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Emission of hydrogen energetic neutral atoms from the Martian subsolar magnetosheath

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Abstract We have simulated the hydrogen energetic neutral atom (ENA) emissions from the subsolar magnetosheath of Mars using a hybrid model of the proton plasma charge exchanging with the Martian exosphere to study statistical features revealed from the observations of the Neutral Particle Detectors on Mars Express. The simulations reproduce well the observed enhancement of the hydrogen ENA emissions from the dayside magnetosheath in directions perpendicular to the Sun-Mars line. Our results show that the neutralized protons from the shocked solar wind are the dominant ENA population rather than those originating from the pickup planetary ions. The simulation also suggests that the observed stronger ENA emissions in the direction opposite to the solar wind convective electric field result from a stronger proton flux in the same direction at the lower magnetosheath; i.e., the proton fluxes in the magnetosheath are not cylindrically symmetric. We also confirm the observed increasing of the ENA fluxes with the solar wind dynamical pressure in the simulations. This feature is associated with a low altitude of the induced magnetic boundary when the dynamic pressure is high and the magnetosheath protons can reach to a denser exosphere, and thus, the charge exchange rate becomes higher. Overall, the analysis suggests that kinetic effects play an important and pronounced role in the morphology of the hydrogen ENA distribution and the plasma environment at Mars, in general.

1. Introduction

Energetic neutral atoms (ENAs) are formed from ions in space plasmas when they undergo neutralizing collisions with neutral matter, such as a gaseous medium, dust grains, or a solid surface [see Gruntman, 1997]. For the case of the solar wind-Mars interactions, the neutralizing process at work is mainly the charge exchange (CX) reaction between the solar wind ions and the exospheric neutral particles. Because the energy loss in the CX reaction is very small compared to the original ion kinetic energy, an ENA retains the velocity vector of its parent ion. Also, an ENA does not feel the electromagnetic field, and its kinetic energy is usually much higher than the escape energy at Mars; therefore, it travels practically in a straight line. The recording of directional ENA flux, sometime called ENA diagnostic, allows for the remote sensing of plasma dynamics in the solar wind-atmosphere interaction region where continuous in situ measurements are impossible. Under suitable upstream conditions, ENA diagnostic is also capable of detecting the density distribution of the upper part of the Martian exosphere. For a more detailed review about ENAs from Mars-solar wind interaction, see Futaana et al. [2011].

Due to the complexity of the plasma flow and the uncertainty of the exospheric neutral density distribution, modeling effort has helped to understand the properties of ENAs from Mars. Kallio et al. [1997] first attempted to predict the properties of the ENAs in the Martian environment using plasma observations which were available at that time. The authors employed the empirical plasma flow model derived from Phobos-2 plasma data [Kallio, 1996], and the exospheric density profiles corresponding to the solar maximum and solar minimum conditions. The authors anticipated an ENA flux of $10^6 \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$ to $10^7 \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$ to be emitted from the dayside. The results also included the ENA flux distribution, energy spectra depending on the observation positions close to Mars, and the precipitation pattern of ENAs onto the upper atmosphere. Later, a series of model predictions were made in the light of Mars Express (MEX) mission, on which the Analyzer of Space Plasmas and Energetic Atoms (ASPERA-3) [Barabash et al., 2006] is capable of detecting ENAs from near-Mars space. Holmström et al. [2002] used an analytical plasma flow model for the ENA production rate distribution but calculated the line-of-sight-integrated ENA flux images for a given vantage point in order for the
estimations to be directly comparable with future observations. Lichtenegger et al. [2002] predicted the production of planetary hydrogen ENAs using a test particle model based on the gas dynamic model of solar wind flowing past a nonmagnetized atmosphere [Spreiter and Stahara, 1980]. Barabash et al. [2002] predicted the flux, energy spectrum, and images of the planetary oxygen ENAs using the empirical plasma flow model from Kallio [1996]. Gunell et al. [2006a] compared the hydrogen ENA simulations using empirical, MHD, and hybrid plasma models and discovered that the production rate distributions and resultant ENA images differ substantially among three model approaches although the total production rates agree better. This comparison demonstrates the importance of a more sophisticated plasma model. All these model efforts were predictive, since there was no observation to compare with at that time.

This situation has been changed since the operation of the Neutral Particle Detectors (NPD) [Grigoriev, 2007] and Neutral Particle Imager (NPI) [Brinkfeldt, 2005] as the first ENA sensors at Mars. The first ENA observations confirmed that the dayside hemisphere of Mars is a spread source of hydrogen ENAs, including the ENAs produced upstream to the bow shock [Brinkfeldt et al., 2006], in the magnetosheath [Futaana et al., 2006a; Galli et al., 2006; Gunell et al., 2006b] and reflected from the dayside upper atmosphere [Futaana et al., 2006b]. The typical directional flux intensity is in the order of $10^5 \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ to $10^6 \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$. On the other hand, no clear signature of oxygen ENAs was identified from the data [Galli et al., 2006]. Later, various possibilities of ENA remote sensing as a diagnostic technique to monitor the plasma environment of Mars have been investigated. For example, Futaana et al. [2006c] observed the enhancement and fluctuation of detected ENA flux as a response to an interplanetary structure with very strong solar wind dynamic pressure pulse. Mura et al. [2008] analyzed the ENA flux distribution with respect to the spacecraft position and compared the results to the updated version of the model used in Kallio et al. [1997]. Wang et al. [2014] discovered the enhancement of ENA emission caused by the crustal magnetic anomalies of Mars. Some of these observational results were reported without comparing to any ENA production models, while others were compared to some models but only to the extent of demonstrating their validity.

