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A Brief Review of the Ring Current and Outstanding Problems

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ABSTRACT

This paper reviews a few important concepts and findings pertaining to the ring current research. Also briefly overviewed are the sources and losses of ring current ions. Recent challenges in modeling and observations of the ring current are presented, as is a brief discussion on open questions.

20.1. INTRODUCTION

Time variations in the Earth's magnetic field were reported for the first time around 1634, in a book entitled "A Mathematical Discourse on the Variation of the Magnetical Needle Together with its Admirable Diminution Lately Discovered." However, it was not until 1847, when Carl Friedrich Gauss, together with Wilhelm Weber, established the first magnetic observatory in Göttingen, Germany, that measurements of the terrestrial magnetic field in various regions of the Earth were made possible. Gauss' method of measuring the horizontal component of the terrestrial magnetic field has provided the mathematical foundation in assessing the geomagnetic disturbances on the ground. Ground disturbances were reported to have various periodicities: from diurnal (first discovered in London in 1722 by George Graham, a clockmaker also interested in astronomy and geomagnetism) to secular; however, some irregular disturbances were also reported and remained unexplained until 1912, when Carl Stormer interpreted them as a consequence of the formation of a donut-shaped equatorial ring

of electrons, moving on closed field lines in a region between 30,000 and 10,000,000 km (Störmer, 1912). This is the first time that the existence of a "ring current" is hypothesized.

It wasn't until 1967, that ring current particles were first detected by instruments on board the OGO 3 spacecraft (Frank, 1967); Figure 20.1 shows the first measurements of ring current proton fluxes during the geomagnetic storm of 9 July 1966. Numerous studies that focused on the detection and estimation of ring current characteristic properties followed (Hoffman and Cahill, 1968; Konradi et al., 1973; Longanecker and Hoffman, 1973; Cahill, 1973; Berko et al., 1975).

In 1951, observations of precipitating energetic neutral hydrogen into the upper atmosphere during auroral substorms were linked to the existence of energetic neutral atoms (ENAs) (Meinel, 1951), which were discovered to contribute to the ring current decay (Fite et al., 1958; Dessler and Parker, 1959; Stuart, 1959), by means of charge exchange between protons and neutral atmospheric hydrogen atoms. These discoveries led to the first global image of the ring current, based on measurements of actual energetic neutral atom fluxes (Roelof, 1987) from the ISEE-1 spacecraft.

It is now well known that one consequence of space weather is the occurrence of geomagnetic storms at Earth (Tsurutani and Gonzalez, 1997), which manifest themselves through the formation of an intense, westward toroidal electric current that encircles the Earth. This ring

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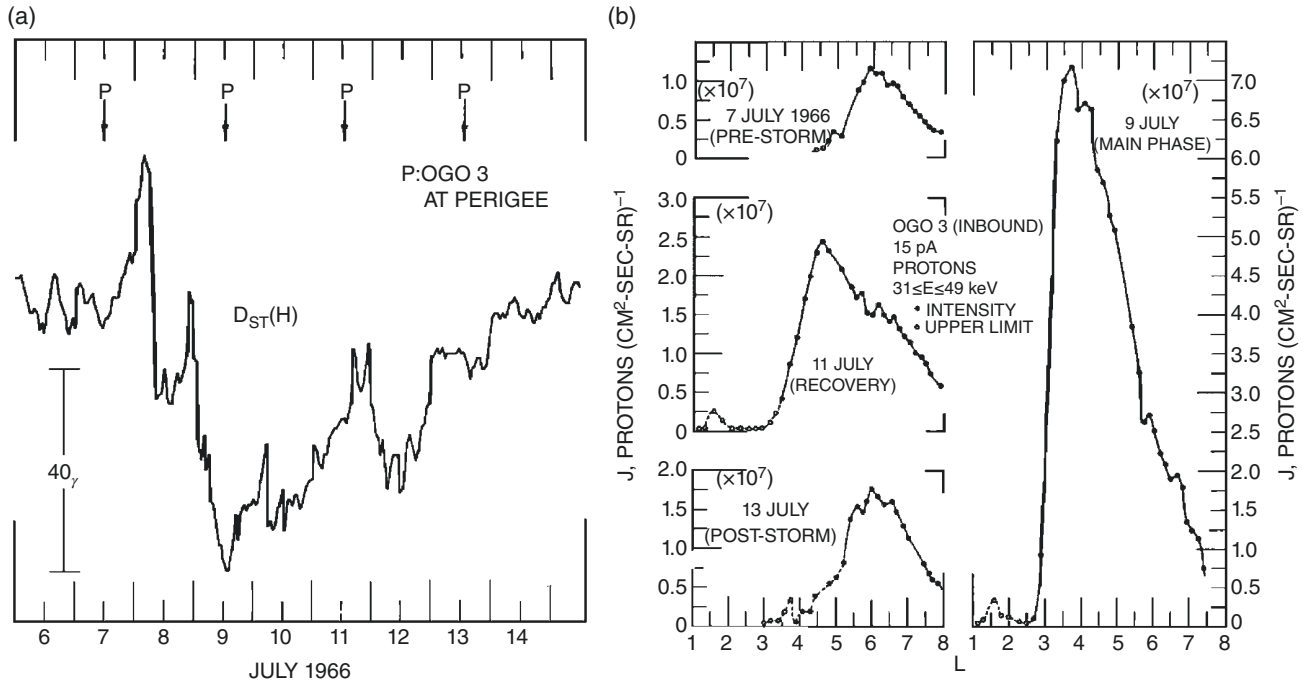


