A possible explanation for the enhancement of energetic particles downstream of the heliospheric termination shock

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Abstract. \textit{Voyager} 2 observations of the energetic particle “time-intensity” profiles from \(~\sim\~1.8\) to \(~\sim\~40\) MeV show that the flux peaks downstream of the heliospheric termination shock (HTS), which is inconsistent with the predictions of classical diffusive shock acceleration (DSA). Previous studies suggest that shocks are effective in generating downstream magnetic flux ropes, islands or plasmoids. These dynamically interacting small-scale structures can accelerate charged particles statistically through reconnection-related processes. We present a preliminary study of the magnetic field and plasma properties together with the energetic particle data during the V2 crossing of the HTS. We apply a local stochastic acceleration model associated with solar wind magnetic island dynamics to explain the unusual behavior of energetic particles observed in the vicinity of the HTS. An analytic solution for the particle velocity distribution function derived from the Zank et al. statistical transport theory is used to fit the observed particle flux amplification downstream of the HTS. The results show that stochastic acceleration by interacting magnetic islands can successfully predict the observed (i) peaking of particle intensities behind the HTS, instead of at the shock front; (ii) increasing of the particle flux amplification factor with increasing particle energy; and (iii) increase in distance between the particle intensity peak and the HTS with increasing particle energy; This study illustrates the possibility of local acceleration in the inner heliosheath due to the dynamical interaction of magnetic islands.

1. Introduction

Diffusive shock acceleration (DSA) is usually considered to be responsible for energizing charged particles at shock waves and provides an explanation for abundant gradual solar energetic particle (SEP) events \cite{e.g., 1 - 6}. As a classical mechanism for particle acceleration \cite{7 - 10}, DSA, in 1D stationary cases, predicts that the particle intensity peaks at the shock, after which it is a constant. The distribution of diffusively accelerated particles at and downstream of the shock is a power law in momentum \(p^{-q}\) with the index \(q = 3r/(r-1)\) depending only on the shock compression ratio \(r\) \cite{6, 12}. However, steady-state DSA predictions do not always describe observations. Particle energization up to MeV energies that is inconsistent with classical DSA has been observed frequently, both at 1 au \cite{e.g., 14 - 19} and in the outer heliosphere \cite{12, 21, 22}. A notable exception is the \textit{Voyager} spacecrafts observation of the anomalous cosmic ray (ACR)
intensity profile that was observed to peak behind the HTS and to posses a spectrum far harder than predicted by classical DSA theory [13, 14]. The accelerated ACR spectrum observed at the HTS crossing in 2007 was hard with a power law index of $\sim 4.6$ despite the shock compression ratio being $\sim 2$, for which classical DSA predicts an index of -6. Previous studies [23, 24] suggest that the energetic particles were accelerated at an earlier time and trapped behind the shock. They convected more slowly than the propagating shock into the distant heliosphere. Below we present another possible explanation.

The DSA mechanism relies on magnetic turbulence to scatter particles back and forth across the shock, but the contribution of the turbulence to the direct energization of particles may be underestimated. MHD turbulence downstream of the shock dissipates via highly dynamical localized reconnection events, generating magnetic islands, which can further energize charged particles through local stochastic processes. Magnetic reconnection in the solar wind can occur at current sheets of various scales [19]. As a fundamental physical process related to energy conservation, magnetic reconnection has been widely invoked to explain the energization and heating of space plasma through the conversion of magnetic energy into plasma kinetic energy [25, 26]. A statistical acceleration mechanism for charged particles related to magnetic reconnection was first proposed by Matthaeus et al. [27], Goldstein et al. [28], and Ambrosiano et al. [29], based on test-particle simulations. They found that turbulent fluctuations appearing in reconnection regions can trap test particles in the strong electric field for a time sufficiently long to produce significant acceleration. Based on these earlier ideas, several numerical simulations for particle acceleration via turbulent magnetic reconnection associated with multiple interacting magnetic islands have emerged [e.g., 29 - 35]. Simultaneous with these simulation developments, comprehensive transport theories for charged particles traversing numerous contracting and merging small-scale magnetic islands have been proposed by Zank et al. [11, 12] and further developed by le Roux et al. [37, 38, 39]. Reconnection associated with merging and contracting magnetic islands can yield a first-order Fermi process for the direct energization of particles trapped in the islands and also can be combined with other acceleration mechanisms, such as diffusive shock acceleration (DSA), to further accelerate trapped particles [12, 38]. Their theoretical solutions yield a power-law-like spectrum for the particle distribution.

