) and the heliosheath (Drake et al. 2010; Zank et al. 2015; Zhoa et al. 2019; Nakanotani et al. 2021), it is necessary to understand the effect of PUIs on magnetic reconnection. An interesting and important question is if PUIs preferentially boost magnetic reconnection, then this may indicate that there are more energetic particles than we currently expect in the outer heliosphere.

It is reasonable to expect that PUIs reduce the reconnection rate since the plasma beta (the ratio of the thermal plasma pressure to the magnetic pressure) becomes much greater than 1 when the PUI pressure is included. Supposing that the PUI plasma system is a single and ideal MHD fluid, the total plasma beta becomes $\beta = \beta_e + \beta_p + \beta_{\rm PUI}$ where the subscripts stand for electron (e) and proton (p), respectively. Since the effective PUI plasma beta (Matsukiyo & Scholer 2014) is typically $\beta_{\rm PUI} = 2\alpha M_{\rm A}^2 \sim 12.8$ in the outer heliosphere where the ratio of the PUI to solar wind plasma density $\alpha \sim 0.1$ and Alfvén Mach number $M_{\rm A} \sim 8$, the total plasma beta becomes much greater than 1. Li & Liu (2021) recently constructed a magnetic reconnection model that includes the effect of thermal pressure based on Liu et al. (2017), finding that the reconnection rate tends to decrease in a high-plasma beta environment. This is a consequence of the heated plasma downstream of the reconnection region stagnating the outflow, which acts to decelerate the outflow and results in a low reconnection rate. Therefore, this suggests that PUIs decrease the reconnection rate.

However, this expectation is based on an ideal-fluid perspective exclusively, and does not include some important PUI-induced physics, these being PUI-driven turbulence, heat conduction, and viscosity. The turbulence is driven by newly born PUIs, which form initially a ring-beam distribution function that is unstable and resonant with parallel-propagating Alfvén waves (Isenberg et al. 2003). This PUI-driven turbulence has been observed as a spectral enhancement in the solar wind turbulence (Hollick et al. 2018) and is strong enough to heat the proton core component as a consequence of the dissipation of turbulence (Williams et al. 1995; Matthaeus et al. 1999; Isenberg et al. 2003). PUI heat conduction and viscosity are the result of the first- and second-order anisotropies in the PUI velocity distribution function, respectively (Zank et al. 2014a). Mostafavi et al. (2017) shows that these effects efficiently smooth the HTS, and that the thickness of the smoothed transition region is consistent with Voyager 2 observations (Richardson et al. 2008). As we discuss in detail below, these effects have the possibility of increasing the reconnection rate. Therefore, the simplified description of PUI magnetic reconnection in the absence of the additional effects introduced by PUI-induced physics can lead to incorrect conclusions about PUI-mediated reconnection in the heliosphere.

In this Letter, we predict that PUI-induced turbulence, heat conduction, and viscosity can act preferentially to increase the reconnection rate at heliospheric current sheets (HCSs) in the outer heliosphere. This Letter focuses on the region beyond the ionization cavity (∼10 au) where PUIs are expected to play a dominant role in the thermodynamics of the solar wind and consider H^+ PUI. Note that since there have been several reports of reconnection events in HCSs at 1 au (Gosling et al. 2006, 2007), it is likely that reconnection also occurs in HCSs in the outer heliosphere.

2. PUI-induced Turbulence, Heat Conduction, and Viscosity

The possibility that turbulence increases the magnetic reconnection rate in space and astrophysical plasmas has been considered before (Matthaeus & Lamkin 1985; Lazarian & Vishniac 1999). This can be interpreted as a consequence of decreasing the current sheet aspect ratio due to magnetic field wandering introduced by the turbulence. According to Higashimori et al. (2013), in which they perform 2D Reynolds-averaged MHD simulations (Yokoi & Hoshino 2011), the condition for the boost in magnetic reconnection due to turbulence can be described in terms of the quantity $C_\tau = \sqrt{C_\beta}\tau_{\rm turb}/\tau_{\rm A}$, where C_β is a turbulence model parameter ($C_\beta = 0.3$; Higashimori et al. 2013), $\tau_{\rm turb}$ the turbulence timescale, and $\tau_{\rm A} = \delta/v_{\rm A}$ the Alfvén crossing time (δ is the half-thickness of a current sheet). When C_τ falls into the range of $0.8 \leqslant C_\tau \leqslant 1.6$, the reconnection rate is dramatically increased (Higashimori et al. 2013). Using this criterion, we check whether PUI-driven turbulence causes explosive reconnection.

