Observations of exosphere variations during geomagnetic storms

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The dominant neutral constituent in Earth’s upper exosphere, atomic hydrogen (H), resonantly scatters solar Lyman-alpha (121.567 nm) radiation, observed as the geocorona. We report here observations of an exospheric response to geomagnetic storms obtained using measurements of the geocorona by Lyman-alpha detectors on the Two Wide-angle Imaging Neutral-atom Spectrometers (TWINS) mission. We introduce a new parameter, $N_H$, the number of H atoms in the spherical shell from a geocentric distance of 3 to 8 Earth radii, to quantitatively characterize in a simplified way global exospheric conditions. Five geomagnetic storms observed during three months in the second half of 2011 are accompanied by abrupt temporary increases, spikes, of $N_H$ from 6% to 17%, lasting not longer than a day. These increases seem to show some correlation with the minimum Dst index reached during the peak of each storm.


1. Introduction

[2] The tenuous extension of Earth’s neutral atmosphere, the upper exosphere, consists predominately of atomic hydrogen (H) [e.g., Chamberlain, 1963]. Exospheric H atoms resonantly scatter solar Lyman-α (121.567 nm) radiation, creating a phenomenon known as the geocorona. The Two Wide-angle Imaging Neutral-atom Spectrometers (TWINS) mission [McComas et al., 2009] includes Lyman-α Detectors (LADs) [Nass et al., 2006] to observe the geocorona and investigate exospheric H atoms. We use LAD measurements to reconstruct exospheric H density distributions for geocentric distances from 3 $R_E$ to 8 $R_E$, where $R_E$ is Earth’s mean radius. Our recent publication [Bailey and Gruntman, 2011a] detailed the process of obtaining such distributions, shown to be consistent with prior work. The commonly used observation-based models of Raider et al. [1986] and Østgaard et al. [2003] describe the exosphere essentially averaged over significant periods of time such that they rely, respectively, on four years of geocoronal measurements by DE-1 and one year by the IMAGE spacecraft. In contrast, LAD/TWINS often allows obtaining global distributions with three-dimensional asymmetries on a daily basis, which opens a way to experimentally probe the response of the exosphere to varying solar and geomagnetic conditions. In this letter, we report observed variations of the exosphere during five geomagnetic storms that occurred in the 3 month time period from 1 August 2011 to 31 October 2011.

2. TWINS Lyman-α Experiment

[3] We focus here on observations of the geocorona made from the TWINS-1 satellite, which is in a highly elliptical Molniya-type orbit with a period of one half of a sidereal day. Two Lyman-α detectors, LAD-1 and LAD-2, observe the geocorona for several hours per orbit around apogee from an instrument platform that rotates about a nominally nadir-pointed axis in a ±99° windshied wiper motion with a rotational rate of approximately 3° per second [McComas et al., 2009]. Thus, it takes about 1 min for the LADs, pointed at ±40° with respect to the rotation axis (Figure 1), to sweep a full circle around the Earth. As the spacecraft proceeds along the orbit, the detectors cover the geocorona, allowing reconstruction of the exospheric H density distribution based on several hours of observations [Bailey and Gruntman, 2011a]. The detectors are single pixel photometers with a field of view of 4° full width at half maximum, spectral band ±5 nm centered at the wavelength 122 nm, and sensitivity of approximately 2, $(cts \ s^{-1})/R$ ($1 \ R = 1$ Rayleigh $= 10^{8}/(4\pi) \ photon \ cm^{-2} \ s^{-1} \ sr^{-1}$) [Nass et al., 2006]. The platform positions at ±90° are such that LAD-1 points in nearly the same direction as LAD-2 in the opposite orientation, and vice versa, allowing for relative cross-calibration of the detectors. The observational geometry usually provides excellent coverage of the Northern Hemisphere, where the TWINS orbit apogee is located, but may be limited in the Southern Hemisphere.