Among all the ENA observations, Wang et al. [2013] used ENA diagnostics to explore the properties of plasma flow in the dayside magnetosheath of Mars. The dayside magnetosheath is a region of dynamic interactions between the solar wind and Martian atmosphere, where Mars orbiters have provided very little situ plasma measurements because of the very small geometric dimensions. Wang et al. [2013] discovered that stronger hydrogen ENA emissions were more frequently observed in the opposite direction of the convective electric field of the solar wind and proposed an asymmetric shape of the induced magnetic boundary (IMB) [e.g., Bertucci et al., 2011]. This proposal has not been verified with any modeling effort yet. Also, the authors discovered a positive correlation between the ENA flux and upstream solar wind dynamic pressure but could not distinguish this correlation from that with the solar wind proton flux.

In this study, we will interpret and expand the results of Wang et al. [2013] with a hybrid model. Hybrid models are suitable for this study because the models are capable of tracing individual ions, which can be converted to ENAs by employing a neutral exospheric model. This study is the first attempt to systematically compare the modeled and the observed characteristics of the dayside ENA emissions at Mars, in order to understand the plasma environment of Mars and to exploit ENA diagnostics as a universal remote sensing tool to explore other planetary bodies.

This paper is arranged as follows: We firstly introduce the plasma and the neutral exosphere models in section 2. We then describe the ENA production rate distribution in section 3. The ENA simulation results, including the subsolar emission pattern and the dependence on upstream solar wind dynamic pressure, are then described in sections 4 and 5, respectively. Finally, we discuss the implications of the simulation results in section 6.

## 2. Model Description

### 2.1. Plasma Flow Model

The plasma flow in this study is simulated with the HYB-MARS model [Kallio et al., 2010], an up-to-date version of the three-dimensional quasi-neutral hybrid model developed for simulating the global interaction between the solar wind and a planetary atmosphere [Kallio and Janhunen, 2002]. We use Mars-centered solar electric field coordinate system in this study. The origin of the frame is the center of Mars, and the upstream solar wind velocity is along the $-x$ direction. The $y$ axis lies in the same plane as the interplanetary magnetic field (IMF). The $z$ axis completes the right-handed coordinate system so as to be aligned with the convective electric
Table 1. Fixed Parameters Used in the Simulation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{SW}$</td>
<td>$1.5 \times 10^5$</td>
<td>K</td>
</tr>
<tr>
<td>$B$</td>
<td>$(-1.63, 2.52, 0)$</td>
<td>nT</td>
</tr>
<tr>
<td>$</td>
<td>B</td>
<td>$</td>
</tr>
<tr>
<td>$r_{nh+H}$</td>
<td>$5.58 \times 10^{-8}$</td>
<td>s$^{-1}$</td>
</tr>
<tr>
<td>$r_{e+H}$</td>
<td>$1.5 \times 10^{-14}$</td>
<td>cm$^{-3}$ s$^{-1}$</td>
</tr>
<tr>
<td>$\sigma_{HH}$</td>
<td>$2.5 \times 10^{-19}$</td>
<td>m$^2$</td>
</tr>
<tr>
<td>$\sigma_{HO}$</td>
<td>$10^{-19}$</td>
<td>m$^2$</td>
</tr>
</tbody>
</table>

The simulation domain is $-4R_{IB} < x, y, z < 4R_{IB}$, where $R_{IB}(=R_M + 207$ km) is the radius of the inner boundary used in the simulation, taken to be 207 km larger than the Mars radius used in this model $R_M(=3393$ km). The inner boundary mimics the exobase of Mars, below which the collision processes should have been taken into account.

The hybrid model treats ions as macroparticles that represent clouds of identical physical particles. Electrons are treated as a massless, charge-neutralizing fluid. The electric and magnetic fields are registered on a grid. The grid size increases from 0.05 $R_M$ at the inner boundary to 0.2 $R_M$ for radial distance greater than 2 $R_M$. Each macroparticle has a statistical weight, chosen a priori so that the macroparticle count in a grid cube is sufficiently large to represent the physical particles but yet small enough to be computationally feasible. Macroparticle per cube count was set to 30 in these simulations initially. Macroparticles may be split to retain sufficient statistics or joined to gain computational efficiency. The model tracks the ion species that carry almost all kinetic energy and momentum in the region of interest: solar wind H$^+$, ionospheric O$^+$ and O$_2^+$, and exospheric H$^+$ and O$^+$. The solar wind protons are injected uniformly and constantly from the +x boundary.

The ionospheric oxygen ions are injected at the inner boundary, i.e., the exobase, at a given rate, with a cosine dependence on the solar zenith angle. At nightside, the ionospheric emission is taken to be a constant. The total ionospheric flux is taken to be $2 \times 10^{25}$ s$^{-1}$ for O$_2^+$ and $1.4 \times 10^{25}$ s$^{-1}$ for O$^+$. Extended sources are included as exospheric populations, which are generated from a static neutral exosphere (section 2.2) via photoionization (reaction rate $r_{nh+H}$), electron impact ionization (reaction rate $r_{e+H}$), and charge exchange (cross sections $\sigma_{HH}$, $\sigma_{HO}$) processes, respectively. Reaction rates and cross sections are given in Table 1. In the simulation, the positions and velocities of all ions are calculated in a time step of 0.02 s. This is repeated until the whole simulation reaches a quasi steady state around 200 s. A comprehensive description of the plasma flow model can be found in Kallio et al. [2010]. The fixed input parameters used throughout all the runs in this study are listed in Table 1.