Observational evidence suggests that the heliospheric current sheet (HCS) generates and confines small-scale flux ropes when disturbed. Due to the variability of the solar wind, magnetic reconnection occurs recurrently at the HCS [40], resulting in effective magnetic island merging in the vicinity of the HCS. When the HCS interacts with interplanetary shocks, magnetic island merging and contracting are likely to be more efficient because of the increased reconnection rate and strong compression [17, 18]. After the HTS crossing by V2, the direction of the magnetic field varied in a complicated and irregular manner [42]. Hill et al. [43] suggest that energetic particle intensities are enhanced in sectored inner heliosheath regions, i.e., in the vicinity of the wavy HCS that has been carried out into the inner heliosheath. This may indicate that the stochastic acceleration described by Zank et al. [11] may well be responsible for particle energization in the sectored heliosheath due to the interaction between HTS and the HCS. This provides a possible explanation for the observed strong enhancements in energetic particle flux behind the HTS.

2. Overview of the Observations

Figure 1 displays the variation of magnetic field and plasma properties associated with the V2 crossing of the HTS during the period between 2007 May 1 and 2008 May 1. The panels from top to bottom show, respectively, the interplanetary magnetic field (IMF) strength $|B|$, bulk flow speed $V_{sw}$, proton density $N_p$, proton temperature $T_p$, thermal pressure, magnetic pressure, total plasma pressure, and proton beta $\beta$. All data have been averaged over 1 day. During this period, Voyager 2 crossed the HTS at $\sim 84$ au on 2007 August 30, as indicated by
the dashed vertical line in each panel. The HTS crossing was characterized by a sudden drop in bulk flow speed, from supersonic to subsonic, the latter of which is due to the modification of the sound speed caused by PUIs [12, 45, 46, 47]. It is also accompanied by abrupt increases in the proton density, temperature, and plasma beta. The IMF strength did not show a large increase, but became very turbulent after the HTS crossing. It indicates that the HTS was a weak, quasi-perpendicular shock [45, 46, 47, 48]. The other properties, such as proton density, temperature, total pressure, and plasma beta all increase significantly after the crossing of HTS and exhibit a high level of fluctuations downstream of the shock.

![Figure 1.](image)

Figure 1. **Voyager 2** observations from 2007 May 1 to 2008 May 1. From top to bottom, the panels are the daily averaged magnetic field strength $B$, solar wind speed $V_{sw}$, proton density $N_p$, proton temperature $T_p$, thermal pressure, magnetic pressure, total plasma pressure, and proton beta $\beta$. The HTS crossing is taken to be 2007 August 30 (dashed vertical line).

Figure 2 shows the probability distribution of the plasma beta in the upstream, downstream, and further downstream region. The changes of plasma beta in the upstream region were stable and most of them were less than or concentrated around 1, but in the downstream region, beta increased significantly and changed dramatically. About 35% of plasma beta has a value greater than 2 downstream of the HTS. The large plasma beta corresponds to a decrease in the magnetic field magnitude or an increase in plasma density and temperature, which indicates the possible existence of current sheets or discontinuities that bound the small-scale flux ropes. However, this is a curious result since only the thermal plasma is included and PUIs are neglected in the calculation of the plasma beta. Previous studies suggest that the thermal plasma remains relatively cold on transmission through the HTS and it is the PUIs that carry much of the energy [45, 46, 47]. The value of plasma beta calculated here is probably very much a lower bound.
Figure 2. The probability distribution of the plasma beta during the period between 2007 May 1 to 2008 May 1. From left to right, panels correspond to the upstream region, downstream region, and further downstream region.