[4] The LAD measured photon intensity is the sum of the geocoronal and interplanetary glows [Bailey and Gruntman, 2011a]. The interplanetary glow occurs as interstellar H atoms inflow into the heliosphere and also resonantly scatter solar Lyman-α radiation. Thus, the intensity, $F_p$ (in Rayleighs), observed by the LADs is

$$F_p = \frac{g^*}{10^6} \int_0^{L_{lim}} n(\vec{L}) \ I(\alpha) \ dL + F_{ip},$$

where $n(\vec{L})$ is the local H number density along the line of sight $\vec{L}$; $I(\alpha)$ is the angular dependence of Lyman-α photon scattering on atomic hydrogen [Brandt and Chamberlain, 1959]; $g^*$ is the local (adjusted to the actual Earth heliocentric distance) photon scattering rate or $g$-factor; and $F_{ip}$ is the interplanetary glow (in Rayleighs). For this work, we use daily all-sky maps (W. Pryor, personal communication, 2012) of the interplanetary glow [Pryor et al., 2013] derived directly from SWAN measurements on the SOHO mission.
3. Model

[5] The experimental and data reduction approach restricts our reconstructed exospheric H density distributions to geocentric distances between 3 \( R_E \) and 8 \( R_E \) [Bailey and Gruntman, 2011a]. The lower limit is determined by the requirement of an optically thin geocorona. The interplanetary glow becomes comparable to or dominates geocoronal intensities beyond the upper limit and introduces uncertainties that make determination of exospheric H densities at larger distances less reliable.

[6] The three-dimensional distribution of H number densities is modeled by a second-order spherical harmonic expansion with 18 free parameters that are best fit to LAD observations using the method of least squares [Bailey and Gruntman, 2011a]. A successful fit predicts measured intensities between 1000 \( R \) and 10000 \( R \) to within a standard deviation of 125 \( R \). The propagated fitting uncertainty in reconstructed exospheric H number density distributions typically increases from 7% to 9% from 3 \( R_E \) to 6 \( R_E \) and then rapidly increases up to 25% at 8 \( R_E \).

[7] A global fitting is only sensitive to observed regions of the geocorona. The LAD/TWINS experiment requires measurements during a large part of an orbit for adequate coverage around the Earth. Consequently, the experimental data do not allow reconstruction of the global exosphere for time intervals shorter than the several hours of observations that are available along each orbit (orbital period \( \sim 12 \) h).

4. Observations

[8] The upper exosphere is a complex three-dimensional distribution of mostly H atoms that usually requires a large number of parameters for its description [Hodges, 1994; Nass et al., 2006; Zoennchen et al., 2010, 2011; Bailey and Gruntman, 2011a]. To gain insight and determine possible dominant drivers of the dynamic exosphere, one could benefit from quantitatively characterizing conditions in a simplified...
way. Here we introduce a new parameter, $N_{H1}$, the number of H atoms in the spherical shell from a geocentric distance of 3 $R_E$ to 8 $R_E$, which is obtained from LAD experimental data. Typical H number densities vary from around 400–1000 cm$^{-3}$ to 10–100 cm$^{-3}$ at 3 $R_E$ and 8 $R_E$, respectively. The observed total number of H atoms, $N_{H1}$, in the selected spherical shell is typically $(4–7) \times 10^{31}$. The propagated fitting uncertainty, estimated as described in Bailey and Gruntman [2011a], is expected to be smaller for the integral quantity of $N_{H1}$ than for three-dimensional H density distributions and it does not exceed 3% for obtained values.

[9] The balance of injection of H atoms to the exosphere and their loss determines the total number of atoms in the shell. Changes in the solar EUV and Lyman-α fluxes as well as geomagnetic activity may cause variation of the injection and loss rates, which would in turn cause changes in $N_{H1}$. Therefore, this new parameter, $N_{H1}$, may serve as a measure of global exospheric conditions and provide some insight into its possible correlations with changes in the solar output and geomagnetic activity.