We do not include the crustal magnetic field of Mars [Acuña et al., 1998] in this study in spite of its impacts on the Mars plasma environment. Both Mars Global Surveyor and MEX observed a higher IMF near the strong crustal field region [Crider et al., 2003; Brain et al., 2005; Edberg et al., 2009]. MEX also observed stronger ENA emissions from the subsolar magnetosheath if the strong crustal field region is in the dayside [Wang et al., 2014]. The reasons to neglect the crustal field are as follows: (1) A simulation without the crustal field is in any case needed in order to separate the effects of the crustal field from the effects of the convective electric field, even if we perform a simulation with the crustal field. (2) Neglecting the crustal field can reduce the computational expense significantly. Because the crustal magnetic fields are confined in spatial scale, such fields would require the hybrid model to be run at very high temporal and spatial resolutions.

We use three simulation runs in this study, represented by different solar dynamic pressures of the upstream solar wind: the low-pressure (LP), medium-pressure (MP), and high-pressure (HP) cases (Table 2). We set identical proton fluxes for the LP and MP runs in order to investigate the effect of the dynamic pressure. Because a higher solar wind proton flux is usually associated with a higher dynamic pressure, it remained unclear whether the dynamic pressure dependence observed by Wang et al. [2013] was actually caused by the variation of the proton flux. We set identical upstream velocity for the MP and HP runs in order to investigate the effect from proton flux and dynamic pressure.

Table 2. Parameters That Are Different for Three Runs

<table>
<thead>
<tr>
<th>Runs</th>
<th>$V_{SW}$ (km/s)</th>
<th>$n_{sw}$ (cm$^{-3}$)</th>
<th>$\rho_{dyn}$ (nPa)</th>
<th>$f_p$ (cm$^{-2}$ s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LP</td>
<td>335</td>
<td>2.7</td>
<td>0.51</td>
<td>$9.1 \times 10^7$</td>
</tr>
<tr>
<td>MP</td>
<td>502</td>
<td>1.8</td>
<td>0.76</td>
<td>$9.1 \times 10^7$</td>
</tr>
<tr>
<td>HP</td>
<td>502</td>
<td>5.4</td>
<td>2.3</td>
<td>$27 \times 10^7$</td>
</tr>
</tbody>
</table>
Figure 1. Modeled plasma flow for the MP run: (a and e) the proton flux magnitude and components along the (b and f) \(x\), (c and g) \(y\), and (d and h) \(z\) axes in the \(z = 0\) plane (Figures 1a–1d) and \(y = 0\) plane (Figures 1e–1h). The plotting spatial resolution is 0.1 \(R_M\). The value plotted in a pixel is the average over all particles in the pixel. Thick solid contours show the boundary between positive (red colors) and negative (blue colors) values for the flux component along the corresponding axis. The upstream magnetic field is in the \(z = 0\) plane, and the convective electric field (\(E_c\)) is along the +z direction.

Figure 1 shows the vector flux of the solar wind protons obtained from the MP run. All components of the flux vector are shown for the discussion of the directionality of the ENA emission in later sections.

2.2. Exosphere Model and Charge Exchange Processes

The exosphere impacts the characteristics of generated ENAs in two aspects: (1) it serves as the reservoir for the planetary ions, which provides the mass to load the solar wind flow, altering the flow pattern of the plasma. (2) It neutralizes both solar wind and planetary ions into ENAs via CX reactions. The first effect has been discussed in section 2.1 and modeled by the existing hybrid model. The second effect, on the other hand, has not been well modeled previously. In our model for this study, this effect is implemented such that the exosphere neutralizes the incoming ions at a certain probability. The neutralizing CX probability for a given ion of species \(i\) (proton herein) along its path per unit distance is

\[
p_i = \sum \sigma_{is} \cdot n_s
\]

where \(\sigma_{is}\) is the CX cross section between the ion species \(i\) and the neutral species \(s\), \(n_s\) is the exospheric number density of species \(s\).

We use a spherically symmetric exosphere density model for this study (Figure 2), as widely used in the modeling of the solar wind interaction with Martian atmosphere [e.g., Kallio and Janhunen, 2002; Bößwetter et al., 2004; Modolo et al., 2005; Brecht and Ledvina, 2006]. Although arguments have been made that the Martian exosphere should be asymmetric with respect to the Sun-Mars line [Holmström, 2006], we expect that potential effects from such an asymmetry should have been averaged out in the observations by the variation of the IMF direction.

The exosphere contains \(CO_2\) molecules, \(O\) atoms, and \(H\) atoms, whose density profiles correspond to the solar minimum conditions. The \(CO_2\) profile comes from the Mars Thermospheric General Circulation Model [Bougher et al., 2009]. The atomic oxygen and hydrogen exospheres further contain cold (thermal) and hot
(nonthermal) components. The cold component of a species follows Chamberlain's formation theory of planetary exospheres [Chamberlain, 1963; Chaufray et al., 2007]. The hot component of the atomic oxygen mainly comes from the dissociative recombination of O$_2^+$, with the suprathermal tail of the velocity distribution as a secondary source [Hodges, 2000; Valeille et al., 2009]. The hot hydrogen component was proposed to explain the Lyman $\alpha$ observations at Mars, while the generation mechanism is yet unclear [Chaufray et al., 2008].

