Where is the cosmic-ray modulation boundary of the heliosphere?

Ming Zhang,[1,a)] Xi Luo,[2,3] and Nikolai Pogorelov[4]
[1]Department of Physics and Space Sciences, Florida Institute of Technology, Melbourne, Florida 32901, USA
[2]Center for Space Research, North-West University, Potchefstroom 2520, South Africa
[3]State Key Laboratory of Space Weather, Center for Space Science and Applied Research, Chinese Academy of Sciences, Beijing 100190, China
[4]Center for Space Plasma and Aeronomic Research and Department of Space Science, University of Alabama in Huntsville, Huntsville, Alabama 35899, USA

(Received 7 May 2015; accepted 26 June 2015; published online 20 August 2015)

The intensity of Galactic cosmic rays in the heliosphere is modulated by solar activities. The outer boundary where the solar modulation begins has always been a subject matter of debate in the cosmic-ray and heliophysics community. Various experimental methods and theoretical model calculations have been used to determine the boundary. Although the heliopause was always suspected to be the boundary, it is only until very recently after Voyager 1 had crossed the heliopause did we confirm that the boundary is indeed the heliopause. In this paper, we use a model simulation and detailed Voyager observation of cosmic rays at the heliopause crossing to show that the modulation boundary, in fact, is a fraction of an AU beyond the heliopause. Such a conclusion requires a very low turbulence level of the interstellar magnetic field in the outer heliosheath. According to the quasi-linear theory, a low level of turbulence should result in a very large diffusion coefficient parallel to the magnetic field and a very small perpendicular diffusion coefficient. For the first time, we are confident that Voyager 1 has obtained the truly pristine local interstellar cosmic-ray spectra down to the energies below 1 MeV. The cosmic-ray intensity is rapidly filtered by a thin layer of the interstellar magnetic field immediately outside of the heliopause. Its filtration amount depends on the conditions of magnetic field turbulence on the both sides of the heliopause, thus making it solar-cycle dependent as well. [http://dx.doi.org/10.1063/1.4928945]

I. INTRODUCTION

Galactic cosmic rays originate in the Galaxy, most possibly from past supernova explosions and their remnant shock waves. From radioactive isotope abundance measurements, it has been determined that their average residence time in the Galaxy is about 20 Myr.[1] Presumably the loss of cosmic rays is mainly through diffusive escape from the Galactic disk with some extended halo of typically a few kpc thick. One can figure out the diffusion coefficient of cosmic rays in the Galactic magnetic field is very large, in the order of $\kappa_{ism} = 10^{28}\,\mathrm{cm^2 s^{-1}}$ for cosmic rays of $\sim$1 GeV (see, e.g., Ginzburg and Syrovatsky,[2] Strong and Moskalenko,[3] Ptuskin,[4] Busching and Potgieter[5]). If the cosmic rays in the vicinity of the solar system are represented by a continuous component from the entire Galaxy, its spatial gradient scale should be equal to the Galactic halo thickness or a few kpc. There could be a significant contribution from a relatively recent and nearby supernova explosion (within $\sim$0.1 Myr and a few hundred pc). Even in this situation, the cosmic-ray density distribution should still be quite uniform within a few pc in the local interstellar medium. In fact, measured TeV cosmic-ray anisotropy is of the order of 10^{-4} (Amenomori *et al.*[6]). Assuming that the anisotropy comes entirely from the $\boldsymbol{B}$ cross the gradient of cosmic-ray density,[7] one can estimate the cosmic-ray density gradient scale to be 10^4 times the gyroradius of cosmic-ray particles. In a typical interstellar magnetic field of 3 μG, the gyroradius of a 5 TeV proton is 1.8×10^{-3} pc. Then the cosmic-ray density gradient scale is at least 18 pc. The size of the heliosphere is only a few hundred AU (1 AU = 4.8 $\times 10^{-6}$ pc) in the nose direction to a few thousand AU in the tail direction. Therefore, we expect that the heliosphere is immersed in the local interstellar medium with a nearly uniform cosmic-ray density.

The cosmic-ray intensity inside the heliosphere is modulated by the solar activity. Its level at 1 AU approximately anti-correlates with the sunspot number, but other solar activity indicators, such as the tilt of the solar magnetic dipole or the heliospheric current sheet, also have a close correlation. This solar modulation effect is most prominent at low energies and can extend up to many GeV. Although there is a hint of solar modulation at 70 GeV,[8] the amplitude of solar modulation at this high energy becomes diminishingly small.

The modulation effect originates in the solar wind. The outward motion of the solar wind with embedded magnetic field will try to prevent charged cosmic-ray particles from coming in. So the cosmic rays have to rely on either scattering/diffusion by the magnetic field fluctuations or drift across the inhomogeneous ambient heliospheric magnetic field to reach Earth deep inside the heliosphere. For cosmic rays below tens of MeV, their drift speed and diffusion coefficient are not large enough. The outward convection with the solar wind can effectively shield them out. Above tens of MeV, the drift speed and diffusion coefficient become large enough to permit their access into the inner heliosphere. At these energies, the convective expulsion effect is negligible. However,

[a)]Electronic mail: mzhang@fit.edu

when cosmic-ray particles traverse through the radially expanding solar wind, they suffer an adiabatic energy loss. In other words, the particles that we see inside the heliosphere originally have higher energies in the local interstellar medium before they enter the heliosphere. Since the cosmic-ray distribution function decreases steeply with energy, a small amount of energy loss can result in a fairly visible reduction of cosmic-ray intensity. The adiabatic energy loss is the most prominent cosmic-ray modulation mechanism at these energies. The amount of energy loss depends on the conditions of the solar wind, heliospheric magnetic configuration, and its turbulence level, all of which vary with the solar cycle.