[10] We consider here LAD observations during the 3 month time period from 1 August 2011 to 31 October 2011 when geomagnetic activity finally began to increase after an unusually quiet solar minimum. Five geomagnetic storms occurred during this interval: on 6 August 2011 ($\Delta$DST = –107 nT), 9 September 2011 (~69 nT), 17 September 2011 (~70 nT), 26 September 2011 (~101 nT), and 25 October 2011 (~132 nT) (Figure 2). The bottom panel of Figure 2 shows the temporal variation of $N_{H1}$ obtained by us from LAD data where one can clearly see abrupt responses, spikes, of exospheric H densities with characteristic times not longer than a day associated with the geomagnetic storms. Figure 2 also shows daily averages of the solar Lyman-α and S10.7 index important to properties of the exosphere. The trajectories of H atoms beyond a few Earth radii are highly susceptible to an effective pressure caused by solar Lyman-α radiation which modifies the three-dimensional distribution and also causes losses. The S10.7 index is the EUV flux between 26–34 nm, contributing to the thermospheric heating and expansion [Tobiska et al., 2008] that affects injection of H atoms into the exosphere as well as their loss due to photoinitization.

[11] One can see that $N_{H1}$ exhibits abrupt increases and decreases, spikes, superimposed over more gradual smooth variations that could be caused by seasonal changes of the exosphere [Bailey and Gruntman, 2011b] and cumulative responses to changes in the solar X-ray, EUV, and Lyman-α output. In addition, possible systematic effects due to the imperfect observational coverage, which are not yet completely understood but could also result in gradual smooth variations, are not excluded.

[12] The uncertainty introduced by the optically thin assumption could be evaluated [Bailey and Gruntman, 2011a] based on detailed simulations of the geocorona by Bishop [1999]. The transition from the optically thick to optically thin regime in the geocorona is gradual with increasing geocentric distance. We tested the adopted 3 $R_E$ boundary assumption for the lower limit by refitting the results to a 4 $R_E$ boundary and obtained nearly the same $N_{H1}$ spikes.

[13] The possibility that the observed $N_{H1}$ spikes are detector artifacts caused by the local energetic particle environment seems to be unlikely. Two of the Geostationary Operational Environmental Satellites, GOES-13 and -15, reported (http://www.swpc.noaa.gov/today.html) intensities of protons ($\geq$ 10 MeV) and electrons ($\geq$ 2 MeV) at geostationary orbit during the considered geomagnetic storms that did not exceed specified alert levels of 10 protons cm$^{-2}$ s$^{-1}$ sr$^{-1}$ and 1000 electrons cm$^{-2}$ s$^{-1}$ sr$^{-1}$, respectively. Similarly, in situ particle fluxes measured by environmental monitors on the TWINS-1 spacecraft were also minimal such that artifacts in LAD measurements, particularly due to high energy (~MeV)
electrons that could penetrate the sensor and trigger the channel electron multipliers, would not be expected.

[14] The TWINS-1 spacecraft carries two types of environmental monitors [McComas et al., 2009]. A three-channel dosimeter (DOS) measures electrons (protons) with energies $\geq 1.5$ (16) MeV and $\geq 3$ (25) MeV (T. Guild, personal communication, 2012). An electrostatic plasma analyzer that serves as a surface charging monitor (SCM) measures charged particles from 3 eV to 30 keV. We analyzed the in situ particle fluxes observed by DOS and SCM (Figure 3) for the few days before (quiet-time conditions; gray shaded in Figure 3), during (blue shaded), and after (gray shaded) all five storms to specifically establish any possible correlation with LAD measurements.

[15] The reported fluxes of energetic particles measured by the DOS monitor were zero, as expected, when the LADs were taking measurements above an orbital radius of approximately 4.5 $R_E$. Figure 3 presents, as an example, fluxes measured by SCM in two energy bands from 3 eV to 15 keV and 15 keV to 30 keV for electrons (Figure 3, upper two panels) and ions (Figure 3, lower two panels) during the storm on 6 August 2011. If electrons and/or ions were to somehow “leak” into the LADs and trigger the photon-counting detectors, then one would anticipate correspondingly higher fluxes of particles during the observed $N_{H}$ spikes. One can see, however, that the particle fluxes are typically higher during orbits either preceding or following the orbits of the observed $N_{H}$ enhancements. Therefore, it seems unlikely that the observed $N_{H}$ enhancement was caused by an increase in local fluxes of electrons and ions. Other storms exhibit similar particle fluxes as in the example above.