Figure 20.1 (a) Hourly $D_{ST}(H)$ values during the geomagnetic storm of 9 July 1966 based on ground-based data from Honolulu, Tucson, San Juan, Guam and Surlari magnetometers. (b) Directional intensities of protons with energies between 31 and 49 keV as a function of radial distance during the 9 July 1966 geomagnetic storm. Figure adapted from Frank (1967).

of current is nominally situated between two to nine Earth radii (R_E), centered on the magnetic equatorial plane, and is formed through convective transport and azimuthal drift (due to the inhomogeneity in the magnetic field) of trapped particles that move under the influence of the Lorentz force (Daglis et al., 1999; Daglis, 2006). Although all trapped particles in the inner magnetosphere contribute to the ring current, the main carriers are positive ions with energies ranging from a few keV to hundreds of keV; electron contribution is minimal due to their small mass and energy density relative to the protons (Baumjohann, 1993). Because the particle drift is charge dependent, the result is a net charge transport with electrons and ions moving in opposite directions.

The ring current is the one of three major populations in the inner magnetosphere, together with the plasmasphere and the radiation belts (Wolf, 1995). Though colocated, these particle populations are differentiated through their overall composition, density, energy range, radial extent, source, and dominant physical processes that dictate their overall behavior. The ring current consists of energetic ($\sim 1\text{--}400$ keV) charged particles, but lower densities ($\sim 0.1\text{--}10$ cm $^{-3}$) (Daglis et al., 1999), whereas the plasmasphere is made out of the cold (~ 1 eV) and dense ($\sim 1,000$ cm $^{-3}$) plasma (Carpenter and Anderson, 1992), usually colocated with the ring current. The radiation

belts are composed of relativistic particles and also colocated with the ring current (Walt, 1996; Baker et al., 1996).

20.2. RING CURRENT SOURCES

The ring current stores a large amount of energy, especially during geomagnetic storms, and its intensity can exceed several million Amperes during such times. Its main contributors are protons and heavier species, such as He^+ , O^+ , and possibly N^+ (Ilie and Liemohn, 2016). While the source of these energetic protons can be either the solar wind or the ionosphere, as they are the primary constituent of both, the heavier species must come from the ionosphere via the plasma sheet. Therefore, the plasma sheet is the source of high-energy plasma injected into the inner magnetosphere by strong magnetospheric convection during geomagnetic storms and substorms. Plasma sheet density, which varies between 10^6 and 10^7 m $^{-3}$, has a direct influence on the strength of the ring current (Thomsen et al., 1998; Kozyra et al., 1998), as it can have direct access to the inner magnetosphere during times of enhanced convection (Friedel et al., 2001; Denton et al., 2005).