Because the solar modulation effect originates in the solar wind, we expect the amount of modulation to decrease as we go out. In fact, in the 1990s, Pioneer 10, Pioneer 11, Voyage 1, and Voyager 2 all saw decreases in the solar modulation with the radial distance from the Sun.[9] This phenomenon is expected because the solar modulation should eventually disappear far enough from the heliospheric influence in the interstellar medium. Where is the boundary of solar modulation? Resolving this problem automatically leads to the determination of the true interstellar cosmic-ray spectrum.

The heliopause is a boundary that separates the flow with embedded magnetic field of solar origin in the inner heliosheath from that of the interstellar origin in the outer heliosheath. According to the theory of ideal MHD, it should be a tangential discontinuity. It has long been suspected to be the boundary of cosmic-ray modulation. First, interstellar flows bring the cosmic rays with the magnetic field to the heliopause, so it is a natural convective boundary. Second, the cosmic-ray diffusion coefficient in the interstellar magnetic field is roughly $\kappa_{ism} = 10^{28}$ cm^2 s^{-1}, while in the heliospheric magnetic field, it is several orders of magnitude lower (probably $10^{23} - 10^{24}$ cm^2 s^{-1}) due to the high turbulence levels brought by the Sun and the solar wind termination shock. Using the principle of diffusion flux conservation, one could get a nearly flat density profile on the interstellar side if the cosmic-ray density gradient inside the heliopause is not too large. In other words, the cosmic-ray spectrum should be nearly the interstellar spectrum outside the heliopause. It is a view derived from cosmic-ray transport behavior in the spatial coordinates. On the other hand, most low-energy cosmic-ray modulation occurs due to adiabatic energy loss. Recent studies by Scherer *et al.*,[10] Herbst *et al.*,[11] and Strauss *et al.*[12] suggested that the cosmic-ray spectrum at the heliopause is still significantly modulated even though large diffusion coefficients of cosmic rays outside the heliopause are taken into account. It is probably because cosmic rays immediately outside the heliopause still have a finite chance to get into the heliosphere where they lose their partial energy. The large diffusion coefficients in the interstellar magnetic outside of the heliopause alone do not prevent it from happening.

Historically, the search for cosmic-ray modulation boundary has been equivalent to finding the radial distance of the heliopause. In the 1990s when Pioneer 10, Pioneer 11, Voyager 1, and Voyager 2 got to sufficiently large radial distances from the Sun so that the radial gradient of cosmic-ray density and 11-yr solar cycle modulation amplitude could be accurately determined, one can extrapolate the cosmic-ray modulation outward to zero to locate the modulation boundary. Van Allen was among those who pioneered this technique.[9,13–17] In doing so, an assumption about the behavior of the radial gradient of cosmic-ray modulation has to be made. Nevertheless, heliocentric distance to the predicted heliopause was somehow always $\sim$2 times the distance of the spacecraft at the time of measurement, which was as good as one could do at that time. Because of the uncertainty of cosmic-ray radial gradient, an accurate determination of cosmic-ray modulation boundary still relies on direct measurements when a spacecraft gets there.

Voyager 1 crossed the heliopause in August 2012 at a radial distance of 122 AU from the Sun. The Galactic cosmic-ray intensity exhibited a sudden increase, and afterward it stayed at a roughly constant level. Although the sudden increase in the cosmic-ray intensity at the boundary crossing was not predicted before, the constant cosmic-ray intensity level after the heliopause crossing is consistent with the large particle diffusion coefficient in the interstellar magnetic field of the outer heliosheath. If this is true, then the spectrum obtained by Voyager 1 in the outer heliosheath is the true cosmic-ray interstellar spectrum. However, this does not preclude a possibility that there is small, undetectable, radial gradient in the outer heliosheath over a very large distance for hundreds of AU.

In this paper, we review recent detailed observations from Voyager 1 at the heliopause crossing. Then we use model simulations to demonstrate several scenarios of cosmic-ray modulation at the boundary. In particular, we will set up conditions for particle transport coefficient for locating the cosmic-ray modulation boundary.

