Abstract

This study aims at revealing ion and neutral particle environments and their interactions in Saturn's inner magnetosphere (L < 10) through solving the following two questions.

1. What is the dominant loss process for energetic ions in the inner magnetosphere ?

2. How does the loss process work for forming the characteristic ion distrisbutions ?

Some researchers suggest that Saturn's inner magnetosphere is likely dominated by loss processes, especially energetic ions with several tens of keV observed by the Cassini spacecraft always disappear around L ~ 5 – 6.5 Rs [e.g., *Krimigis et al.,* 2005]. This disappearance structure is unique in comparison with Earth and Jupiter. Some researchers suggest, based on energetic ion observations, that these ions are depleted by charge exchange with neutrals originated in plumes on Enceladus [e.g, *Paranicas et al.*, 2008]. *Paranicas et al.* [2008] suggest that the strong charge exchange loss for protons is significantly important below 100 keV. Abundant neutrals and energetic ions are required to reduce these energetic ions through charge exchange. Such copious neutrals were observed by the Hubble Space Telescope (HST) [e.g., *Shemansky et al.,* 1993] and Cassini [e.g., *Esposito et al.,* 2005]. Some researchers suggest that the inner magnetosphere is dominated by water group neutrals (H_2O, OH, and O) [e.g., *Richardson,* 1998]. ENA observations also suggest that the energetic ions are depleted by these neutrals through charge exchange. *Santos-Costa et al.* [2003] examined source and loss processes of energetic protons and electrons without wave-particle interactions by performing a numerical simulation. However, their three-dimensional model was limited to regions within 6 Rs, and they mainly discussed the energetic particles with several hundred keV.

Thus, a quantitative investigation, especially a theoretical approach, of these loss processes focusing on energetic ions with several tens of keV, whose energy range is likely dominated by charge exchange, has not been performed. Also, how these loss processes affect

energetic ion distributions has not been studied. The purpose of the present study is to reveal ion and neutral particle environments and interactions in Saturn's inner magnetosphere particularly through solving the two questions denoted above. The advantages of the present study in comparison with previous modeling studies are as follows:

1. clarifying energetic ion distributions in a steady state,
2. including the energy range of 1 keV − 1MeV,
3. including the wide L shell range of 3.5 – 10.0,
4. including not only energetic protons but also oxygen ions, and
5. including a loss process of wave-particle interactions.

Neutral density distributions are required to estimate the lifetimes of charge exchange for energetic ions. However, these distributions are not clear, especially the plume's contribution to the global distribution of the neutral density, which has been one of the biggest problems since the discovery of the plumes. To clarify the neutral density distributions, we have calculated the global distribution consisting of the water group neutrals by following a Monte-Carlo method as a first step to examining the loss processes of energetic ions. The H_2O sources considered in our model are the plumes on Enceladus, satellite and E ring sputtering by magnetospheric ions. The OH and O considered in our model originate in dissociation reactions from their parent molecules. Energy increments for OH and O due to excess energies through the dissociation reactions are first added in our model. The main results are as follows:

1. The H_2O distribution shows an asymmetric structure along the Enceladus orbital path.
2. The H_2O density asymmetry ranges from a maximum ratio of five to one to a minimum ratio of eight to one.
3. The peak densities for H_2O, OH, and O are around Enceladus' L shell due to the plumes.
4. The OH and O distributions extend to a far radial distance, centered at Enceladus' L shell,

due to the dissociation reactions.

5. The OH and O distributions form an azimuthally symmetric structure.

6. The calculated H_2O density is consistent with the observation.

7. The radial density distributions calculated for OH and O cannot explain the observations although the calculated OH column density is consistent with the observation close to the source region due to the plumes.

These results suggest that the plumes alone from Enceladus cannot explain the observed global distributions.

Estimations of lifetimes of the loss processes have been made in this study using the simulation results for the neutrals. The loss processes considered in this calculation are charge exchange, absorption by satellites and E ring grains, energy degradation by the E ring grains and Coulomb interactions, and wave-particle interactions with EMIC waves. The modeled H_2O density is used in this calculation to estimate the lifetimes of charge exchange, while for OH and O, we use densities based on observations. By using derived lifetimes for various loss processes we estimate energetic proton and oxygen ion distributions, and compare them with observations by Cassini. Our main results obtained from the lifetimes and ion distribution calculations are summarized as follows:

1. The calculated lifetimes due to charge exchange are the dominant loss process.

2. The calculated proton and oxygen ion fluxes are depleted by the strong charge exchange loss process around L ~ 5-6.5. This characteristic is consistent with that of the observation.

3. The distributions for off-equator protons may be dominated by the loss process of wave-particle interactions with EMIC waves.

4. Satellite absorption of ions with more than 100 keV is the dominant loss process for local satellite positions.

5. The flux enhancement inside L ~ 3.5 is not reproduced in this model under the diffusion process.

6. The calculated pitch angle distributions for oxygen ions show butterfly type distributions while those for protons depend on energies due to wave-particle interactions by EMIC waves.

These results give answers to the above two questions:

1. What is the dominant loss process for energetic ions in the inner magnetosphere ?

→ The dominant loss process is charge exchange at the equator although wave-particle interactions due to EMIC waves may be the dominant loss process for off-equator protons.

2. How does the loss process work for forming the characteristic ion distributions ?

→Charge exchange is the valid explanation for the location where the depleted ion fluxes are observed.

The results of this study give some suggestions on future works as follows:

1. Statistical analysis of local time and energy distributions for energetic ions by MIMI and CHEMS onboard Cassini makes it possible to accurately discuss the calculated flux structure.

2. Observations of pitch angle distribution by MIMI and CHEMS onboard Cassini are required for confirming the validity of the calculated pitch angle distributions.

3. Statistical analysis of magnetic field intensities of EMIC waves is required to estimate the accurate lifetimes of wave-particle interactions.

4. Further development of the model calculation, specifically from three-dimensional to four-dimensional Fokker-Planck equation, is required to discuss the dynamic variation phenomena such as injections.