The average solar and resultant geomagnetic activities are likely the dominant external parameters affecting the

amount and composition of the ion escape from the terrestrial ionosphere (Young et al., 1982; Moore et al., 1999; Cully et al., 2003; Peterson et al., 2006; Brambles et al., 2013; Chappell, 2015). The abundance of heavy ions in the ring current seems to increase with increasing geomagnetic activity, i.e. larger storms display a larger O^+ contribution to the ring current population (Daglis, 1997; Nosé et al., 2003) and both O^+ and N^+ ions have the potential to become the dominant ring current ions (Hamilton et al., 1988; Daglis et al., 2003) in terms of energy density, throughout the main phase of a magnetic storm. This is also confirmed by Cluster/RAPID data, in the region $>6 R_E$, at the dusk dayside the energy density of CNO group always dominates hydrogen, even during quiet conditions and the ratio of O^+/H^+ in the dayside dusk region is always larger than one (Kronberg et al., 2015). In addition, during the recovery phase, He^+ ions can contribute about 16% to the total plasma pressure (Kronberg et al., 2017).

Geotail observations also show that both O^+ and N^+ are major constituents of the dayside outer ring current (9–15 R_E) during large geomagnetic storms (Christon et al., 2002), with N^+ as the third in importance, after hydrogen and oxygen ions, even during moderate storm times. In addition, the relative abundance of N^+ seems to vary by a factor of two with solar activity (Christon et al., 2002), while exhibiting an inverse relationship with the solar cycle (Mall et al., 2002). It has been reported that O^+ (and hence heavy ions) can dominate not only the mass density but also the number density in the magnetosphere, therefore controlling the large-scale processes of mass and energy flow through geospace (Hamilton et al., 1988; Daglis et al., 1999; Winglee et al., 2002; Kozyra et al., 2002; Nosé et al., 2005; Ferradas et al., 2015; Denton et al., 2016), and its presence in the inner magnetosphere varies both with geomagnetic activity and solar cycle (Young et al., 1982; Maggiolo and Kistler, 2014; Kistler and Mouikis, 2016).

The first discovery of nitrogen ions (both N^+ and N^{++}) in the magnetosphere was reported by Chappell et al. (1982), based on measurements from the Dynamic Explorer 1, during the moderate geomagnetic storm of 30 December 1981. The fluxes of high-energy ring current N^+ are comparable with those of O^+ during storm time, as reported by the AMPTE CCE measurements (Hamilton et al., 1988). This is important, since recent observations from the Magnetospheric MultiScale (MMS) mission suggest that the high energy population (>150 keV) of the middle magnetosphere (beyond 7 R_E) is comprised predominantly of heavy ions species (Cohen et al., 2017), contrary to previous assumptions that protons are the dominant species in this region (Berko et al., 1975). These results complement the Cluster observations, which show that CNO group (274–955 keV) contributes at least

equally to protons in the region between six and ten R_E (Kronberg et al., 2012).

20.3. RING CURRENT LOSSES

To date, there are still concerns about the dominant loss mechanisms of the ring current. In particular, there is a debate about when the flow-out loss to the magnetopause is larger than the charge exchange loss within the magnetosphere, and questions still remain about when and how these two loss mechanisms relate to the ring current drivers and morphology. Energetic ions have been frequently observed at the dayside magnetopause (Christon et al., 2000; Keika et al., 2004). During times of enhanced magnetospheric convection, ions injected from the plasma sheet move primarily on open drift paths, and therefore are lost to the dayside magnetopause (Liemohn et al., 2001), which leads to the formation of a highly asymmetric ring current (Mitchell et al., 2001). The time scale of this ion loss is proportional with the convection strength and the nightside plasma sheet density (Liemohn et al., 2001; Kozyra and Liemohn, 2003). In addition, Geotail data reveal that the fluxes of energetic ring current ions flowing out to the dayside magnetosphere are similar both during a storm main phase and during the recovery phase, and can account for at least $\sim 23\%$ loss of ring current ions. The dayside outflow (ion drift in the low-latitude boundary layer), while higher on the afternoon side than the morning side, seems to be mostly due to the radial component of gradient of the magnetic field (Keika et al., 2005), which arises from the compression on the dayside magnetosphere. This dayside outflow of energetic ring current ions seems to be well correlated to the square root of the solar wind dynamic pressure, rather than the solar wind electric field, with a high correlation in the afternoon side. The high correlation is indicative of the fact that the high solar wind ram pressure is increasing the radial component of the magnetic field gradient, and the degree of the ion loss in this case depends heavily on the standoff distance of the dayside magnetopause (Keika et al., 2005). This loss mechanism is most likely linked with the fast decay of ring current.