II. VOYAGER OBSERVATIONS AT THE HELIOPAUSE

Figure 1 shows an overview of the E > 70 MeV cosmic-ray intensity as measured by Voyager 1 and Voyager 2. For comparison, measurements of secondary neutrons in the Earth's atmosphere by McMurdo Neutron Monitor are also shown. The rigidity cutoff of incoming cosmic rays at the McMurdo station is $\sim$1 GV. Because of the mismatch in the cutoff energy and type of measured particle species, the sensitivity of the instruments on the Voyagers to cosmic-ray modulation is not the same as the neutron monitor. Nevertheless, the neutron monitor data can serve as an indicator of modulation on its own relative level. After the Voyagers get to large enough radial distances (starting 1996), the cosmic-ray intensities at the spacecraft increase, but the cosmic-ray intensity at Earth is decreasing. This phenomenon indicates that cosmic-ray modulation becomes weaker with larger radial distance or closer to the modulation boundary. During the solar maximum around 2001, the cosmic-ray intensities at the Voyagers still decrease, meaning that the solar-cycle modulation amplitude is bigger than the radial distance effect at these locations. Once out of the solar maximum in 2004, the cosmic-ray intensities at the Voyagers increase much faster than at Earth, again due to the radial distance effect. At the end of 2004 and the middle of 2007 Voyager 1 and Voyager 2, respectively, cross the solar wind termination shock, but the cosmic ray does not

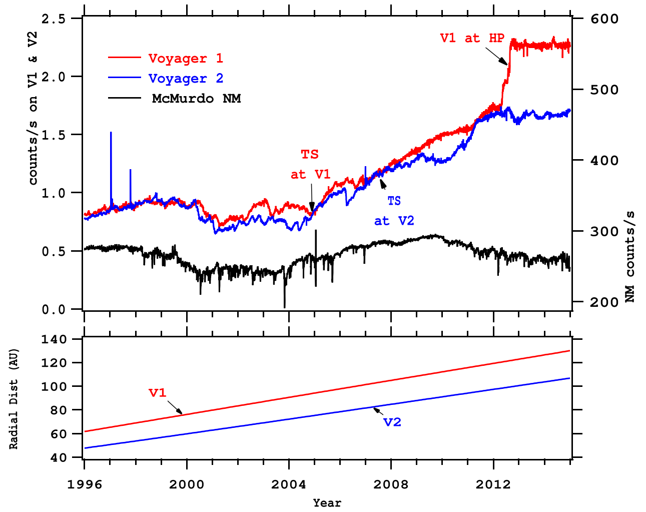

FIG. 1. Voyager observations of E > 70 MeV Galactic cosmic-ray intensity along with baseline neutron monitor measurements at Earth. The lower panel shows the Voyager radial distances from the Sun. TS stands for the termination shock, and HP stands for the heliopause.

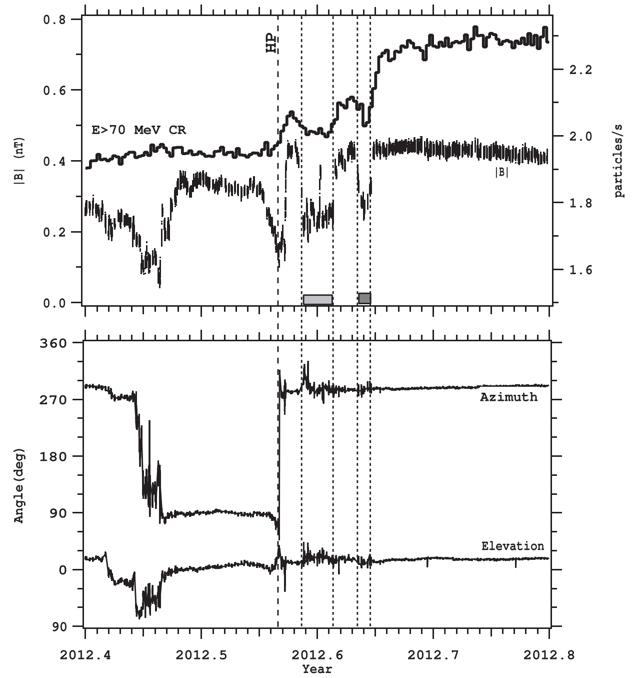

FIG. 2. Variation of E > 70 MeV cosmic-ray intensity near the heliopause crossing by Voyager 1 along with magnetic field strength and its azimuth and North-South elevation angles. Short shaded bars indicate the time periods when Voyager 1 passes through regions of the interstellar magnetic field remotely connected back to the heliospheric magnetic field of the inner heliosheath.

show any effect. Although there is a ~20 AU difference in the heliocentric distances between the two spacecraft, the cosmic-ray intensities measured by Voyager 1 and Voyager 2 track each other pretty well until the middle of 2012. At that time, the cosmic-ray intensity at Voyager 1 suddenly increases dramatically, but the intensity at Voyager 2 levels off. After that, the cosmic-ray intensity at Voyager 1 stays at a nearly constant level, which is significantly higher than at Voyager 2. Along with other signatures such as the disappearance of anomalous cosmic rays in the 40 keV to a few MeV energy range, the increase of cosmic-ray intensity eventually leads to the confirmation of the heliopause crossing by Voyager 1 in August 2012 at 122AU.[18,19] In the meantime, Voyager 2 stays in the inner heliosheath and still sees modulated cosmic rays with a reduced intensity.