[16] To conclude, LAD measurements did not show correlation with the in situ particle fluxes observed by DOS and SCM for the few days before (quiet-time conditions), during, and after all five storms. Consequently, the possibility that the observed $N_{H}$ enhancements are detector artifacts caused by the local energetic particle environment is not supported by the TWINS environmental monitors. The described procedure of assessing environmental fluxes during geomagnetic events could be applied for ruling out possible artifacts in future LAD measurements.

[17] Table 1 lists for each geomagnetic storm the minimum $Dst$ index and the corresponding relative $\Delta N_{H}$ increase. All five observed storms with $Dst < -60$ nT are accompanied by spikes in $N_{H}$, indicated by blue and red arrows in Figure 2 (bottom), from 6% to 17% (Table 1). The spike on 6 August 2011 (blue arrow) reveals a $\Delta N_{H}$ increase lasting for two orbits, or one day. The red arrows point to spikes that last only half a day (e.g., 9 September 2011) or for which an $N_{H}$ value from the orbit prior to the event (e.g., on 26 September 2011) as well as the orbits prior and immediately after the event (e.g., on 25 October 2011) are not available. The $N_{H}$ values immediately before and after the spike on 9 September 2011 are equal to each other within 1%. Clearly, the introduced simple parameter, $N_{H}$, shows enhancements associated with all standalone $Dst$ events that decrease below $-60$ nT.

[18] On the other hand, two observed $N_{H}$ increases on 15 September 2011 and 28 October 2011 appear uncorrelated with geomagnetic disturbances. In addition, two black arrows point to $N_{H}$ enhancements during intervals of geomagnetic activity with significantly smaller $Dst$ decreases (above $-50$ nT). There is also uncertainty about a spike on 9 October 2011 (right black arrow) because $N_{H}$ values for the orbits immediately before and after the event are not available.

[19] Figure 4 presents the minimum $Dst$ index for each observed storm ($Dst < -60$ nT) versus the corresponding relative $\Delta N_{H}$ increases. A nearly linear dependence emerges between the minimum $Dst$ index and $\Delta N_{H}$ if we exclude 9 September 2011. While it cannot be ruled out that this apparent outlier is due to sparse coverage of the storm time, it seems that it is more likely caused by a peculiar $Dst$ dependence, as discussed below, of that storm. Note that uncertainty

**Table 1. Minimum $Dst$ Index and the Corresponding Relative $\Delta N_{H}$ Increases for Five Geomagnetic Storms ($Dst < -60$ nT) Observed in the 3 Month Time Period From 1 August 2011 to 31 October 2011; Estimated Fitting Uncertainty is Less Than 3% for All Obtained $N_{H}$ Values**

<table>
<thead>
<tr>
<th>Date</th>
<th>$Dst$, nT</th>
<th>$\Delta N_{H}$, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 August 2011</td>
<td>-107</td>
<td>9, 11</td>
</tr>
<tr>
<td>9 September 2011</td>
<td>-69</td>
<td>17</td>
</tr>
<tr>
<td>17 September 2011</td>
<td>-70</td>
<td>6</td>
</tr>
<tr>
<td>26 September 2011</td>
<td>-101</td>
<td>12</td>
</tr>
<tr>
<td>25 October 2011</td>
<td>-132</td>
<td>16</td>
</tr>
</tbody>
</table>

**Figure 5.** Time intervals (orbits) of obtained sparse $N_{H}$ data points and disturbance storm time, $Dst$, index (data from http://wdc.kugi.kyoto-u.ac.jp/, Kyoto University) during five observed geomagnetic storms. The blue, red, and gray shaded areas are the time intervals (orbits) for which $N_{H}$ values were obtained by LAD observations. The red and blue areas correspond to the observed spikes in $N_{H}$. The color coding of events is similar to that in Figure 2.
of the daily solar Lyman-\(\alpha\) averages (Figure 2, top) is significantly smaller than the estimated errors of the \(\Delta N_{\text{H}}\) increases (Figure 4). In addition, no noticeable solar flares occurred during the times of the observed \(N_{\text{H}}\) enhancements.