On the other hand, the charge exchange of geocoronal neutral atoms with charged energetic particles is linked to ring current decay during the late recovery phase. The rate of charge exchange loss has been shown to be comparable to the decay of ring current during the slow recovery phase (Hamilton et al., 1988; Jorgensen et al., 2001; Kozyra et al., 2002; Keika et al., 2006). Measurements of ENA fluxes from instruments on board of Polar spacecraft indicated that high energy (<17.5 keV) ENAs can account for three quarters of the estimated energy loss from the ring current during the slow recovery phase, while during

the fast decay of the ring current, the measured contribution from charge exchange to the overall ring current decay is small. ENA measurements made by the High Energy Neutral Atom (HENA) instrument on board the Imager for Magnetopause to Aurora Global Exploration (IMAGE) spacecraft were the first to provide an estimate of ring current energy loss due to charge exchange collisions, and put it into the context of the slow ring current. In addition, it has been shown the loss of oxygen ions due to electron transfer collisions is only slightly smaller than those of hydrogen, suggesting that the O^+ ions play an important role in the slow decay of the ring current. However, for extreme events (Dst index exceeding -300 nT), the charge exchange collision could potentially account for the fast recovery phase of those geomagnetic storms (Keika et al., 2006).

Therefore, the geocorona plays a key role in the energy budget of the ring current, as electron transfer collisions between ring current ions with exospheric neutrals make the exosphere act as an energy sink for ring current particles, replacing a hot ion with a cold ion. This greatly affects the formation and the decay of the ring current during magnetic storms (Ilie et al., 2013) as the geocorona has been suggested to be both time and activity dependent (Bailey and Gruntman, 2013). The newly formed energetic neutral atoms, now on ballistic trajectories and unaffected by electromagnetic fields, can be re-ionized in several ways and converted back to ionized particles forming a secondary ring current, now residing at lower altitudes (Tinsley, 1981; Bishop, 1996). Such low L-shell ring current has been confirmed by observations (Søråas et al., 2003; Sørbo et al., 2006) from the NOAA low altitude satellites.

While charge exchange is the most important collisional loss mechanism for ring current ions, a second collisional loss process, affecting principally low-energy ring current ions, is Coulomb collisions of ring current particles with the thermal plasma of the plasmasphere. An energetic charged particle will interact with the electric field of a thermal electron or ion, lose energy and is pitch-angle scattered by both electrons and ions into the loss cone. The coupling between ring current and plasmasphere manifests through the interaction between hot and cold plasma, which leads to the decay of ring current energetic ions and heating of cold plasma in the plasmasphere (Kozyra et al., 1987; Fok et al., 1993) through energy transfer by means of Coulomb collisions and wave-particle interaction (Fok et al., 2005). The Coulomb collisional interaction allows the ring current ions to transfer energy to the plasmaspheric cold electrons of comparable velocities. This loss mechanism is often dominant over the charge exchange loss at low energies (Fok et al., 1991). The angular scattering is especially important for electrons and low-energy (≤ 10 keV) ions but negligible for high-energy ions (Wentworth, 1963; Fok et al., 1991),

due to the reduction in the size of the plasmasphere during geomagnetic active times. In addition, the Coulomb losses preferentially affect the lower L-shells ($L < 3$), when the strength of magnetospheric convection increases, due to a reduction in plasmasphere size (Ebihara et al., 1998).