Figure 2 shows some detailed variations of cosmic rays around the heliopause crossing by Voyager 1. For comparison, magnetic field strength $|B|$ and its direction (azimuth and elevation angles) at Voyager 1 are also shown. The heliopause crossing is identified to be at the vertical dashed line (2012.569), where the azimuth angle of magnetic field direction nearly reverses, but the elevation angle stays nearly the same.[20] The reversal of magnetic field in the azimuth angle is very much like a regular heliospheric current sheet crossing that the Voyagers have seen from time to time for decades. The magnetic field strength at the heliopause crossing appears to be at a temporary minimum. A relatively strong interstellar magnetic field of 0.4 nT is not seen until 2012.573 or ~35 h later. Perhaps the heliopause is not a traditional tangential discontinuity. Borovikov and Pogorelov[21] argue that the heliopause is not a smooth tangential discontinuity but may be subject to Rayleigh-Taylor instability that creates additional structures and enhances mixing of the solar wind and local interstellar plasmas. As a result, a few regions of the solar wind may be followed by the local interstellar plasma, exhibiting multiple crossings of the interface. There is also a possibility of magnetic reconnection at the heliopause so that the heliopause has a finite thickness where magnetic field reconnection/annihilation occurs. The cosmic-ray intensity does not start to increase until the heliopause crossing. It means the heliopause is not exactly the modulation boundary. There are two episodes of partial drops accompanied by lower magnetic field strengths in the shaded bar regions. Perhaps it is due to that the spacecraft is going through those interstellar magnetic field lines remotely connected to the heliospheric magnetic field through the heliopause instability or magnetic reconnection. In these regions, the cosmic-ray intensity tends to go back to its lower levels of the inner heliosheath. In all those other regions of the strong interstellar magnetic field of ~0.4 nT, the cosmic-ray intensity tends to rise. At the beginning after the heliopause crossing, it rises sharply. Once it reaches the region of steady strong interstellar magnetic beyond 2012.65, the cosmic-ray intensity increase decelerates, and it is followed by a gradual increase that lasts until 2012.70. Afterward, the cosmic-ray intensity stays at a roughly constant level except two occasions when the interstellar magnetic field is disturbed by heliospheric shock waves penetrating through the heliopause (see Figure 1 or Burlaga and Ness[20]). This steady high level of cosmic rays remains through April 2015. During this period, the spacecraft has moved out 8 AU, but we do not see any radial gradient. It is quite possible that the cosmic-ray intensity has reached its local interstellar level. However, if there is a small radial gradient in the outer heliosheath over a large radial distance of a few hundred AU, it will not be noticeable until Voyager 1 penetrates much deeper into the interstellar medium.

III. LARGE-SCALE MODELING OF COSMIC-RAY MODULATION

The observation of cosmic-ray intensity variation at the heliopause is a partial surprise. We expect the cosmic-ray intensity to rise towards the heliopause, and there may or may not be, depending on the particle diffusion coefficient, a radial gradient in the outer heliosheath. However, no one predicted there is a sharp, almost step-wise, increase of cosmic rays at the heliopause. The observation has triggered a few modeling efforts trying to explain the Voyager 1 observation there.[22–24] Below, we follow Luo *et al.*[24] to set up constraints on the particle diffusion for a sharp cosmic-ray intensity increase at the heliopause.

Our modeling of cosmic-ray modulation is based on Parker transport equation,[25] in which the isotropic part of particle distribution function $f(\boldsymbol{x},p,t)$ as a function of position $\boldsymbol{x}$, momentum p, and time t for any given species of charge q and mass m with speed v obeys

$$\frac{\partial f}{\partial t} = \nabla\cdot\boldsymbol{\kappa}\cdot\nabla f - (\boldsymbol{V}+\boldsymbol{V}_d)\cdot\nabla f + \frac{\nabla\cdot\boldsymbol{V}}{3}\frac{\partial f}{\partial \ln p}, \quad (1)$$

where $\boldsymbol{V}$ is the plasma velocity, $\boldsymbol{V}_d = pv\nabla\times(\boldsymbol{B}/B^2)/(3q)$ is the average particle drift velocity in a non-uniform ambient magnetic field $\boldsymbol{B}$, and $\boldsymbol{\kappa}$ is the particle diffusion tensor. The diffusion tensor is anisotropic, having a form $\boldsymbol{\kappa} = \kappa_\perp\mathcal{I} + (\kappa_{||}-\kappa_\perp)\hat{\boldsymbol{b}}\hat{\boldsymbol{b}}$, where $\kappa_\perp$ is the diffusion coefficient perpendicular to the ambient magnetic field, $\kappa_{||}$ is the parallel diffusion coefficient, $\hat{\boldsymbol{b}}$ is the unit vector of magnetic field direction, and $\mathcal{I}$ is the identity tensor.

If we recast Equation (1) into a set of time backward stochastic differential equations describing random trajectories of pseudoparticles,[26] we can obtain an exact solution to Equation (1). It can be expressed as an ensemble average of boundary values at the locations $\boldsymbol{x}_b$ and momentums p_b where the time backward stochastic trajectories hit the boundary for the first time, i.e.,

$$f(\boldsymbol{x},p,t) = \langle f_b(\boldsymbol{x}_b,p_b,t-t_p)\rangle, \quad (2)$$

where t_p is the particle propagation time from the boundary to the location of observation. The pseudoparticle represents a bunch of particles with a number proportional to the boundary value of entering cosmic rays. For the cosmic-ray modulation problem, the boundary is mainly the outer boundary with the local interstellar medium, where $f_b = f_{ism}(p)$ is only a function of cosmic-ray momentum. We typically set the outer boundary at a far enough distance where the cosmic-ray spectrum is not influenced by the heliosphere. In our models, we set it at 300 AU for optimal computation speed and model accuracy. The interstellar spectrum is taken from Section V below.

