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The impact of geocoronal density on ring current development

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ABSTRACT

Long-term ring current decay following a magnetic storm is mainly due to charge exchange collisions of ring current ions with geocoronal neutral atoms forming energetic neutral atoms (ENAs) that leave the ring current system. Therefore, the density distribution of these cold and tenuous neutral hydrogen atoms plays a key role in the ring current recovery. TWINS ENA images provide a direct measurement of these ENA losses and therefore insight into the dynamics of the ring current decay through interactions with the geocorona. To assess the influence of geocoronal neutrals on ring current decay, we compare the predicted ENA emission using five different geocoronal models and the HEIDI ring current model to simulate the July 22, 2009 storm.

We show that for high energy H^+ (≥ 100 keV), all geocoronal models predict similar decay rates of the ring current ions. However, for low energy ions (≤ 100 keV), the decay rate varies significantly depending on the geocoronal density model. Comparison with TWINS ENA images shows that the location of the peak ENA enhancements is highly dependent on the distribution of geocoronal hydrogen density. The ring current topology depends greatly on the hydrogen model used, therefore knowing the H-distribution is very important in understanding how the ring current recovers following a magnetic storm.

1. Introduction

Except during times of high convective drift, the dominant mechanism for the decay of the ring current is charge exchange of the ring current ions with geocoronal neutral atoms. The neutralized ring current ions follow ballistic trajectories and are removed from the system. The geocorona is a halo-like extension of the exosphere out to several Earth radii, consisting of relatively cold (~ 1000 K), tenuous neutral hydrogen atoms with densities ranging from thousands of atoms per cubic centimeter at the inner edge of the ring current to less than a hundred at geosynchronous orbit. Solar far-ultraviolet light is scattered off this hydrogen population (Chamberlain, 1963) and its measurement enables insight into the structure of the exosphere (Fahr, 1974; Rairden et al., 1986; Hodges, 1994; Østgaard et al., 2003; Fuselier et al., 2010; Zoennchen et al., 2010, 2011; Bailey and Gruntman, 2011).

Because the geocoronal hydrogen density generally decreases exponentially with radial distance from Earth, at large altitudes down the magnetotail the collisions of plasma ions with the neutral hydrogen become a negligible component of plasma dynamics (although solar far-ultraviolet photons scattered by exospheric hydrogen have been observed as far as 16 Earth radii away from Earth). However, in the ring current region, the neutral atom density is large enough that these collisions become increasingly important and account for significant loss of ring current particles. In the charge exchange process, the incident ring current ion picks up the orbital electron of a cold geocoronal hydrogen atom resulting in the formation of an energetic neutral atom (ENA). The ENA is not affected by magnetic or electric field forces, and therefore is no longer trapped in the geomagnetic field. It thus leaves the interaction region in a ballistic orbit in the direction of the ring current ion velocity at the time of impact. If the ENA velocity exceeds that required to escape Earth's gravitational field, then it is lost into space or precipitates down into the ionosphere. The low energy ENAs are the neutrals that populate the plasmasphere.

The existence of an energetic neutral atom population in space was first reported by Meinel (1951) based on observations of precipitating energetic neutral hydrogen into the upper atmosphere during auroral substorms. A few years later, Dessler and Parker (1959) were the first to suggest the charge exchange between protons and neutral atmospheric hydrogen atoms would effectively contribute to the decay of the ring current, although the effectiveness of ion removal from the ring current through charge exchange processes was previously investigated (Stuart, 1959; Fite et al., 1958). The probability of charge exchange with neutral

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atoms from the exosphere depends strongly on the energy of the incident ion and is governed by the charge exchange cross sections. Because charge exchange cross sections are both energy and species dependent, different ion species have different lifetimes in the ring current (Spjeldvik, 1977; Smith and Bewtra, 1978; Phaneuf et al., 1987; Barnett et al., 1990; Orsini et al., 1998).

The charge exchange process strongly affects the ring current plasma structure and dynamics and charge exchange loss processes are particularly important after the initial phase of the ring current decay (Liemohn and Kozyra, 2005 and references therein). Therefore ENA imaging of the inner magnetosphere represents an important method for probing the complex processes that govern ring current physics (Roelof et al., 1985; Roelof, 1987; Fok et al., 2003, 2010a; McComas et al., 2002, 2009; Denton et al., 2005; Liemohn et al., 2006; Buzulukova et al., 2010; Valek et al., 2010).

Measurements of energetic neutral atoms made by the High Energy Neutral Atom (HENA) imager on the Imager for Magnetopause-to-Aurora Global Exploration (IMAGE) mission reveal that the rate of energy lost by the system through the charge exchange process is comparable to the ring current decay rate for the intervals of slow decay, while the loss rate is much smaller than the decay rate in the rapid decay phase in particular for the early stage of a storm recovery (Keika et al., 2003, 2006). Therefore during the fast recovery the ENA population measured by HENA can only account for a small portion of the total energy loss. The lifetime of the trapped ions is significantly shorter during the fast recovery phase than during the late recovery phase, and this suggests that different processes are operating during the two phases (Jorgensen et al., 2001). However, charge exchange losses can be solely responsible for the decay of the ring current during the recovery phase if the IMF abruptly turns northward at the end of the main phase (Kozyra et al., 2002).