[20] The obtained \(N_{\text{H}}\) data points are sparse and do not cover storm phases uniformly in time. Figure 5 shows the hourly \(D_{\text{st}}\) index during each of the observed storms and orbital coverage periods (shaded areas) where it was possible to obtain \(N_{\text{H}}\) values. Only for two storms, 6 August 2011 and 9 September 2011, were we able to obtain three consecutive values of \(N_{\text{H}}\).

[21] The storm on 9 September 2011 seems to differ from the other four storms. One can see that all other storms follow relatively similar \(D_{\text{st}}\) profiles for the sudden commencement, initial, main, and recovery phases. The storm on 9 September 2011 reaches its minimum \(D_{\text{st}}\) index of \(-69\) nT at 1700 UTC and then 12 h later drops again to \(-64\) nT at 0500 UTC on the following day before finally beginning to recover. The longer duration of an effective main phase may have contributed to the higher observed \(\Delta N_{\text{H}}\) increase for this event. More storm observations are needed to better establish the relationship, as well as gain some insight into the possible causal link, between geomagnetic activity and exospheric H density enhancements.

5. Conclusions

[22] TWINS-I LAD measurements from 1 August 2011 to 31 October 2011 revealed temporal variations of the exosphere during geomagnetic storms. We introduce a new parameter, \(N_{\text{H}}\), to quantitatively characterize in a simplified way exospheric conditions in the spherical shell from a geocentric distance of 3 \(R_{\oplus}\) to 8 \(R_{\oplus}\). Abrupt temporary increases in the total number of H atoms in this shell, from 6\% to 17\%, have been recorded for five observed storms from 6 August 2011 to 25 October 2011. The increases seem to show some correlation with the minimum \(D_{\text{st}}\) index reached during the peak of each storm.

[23] As initially described by Chamberlain [1963], the exosphere comprises three main particle populations: ballistic, escaping, and satellite. The orbital periods of satellite atoms increase from 0.3 to 1.3 days for orbit semimajor axes increasing from 3 \(R_{\oplus}\) to 8 \(R_{\oplus}\). The lifetime of H atoms in satellite orbits could thus be up to several days while the observed \(N_{\text{H}}\) enhancements last not longer than a day. This difference seems to limit if not eliminate the possible contribution by satellite H atoms to the observed \(N_{\text{H}}\) increases. In contrast, a ballistic H atom leaving the exobase (~500 km altitude) or produced in the plasmasphere and reaching an apogee of 8 \(R_{\oplus}\) and returning back would have a roundtrip time-of-flight 13–18 h, consistent with the observed \(N_{\text{H}}\) increases lasting half a day or perhaps one day. Future observations of more geomagnetic storms with better coverage in time and examination of altitude dependences of H density enhancements may help to better understand the exospheric response as well as the possible coupling effects via charge exchange that exist between the exosphere and plasmasphere.

[24] Our proposed characterization of the exosphere by the total number of H atoms, \(N_{\text{H}}\), in a selected spherical shell looks promising for investigation of possible effects and specific mechanisms of interaction with the solar output, magnetosphere, and plasmasphere. We note that the observed denser exosphere in the spherical shell from 3 \(R_{\oplus}\) to 8 \(R_{\oplus}\) during storms would increase ring current loss rates due to charge exchange. Interpretation of magnetospheric images in energetic neutral atom fluxes essentially relies on a line-of-sight integration that directly depends on the H number density distribution [Williams et al., 1992; Gruntman, 1997; McComas et al., 2009]. Consequently, temporal variations of the exosphere during storms are of particular interest for energetic neutral atom imaging of the magnetosphere.

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References