Furthermore, the ring current particles are affected by waves and irregularities in the magnetic and electric fields within the inner magnetosphere, and the subsequent interactions allow for the transfer of energy between different components of the ring current, plasmasphere, and radiation belts. Plasma waves can be generated by instabilities within the energetic particle distributions and transfer of energy from the charged particles to the waves becomes possible. When the period of ring current particle drift becomes comparable with the period of the ultralow frequency (ULF) waves, drift resonance or drift-bounce resonance can be excited, leading to a transfer of energy between the waves and particles (Elkington et al., 2003; Ozeke and Mann, 2008), making the ULF standing waves efficient accelerators of magnetospheric electrons. Multi-satellite observations by Cluster spacecraft have confirmed that oxygen ions in the outer ring current ($\sim 5.5 R_E$) can be accelerated or decelerated by the ULF standing waves during active times; therefore, these waves can significantly impact the dynamics in the inner magnetosphere (Yang et al., 2011). In addition, observations from Van Allen Probes data reveals that proton fluxes in the energy range 67.0–268.8 keV are modulated with the same frequency of the poloidal Pc4 wave. The energy transfer from the ring current protons to the poloidal Pc4 wave via the drift-bounce resonance is reported to contribute to up to $\sim 85\%$ of the increase of the Dst* index (Oimatsu et al., 2018). Therefore, the wave-particle interaction mechanism is important primarily during the main phase of the storm and contributes to the geomagnetic trapping and acceleration/deceleration of ions that are injected into the inner magnetosphere during storm time. Resonant pitch-angle scattering also has the potential to remove resonant ions on timescales of under one hour. This timescale is, however, much shorter than the loss rate associated with collisional processes (Feldstein et al., 1994). Due to the localized nature of wave-particle interactions (Jordanova et al., 1998), their contribution to the decay of the ring current is small relative to flow-out, charge exchange, and Coulomb collision losses. However, the wave-particle interactions facilitate the transfer of energy between the ring current, plasmasphere, and radiation belt populations through plasmaspheric heating and ring current-radiation belt loss and buildup. Temperature anisotropies act as a free energy source to excite the plasma waves in the ring current and radiation belts region, which leads to pitch-angle and energy diffusion of the energetic plasmas. The electromagnetic ion cyclotron (EMIC) waves, whistler mode chorus, and

plasmaspheric hiss play an important role in the energy budget in these regions. Through cyclotron resonance, EMIC waves are responsible for the pitch-angle diffusion and precipitation losses of ions for the ring current (Jordanova et al., 2001) and of electrons for radiation belts (Summers and Thorne, 2003), whereas whistler mode chorus (Summers and Ma, 2000) and plasmaspheric hiss (Lyons et al., 1972) are responsible for losses from radiation belt energetic electrons (~ 10 – 100 keV).

20.4. OUTSTANDING PROBLEMS

20.4.1. Modeling

The terrestrial inner magnetosphere is a highly intricate and dynamic system containing complex plasma populations that can change dramatically on many timescales, both in structure and intensity, depending upon the level of disturbances encountered from the solar wind. The motions of these different particle populations are energy dependent and the coupling between plasma and fields in the inner magnetosphere plays a key role in the overall behavior of the plasma in the region. While most kinetic models treat the plasma transport realistically, they lack a consistent treatment of the fields. On the other hand, MHD numerical models have self-consistency but they lack the ability to reproduce essential gradient curvature drifts; therefore, their description of the inner magnetosphere is simplified. Particle tracing models have the capability to follow the distributions of ions and electrons with arbitrary pitch angles in time-dependent magnetic and electric fields; however, these models remain computationally expensive, hence limited in scope. Therefore, many efforts have been made recently to develop kinetic drift ring current models to allow solutions for arbitrary fields and to couple them with MHD codes, improving both the kinetic and the MHD solution (De Zeeuw et al., 2004; Ilie et al., 2012; Glocer et al., 2013; Yu et al., 2017; Welling et al., 2018). These efforts have shown that the rise and the demise of the ring current are highly dependent on the ability of the system to inject the particles deep into the inner magnetosphere, which in turn is strongly coupled with the strength of the electromagnetic field, the ion abundances in the inner magnetosphere, and the controlling factors that dictate the occurrence rates for collisional and collisionless losses.

An important consideration in the ring current modeling efforts is the influence of the choice of realistic magnetic field models, in combination with electric field models on the ring current development during storms. Model limitations (Ebihara and Ejiri, 2000; Fok et al., 2001; Liemohn et al., 2004; Ganushkina et al., 2006; Ilie et al., 2012, 2017) have left unquantified the relative

importance of the large-scale convection electric field and the substorm-associated electric fields in the energization and transport of ions into the ring current. The relative contribution of potential and inductive electric field-driven convection resulting in the development of the storm-time ring current is still open to debate, as it is not clear if ring current buildup is entirely due to potential fields (Iyemori and Rao, 1996; Grafe and Feldstein, 2000; Keller et al., 2005; Zaharia et al., 2008), inductive fields (Akasofu and Chapman, 1963; Liu and Rostoker, 1995; Lemon et al., 2004; Ono et al., 2009; Nosé et al., 2016), or some mixture of the two (Fok et al., 1999; Clauer et al., 2003; Ganushkina et al., 2005). This is a crucial question when developing predictive models for the inner magnetosphere, as the former is directly set up by the solar wind–magnetosphere interaction and can be derived from solar wind measurements, while the latter depends on details of the magnetospheric dynamics.