1.1. Geocoronal hydrogen models

The geocorona plays an important role in the energy budget of Earth's inner magnetosphere since charge exchange of ions with exospheric neutrals makes the exosphere act as an energy sink for ring current particles, replacing a hot ion with a cold ion. The number of ENAs emitted from a given region of space depends on several factors, such as the energy and species of the energetic ion population in that region and the density of the neutral gas with which the ions undergo charge exchange. However, the density and structure of the exosphere are strongly dependent on changes in atmospheric temperature and density as well as charge exchange with the ions of plasmaspheric origin, which depletes the geocorona (by having a neutral removed from the system). Moreover, the radiation pressure exerted by solar far-ultraviolet photons pushes the geocoronal hydrogen away from the Earth in an anti-sunward direction to form a tail of neutral hydrogen (Thomas and Bohlin, 1972; Carruthers et al., 1976; Rairden et al., 1986; Østgaard et al., 2003; Zoennchen et al., 2010, 2011; Bailey and Gruntman, 2011). The strength of these interactions determines the geocoronal structure.

Reliable measurements of the geocoronal density are essential for inversion of ENA images to determine ion distributions as well as in forward modeling of the inner magnetosphere. Several models have attempted to describe the distribution of exospheric neutrals. A radial profile of the neutral hydrogen density is provided by Rairden et al. (1986). Their description is based on the spherically symmetric isothermal Chamberlain (1963) model of the exospheric hydrogen density and observations from 1981 to 1985 from the ultraviolet imaging photometer on the Dynamic Explorer 1 mission. More recently, another model of the geocoronal hydrogen distribution was developed based on Hydrogen Lyman α measurements by the Geocoronal Imager (GEO) from the IMAGE mission (Østgaard et al., 2003). Complementary to the Rairden et al. (1986) picture, this model allows for solar zenith angle dependency in addition to the radial dependence. Although the derived density profiles are similar in magnitude to the ones reported by Rairden et al. (1986), the Østgaard et al. (2003) model reveals an asymmetric exosphere with higher densities on the nightside produced by solar Lyman-α radiation pressure.

Based on Monte Carlo simulations, Hodges (1994) developed a mathematical model of the exosphere that provides three dimensional density profiles for the geocoronal hydrogen. This description explicitly includes local time dependence, while the temporal dependence is only implicit (spherical harmonic coefficients are provided for both equinox and solstice for four different solar cycle conditions). The Hodges (1994) model considers a large number of coefficients for each solar condition. This theoretical model predicts an increase in the geocoronal density at solstice as well as enhancement in the hydrogen concentrations in both the solar and anti-solar directions.

More recently, Nass et al. (2006) modified the Hodges (1994) model such that a reduced number of expansion parameters could be fit to observations from the Two Wide-angle Imaging Neutral-atom Spectrometers (TWINS) mission (McComas et al., 2009). The TWINS mission is the first to stereoscopically image the magnetosphere. In addition to the ENA imagers on each spacecraft, Hydrogen Lyman α detectors (LADs) measure the radiation produced by resonant scattering of solar Lyman-α from geocoronal neutral hydrogen. Based on the TWINS LAD observations and the Nass et al. (2006) model, Zoennchen et al. (2011) developed a time averaged (based on the data from June to September 2008), solar minimum, three dimensional model for the neutral hydrogen density. Their model allows for day–night asymmetries but assumes a longitudinally symmetric exosphere.

Also using TWINS LAD measurements, Bailey and Gruntman (2011) expanded the Nass et al. (2006) model to derive a more complex 3D model of the geocoronal density that allows for dawn–dusk as well as day–night asymmetries. Reconstruction of a geocoronal model using TWINS LAD measurements reveals exosphere asymmetries as well as confirms the existence of a geotail-like H-density structure (Zoennchen et al., 2011; Bailey and Gruntman, 2011).

Fig. 1 presents the density profiles from five different geocoronal models derived at midnight local time (since this location shows the largest variation between the models): the black line shows the profile as described by Rairden et al. (1986), the dark blue line presents the Hodges (1994) averaged equatorial profile for Solstice conditions and a $F10.7$ cm radioflux of 80×10^{-22} W m^{-2} Hz^{-1}, the red line gives the Østgaard et al. (2003) H density, while the green (light blue) line presents the TWINS derived exponential model results of Bailey and Gruntman (2011) (Zoennchen et al., 2011). We note that the Hodges (1994) model predicts the highest geocoronal hydrogen density for all geocentric distances, followed closely by the density profile derived from the Zoennchen et al. (2011) model. The other three models predict densities that overlap values with increasing radial distance. However, Fig. 1 shows only the midnight values. To get a better picture, color contours of the equatorial densities as depicted by the five models are shown in Fig. 2: Rairden et al. (1986) top left, Østgaard et al. (2003) top right, Hodges (1994) center left, Zoennchen et al. (2011) center right and Bailey and Gruntman (2011) on the bottom row. A black disk with radius 2.0 R_e is centered at the origin and indicates the equatorial plane inner boundary of our ring current model (see Section 1.2). The color indicates the logarithm of the neutral density and the color bar for each plot is the same (white indicates values higher than the maximum in the color bar). The Rairden et al. (1986) and