Figure 3. Voyager 2 magnetic field observations from 2007 May 1 to 2008 May 1. From top to bottom, the panels are the daily averaged magnetic field strength $B$, three components $B_R$, $B_T$, and $B_N$ in the RTN coordinate system, the elevation $\theta$ and azimuthal $\phi$ angles of the magnetic field direction in the RTN coordinate system. The uncertainty of $B_R$, $B_T$, and $B_N$ is also shown, respectively.
Figure 3 shows the evolution of the daily averaged magnetic field strength $|B|$, three magnetic field components $B_R$, $B_T$, $B_N$, and the elevation $\theta$ and azimuthal $\phi$ angles of the magnetic field direction measured by Voyager 2 from 2007 May 1 to 2008 May 1. The uncertainties in $B_R$, $B_T$, and $B_N$ are also shown by way of reference. In the turbulent downstream region, we can clearly see frequent direction changes of the magnetic field as shown in the IMF elevation $\theta$ and azimuthal $\phi$ panels. It indicates that the HTS may generate high levels of MHD turbulence, waves, vortices, and structures downstream. Furthermore, the HTS may be located in the vicinity of interplanetary sector boundaries, i.e., the wavy HCS, due to the rapid changes in magnetic field directions. The interaction of the HTS and the HCS may trap plasmoids that are formed downstream of the HTS and produce more structures because of an increased reconnection rate. All these factors suggest that plasmoid-related particle acceleration downstream of the HTS is likely to be important.

Figure 4 shows the Voyager 2 CRS observations of ACR proton flux immediately upstream and downstream of the HTS. The panels from top to bottom show the daily averaged energetic proton flux for the 7 energy bins corresponding to an energy range of [1.8, 12.8] MeV. Several key points are apparent. The first is that an exponential-like increase in the particle flux ahead of the shock is present, especially for low energies. This is consistent with DSA only and no additional acceleration processes ahead of the HTS are necessary, as discussed in Zank et al [12]. However, the downstream fluxes are completely different from the predictions of conventional DSA theory, which predicts that the particle intensity downstream of the shock should be constant with distance for all energies. Instead, each energy is amplified above its value at the HTS and the amplification is very clearly ordered by increasing energy, i.e., an increasing amplification with increasing particle energy.

Figure 5 shows the ACR proton spectra measured by the Voyager 2 CRS detector at 9 representative instances in panels from top left to bottom right, and organized in chronological order. We plot spectra using the 1-day averaged particle flux data. The 10 energy bands used here are 1.8–2.2 MeV, 2.2–3.0 MeV, 3.0–4.6 MeV, 4.6–6.2 MeV, 6.2–7.7 MeV, 7.7–10.3 MeV, 10.3–12.8 MeV, 12.8–15.3 MeV, 15.3–17.9 MeV, 17.9–22.3 MeV. We plot the average energy for each channel as the representative energy. To understand the spectral evolution, a linear fit is applied when a power-law shape is exhibited, and the corresponding power-law index is obtained and listed in the title of each panel. The top three panels show examples of the upstream particle spectra between 2007/7/16 and 2007/8/30. The top right panel shows that at the HTS crossing time, 2007/8/30, the lower end of the particle spectrum is enhanced dramatically and the spectrum looks like a power law. The best-fit power-law index is calculated to be -2.9 using the considered 10 channels (1.8 MeV–22.3 MeV). The number is quite different from the DSA prediction of -2.0, using the shock compression ratio $r \approx 2.0$. This suggests that DSA may not be fully applicable to explain the energetic particle spectrum.

The observed energetic particle intensities are further enhanced behind the HTS. Here, we illustrate the evolution of the spectrum immediate downstream of the HTS in the middle three panels. The middle left panel shows the spectrum near the HTS crossing at 2007/10/13, where there is a slight increase for all energies compared to the top right panel. After this point, the low-energy particle fluxes do not change much while the medium to high-energy particles fluxes continue increasing until 2007/11/20 (middle panel), and then all the energy channels start to decrease as shown in the middle right panel. From the top right panel to the middle right panel, the spectrum becomes harder in the immediate downstream region and the power-law index varies from -2.9 to -2.0 corresponding to the period between 2007/8/30 to 2007/12/21. The spectra further downstream are plotted in the bottom panels. The spectrum becomes softer as the high energy particle fluxes decrease rapidly. The power-law indices change from -2.07 to -2.85 during this period in the downstream region further from the shock. The observed increase in distance between the particle intensity peak and the shock front with increasing energy was
3. Particle acceleration by magnetic island dynamics