Our cosmic-ray modulation simulation is built on an MHD heliosphere model, which is regarded to be among the most sophisticated models of this kind.[27,28] This heliosphere model and a corresponding package of numerical codes supporting it uses an MHD treatment of ions and kinetic description of interstellar neutral particles. It addresses the complexity of the charge-exchange processes and the coupling of the interstellar and heliospheric magnetic fields at the heliospheric interface. It has been used to analyze the influence of the interstellar environment on the heliospheric interface and allowed us to investigate some sophisticated unsteady interaction patterns of the solar wind interaction with the interstellar medium. This model has been successfully compared with *in-situ* plasma and magnetic field observations by the Voyagers in the heliosheath,[29] and it has been used to explain the first image of energetic neutral atom ribbon observed by Interstellar Boundary Explorer (IBEX).[30,31]

We take a snapshot of the time-varying MHD heliosphere model that corresponds to the epoch when Voyager 1 crossed the heliopause. Among the output of MHD heliosphere model simulation are plasma velocity and magnetic field vectors on three-dimensional grids. These are directly used to calculate particle transport rates in Equation (1). For simplicity in demonstrating the overall effects of diffusion coefficients in the outer heliosheath, we choose a form

$$\kappa_j = \kappa_{j0}\beta(p/\mathrm{GeVc}^{-1})^{0.5}(\mathrm{B}/\mathrm{B}_\oplus)^{-1}, \quad (3)$$

where $j = (\perp, ||)$, β is the ratio of particle speed v to the speed of light c, and $B_\oplus$ is the heliospheric magnetic field strength at Earth. $\kappa_{||0}$ and $\kappa_{\perp 0}$ are prescribed constants and the variation of particle diffusion from the inner to the outer heliosheath is mainly controlled by them. We set $\kappa_{||0}^{hm} = 5\times10^{21}$ cm^2 s^{-1} and $\kappa_{||}^{hm}/\kappa_{\perp}^{hm} = 10$ at 1 AU in the heliospheric magnetic field to approximately satisfy the constraints by observations of cosmic-ray modulation in the inner heliosphere.

Figure 3 shows our calculation results of 100 MeV cosmic-ray proton intensities as a function of radial distance along the Voyager 1 direction (~35 °N heliolatitude toward helionose longitude). The Parallel and perpendicular particle diffusion coefficients along the radial line are plotted in the lower panel. A few different assumptions of cosmic-ray diffusion in the interstellar magnetic field κ_0^{ism} of the outer heliosheath are used in our calculations. The parallel diffusion has three choices (A, B, and C), and the perpendicular diffusion has four choices (1–4). For case C2, in which the diffusion coefficients in the interstellar magnetic field have the same κ_0 values as those in the heliospheric magnetic field, the radial gradient of cosmic-ray intensity does not see the presence of the heliopause, and a significant amount of cosmic-ray modulation persists in the outer heliosheath even beyond 200 AU. For case A1, both the parallel and perpendicular diffusion coefficients in the interstellar magnetic field are enhanced by 100, so that their ratio remains the same as in the heliospheric field. In this case, we see some change of radial gradient across the heliopause, but the cosmic-ray intensity at the heliopause is still modulated (lower than the local interstellar level) and a definitely positive radial gradient persists throughout the outer heliosheath. This result is a similar to Scherer *et al.*[10] and Strauss *et al.*,[12] and it does not resemble what is observed by Voyager 1. In case A2, there is no enhancement in the perpendicular diffusion but the parallel diffusion is enhanced by 100 over its heliospheric value. In this case, we begin to see a more dramatic increase of radial gradient at the heliopause, but the radial gradient disappears after ~20 AU beyond the heliopause. In case A4, we