PUI-driven turbulence provides a favorable mechanism to boost magnetic reconnection. Assuming that the PUI-driven turbulence is highly Alfvénic (Zank & Cairns 2000), we can approximate the turbulence timescale as $\tau_{\rm turb} \approx \lambda_{||}/v_{\rm A}$, where $\lambda_{||}$ is the parallel turbulence length scale and defined by $\lambda_{||} = 2\pi c_p/\Omega_c$ (Isenberg 2005; Oughton et al. 2011). Here, c_p is the PUI characteristic speed, which is equivalent to solar wind speed, Ω_c is the proton-cyclotron frequency, and we assume that the magnitude of the interplanetary magnetic field is described as $B = B_0(R_0/R)$ with $B_0 = 0.5$ nT at $R_0 = 10$ au. The condition C_τ then results in $C_\tau = \sqrt{C_\beta}\lambda_{||}/\delta$. The half-thickness of HCSs is assumed to be $\delta \sim 10^5$ km (Liou & Wu 2021). Figure 1 shows C_τ for several PUI characteristic speeds, $c_p = 300$, 400, and 500 km s^{-1}, which we assume a constant solar wind speed for simplicity. The gray shadowed region corresponds to the condition of explosive turbulent reconnection. For instance, with a PUI characteristic speed of 400 km s^{-1}, efficient turbulent reconnection can occur from 30 to 55 au. The slower (300 km s^{-1}) and faster (500 km s^{-1}) speed covers 20–40 and 30–70 au, respectively. Therefore, this indicates that the PUI-driven turbulence can boost magnetic reconnection over a wide range of distances for several PUI characteristic (or solar wind) speeds.

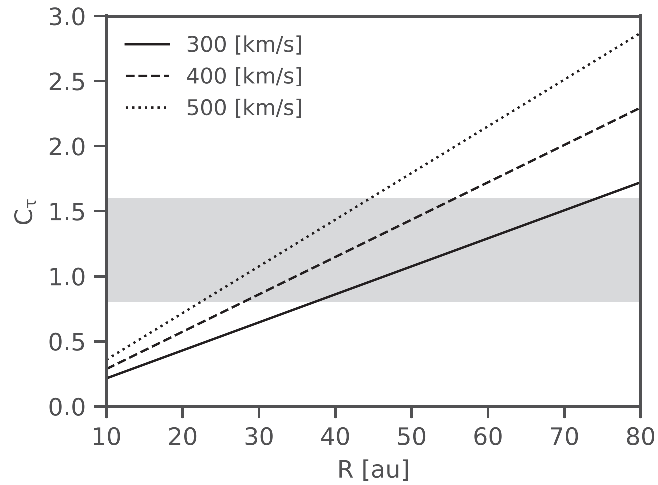

Figure 1. Reconnection boost parameter, C_τ, due to PUI-driven turbulence for several PUI characteristic speeds $c_p = 300$, 400, and 500 km s^{-1}, which are equivalent to solar wind speed. The gray shadowed region corresponds to the condition of explosive magnetic reconnection (Higashimori et al. 2013).

The PUI-induced heat conduction and viscosity yields the fluid and magnetic Prandtl numbers, $Pr_p = \nu_p/(m_p n_t \kappa_p) \ll 1$ and $Pr_{mp} = \nu_p/(m_p n_t \eta) \gg 1$ in the outer heliosphere. Here, m_p is the proton mass, ν_p the PUI viscosity, κ_p the PUI heat conduction, and η the magnetic resistivity in the solar wind. We set the total plasma density to be $n_t = n_0(R_0/R)^2 + n_p$ where a core-plasma density $n_0 = 0.1$ cm^{-3} at $R_0 = 10$ au, and a constant PUI density $n_p \sim 8 \times 10^{-4}$ cm^{-3} (McComas et al. 2021). According to Zank et al. (2014a), $\nu_p = P_p\tau_s/15$ and $\kappa_p = c_p^2\tau_s/3$, where τ_s is the scattering time of PUIs, and we set $\tau_s = \Omega_c^{-1}$. We assume that the PUI pressure can be derived from either a shell ($P_p = m_p n_p c_p^2/3$) or filled-shell ($P_p = m_p n_p c_p^2/7$) distribution (Vasyliunas & Siscoe 1976; Zank 2016; Zhao et al. 2019). We use a Spitzer formalism for magnetic resistivity, $\eta = d_e^2\tau_e^{-1}$(Spitzer 1962) where d_e is the electron inertial length, and τ_e the dissipation timescale. Here, we assume $\tau_e = d_i/v_{te}$ based on the scale of wave–particle interaction (Verma 1996) where d_i is the ion (proton) inertial length, and v_{te} the electron thermal speed, being set as a constant using a temperature of 10^4 K (McComas et al. 2021). Figure 2 shows the PUI fluid (top panel) and magnetic (bottom panel) Prandtl numbers for a shell (solid) and filled-shell (dashed) distributions. Here, we use a constant PUI characteristic speed, $c_p = 400$ km s^{-1}. Both the fluid and magnetic