In the Zank et al. statistical transport theory, three basic processes associated with magnetic islands are thought to be responsible for the energization of ions and electrons. The first is due to magnetic island contraction. Particles trapped within a contracting island experience repeated reflections at the ends of converging mirrors, gaining energy in a first-order Fermi manner [30]. The magnetic island contraction leads to an increase in the particle velocity both parallel and perpendicular to the local magnetic field. A second process for particle energization is due to magnetic islands merging. The magnetic field lines shorten as the merging progresses. By sampling multiple merging magnetic islands, particles can be energized via a second-order Fermi process [44]. In this case, a particle gains in parallel energy and loses in perpendicular energy. A third energization mechanism is due to the reconnection induced electric field generated by island merging. Particles trapped in a merging magnetic island experience an extended period of interaction with the reconnection electric field, and thus gain significant energy. Zank et
Figure 5. Energetic proton spectra at 9 instances over the energy range 1.8-22.3 MeV. Panels from top left to bottom right show, in chronological order, the spectra in the upstream region (top three panels), immediate downstream region (middle three panels), and further downstream region (bottom three panels). A power-law fitting is applied to the data for each case. Approximate power-law indices are obtained and listed in the title of each panel together with the time of occurrence.

al. combined these three acceleration processes and developed a stochastic transport theory for charged particles propagating in a turbulent region filled with numerous interacting small-scale magnetic islands. They derived a gyrophase-averaged transport equation that describes the transport of charged particles in a “sea” of interacting magnetic islands. By supposing that particle scattering over the large-scale is sufficiently fast, one can simplify the gyrophase-averaged transport equation by assuming that the particle distribution is nearly isotropic. The general transport equation for a nearly isotropic particle distribution is given by [11]

\[
\frac{\partial f}{\partial t} + \left( U + 3V_E \right) \frac{\partial f}{\partial x} = \frac{v}{3} \frac{\partial U}{\partial x} \frac{\partial f}{\partial v} + \frac{1}{v^2} \frac{\partial}{\partial v} \left( \frac{v^3}{3} \eta_c f \right) - \frac{\eta}{\tau_s} \frac{\partial}{\partial x} \left( \frac{v^2}{\tau_s} \frac{\partial f}{\partial v} \right) + 3 \frac{V_E^2}{\tau_s} \frac{1}{v^2} \frac{\partial}{\partial v} \left( \frac{v^2}{\tau_s} \frac{\partial f}{\partial v} \right)
\]
where $U$ is the bulk flow velocity, $V_E$ is the anti-reconnection electric field induced velocity, $\eta_c$ and $\eta_m$ are characteristic magnetic island contraction and merging rates, $\tau_s$ is the particle scattering time, $\kappa$ is the spatial diffusion tensor, $x$ and $v$ are particle position and speed, respectively. Two particle energization terms are present, one due to the divergence of the large-scale flow velocity, $\nabla \cdot U$, which is the familiar term responsible for the energization of particles at shocks, and the other energization terms are due to magnetic island contraction ($\eta_c$) and merging ($\eta_m$). The energization term associated with magnetic island merging enters at the second order.

We consider a steady-state 1D problem with an incompressible large-scale flow, $\nabla \cdot U = 0$. Particles are injected at the origin $x = 0$ with a fixed initial speed $v_0$. We neglect second-order energy diffusion terms and assume a constant spatial diffusion coefficient. An escape term corresponding to particle loss from a finite acceleration region was introduced in Zhao et al. [21]. Based on these assumptions, Equation (1) can be simplified as follows.

$$
\frac{\partial^2 f}{\partial x^2} - \frac{2V_E}{\kappa} \frac{\partial^2 f}{\partial x \partial \xi} - \frac{U}{\kappa} \frac{\partial f}{\partial x} - 2\eta_c \frac{\partial f}{\partial \xi} - 2\eta_m f = -\frac{Q}{\kappa} v_0 \delta (v - v_0) \delta (x) + \frac{f}{\kappa \tau_e},
$$

(2)

where $\xi = (v/v_0)$, $\tau_e$ is the particle escape time, and $Q = n_0/(4\pi v_0^2)$ with $n_0$ particle number density. Equation (2) can be solved analytically by assuming that all parameters ($U$, $V_E$, $\tau_e$, $\kappa$, and $\eta_c$) are homogeneous in time and space, and are energy independent.