The ring current is a very dynamic population, strongly coupling the inner magnetosphere with the ionosphere. The plasma sheet density and its composition information, ionospheric outflow, substorm occurrence, seem to play important roles in the ring current development and decay. In addition, recent observations indicate that the low- and high-energy component of ring current proton population vary on different timescales, with the low-energy protons being affected mostly by convective drifts, while the behavior of high-energy protons seems to be significantly different to their lower energy counterparts (Gkioulidou et al., 2016).

20.4.2. Role of N^+ Ions in Altering the Ring Current Dynamics

Changes in the magnetospheric composition can have profound influences on plasma structures and dynamics, including modification of temperature and the magnetic field configuration, leading to altered convection patterns inside the magnetosphere. The heavy ion contribution to the plasma sheet and ring current, and in particular the physical mechanisms that control their entry, transport, and evolution, are still unknown and, when it comes to ring current modeling, specifying the ion composition seems to be one of the most elusive questions. Many studies have considered how the outflowing ionospheric oxygen ions impact the magnetospheric processes (see Keika et al. (2013) for a thorough review of energization of oxygen ions in the inner magnetosphere). However, the contribution of nitrogen ions to the ring current population, in addition to that of oxygen ions, has not been considered for a long time, primarily because most instruments flying in space could not distinguish between O^+ and N^+ due to their close masses.

In order to quantify the role of N^+ , the theoretical modeling of EMIC waves in cold multi-ion (H^+ , He^+ , O^+ , N^+)