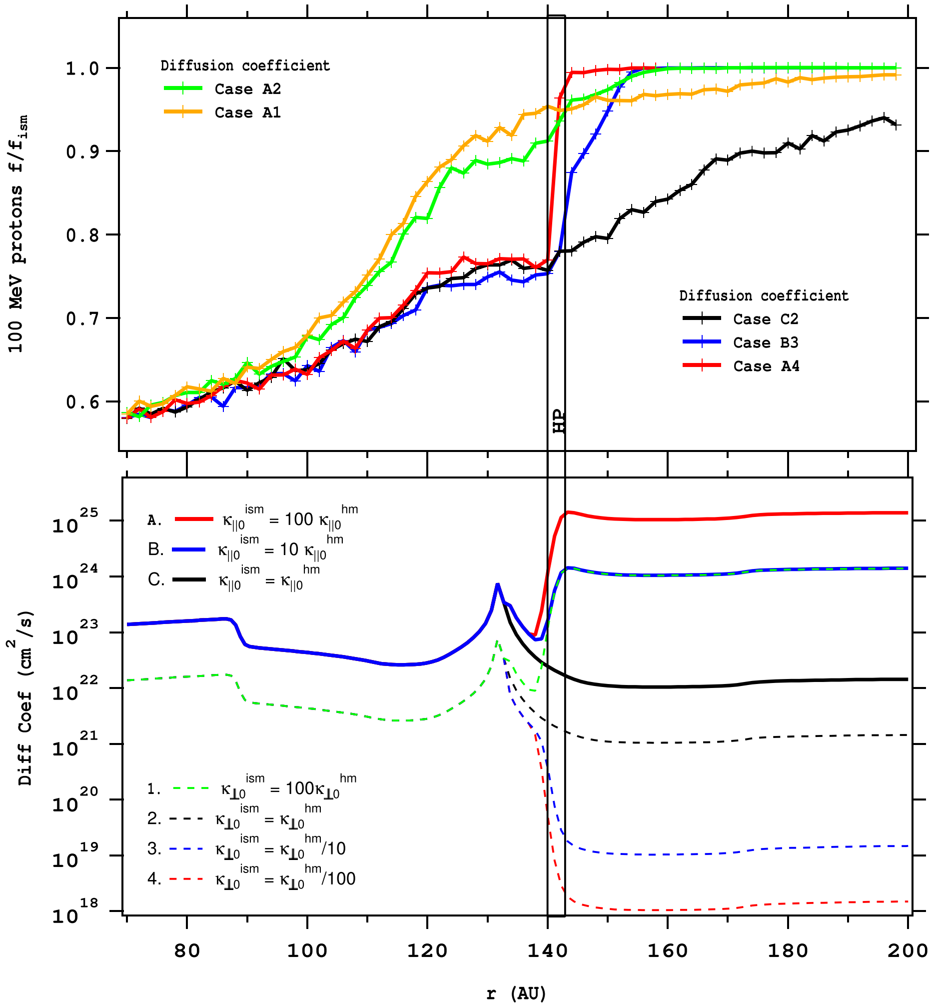

FIG. 3. Radial variation of 100 MeV cosmic-ray protons from global cosmic-ray modulation simulations with various assumptions of parallel and perpendicular diffusion coefficients in the interstellar magnetic field of the outer heliosheath in the lower panel.

further reduced the perpendicular diffusion to 1/100 times its heliospheric value. The intensity shows a sharp increase at the heliopause and soon after the heliopause the radial gradient of cosmic-ray intensity disappears. This result is in the right trend towards explaining the Voyager 1 observation. If we do not enhance the parallel diffusion or reduce the perpendicular diffusion as much, like in case B3, the increase of cosmic rays at the heliopause is not as sharp and radial gradient disappears at a radial distance further out. All these point to us that the cosmic-ray diffusion coefficient in the interstellar magnetic field has a large value only for the parallel direction, but in the perpendicular direction, it needs to be reduced.

The dramatic increase of cosmic rays observed by Voyager 1 at the heliopause, which lasts about ∼0.13 year or ∼0.5 AU as shown in Figure 2, is much sharper than what is shown in case A4 of our simulation. Ideally, we could further increase the parallel diffusion coefficient up to 10^{28} cm^2 s^{-1} and further reduce the perpendicular diffusion. However, the heliopause in our global MHD model simulation is not well defined within 3 AU accuracy (rectangular box in Figure 3). Such a slow transition is reflected in the diffusion coefficient in Figure 3, because our diffusion coefficient has a dependence on the magnetic field strength. Sharpening the transition of the diffusion coefficients does not help either, because the magnetic field lines near the boundary in the global MHD simulation do not have a clear origin due to numerically driven magnetic reconnection. To overcome this difficulty, we have to rely on analytical models of magnetic field structures at the boundary. An example of such a study is presented in Section IV.

If the property of cosmic-ray diffusion in the interstellar magnetic field of the outer heliosheath is similar to case A4, i.e., a much enhanced parallel diffusion and much a reduced perpendicular diffusion than their heliospheric values, then cosmic-ray spectrum can approach to its interstellar spectrum soon after the heliopause, probably within a fraction of an AU. Thus, we can almost say, the cosmic-ray modulation boundary is at the heliopause. Figure 4 shows some radial variations of cosmic-ray intensity along five different directions with the diffusion coefficients in case A4. There are jumps of intensity at the heliopause in all the directions and soon after the heliopause the cosmic-ray intensity reaches its interstellar level. However, the magnitude of intensity jump is different in each direction. It reflects the balance between the speed of particle transport in the heliospheric magnetic field and that in the interstellar field in the surrounding volume. So a precise modeling of cosmic-ray modulation cannot place its boundary

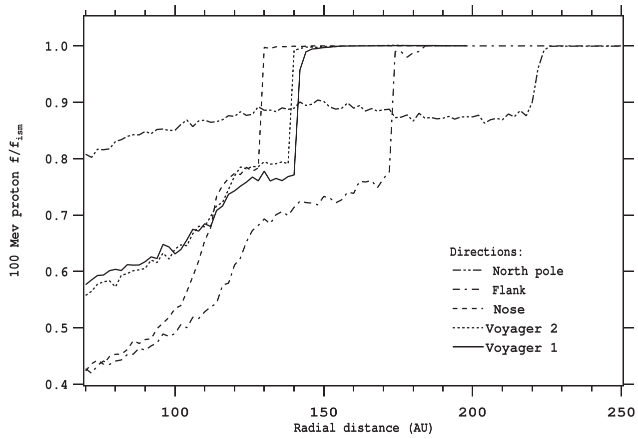

FIG. 4. Model calculation of the radial dependence of 100 MeV cosmic-ray protons along five different directions. The step-like increases of the cosmic-ray intensity coincide with the approximate location of the heliopause.

exactly at the heliopause, because we need the media both inside and outside of the heliopause to determine the amount of intensity jump at the heliopause. The interstellar magnetic field in the outer heliosheath that needs to be considered is just a thin layer, probably up to a few AU thick.