The charge exchange reactions taken into account are

$$
H_{SW}^+ + H_{exo} \rightarrow H_{SW}^+ + H^+ : \sigma_{HH}
$$

$$
H_{SW}^+ + O_{exo} \rightarrow H_{SW}^+ + O^+ : \sigma_{HO}
$$

$$
H_{exo}^+ + H_{exo} \rightarrow H_{exo}^+ + H^+ : \sigma_{HH}
$$

$$
H_{exo}^+ + O_{exo} \rightarrow H_{exo}^+ + O^+ : \sigma_{HO}
$$

where the subscripts “SW” and “exo” denote the origin of the energetic ions and the asterisk means an ENA. Corresponding cross sections are shown in Table 1. The cross sections are taken independent with the relative velocity between the two particles, because the cross sections within the energy range of the solar wind plasma are not sensitive to energy [Barnett et al., 1990]. We neglect charge exchange reactions with CO$_2$ due to its low density above the IMB where the solar wind protons can access.

The neutralizing CX probability of an ion within a time step $dt = 0.02$ s is therefore

$$
P_i = p_i \cdot |v_i| \cdot dt
$$

where $v_i$ is the velocity of the ion. For each ion at each time step, a random number is generated and checked with the probability $P_i$ to evaluate whether the ion experiences charge exchange or not. If true, the position, the velocity, and the weight of the ion are recorded as the generation position, velocity, and weight of an

Figure 2. The exosphere density model used in this study within the simulation domain. The cold hydrogen component is a Chamberlain exosphere [Chamberlain, 1963; Chaufray et al., 2007]. The hot hydrogen component is as observed by MEX [Chaufray et al., 2008]. The CO$_2$ and cold oxygen components are from the Mars Thermospheric Global Circulation Model running for solar longitude = 270°, $F_{10.7} = 34$ [e.g., Bougher et al., 2009]. The hot oxygen component is from a Monte Carlo model for the oxygen exosphere [Valeille et al., 2009]. This exosphere model corresponds to the solar minimum condition.
Figure 3. Production rate distributions of hydrogen ENAs originated from the (a and d) solar wind protons, the (b and e) planetary protons, and (c and f) their sum. Result from the MP run is shown. Figures 3a–3c and Figures 3d–3f show the slices at $z = 0$ and $y = 0$, respectively. The direction of the convection electric field is +z direction in all panels. The ENA production rate is binned into 0.1 $R_J$ bins. The neighboring contours show values 1 order of magnitude apart. ENAs generated beyond 2 $R_J$ from Mars center are not recorded. Dashed curves are the empirical models of the bow shock (curve at higher altitude) and the IMB (curve at lower altitude) [Trotignon et al., 2006].

3. ENA Production Rate Distribution

The production rate distribution of hydrogen ENAs in the MP run is shown in Figure 3, with the separation of the parent plasmas. CX reactions with both the hydrogen and the oxygen exospheres are taken into account. The production rate of solar wind hydrogen ENAs is higher than that of the planetary hydrogen ENAs by more than 1 order of magnitude in most regions of the simulation domain. This is natural since the solar wind proton is the dominant ion population in the region higher than the IMB, and the effect of the exosphere as a neutralizer is identical for the same ion species. The dominance of the solar wind ENAs in the total ENA. The ion is then removed from the plasma model. The new ion created by this CX reaction is just the exospheric ion already included in the plasma model. We record the generation of ENAs for 80 s after the plasma model reaches a steady state. The recording time is good to be longer than the ion gyration period in order to capture the full range of gyromotion timescales (up to $\sim 60$ s in our model). We only record the ENAs generated within the distance of 2 $R_J$ from the Mars center. This restriction significantly reduces the data volume without changing the results of the magnetosheath ENA emissions. This simplification will not change the result because the upstream solar wind ENAs produced above 2 $R_J$ follow the velocity distribution of solar wind protons, therefore, form an ENA beam that only covers a narrow angular spread in the tailward directions.
production rate indicates that the majority of hydrogen ENAs emitted into space originates from the solar wind. Therefore, we focus on analysis of the solar wind ENAs hereafter.

Figure 3a reveals that the dayside magnetosheath is the most intense ENA source region. Quantitatively, we take the region where $1 < r < 2 R_M$ and $\sqrt{y^2 + z^2} < R_M$ as the source region of interest in this study. This region is an intense source of ENAs, as has been seen not only in the simulation but also by the observation of the subsolar ENA jet [Futaana et al., 2006a] from NPD and by the observation of charge exchange ENAs in the subsolar magnetosheath [Gunell et al., 2006b] from NPI. We do not use a larger region because Wang et al. [2013] used the same region for the statistical investigation of the dayside ENA emissions. Also, the emission directionality may vary drastically inside the region if the volume of the region considered is too large. We refer to the region of interest as the “subsolar region” hereafter.

4. Directionality of ENA Emission From the Subsolar Region

4.1. Calculation of the ENA Directional Flux Intensity

As in section 2.2, we obtain the list of generated ENAs with the birth time, birth location, velocity vector, and statistical weight. We further convert these data to the “directional flux intensity,” which is the differential flux integrated over energy, a quantity to be compared with previous observations [e.g., Futaana et al., 2006a, 2006b; Gunell et al., 2006b; Wang et al., 2013].