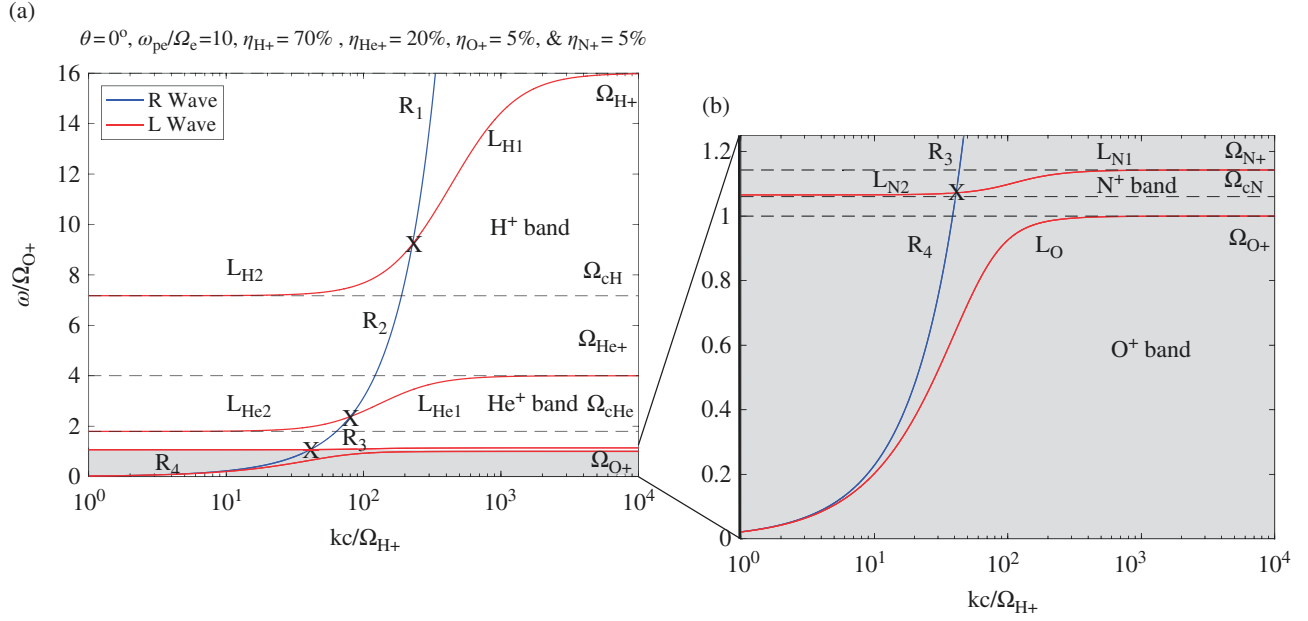


Figure 20.2 (a) Normalized wave frequency (ω/Ω_{O^+}) vs normalized wavenumber (ck/Ω_{H^+}) showing EMIC wave cold plasma dispersion curves for L-waves (red) and R-waves (blue) for a fixed electron density to magnetic field ratio, $\omega_{pe}/\Omega_e = 0$ and density ratios of $\eta_{H^+} = 70\%$ and $\eta_{He^+} = 20\%$. The remaining 10% is divided equally among η_{O^+} and η_{N^+} . (b) The enlarged part of (a) depicting the comparative properties of N and O^+ bands. Both figures show that there exist four frequency bands: H^+ Band ($\Omega_{cH} \leq \omega \leq \Omega_{H^+}$), He^+ Band ($\Omega_{cHe} \leq \omega \leq \Omega_{He^+}$), N^+ narrow Band ($\Omega_{cN} \leq \omega \leq \Omega_{N^+}$), and O^+ Band ($0 < \omega \leq \Omega_{O^+}$). In addition, three crossover frequencies (cross symbols (X)) dividing R-waves into four parts giving corresponding transitions ($R_1 \rightarrow L_{H^2}$, $L_{H^1} \rightarrow R_2 \rightarrow L_{He^2}$, $L_{He^1} \rightarrow R_3 \rightarrow L_{N^2}$ & $L_{N^1} \rightarrow R_4$) with four L-wave resonances (Ω_{H^+} , Ω_{He^+} , Ω_{O^+} and Ω_{N^+}) and three cutoff frequencies (Ω_{cH} , Ω_{cHe} and Ω_{cN}).

plasma revealed a new N^+ band (Bashir and Ilie, 2018) that altered the dispersion properties of EMIC waves significantly by introducing new cutoff, resonance, and crossover frequencies, as shown in Figure 20.2. It also affects the properties of other bands, especially the He^+ band. This new band has the potential to advance our understanding about the ring current loss mechanism based on the relative contribution of O^+ and N^+ and also to address the discrepancy of the He^+ band just above the oxygen cyclotron frequency. In order to complement the limitations of current missions for separating O^+ and N^+ , the heavy ion concentrations were also determined through modified dispersion relation by using the cutoff frequency method. The results confirm the existence of N^+ in amounts as large as 60–90% of the total abundance of O^+ . However, the evidence of the N^+ band in the wave data of current missions can provide not only the first observational evidence to study the wave properties, but also attract the scientific community towards developing the tools for improving the mass resolution for exploring the ring current dynamics.

Recent modeling efforts using the Hot Electron Ion Drift Integrator Model (HEIDI) (Ilie et al., 2018) show

that equatorially mirroring N^+ ions with energies >10 keV are removed faster from the system than O^+ ions, and their lifetime is at least one order of magnitude shorter. This implies that the presence of N^+ ions in the inner magnetosphere leads to different pathways to dissipate the ring current energy. Figure 20.3 shows a comparison between the lifetimes of O^+ and N^+ ring current ions.

The existence of nitrogen ions could explain the Van Allen Probes' observations of very fast decay of high-energy oxygen ions (~ 1.5 h) across all L-shells (reported by Gerrard et al., 2014). Since the Radiation Belt Storm Probes Ion Composition Experiment (RB-SPICE) (Mitchell et al., 2013) instrument on board of the Van Allen Probes lacks the mass resolution to distinguish between oxygen and nitrogen ions, it is likely that the observations of a rapidly decaying high-energy oxygen population, might actually be observations of decaying nitrogen ions instead. This is because, at high energies, the charge exchange cross-section of nitrogen ions with ambient neutral hydrogen is significantly higher than that of the reaction involving the oxygen ions and the geocoronal hydrogen. In addition, the presence of nitrogen ions in the ionosphere–magnetosphere system might provide

