SCATTER-FREE PICKUP IONS BEYOND THE HELIOPAUSE AS A MODEL FOR THE INTERSTELLAR BOUNDARY EXPLORER RIBBON

S. V. Chalov1, D. B. Alexashov1,2, D. McComas3,4, V. V. Izmodenov1,2,5, Y. G. Malama1,2, and N. Schwadron6,3

1 Institute for Problems in Mechanics, Russian Academy of Sciences, Moscow, Russia
2 Space Research Institute (IKI), Russian Academy of Sciences, Moscow, Russia
3 Southwest Research Institute, San Antonio, TX, USA
4 Department of Aeromechanics and Gas Dynamics, Faculty of Mechanics and Mathematics, Lomonosov Moscow State University, Moscow 119899, Russia;
izmod@ipmnet.ru
5 University of Texas, San Antonio, TX, USA
6 Boston University, Boston, MA, USA

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ABSTRACT

We present a new kinetic-gasdynamic model of the solar wind interaction with the local interstellar medium. The model incorporates several processes suggested earlier for the origin of the ribbon—the most prominent feature seen in the all-sky maps of heliospheric energetic neutral atoms (ENAs) discovered by the Interstellar Boundary Explorer (IBEX). The ribbon is a region of enhanced fluxes of ENAs crossing almost the entire sky. Soon after the ribbon’s discovery, it was realized that the enhancement of the fluxes could be in the directions where the radial component of the interstellar magnetic field around the heliopause is close to zero. Our model includes secondary charge exchange of the interstellar H atoms with the interstellar pickup protons outside the heliopause. Previously, in the frame of a kinetic-gasdynamic model where pickup protons are treated as a separate kinetic component, it was shown that the interstellar pickup protons outside the heliopause may be a significant source of ENAs at energies above 1 keV. The key difference between the current work and the previous models is in the assumption of no pitch-angle scattering for newly created pickup protons outside the heliopause. We demonstrate that in the limit of no pitch-angle scattering ribbon of enhanced ENA fluxes appears in the model, and this may qualitatively explain the ribbon discovered by IBEX.

Key words: interplanetary medium – ISM: atoms – solar wind

1. INTRODUCTION

The collision of the supersonic solar wind (SW) with the interstellar plasma flow results in the formation of a complex interaction region or a heliospheric interface. This region includes the termination and, possibly, bow shocks decelerating the SW and interstellar plasma, respectively, and the heliopause separating the two plasmas. The region of the heated SW behind the termination shock (TS) is known as the inner heliosheath, while the region behind the heliopause is called the outer heliosheath. The local interstellar medium (LISM) is a partly ionized medium consisting mainly of neutral atoms. It has become evident within recent years that the interstellar atoms have a pronounced effect on the global structure of the interface region and on the physical processes operating in the heliosphere. Apart from the fact that the position and shape of the TS and the heliopause are significantly determined by the action of the atoms, they give rise to a specific hot population of pickup ions (PUIs). The first direct measurements of pickup helium (Möbius et al. 1985) and pickup hydrogen (Gloeckler et al. 1993) showed that the velocity distributions of the PUIs differ in significant ways from the velocity distributions of primary SW ions.

The first measurements of the Interstellar Boundary Explorer (IBEX) spacecraft (McComas et al. 2009; Fuselier et al. 2009; Funsten et al. 2009; Schwadron et al. 2009) show results that were entirely unexpected. The objective of the IBEX mission is to image the complex interaction between the LISM and the outflowing SW by measuring the fluxes of energetic neutral atoms (ENAs) originating in the outer parts of our heliosphere and beyond. The first scan of the whole sky showed that maxima of ENA fluxes form a long (∼250°–300°) and narrow ribbon-like feature that was not predicted by any model prior to the IBEX observations.

The speed of the original interstellar atoms entering the heliosphere is ∼26.4 km s⁻¹, which for hydrogen atoms corresponds to a kinetic energy of about 3 eV. Some portion of the atoms experiences charge exchange with shock heated SW protons and PUIs, and a new population of energetic atoms, created as a result of this process, has the broad energy distribution extending over several keV. These ENAs represent the energy distributions of the parent charged particles and, therefore, when measured at the Earth’s orbit, can be used as a remote sensing of the ions in the interaction region.