The directional flux intensity $j$ (cm$^{-2}$ s$^{-1}$ sr$^{-1}$) is defined as the particle flux emitted into a specific direction $\vec{n}$ (expressed in azimuth (“longitude”) $\varphi$ and elevation (“latitude”) $\theta$) within a unit solid angle. The directional flux intensity is derived from the simulation data as

$$j(\vec{n} = (\varphi, \theta)) = \frac{N}{dA \, dT \, d\Omega}$$

(7)

where $dT$ is the accumulation time, $d\Omega$ is the solid angle of the spherical cone centered at $\vec{n}$, and $dA$ is the area of the subsolar region projected on a plane perpendicular to $\vec{n}$. $N$ is the number of particles produced within the area $dA$, moving in the directions within $d\Omega$ at $\vec{n}$ and having energies between 0.3 keV and 3 keV. This energy range is taken for comparison with the observational ENA characteristics reported by Wang et al. [2013]. The particles whose trajectories intersect with the inner boundary are removed. In practice, $dT$ is 80 s, the time interval we have gathered particles in the simulation. For a specific direction $\vec{n}$, we collect all particles that move in the directions closer than 6° from the specific direction, $\vec{n}$; therefore, $d\Omega = 2\pi(1 - \cos 6°) = 3.44 \times 10^{-2}$ sr. The projected area $dA$ is the area covered by all collected particles in the plane perpendicular to $\vec{n}$. 

Figure 4. Conversion from collected particles to the directional flux intensity $j$ in an emission direction $\vec{n}$ ($\varphi = 54°, \theta = 6°$ as an example). All collected particles are shown as filled circles with black edge. Bleached circles without edge represent particles outside the 0.3 keV–3 keV energy range. The projected area of the source region is the area within the blue boundary, in the plane perpendicular to the emission direction $\vec{n}$. The red circle with 1 $R_M$ radius represents Mars. The red, green, and black curves on the surface of Mars show its intersections with the planes $z = 0$, $y = 0$, and $x = 0$, respectively.
Directional flux intensity distribution of the subsolar hydrogen ENAs with the energy in 0.3 keV–3 keV range for the MP case. (a) The emission map in the Mollweide projection. The directional flux intensity \( j \) is shown as a function of the emission direction expressed in the cone angle (dashed contours, 0° to 120°) and the clock angle (solid lines, 0° to ±180°). See text for the definitions of the cone angle and clock angle. The size of a bin is 6° (d\( \phi \)) \times 6° (d\( \theta \)). White bins either have no ENAs within the energy range or are outside 120° cone angle.

\( j \) as a function of the (b) cone angle and the (c) clock angle, color coded by the other angle, respectively.

Because simulated macroparticles do not occupy any physical volume, we divide the perpendicular plane into square cells and define the projected area as the total area of the cells covering at least one particle (cells within the blue boundary in Figure 4, which is consistent with Figure 3 in Wang et al. [2013]). The side length of a cell is a free parameter and taken to be 0.5 \( R_{\infty} \). Smaller cell size gives more accurate estimation on the projected area but may cause gaps between cells and poorer particle statistics in each cell.

4.2. ENA Emission From the Subsolar Region

Using equation (7), we calculate the directional flux intensity for all emission directions at a resolution of 6° for both \( \phi \) and \( \theta \). Here we switch to the cone angle and the clock angle to express the directions, in order to discuss the directional asymmetry. The cone angle is defined as the angle between the +x direction and the direction of interest. It ranges from 0° (sunward direction) to 180° (antisunward direction), and we only consider the cone angles up to 120° as in Wang et al. [2013]. The clock angle is defined as the angle in the terminator plane between the projection of the direction of interest and the +\( E_{\perp} \) direction (0° clock angle), ranging from –180° to 180° and increasing counterclockwise. Figure 5a shows the obtained emission map. The dependencies of the directional flux intensity on the cone angle and the clock angle are also shown in Figures 5b and 5c.

The average directional flux intensity of the subsolar emission within 120° cone angle in the model is \( 1.92 \times 10^{5} \) cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\). The observed directional flux intensity ranges from \( 10^{5} \) cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\) to \( 10^{6} \) cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\), with 71% of the observations falling between \( 10^{5} \) cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\) and \( 5 \times 10^{5} \) cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\) [Wang et al., 2013]. The simulation agrees well with the observation, considering the variable nature of ENA emissions. This result suggests that the parameters used in these models are constrained rather well, not only those that have been well established (the solar wind proton density, the IMF, and the ionospheric ion density) but also those less constrained (e.g., the exospheric density profile and the chemical reaction cross sections) due to difficulty in measurement.