Zhao et al. [21] obtained the analytic solution of Equation (2) for the particle velocity distribution function

$$
f(x, v/v_0) = \frac{n_0}{8\pi v_0^3 V_E} \left( \frac{v}{v_0} \right)^{- \left( 3 + M_E + 2\tau_d/(3\tau_c) M_E^2 \right)/2} \exp \left[ -\frac{\tau_d}{3\tau_c} M_E \frac{x}{L_{diff}} \right] \times I_0(\Phi) H \left( \frac{v}{v_0} \right) \frac{v}{v_0} \frac{x}{L_{diff}} \right),
$$

(3)

$$
\Phi = \sqrt{\frac{\tau_d}{3\tau_c} \frac{M_E^2}{M_E - 3 + \frac{\tau_d}{3\tau_c} M_E^2}} - \frac{\tau_d}{\tau_c} M_E \left[ \ln^2 \left( \frac{v}{v_0} \right) + \frac{2}{M_E} \ln \left( \frac{v}{v_0} \right) \frac{x}{L_{diff}} \right]^{1/2},
$$

(4)

where $\tau_c = 1/\eta_c$ is the characteristic island contraction time, $\tau_d = \kappa U^2$ is the characteristic particle diffusion time, $L_{diff} = \kappa/U$ is the diffusion length scale, $M_E = U/V_E$ is a dimensionless parameter that characterizes the strength of the anti-reconnection electric field, and $I_0$ denotes the zeroth order modified Bessel function of the first kind.

Equation (3) is a power-law like solution. The power-law slope depends on $M_E$, $\tau_d$, and $\tau_c$. Figure 6 shows several examples of the solution (3) for two values of $\tau_d/\tau_c$ and four values of $\tau_d/\tau_c$. The solutions are normalized to $f_0 = f(v/v_0 = 1)$ and evaluated at a fixed location $x/L_{diff} = 1$. For all cases, the spectrum is essentially a power law. Efficient particle escape corresponds to a small escape time $\tau_e$ or a large $\tau_d/\tau_c$ value. Figure 6 shows that a larger $\tau_d/\tau_c$ value produces a steeper spectrum, which is a natural consequence of particle escape.

Figure 7 illustrates the amplification factor and spatial distribution of particles accelerated via reconnection-associated processes with dynamically evolving and merging magnetic islands. The solution (3) requires the prescription of three parameters, $M_E$, $\tau_d/\tau_c$, and $\tau_d/\tau_c$. The colored lines represent solutions for different values of the normalized particle speed $v/v_0$. Figure 7 shows that the particle intensity amplification for a particular particle energy is predicted to increase with increasing energy.

We use solution (3) to model the observed ACR proton flux enhancement downstream of the HTS. Classical DSA theory predicts that the particle intensity downstream of the shock...
The spatial profile of solution (3) using fixed values of $\tau_d/\tau_c$. After the crossing of the injection region, particles interact primarily with magnetic islands and cannot propagate back to the quasi-perpendicular HTS front easily. Therefore, locating the injection point a short distance downstream allows us to examine particle acceleration via flux rope-related processes.

is constant with distance. Figure 4 shows that the downstream proton intensities depart significantly from the predictions of DSA since the flux of each energy channel is amplified relative to its value at the shock. High-energy particle (>4.6 MeV) fluxes peak more than 2 months after the HTS crossing. To model the observed flux amplification using solution (3), we need to determine the particle injection point. Although the most natural injection point might appear to be the shock front, low-energy particle fluxes decrease rapidly after the shock passage. To eliminate this DSA-attributed effect, we choose a point ∼22 days behind the shock as the injection point (on 2007/9/21) where particle intensities are near a local minimum. This injection point is characterized by abrupt changes in the magnetic field direction (Figure 3), which signals the formation of a current sheet. After the crossing of the injection region, particles interact primarily with magnetic islands and cannot propagate back to the quasi-perpendicular HTS front easily. Therefore, locating the injection point a short distance downstream allows us to examine particle acceleration via flux rope-related processes.