Current theoretical models of the SW/LISM interaction fall into two categories: standard models which assume instantaneous assimilation of PUIs in the SW (Baranov & Malama 1993) and the compound or multi-component model (Malama et al. 2006) in the framework of which the pickup particles are considered as separate isotropic (in the SW rest frame) populations with their specific energy distributions. Izmodenov et al. (2009) presented an extension of the Malama et al. (2006) model by introducing a non-thermal population of pickup protons in the interstellar medium. These authors showed that the interstellar pickup protons form significant fluxes of ENAs dominating at energies above ∼1 keV. Although the multi-component models are more comprehensive, all of the current numerical models predict that the ENA fluxes have maxima near the upwind direction of the heliosphere and minima at the flanks, though, of course, the position of maxima can slightly deviate from the upwind direction due to effects of the interstellar magnetic field and SW asymmetry (e.g., Izmodenov et al. 2009).
McComas et al. (2009) presented six possible concepts for the formation of the ribbon observed by IBEX. Among these concepts was the idea that neutralized SW propagates out beyond the heliopause, becomes ionized, gyrates about interstellar magnetic field lines, and then charge exchanges again to become ENAs. Some of these ENAs move back toward the Sun where they can be imaged by IBEX. The advantage of this mechanism is that it produces sharply peaked ENA emissions in directions roughly perpendicular to the interstellar magnetic field beyond the heliopause—the same alignment inferred by comparing the IBEX ribbon to an MHD simulation of the heliosphere (Schwadron et al., 2009). Another concept suggested by McComas et al. (2009) is that compression of the interstellar magnetic field beyond the heliopause may cause ions to align preferentially perpendicular to the interstellar magnetic field through conservation of the first adiabatic invariant and conservation of energy. This will also lead to a special orientation of peaked ENA emissions perpendicular to the interstellar magnetic field, and may help to explain both how the ribbon is formed and the fine structure observed in it (McComas et al., 2009). The basic idea of secondary ENA generation of the IBEX ribbon was further examined by Heerikhuisen et al. (2010). These authors assumed that pickup protons in the outer heliosheath have and retain a partial shell distribution and that their re-neutralization is effectively instantaneous. This approach is significantly different from ours in this study since we solve consistently for the motion of pickup protons along magnetic field lines in the scatter-free limit, and thus include the motion of PUIs along the field line between their pickup and re-neutralization.

2. APPROACHES TO THE PROBLEM

The IBEX observations of an unexpected narrow ribbon of enhanced ENA fluxes raise fundamental questions about the origin of these particles. McComas et al. (2009) considered six possible sources of the ribbon including both sources inside and beyond the heliopause. The idea that the source lies in the outer heliosheath has at least two arguments. First, it was recently demonstrated in IZMODENOV et al. (2009) that high-energy charged (pickup) protons can arise in the outer heliosheath due to charge exchange between interstellar protons and ENAs originating inside the heliopause. The energy distribution of the pickup protons has maximum near 1 keV and extends to energies of about 10 keV. Second, it was noted in McComas et al. (2009) and Schwadron et al. (2009) that the ribbon position, as seen from the Earth, coincides closely with the likely magnetic field direction located just beyond the heliopause, where, according to the recent MHD models, the magnetic field is perpendicular to the heliocentric radial direction. The latter circumstance means that the interstellar magnetic field beyond the heliopause plays a very important role in the formation of the ribbon. This role is twofold. On the one hand, the dynamical effect of the magnetic field essentially changes the shape of the heliosphere and the pattern of the plasma flows in the interface region (see, e.g., IZMODENOV et al. 2009). On the other hand, the magnetic field influences the transport of energetic charged particles (PUIs). While the primary interstellar plasma can be considered as a collisional medium and can be described in the framework of the MHD approach (BARANOV 2000), pickup protons originating in the outer heliosheath from heliospheric ENAs with energies of about 1 keV are collisionless. The more comprehensive global theoretical models of the heliospheric interface (MALAMA et al. 2006; IZMODENOV et al. 2009), treated PUIs as a separate population of charged particles, assume that the velocity distributions of the PUIs in both inner and outer heliosheath are isotropic (in the plasma rest frame). In other words, the isotropization time in these models is considered to be the smallest characteristic time. This is a fairly good approximation for the supersonic SW and, possibly, for the inner heliosheath. However, in the interstellar medium this time is unknown. Here, we consider the opposite limiting case when the scattering of PUIs in the outer heliosheath due to wave–particle interactions is completely ignored. We show that in this limiting case a feature arises from simulations that is qualitatively similar to the observed ENA ribbon, much as Heerikhuisen et al. (2010) found.