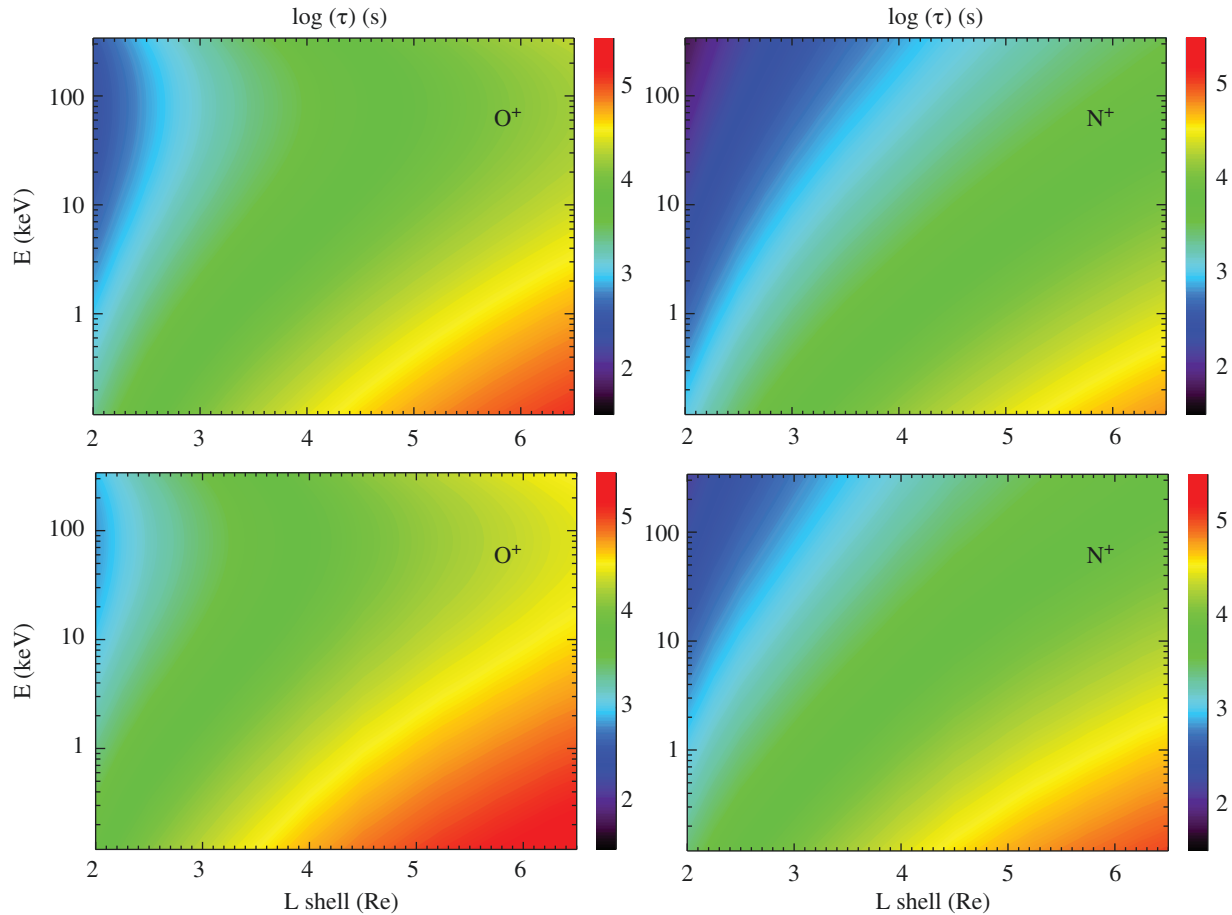


Figure 20.3 Color contours show the bounce averaged lifetimes of O^+ (left) and N^+ ions (right) as a function of energy and radial distance. Top (bottom) panels show the bounce averaged lifetimes of O^+ (left) and N^+ (right) ions with 90° (30°) pitch angles.

clues regarding the IMAGE observations of high (unexplained) fluxes of high energy ENAs (Keika et al., 2006).

20.5. CONCLUDING REMARKS

To date, we do not know how the temporal evolution of the geocorona impacts the time evolution of the ring current populations, as well as the formation of energetic neutral atoms during geomagnetic storms. On the other hand, since the concentration of particles in the ring current is a consequence of overall magnetospheric convection, it is not understood if the potential or the inductive components of the electric field provide the most effective means of particle acceleration. Acceleration of charged particles is an essential phenomenon throughout the magnetosphere, therefore the changing morphology of the plasmasphere and ring current is critical to our understanding of geospace, since the ring current is a defining element of magnetic storms (Gonzalez et al., 1994).

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