Figure 6. Normalized solution (3) at a fixed spatial location $x/L_{diff}=1$. The two panels show solutions with $\tau_d/\tau_c = 2.0$ and 0.2, respectively. We choose four different $\tau_d/\tau_c$ values: 0, 0.2, 1.0 and 5.0. The solutions are normalized to $f_0 = f(v/v_0 = 1)$, and $M_E = 10$ is assumed in all cases.

Figure 7. The spatial profile of solution (3) using fixed values of $M_E$, $\tau_d/\tau_c$, and $\tau_d/\tau_e$ at different energies. The solutions are normalized to $f_0 = f(x = 0, \frac{v}{v_0})$ as measured at a boundary.
Figure 8(a) shows the theoretical solution (3) with the observed ACR flux amplification overplotted as dashed lines. The boundary of the acceleration region is chosen on 2008/1/28 (corresponding to \(x/L_{\text{diff}} = 19.5\)), where the observed particle fluxes return to quiet levels. Both the analytic solutions and data are normalized to the values at the injection position \(x = 0\) (dot-dashed vertical line). The trial-and-error fitting is done by adjusting the dimensionless parameters \(M_E, \tau_d/\tau_c, \tau_d/\tau_e\) and \(v_1/v_0\). The particle velocity \(v\) is calculated as an average velocity in their corresponding energy range, and \(v_1\) is the velocity corresponding to the lowest energy channel. To convert the time series data to the spatial coordinate \((x)\), we assume a constant flow velocity \(U_{\text{flow}} = 140\) km/s, which is the observed solar wind speed during this period. The spatial coordinate \(x\) is normalized by the diffusion length \(L_{\text{diff}}\). The set of best fit parameters is: \(M_E = 21, \tau_d/\tau_c = 0.2, \tau_d/\tau_e = 8.0, v_1/v_0 = 3,\) and \(L_{\text{diff}} = 8.1 \times 10^{12}\) cm. Although Voyager 2 measures the particle differential intensity instead of the velocity distribution function, the amplification factor is the same for both quantities.

Figure 8(a) shows clearly that the particle intensities are strongly enhanced with respect to the injection position for an extended period (~ 2 months), and the enhancement is more pronounced for high-energy particles. The largest amplification is about 1.6 times for the 1.8–2.2 MeV energy range and 2.6 times for the 10.3–12.8 MeV energy range. The amplification factor is in ascending order with increasing energy. The distance between the particle flux peak and the injection point appears to increase with increasing energy. For example, the flux amplification peaks at \(x/L_{\text{diff}} \sim 5\) for the 1.8–2.2 MeV range, and at \(x/L_{\text{diff}} \sim 10\) for the 10.3–12.8 MeV range. These features are quantitatively reproduced by our analytic model.

Figure 8. Left panel: particle flux amplification factor as a function of position. The dotted-dashed vertical line identifies the particle injection point at 2007 September 21. Both the observed fluxes and the theoretical distribution functions are normalized to their respective values at the injection point. Dashed lines of different colors denote the observed proton flux amplification factor. Solid lines show the theoretical amplification factor \(f(x, v/v_0)/f(0, v/v_0)\) for the corresponding energy channel. Right panel: Evolution of the differential intensity spectrum. Solid dots denote observed particle intensities and solid lines the theoretical solutions. Both observational data and theoretical solutions are color coded according to the time after the injection point.

Consider now the energetic particle spectra downstream of the HTS. To directly compare
with observations, Zhao et al. [21] converted the theoretical velocity distribution function $f$ to the particle differential intensity $j(E)$. The differential intensity solution corresponding to Equation (3) is then

$$j(x, E) = j_0 \left( \frac{E}{E_0} \right)^{-\left(3+M_E+2\tau_d/(3\tau_c)M_E^2\right)/2} \frac{E}{E_0} \exp \left[ -\frac{\tau_d}{3\tau_c} M_E \frac{x}{L_{diff}} \right] \times I_0(\Phi) H \left( \ln \left( \frac{E}{E_0} \right) \right) \left[ \ln \frac{E}{E_0} + \frac{1}{M_E} \frac{x}{L_{diff}} \right];$$

(5)

where $j_0$ is a normalization factor. The values of $M_E$, $\tau_d/\tau_c$, $\tau_d/\tau_e$ and $L_{diff}$ have been discussed. The factor $j_0$ is determined by applying a least squares fit of Equation (5) to the observed intensities at the injection point $x = 0$ (at 2007/9/21), which yields $j_0 = 5 \times 10^7$ cm$^{-2}$sr$^{-1}$MeV$^{-1}$.