The efficiency of wave–particle interactions resulting in pitch-angle scattering of PUIs depends on the wave intensity. Sources of the waves in the SW are the Sun and instabilities connected with non-uniformity of the SW flow (boundaries between low- and high-speed streams). On the contrary, the intensity of plasma waves in the circumsolar interstellar medium is not known. That is why it is very useful to consider limiting cases and compare them with available data. One limiting case was considered in IZMODENOV et al. (2009). Here, as we have mentioned above, we consider another limiting case when the scattering of PUIs outside the heliopause is completely ignored. In fact, detailed comparisons of the IBEX measurements with predictions of the present model with no pitch-angle scattering and models which take it into account will potentially allow us to estimate the efficiency of this process.

The population of pickup protons beyond the heliopause is the product of the charge exchange process between interstellar protons and heliospheric ENAs. The ENAs can be subdivided into two types. Type 1 originates in the supersonic SW—the so-called neutral SW. The energy of these atoms is about 1 keV. Type 2 originates in the inner heliosheath. The ENAs from this region have a broad energy distribution extending up to several tens of keV.

3. NUMERICAL MODEL

In the case of negligible scattering, which we consider here, the motion of a pickup proton in the outer heliosheath consists of gyration around a magnetic field line and free motion of its guiding center along this line. Figure 1 shows the spatial distribution of the interstellar magnetic field around the heliopause in the BV plane, where B is the magnetic field vector and V is the vector of the interstellar plasma velocity. The arrows show the direction of the magnetic field, while the color indicates the magnetic field magnitude. The results presented here are obtained in the framework of the numerical three-dimensional model, with an MHD description of the plasma flows and a kinetic description of atoms (IZMODENOV et al. 2005). The process of generating an ENA in the outer heliosheath is also shown schematically in Figure 1. An energetic atom from the heliosphere (ENA1) penetrates into the outer heliosheath. Due to the charge exchange reaction between the ENA1 and an interstellar proton, a new pickup proton is “born.” Once produced, it moves along a magnetic field line until a subsequent charge exchange results in the formation of a new energetic atom (ENA2). Under appropriate conditions, this new ENA reaches the vicinity close to the Sun where it can be detected by IBEX.

Note that neutrals from the SW will be picked up over a huge range of distances from the heliopause (~1000 AU).
In Figure 1, one can see the domains of the increased magnetic field magnitude and domains where the magnitude reaches its minimal values. The transport of pickup protons in the outer heliosheath is substantially determined by these features. The regions of the strong magnetic field can be considered as magnetic mirrors or stagnation regions where the motion of charged particles along field lines is decelerated and some portion of the particles is reflected. A pronounced magnetic mirror is located near the red color region in Figure 1. Moreover, there are other magnetic mirrors, one of which is marked by the circle. For instance, when a proton inside the circle moves along a field line from the region of the weak magnetic field (blue color) toward the region of the increased magnetic field (green color), its parallel motion is decelerated and the proton can potentially be reflected. Figure 2 schematically illustrates the velocities of individual particles in the vicinity of the magnetic field maximum presented in Figure 1. The maximum of the magnetic field (the magnetic mirror) is marked by the dotted line Λ. The velocity, \( v \), of a pickup proton originating from a heliospheric energetic atom can be obtained as the sum of velocity along the magnetic field line, \( v_\parallel \), and the gyration velocity, \( v_\perp \). In the case of no scattering, the magnetic moment of charged particles propagating in the slowly varying magnetic field is an adiabatic invariant; we use this simplification in our model. Furthermore, we ignore the effects of the drift motion of the pickup protons in the charge exchange process. This assumption is well founded since the speeds of the drift motion are about 20 km s\(^{-1}\), small compared with the proper speeds of the particles. Thus we have

\[
v_\perp^2 / B = \text{const}, \quad v_\parallel^2 + v_\perp^2 = \text{const}.
\]