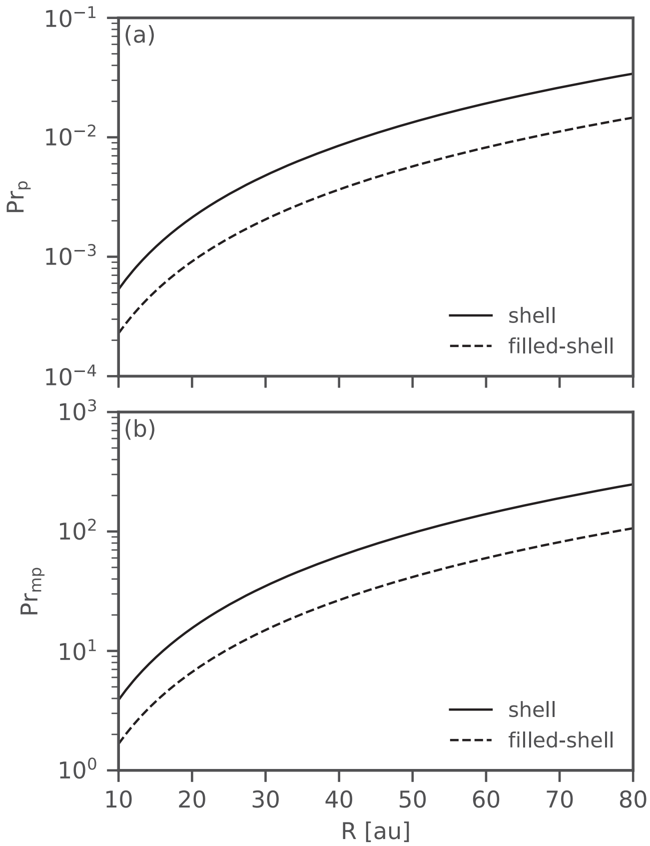

Figure 2. (a) PUI fluid Prandtl number $Pr_p = \nu_p/(m_p n_t \kappa_p)$. (b) PUI magnetic Prandtl number $Pr_{mp} = \nu_p/(m_p n_t \eta)$. Solid and dashed lines correspond to shell and filled-shell distributions.

Prandtl numbers follow Pr_p, $Pr_{mp} \propto R^2$. We can see that the fluid (magnetic) Prandtl number is much less (larger) than 1 in the outer heliosphere. This indicates that the PUI viscosity dominates the magnetic resistivity, and the PUI heat conduction process is much faster than the viscous timescale. Note that the fluid Prandtl number does not depend on c_p.

These Prandtl numbers match a condition that corresponds to a boost in magnetic reconnection. Minoshima et al. (2016) perform 2D single-fluid MHD simulations that include heat conduction and viscosity effects, and find that a small fluid Prandtl number and a large magnetic Prandtl number ($Pr < 1$ and $Pr_m > 1$) preferentially boosts magnetic reconnection. Their interpretation is that having the viscosity stronger than the resistivity ($Pr_m > 1$) results in a broader vortex layer than the current sheet layer, and the quadrupolar vortex excited in the vortex layer efficiently carries the upstream magnetic flux toward the reconnection region and the reconnection rate increases. The heat conduction plays a role in sustaining a current layer narrower than the vortex layer by convecting heating energy generated by viscous dissipation away from the reconnection site. Since the PUI heat conduction and viscosity precisely satisfy the condition ($Pr_p \ll 1$ and $Pr_{mp} \gg 1$), we conclude that PUIs can effectively accelerate magnetic reconnection.

PUI heat conduction introduces a further very interesting possibility, and this is to relax the condition of the Li & Liu (2021) reconnection model. A primary reason for the decrease of the reconnection rate in a high-beta plasma is that the heated plasma downstream acts to decelerate the outflow. Consequently, if the PUI heat conduction efficiently removes the thermal (heated) energy along the magnetic field, this can lead to a relaxation of the Li & Liu (2021) model, with the result that the reconnection rate may increase. A similar effect has been found in single-fluid MHD simulations with heat conduction (Chen et al. 1999).

3. Conclusion

In this Letter, we have presented the possibility that PUI-induced turbulence, heat conduction, and viscosity preferentially boost magnetic reconnection at HCSs in the outer heliosphere. This is contrary to the simplified expectation from a single-fluid point of view that PUIs provide a high-plasma beta condition and decrease the reconnection rate. It, therefore, suggests that we must take into account the PUI-induced physics to understand magnetic reconnection in the presence of PUIs. Since PUIs introduce the possibility of boosting magnetic reconnection, this indicates that PUIs can be accelerated efficiently in PUI-mediated magnetic reconnection. This may be of particular interest to the acceleration of the anomalous cosmic-ray component in the vicinity of the HCS and just downstream of the HTS (Zank et al. 2015; Zhao et al. 2019). Future work will examine the mediation of magnetic reconnection due to PUIs using nonlinear simulations. We plan to use multifluid MHD simulations that incorporate a turbulence model (Zank et al. 2012), PUI-induced heat conduction, and viscosity effects (Zank et al. 2014a). In the MHD simulation model, the PUI and thermal plasma components are treated separately.

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