Figure 8(b) shows the evolution of the particle differential intensity spectra, which are color-coded by time after injection. The observed intensities are shown by solid dots, and the theoretical intensities (5) by solid lines. We choose 5 instances for the spectral analysis: 0, 42, 60, 78, and 84, all in days after the injection time. The three later-time (60, 78, and 84 days) spectra for both observational and theoretical results are multiplied by a factor of 5, 20, 50, respectively, for presentation purposes. The particle spectra harden with increasing distance from the injection point. This feature is well reproduced by our theoretical solution.

4. Summary

We present Voyager 2 CRS observations showing the unusual enhancement of ACR proton fluxes downstream of the HTS at $\sim 84$ AU. The enhancement is inconsistent with predictions of classical DSA theory but can be explained by local acceleration associated with small-scale magnetic island dynamics. The Zank et al. [11] kinetic transport theory for stochastic particle acceleration via reconnection processes associated with multiple interacting magnetic islands is applied to model the unusual behavior of ACR downstream of HTS. The quasi-perpendicular HTS itself is responsible primarily for generating the downstream islands.

Observational and computational evidence for local particle acceleration associated with magnetically confined magnetic islands is accruing [35, 41]. Here, we employ this local particle acceleration mechanism to explain the puzzling ACR “time-intensity” profile observed at 84 AU. Specifically, we compare the normalized analytical solution (3) and the observed ACR flux amplification in Figure 8(a). The comparison between analytical differential intensities (5) and the observed particle spectra at different locations are shown in Figure 8(b). Our theoretical solutions agree reasonably well with observations. The modeling results show that stochastic acceleration by interacting magnetic islands can successfully predict the observed (i) peaking of ACR intensities downstream of HTS; (ii) increasing in the ACR flux amplification factor with increasing particle energy; and (iii) increase in distance between the particle intensity peak and the HTS with increasing particle energy. This work illustrates that our general theory of stochastic particle acceleration via magnetic reconnection processes, including particle injection, trapping and escape, can explain the observed unusual ACR “time-intensity” profile during the HTS crossing.
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References