The directional flux intensity (Figure 5) varies from \( 6 \times 10^{4} \) to \( 6 \times 10^{5} \) cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\). The variation firstly depends on the cone angle of emission direction (Figure 5b). The lower intensity is found more frequently in the sunward directions. The intensity increases exponentially with increasing cone angle until 90°, and then it remains constant. The cone angle dependence agrees with the observation of the subsolar ENA jet [Futaana et al., 2006a] seen in a time series along a single orbit. The dependence is also in agreement with the statistical result that higher intensity is more frequently observed in the plane perpendicular to the Sun-Mars line [Wang et al., 2013]. The greater intensity in the directions of large cone angles suggests that the proton velocity distribution in the dayside magnetosheath at low altitude has a dominant velocity component close to the 90°...
cone angle. This dominant velocity component comes from the bulk flow of the shocked solar wind. The flux also has clock angle dependence; the range of variation increases with increasing cone angle (Figure 5c). The factors of variations increase from 1 at \(-0^\circ\) cone angle to \(-8\) at \(-90^\circ\) cone angle. The observations, however, did not show such distinctive clock angle dependence, in general. Possible explanations might be insufficient statistics to reveal such a dependence or insufficient accuracy in calculating draping angle so that the dependence has been smeared out.

In the observations reported by Wang et al. [2013], the highest intensities are more frequently observed in the \(-Ec\) direction. The authors proposed that the lower altitude of the dayside IMB in the \(-Ec\) hemisphere therefore higher neutral density gives rise to the higher ENA intensity. In the simulation result (Figure 5c), the directional flux intensity of ENAs close to the \(-Ec\) direction (clock angle \(\pm 180^\circ\)) indeed exceeds that close to the \(+Ec\) direction (clock angle \(0^\circ\)), consistent with the observations. However, the plasma model reproduces a higher IMB altitude in the \(-Ec\) hemisphere (see Figure 3d and compare the production rate with the modeled IMB which is symmetric in \(\pm Ec\) directions), opposite to the proposed scenario by Wang et al. [2013]. The neutral density at the IMB altitude in the \(-Ec\) hemisphere is therefore lower than that in the \(+Ec\) hemisphere (spherically symmetric exosphere assumption), indicating that it is not the reason for a higher ENA intensity obtained from the simulation.

Instead, the feature can be explained by the asymmetry of proton flux distribution in the subsolar region between the \(\pm Ec\) hemispheres. Figure 1h shows the distribution of the \(z\) component of the proton flux in the \(y = 0\) plane. One can see that the majority of the protons close to the IMB have a velocity component in the \(-Ec\) direction. Such an asymmetry is apparently strong enough to compensate for the possibly lower neutral density at the IMB altitude accessible to the protons in the \(-Ec\) hemisphere and produces a stronger ENA flux in the \(-Ec\) direction.

The stronger proton flux in the \(-Ec\) direction can be explained by the finite gyroradius effect of solar wind protons [e.g., Brecht and Ferrante, 1991] and the effect of the mass loading to the shocked solar wind [e.g., Szegő et al., 2000; Kallio and Jarvinen, 2012]. The finite gyroradius effect is significant if the subsolar magnetosheath thickness is comparable to or smaller than the solar wind proton gyroradius, which is the case at Mars. The protons in the subsolar region are in the early phase of their first gyration, when their instantaneous velocity increasingly deviate in the \(-Ec\) direction. One effect of the mass loading process is that it reduces the bulk velocity of electrons in which the IMF is frozen. Therefore, in the reference frame of electrons, where the electric field is zero without resistivity, the solar wind protons moving in the tailward direction are faster than the...
Figure 7. Hydrogen ENA production rate distributions in the (a–c) $z=0$ plane and (d–f) $y=0$ plane for the LP (Figures 7a and 7d), MP (Figures 7b and 7e), and HP (Figures 7c and 7f) runs. Values in the HP run have been normalized (divided by 3, the ratio of upstream proton flux over the MP/LP runs). The boundaries (IMB and bow shock) basically follow the contour at the value of $-2$. MP run results (Figures 7b and 7e) are identical to Figures 3c and 3f. Dashed curves are again the empirical models for the IMB and bow shock as in Figure 3.

5. Dependence on the Upstream Conditions

In this section, we discuss the dependence of the ENA characteristics on the upstream parameters. As shown in Table 2, we did three runs using different upstream parameters: LP, MP, and HP.

The dayside ENA emission is dominated by CX ENAs produced from the solar wind protons. Given the fixed exospheric density distribution, the total CX ENA production rate is determined only by the spatial distribution of the proton flux. If we assume the proton flux to be the only factor controlling the ENA emissions, the resultant ENA production rate and directional flux intensities are then expected to be proportional to the upstream proton flux. In other words, the ENA flux maps normalized by the upstream proton fluxes in the LP and the HP runs are then expected to be identical to the results of the MP run (Figures 3 and 5). However, the
actual normalized simulation results in the LP and HP runs show different features from those in the MP run. Therefore, by comparing the simulation results from different runs, we can learn the effects of the variation of upstream parameters.

Figure 7 shows normalized ENA production rate distributions for three different runs. In the LP (HP) run, the IMB and bow shock are at higher (lower) altitudes than those in the MP run. This is consistent with the observation that higher solar wind dynamic pressure causes the compression of the induced magnetosphere and the decrease in the IMB altitude [Crider et al., 2003; Verigin et al., 2004; Brain et al., 2005; Dubinin et al., 2006; Edberg et al., 2009]. In addition, because the spatial scale of the magnetosheath is wider (narrower) than that in the MP case, a more (less) widespread ENA source region is seen. The asymmetry of production rate distribution along the $E_c$ becomes less apparent with increasing solar wind dynamic pressure. In the LP run (Figure 7d), the induced magnetosphere (roughly the region with production rate lower than $10^{-2} \text{ cm}^{-2} \text{s}^{-1}$) is slightly wider in the dayside than the other cases but deviates more to the $-E_c$ hemisphere. While in the HP run (Figure 7f), the IMB is so low that the induced magnetosphere can be hardly distinguished in the dayside, and the magnetosphere becomes almost axially symmetric.