IV. SMALL-SCALE SIMULATION AT THE HELIOPAUSE BOUNDARY

Because the heliopause is smeared in our global MHD simulation, a correct simulation of cosmic-ray transition at the heliopause must rely on a model that can clearly separate out the heliospheric magnetic field from the interstellar magnetic field within an accuracy of <0.1 AU. We turn to an analytical model by Parker[32] that treats the heliopause as a spherical tangential discontinuity. In the outer heliosheath, the magnetic field is described by

$$\boldsymbol{B} = B_{ism}\left[\hat{\boldsymbol{r}}\left(1 - \frac{r_{HP}^3}{r^3}\right)\cos\theta - \hat{\boldsymbol{\theta}}\left(1 + \frac{r_{HP}^3}{2r^3}\right)\sin\theta\right], \qquad (4)$$

where r_{HP} is the radius of the spherical heliopause and θ is the polar angle from the interstellar magnetic field direction. We set $r_{HP} = 130$ AU and $B_{ism} = 3\mu$G. The magnetic field in the inner heliosheath is taken to be constant (1 μG) in the azimuth direction parallel to the solar equator. We simulate particle transport within a radial distance range of ± 5 AU from the heliopause. Because of near stagnation at the heliopause, the plasma velocity $\boldsymbol{V}$ is taken to be zero. Solar modulation effect is specified as an inner boundary condition at $r = r_{HP} - 5$ AU, where the particle distribution is reduced by a constant factor (0.75) from its interstellar spectrum $f_{ism}(p)$ at the outer boundary $r = r_{HP} + 5$ AU.

Figure 5 shows our calculation of 100 MeV cosmic-ray protons very close to the heliopause. The parallel diffusion in the interstellar magnetic field of the outer heliosheath is further enhanced from that in case A4. The sharp increase in the cosmic-ray intensity occurs in the interstellar magnetic field immediately outside the heliopause, and the sharp increase ceases within a fraction of an AU. The corresponding diffusion coefficients in this model calculation are shown

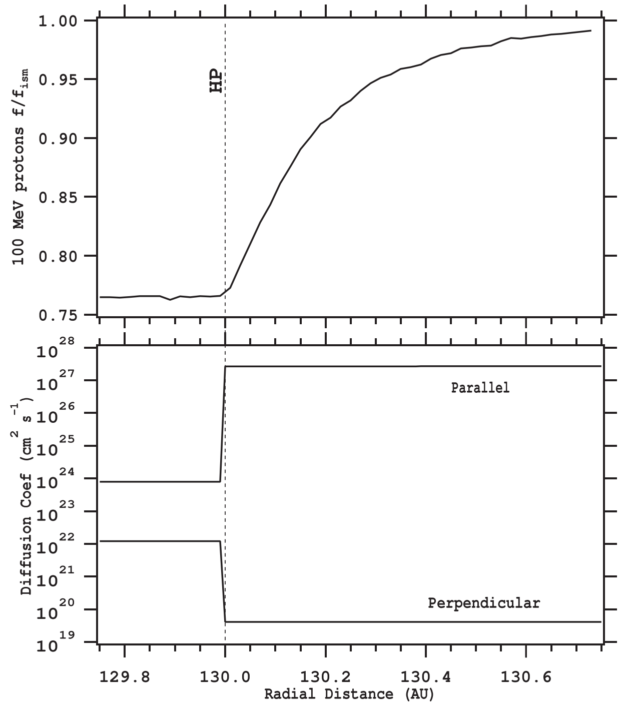

FIG. 5. Variations of cosmic-ray intensity and diffusion coefficients within a thin layer near the heliopause as a tangential discontinuity.

in the lower panel. We find that a parallel diffusion coefficient greater than 10^{27} cm^2 s^{-1} and a perpendicular diffusion coefficient less than 10^{20} cm^2 s^{-1} would be necessary to reproduce the Voyager observations.

The requirement of that large parallel diffusion coefficient and that small perpendicular diffusion coefficient is consistent with a very low turbulence or fluctuation level of the interstellar magnetic field in the wavelengths that resonate with the cosmic rays. In this case, the quasilinear theory of wave-particle interaction[33] is appropriate to use in the estimation of the diffusion coefficients. Assuming a Kolmogorov power-law spectrum for the interstellar turbulence up to the correlation length scale, we find that a 10^{27} cm^2 s^{-1} parallel diffusion coefficient for the 100 MeV protons requires a total magnetic fluctuation power ratio $(\delta B/B_0)^2 = 1$ over a correlation length of $\sim$10 pc. The estimate of perpendicular diffusion would require a finite amount of magnetic fluctuations propagate at oblique angles to the ambient magnetic field. This work is left for the future.