Equation (1) determines the motion of a pickup proton in the fixed magnetic field \( B \). If particles move along the field line in the direction of increasing field magnitude (protons 1 and 2 in Figure 2), \( v_\parallel \) decreases, while \( v_\perp \) increases due to conservation of the first adiabatic invariant and conservation of energy. For some of the particles \( v_\parallel \) may become zero in the region of the increased magnetic field and then these particles are reflected. This is a magnetic mirror effect. In any case, the parallel velocities of pickup protons near the maxima of the magnetic field magnitude are small, so that the pickup protons spend a comparatively long time in these regions. Therefore, these regions in the outer heliosheath are ideal places for the production of ENAs. Note that, as can be seen in Figure 1, the radial component of the magnetic field at the maximum equals zero. In other words, the position of these regions coincides with the observed position of the IBEX ribbon in the sky.

As we have mentioned, many magnetic mirrors can exist in the vicinity of the heliopause. In Figure 1, we show two of them. In this way, a charged particle can be trapped between two mirrors until the charge exchange reaction results in the formation of an ENA. Note that ENAs, originating from protons stagnating near the second mirror marked by the circle, do not contribute to the ribbon since their velocity vectors do not pass through the Sun. However, this magnetic mirror allows protons to return to the regions where the magnetic field is perpendicular to the radial direction.

Results of our calculations of fluxes of energetic hydrogen atoms at 1 AU from the outer heliosheath at the energy about 1 keV are shown in Figure 3. The numerical model makes use of the simplified guiding center approach for pickup protons, which is based on conservation of the magnetic moment and energy, and on the magnetic mirror effects. The interstellar pickup protons are calculated by using the same Monte Carlo code that was developed for H atoms by Malama (1991). The ENA fluxes are calculated directly in the Monte Carlo code.
There is a significant difference between our model and the model of Heerikhuisen et al. (2010), which also attempts to explain the ribbon-like feature considering pickup protons in the case of weak scattering. However, they assume that pickup protons in the outer heliosheath have a partial shell distribution and that re-neutralization is instantaneous. In other words, the motion of the pickup protons along the magnetic field lines is not included.

The ribbon-like structure, similar to the IBEX ribbon, is clearly seen in Figure 3(a). This figure shows the all-sky map of the calculated differential ENA fluxes in the energy range 0.83–1.39 keV in Mollweide projection in ecliptic coordinates. Figure 3(b) shows the ratio of ENA fluxes from the outer heliosheath to ENA fluxes from the inner heliosheath in the case of the Maxwellian distribution of the mixture of pickup and SW protons. ENAs of sort 1 are excluded as parent atoms for pickup protons in the outer heliosheath (see the text). The numbers in the left corner indicate the passband central energy.

Figure 3. All-sky maps of the calculated ENAs in the energy range 0.83–1.39 keV in Mollweide projection in ecliptic coordinates. (a) Differential fluxes in (cm$^{-2}$ sr s keV$^{-1}$). The curves $B_{\parallel} = 0$ near the heliopause, $B_{LISM} \cdot R = 0$, and the $BV$ plane are shown. (b) The ratio of ENA fluxes from the outer heliosheath to ENA fluxes from the inner heliosheath in the case of the Maxwellian distribution of the mixture of pickup and SW protons. ENAs of sort 1 are excluded as parent atoms for pickup protons in the outer heliosheath (see the text). The numbers in the left corner indicate the passband central energy.

4. CONCLUSIONS

Here, we have reported a new model without scattering, but including the effects of ion transport for the pickup protons generated in the region outside of the heliopause by charge exchange of the thermal interstellar protons and heliospheric ENAs. The results of the model yield a feature qualitatively similar to the IBEX ribbon. In future studies, the results of simulations will be quantitatively compared to IBEX ENA observations. These further studies need to take into account ENAs for the inner heliosheath in a proper kinetic way as was done in Malama et al. (2006).

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