The ENA directional flux intensity distribution in the LP run is shown in Figure 8. The average intensity is $1.49 \times 10^5 \text{ cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$, lower than that in the MP run. However, the intensity distribution is clearly different from that obtained from MP run (Figure 5a). In the sunward directions (cone angle <30°) the intensity is slightly higher, while in the perpendicular directions (cone angle ~90°) the intensity is slightly lower ($\sim7 \times 10^5 \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$ in the MP run, $\sim5 \times 10^5 \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$ in the LP run). The cone angle dependence is thus weaker in the LP run. The flux difference between $\pm E_c$ directions appears similar to that in the MP run.

In the HP run (Figure 9) the average intensity after normalization is $2.21 \times 10^5 \text{ cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$ (the average intensity before normalization was $6.62 \times 10^5 \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$), higher than that in the MP run. The normalized intensity in the sunward directions is slightly higher than the intensity in the MP run ($\sim1.5 \times 10^5 \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$ in the HP run, $\sim1.0 \times 10^5 \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$ in the MP run). The cone angle dependence is the same as in the MP run, while the intensity keeps increasing until 120° cone angle in the HP run. The clock angle dependence of the intensity does not show significant difference from that in the MP run. The latter feature implies that despite a more axially symmetric shape of the induced magnetosphere in the HP run (Figures 7c and 7f), the flow pattern of protons in the subsolar region is similar to that in the MP run.

The variation of the average directional flux intensity in the three runs (normalized in the HP run) agrees with the observed characteristics of positive correlation between the solar wind dynamic pressure and the ENA intensity normalized by the solar wind flux [Wang et al., 2013]. The solar wind dynamic pressure dependence is dominated by emissions in the directions close to 90° cone angle, the majority of dayside ENA emissions. This dependence can be explained by the different neutral densities at the IMB of different altitudes in different
Figure 9. Directional flux intensity distribution of the subsolar hydrogen ENAs in the HP case. The directional flux intensity is normalized by the upstream flux (divided by 3, the fraction of upstream flux between MP and LP). Format of the figure is identical to that in Figure 5.

runs. However, the sunward (<30° cone angle) ENA intensity in the LP run is higher than that in the MP run, suggesting that the dynamic pressure is not the dominant controlling factor for these ENAs at least in the LP case. As defined in the model, these sunward ENAs originate from protons with a sunward velocity. The sunward velocity comes from the gyration around the horizontally draped magnetic field at the IMB [Shematovich et al., 2011]. The magnetic field intensity at the IMB is stronger than in the magnetosheath, causing a smaller proton gyroradius. Gyrating protons can thus turn sunward at a relatively low altitude, where the neutral density is still high enough to produce a significant sunward ENA flux. The magnetic field disturbances at a smaller scale than the local proton gyroradius can also scatter the proton velocity. In the LP run, the proton bulk velocity is lower and the distance between the IMB and the bow shock is larger. These conditions might be favorable to the processes mentioned above so that more shocked solar wind protons get sunward direction, resulting in a higher ENA intensity in the sunward directions.

6. Discussion

In this paper the ENA emission directionality is determined by the flux distribution of solar wind protons, since the ENA production rate from which is ∼2 orders of magnitude higher than the planetary hydrogen (Figure 3). In addition, current observations do not distinguish these two origins and consider all detected ENAs are from the solar wind protons [Wang et al., 2013]. Therefore, we only discuss hydrogen ENAs of solar wind origins in this study.

The ENA emission directionality and the solar wind dynamic pressure dependence show both fluid and kinetic characteristics of the magnetosheath plasma in the subsolar region. The anisotropic ENA directional flux intensity distribution reflects an anisotropic proton velocity distribution that has a bulk component perpendicular to the Sun-Mars line. Such a significant bulk velocity exhibits that even in the subsolar region, despite a proton temperature of tens to more than a hundred eV, the shocked solar wind plasma is still not fully thermalized, consistent with in situ observations by MEX/ASPERA-3 [Fränz et al., 2006; Nilsson et al., 2011]. The bulk flow velocity distribution follows the stream lines from a gas dynamic model [e.g., Spreiter and Stahara, 1980] or a MHD model [e.g., Harnett and Winglee, 2005] of the solar wind interaction with Mars, suggesting that the interaction between the solar wind plasma and such a small obstacle as the Mars induced magnetosphere still shows its fluid side.

The nonnegligible ENA flux emitted in the sunward directions, on the other hand, shows the kinetic side of the interaction. In a fluid model with a realistic proton temperature, the plasma flow in the subsolar region does not turn fully sunward. The observation of sunward ENAs [Futaana et al., 2006b; Wang et al., 2013] was hence explained solely by the "ENA albedo," i.e., the scattering of solar wind ENAs from the upper atmosphere [Kallio and Barabash, 2001]. Here our results demonstrate that sunward ENA emissions are already significant
even if only CX reactions are taken into account. This further indicates that a significant part of shocked solar wind protons from the subsolar region moves sunward, which can only be explained by kinetic effects. One example of the kinetic effect is the effective reflection of precipitated protons by a moderate horizontal magnetic field [Shematovich et al., 2011]. Of course, backscattered ENA population can also contribute to sunward moving ENAs.