[1] Reames, D. V. 1999, *Space Science Reviews*, 90, 413
[2] Zank, G. P., Rice, W. K. M., & Wu, C. C. 2000, *J. Geophys. Res.*, 105, 25079
[3] Zank, G. P., Li, G., & Verkhoglyadova, O. 2007, *Space Science Reviews*, 130, 255
[4] Li, G., Zank, G. P., & Rice, W. K. M. 2003, *J. Geophys. Res.*, 108, 1082
[5] Rice, W. K. M., Zank, G. P., & Li, G. 2003, *J. Geophys. Res.*, 108, 1369
[6] Verkhoglyadova, O. P., Zank, G. P., & Li, G. 2015, *Physics Reports*, 557, 1
[7] Axford, W. I., Leer, E., & Skadron, G. 1977, *International Cosmic Ray Conference*, 11, 132
[8] Krymskii, G. F. 1977, *DoSSR*, 234, 1306
[9] Bell, A. R. 1978, *MNRAS*, 182, 147
[10] Blandford, R. D., & Ostriker, J. P. 1978, *ApJ*, 221, L29
[11] Zank, G. P., le Roux, J. A., Webb, G. M., et al. 2014, *ApJ*, 797, 28
[12] Zank, G. P., Hunana, P., Mostafavi, P., et al. 2015, *APJ*, 814, 137
[13] Stone, E. C., Cummings, A. C., & McDonald, F. B., et al. 2005, *Science*, 309, 2017
[14] Decker, R. B., Krimigis, S. M., Roelof, E. C., et al. 2008, *Nature*, 454, 67
[15] Tressen, J. A., Matthaeus, W. H., Wan, M., et al. 2013, *ApJ*, 776, L8
[16] Tressen, J. A., Ruffolo, D., Matthaeus, W. H., et al. 2015, *ApJ*, 812, 68
[17] Khabarova, O., Zank, G. P., Li, G., et al. 2015, *ApJ*, 808, 181
[18] Khabarova, O., Zank, G. P., Li, G., et al. 2016, *ApJ*, 827, 122
[19] Khabarova, O., & Zank, G. P. 2017, *ApJ*, 843, 4
[20] Adhikari, L., Khabarova, O., Zank, G. P., & Zhao, L.-L. 2019, *ApJ*, 873, 72
[21] Zhao, L.-L., Zank, G. P., Khabarova, O., et al. 2018, *ApJ*, 864, L34
[22] Zhao, L.-L., Zank, G. P., Chen, Y., et al. 2019, *ApJ*, 872, 4
[23] Rice, W. K. M., Zank, G. P., Richardson, J. D., & Decker, R. B. 2000, *Geophys. Res. Lett.*, 27, 509
[24] McComas, D. J., & Schwadron, N. A. 2006, *Geophys. Res. Lett.*, 33, L04102
[25] Lu, S., Lu, Q., Huang, C., & Wang, S. 2013, *Physics of Plasmas*, 20, 061203
[26] Wang, H., Lu, Q., Huang, C., & Wang, S. 2016, *ApJ*, 821, 84
[27] Matthaeus, W. H., Ambrosiano, J. J., & Goldstein, M. L. 1984, *Physical Review Letters*, 53, 1449
[28] Goldstein, M. L., Matthaeus, W. H., & Ambrosiano, J. J. 1986, *Geophys. Res. Lett.*, 13, 205
[29] Ambrosiano, J., Matthaeus, W. H., Goldstein, M. L., & Plante, D. 1988, *J. Geophys. Res.*, 93, 14383
[30] Drake, J. F., Swisdak, M., Che, H., & Shay, M. A., 2006, *Nature*, 443, 553
[31] Oka, M., Phan, T.-D., Krucker, S., Fujimoto, M., & Shinohara, I. 2010, *ApJ*, 714, 915
[32] Le, A., Karimabadi, H., Egedal, J., Roytershteyn, V., & Daughton, W. 2012, *Physics of Plasmas*, 19, 072120
[33] Guo, F., Li, H., Du, S., & Liu, Y.-H. 2014, *Physical Review Letters*, 113, 155005
[34] Guo, F., Liu, Y.-H., Daughton, W., & Li, H. 2015, *ApJ*, 806, 167
[35] Du, S., Guo, F., Zank, G. P., Li, X., & Stanier, A. 2018, *ApJ*, 867, 16
[36] Lu, Q., Wang, H., Huang, K., Wang, R., & Wang, S. 2018, *Physics of Plasmas*, 25, 072126
[37] le Roux, J. A., Zank, G. P., Webb, G. M., & Khabarova, O. 2015, *ApJ*, 801, 112
[38] le Roux, J. A., Zank, G. P., Webb, G. M., & Khabarova, O. V. 2016, *ApJ*, 827, 47
[39] le Roux, J. A., Zank, G. P., & Khabarova, O. V. 2018, *ApJ*, 864, 158
[40] Gosling, J. T., McComas, D. J., Skoug, R. M., & Smith, C. W. 2006, *Geophys. Res. Lett.*, 33, L17102
[41] Adhikari, L., Khabarova, O., Zank, G. P., & Zhao, L.-L. 2019, *ApJ*, 873, 72
[42] Burlaga, L. F., & Ness, N. F. 2009, *ApJ*, 703, 311
[43] Hill, M. E., Decker, R. B., Brown, L. E., et al. 2014, *ApJ*, 781, 94
[44] Drake, J. F., Swisdak, M., & Fermo, R. 2013, *ApJ*, 763, L5
[45] Mostafavi, P., Zank, G. P., & Webb, G. M. 2017, *ApJ*, 841, 4
[46] Mostafavi, P., Zank, G. P., & Webb, G. M. 2018, *ApJ*, 868, 120
[47] Zank, G. P., Adhikari, L., Zhao, L.-L., et al. 2018, *ApJ*, 869, 23
[48] Florinski, V., Decker, R. B., le Roux, J. A., & Zank, G. P. 2009, *Geophysical Research Letters*, 36, 12