It appears that the heliosphere does not generate enough turbulence in the outer heliosheath to make the cosmic-ray transport coefficients behave similarly to those in the solar wind. That puts two constraints on the condition of the plasma in the outer heliosheath. First, the interstellar flow of $\sim$26 km s^{-1} is lower than or comparable to Alfven speed in the local interstellar medium. So there is no bow shock in front of the heliosphere.[34] Even if there is a shock-like structure, the flow in the outer heliosheath is most likely to be laminar. Second, the neutral solar wind, which is produced in the inner heliosphere through charge exchange between the solar wind ions and penetrate interstellar neutral atoms, can freely escape the heliospheric magnetic field to reach the

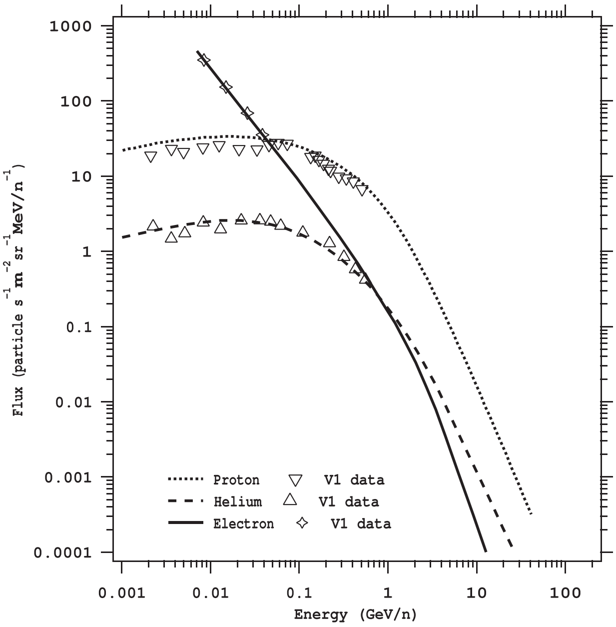

FIG. 6. Interstellar cosmic-ray spectra for three particle species.

dense interstellar medium in the outer heliosheath. Charge exchange with interstellar ions can produce an energetic pickup ion population that has a ring distribution. Although the ring distribution is not stable, it probably cannot generate enough magnetic field fluctuations in the outer heliosheath to scatter cosmic rays significantly. A low level of particle scattering is necessary to explain the IBEX observation of the ribbon in energetic neutral atom images.[30,31] The observations of cosmic rays by Voyager 1 at the heliopause are consistent with the IBEX observation.

V. COSMIC-RAY INTERSTELLAR SPECTRA

It has been almost three years or 8 AU since Voyager 1 crossed the heliopause. During this time, we do not see a significant radial gradient of cosmic-ray intensity in the outer heliosheath. There might be a little chance of a very small, undetectable so far, cosmic-ray radial gradient persisting over a large radial distance of many hundreds of AU. However, this possibility is very slim, as the Voyager 1 observations plus our theoretical/model analysis have allowed us to answer clearly the question about where the cosmic-ray modulation boundary is. The boundary is slightly, probably a fraction of an AU, beyond the heliopause. Voyager 1 has already been observing the pristine cosmic-ray interstellar spectra for some period. Figure 6, adapted from Potgieter,[35] shows the cosmic-ray interstellar spectra for electrons, protons, and helium electron together with actual Voyager 1 data obtained after the heliopause crossing. At the high energy end, the spectra are constrained by PAMELA measurements at 1 AU.

VI. CONCLUSION

Voyager 1 crossed the heliopause in August 2012. The behavior of cosmic-ray intensity with a nearly zero radial gradient in the outer heliosheath suggests that it has reached its true interstellar level. The transition of cosmic rays from the inner heliosheath undergoes a sharp intensity increase immediately after the heliopause. Within a fraction of an AU downstream of the heliopause, the cosmic-ray spectrum down to a few MeV energy range quickly approaches to the interstellar spectrum. If we state precisely, the cosmic-ray modulation boundary is located a fraction of an AU beyond the heliopause. Our modeling efforts show that the cosmic-ray diffusion coefficient in the direction parallel to the ambient interstellar magnetic field of the outer heliosheath should be much enhanced from its value in the heliospheric magnetic field of the inner heliosheath, but the perpendicular diffusion coefficient should be drastically reduced. All these point to a very weak fluctuation in the interstellar magnetic field. The plasma flow in the outer heliosheath should be laminar, and pickup ions produced from the neutral solar wind do not generate enough waves to scatter these cosmic rays significantly.

ACKNOWLEDGMENTS

This work was supported in part by NSF Grant No. AGS-1156056, NASA Grant Nos. NNX10AE46G, NNX14AJ53G, and NNX15AB76G and DOE Grant Nos. DE-SC0008721 and DE-SC0008334. N.P. acknowledges NSF PRAC Award No. OCI-1144120 and related computer resources from the Blue Waters sustained-petascale computing project, which is supported by NSF Award No. OCI 07-25070 and the state of Illinois. Supercomputer time allocations were also provided on SGI Pleiades by NASA High-End Computing Program Award No. SMD-13-4187 and Stampede by NSF XSEDE Project No. MCA07S033. We highly appreciate discussions at the team meeting "Heliosheath Processes and Structure of the Heliopause: Modeling Energetic Particles, Cosmic Rays, and Magnetic Fields" supported by the International Space Science Institute in Bern, Switzerland.

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