One of the most interesting discoveries from the ENA diagnostics of the subsolar magnetosheath is the \( \pm E_z \) asymmetry in the ENA flux. Wang et al. [2013] proposed that a lower IMB in the \(-E_z\) hemisphere was responsible for this asymmetry, because the asymmetric shape of the plasma boundaries had been understood well by the community [e.g., Edberg et al., 2009; Brain et al., 2010, and references therein]. This proposal, however, was based on the assumption of a symmetric proton flux distribution between the \( \pm E_z \) hemispheres, which, although widely used within the community, is not appropriate as revealed by our simulation results. This result further suggests that kinetic effects must be taken into account not only near the plasma boundaries but also in the whole interaction region around Mars.

The simulated \(~22\%\) asymmetry in the ENA flux in the \( \pm E_z \) directions is lower than the observed asymmetry of a factor of 2–3. This means that other factors must have contributed to the observed asymmetry. One possibility is the combination of the influence of the strongest crustal magnetic anomaly and the unevenly distributed IMF clock angle used to derive the convective electric field direction. At the time of the observational study, it was unclear if the crustal field has any impact on the ENA emission at all. In addition, it was assumed that the impact would have averaged out due to the variability of the IMF clock angle. However, if the IMF clock angle has a preference, the strong crustal field region will expose its effect more often in a fixed direction in the electric field frame, breaking the assumption. This might have been the case for the observations by Wang et al. [2013].

In this study, only the CX ENAs emitted from the subsolar region above the exobase (\(~200\ km\ altitude\) are collected. This is only a fraction of the ENA populations that have been detected. The tailward ENAs are generated in the magnetosheath flank and propagate into the nightside of Mars [Galli et al., 2006, 2008]. ENAs generated from upstream solar wind and shocked solar wind will precipitate to the upper atmosphere and cause a series of consequences [Kallio and Barabash, 2001; Holmström et al., 2002; Kallio et al., 2006]. One interesting consequence is the backscattering of ENAs [Futaana et al., 2006b; Shematovich et al., 2011] that shows up in the statistical results of Wang et al. [2013]. Also, the energy distribution of ENAs is not considered in this study. New studies are called for to study these issues which are beyond the scope of the present study.

7. Conclusion

We have simulated the hydrogen ENA emissions from the dayside of Mars to understand its dependence on the solar wind dynamic pressure. We obtained ENA directional flux intensity (in the unit of \( \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \)) as a function of emission direction in the convective electric field reference frame. Direct comparison with the emission pattern measured by the Mars Express/NPD [Wang et al., 2013] reveals the following:

1. Averaged over all directions of interest, the simulated directional flux intensity in the medium solar wind pressure case (0.758 nPa) is in the range of \((1 \sim 5) \times 10^5 \text{ cm}^{-2} \text{s}^{-1} \text{sr}^{-1}\), within which 71% of the observations fall. Taking the high variability of ENA emissions into consideration, the simulated and observed fluxes are in good agreement.
2. The ENA emissions are not isotropic. The simulated directional flux intensity is higher in the perpendicular directions (close to 90° cone angle) with respect to the Sun-Mars line by a factor of \(~5\). This ratio is consistent with what obtained from the ASPERA-3 ENA observations. Therefore, the bulk flow speed of the shocked solar wind in the lower dayside magnetosheath is significant compared to the thermal speed.
3. The ENA emission is not cylindrically symmetric. The simulated directional flux intensity in the direction of the convective electric field is lower than that in the opposite direction. The feature is also consistent with the observation. The simulation result reveals that the asymmetry is due to the higher proton flux in the \( \sim E_z \) direction at lower magnetosheath. Such asymmetry is caused by the finite gyroradius effect and the mass loading effect on the shocked solar wind protons. It is implied that factors other than the convective electric field might have contributed to the observed asymmetry.
4. The average dayside ENA emission rate is positively correlated with (1) the upstream proton flux and (2) the solar wind dynamic pressure. The proton flux dependence is straightforward because the ENA flux is proportional to the proton flux given the fixed exospheric density distribution. The high solar wind dynamic
pressure, on the other hand, causes higher and more anisotropic emissions in directions toward the Sun (with cone angles larger than 30°) than the low solar wind dynamic pressure. This anisotropic emission indicates that the asymmetric proton flow in the subsolar region persists for higher solar wind dynamic pressures. The directional flux intensities in the sunward directions (cone angle less than 30°) indicate that the asymmetric proton flow in the subsolar region persists for higher solar wind dynamic pressures. The directional flux intensities in the sunward directions (cone angle less than 30°), however, has a nonmonotonic dependence on the solar wind dynamic pressure. The nonmonotonic dependence is likely because the protons gyrating around the horizontally draped magnetic field at the IMB can move in these directions, and a slower and/or denser solar wind may promote these effects.

In general, our current model results reproduce well the statistical features reported by Wang et al. [2013]. The simulation reveals both fluid and kinetic characteristics of the solar wind interaction with Martian atmosphere. The kinetic effects, such as the finite gyroradius effect and mass loading process, are indispensable to interpret the simulation results. Particularly, the ±Ec asymmetry of ENA emission reveals the asymmetric proton flux distribution in the dayside magnetosheath of Mars, exemplifying the global effects of the kinetic processes in the solar wind interaction with Mars.

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