BUDGET AND ROLES OF HEAVY IONS IN THE SOLAR SYSTEM

M. Yamauchi[1], **I. Sandahl**[1], **H. Nilsson**[1], **R. Lundin**[1], **and L. Eliasson**[1]

[1] Swedish Institute of Space Physics, Kiruna

Abstract

Oxygen and other major heavy species such as carbon, nitrogen, sodium, and sulfur circulate through the entire planetary system between the subsurface, surface, ocean, atmosphere, exosphere, and even the heliosphere (e.g., as meteors and solar wind) in a complicated manner. The amount of O^+ escaping from Earth/Mars is as large as $1 \sim 10$ kg/s, and may no longer be ignored on the time scale of planetary evolution. Therefore, studying the space-level circulation of the heavy ions has an obvious cross-disciplinary importance on the subjects such as:

- Evolution of the Earth, planets, satellites;
- Modelling ancient Earth (astrobiology);
- Boundary condition for the geochemistry of reservoirs;
- Environmental issue;
- Physics of the planetary exosphere;
- Solar-terrestrial interaction;
- Basic plasma physics;

It is therefore important to measure the thermal and non-thermal heavy ions for different masses (e.g., separation of C, N, O), energy, and flowing direction in both the Earth's and planetary exospheres even in planetology missions.

Key words: Oxygen: circulation – Planets: evolution

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1. Introduction

Terrestrial and Martian studies have revealed that the amount of heavy ion escape is much larger than predicted by the traditional thermal escape (Jean's escape) model. Figure 1 shows one of the first observations of the Martian atmospheric escape. Strong anti-sunward flow of oxygen ions at about 1 keV was unexpectedly found in the nightside of Mars by Lundin et al. (1990). ESA's Mars Express confirmed this quick and strong ion escape (Lundin et al. 2004). The total amount of oxygen escape is as large as ~ 1 kg/s ($\sim 10^7$ kg/year), which is several orders of magnitude larger than thermal (Jean's) escape.

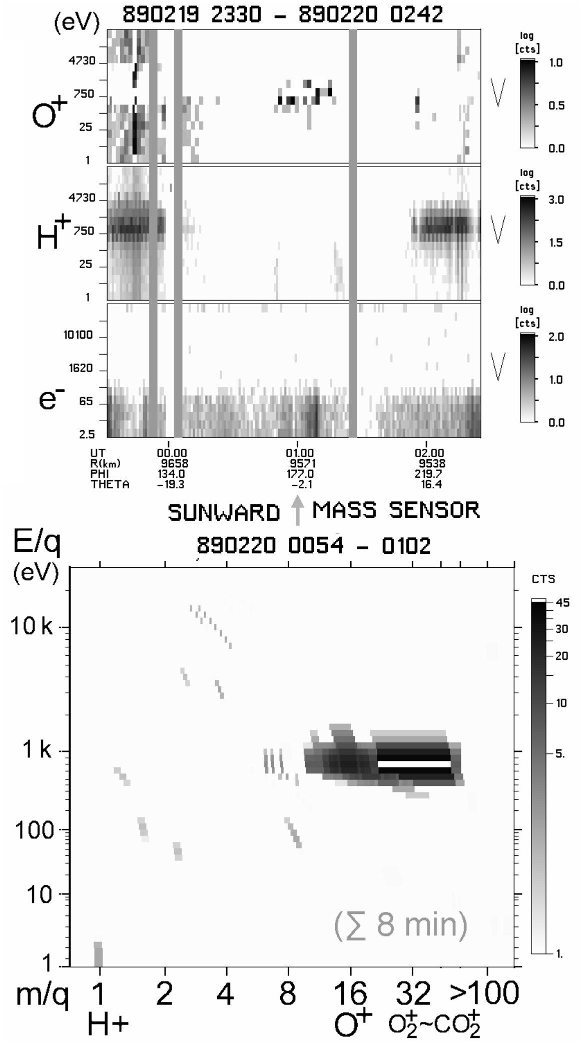

Figure 1. Phobos/ASPERA observation of ion escape using sensors facing sunward. Top: energy-time spectrogram for selected mass channel. Bottom: energy-mass matrix. One can recognize the heavy ion escape, which is most likely O^+, O_2^+, and/or CO_2^+.

Escape of heavy ions (mostly oxygen) from the Earth has also been observed. Figure 2 shows one example observed by ESA's Cluster satellite. The major mass carrier of the ion escape is O^+ except during geomagnetic storms when N^+ escape contributes up to 50% (Yau & Andre 1997), and the escaping oxygen ions are found even outside the dayside magnetopause (Eklund 1997 et al.).

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Table 1. Total number flux of ions above the ionosphere after Moore et al. (1999).

in $10^{25}/s$	H+	O^+	electron
thermal escape (*1)	2∼5	1∼3	-
non-thermal escape (*2)	2∼8	1.5∼20	-
precipitation (*3)	0.2∼0.9	-	9∼60

*1) < 10 eV, observed by Akebono ($h = 1 \sim 2Re$)
*2) > 10 eV, observed by DE-1 ($h = 2 \sim 3Re$)
*3) > 10 eV, observed by DMSP ($h = 840km$)

Table 2. Mass budget of ions between the Earth and space calculated from Table 1

in kg/s	H+	O^+	Meteor
out	0.05∼0.2	0.5∼5	-
in	0.003∼0.02	-	0.5

The total amount of the oxygen escape from the Earth's ionosphere is estimated as much as $\sim 10^1$ kg/s ($\sim 10^8$ kg/year) (Moore et al. (1999) and references therein), although this value is not confirmed at high altitudes. Considering the Martian result, one may easily expect that the heavy ions are escaping from the other planetary atmospheres at quite high rate by non-thermal mechanisms.

Table 1 and Table 2 summarize the current knowledge for the Earth's case. The total amount listed in Table 2 is equal to a thickness of 10^{-1}kg/cm^2 from entire surface over the time scale of planetary evolution ($\sim 4.5 \times 10^9$ years) even if the escape has been constant. This is a substantial to affect the planetary evolution, and hence the oxygen circulation problem may no longer be ignored in studies of many subjects listed in the next section.

Some of the escaped oxygen ions do return back to the Earth in various forms as is demonstrated by McFadden et al. (2003) and Yamauchi et al. (2005a), although the total amount is not yet known. Figure 3 shows examples of such oxygen ion injections into the ionosphere. The amount of return flow should be large because the oxygen content in the inner magnetosphere is known to change dynamically (e.g., Hamilton 1988 et al.), i.e., decreases after magnetic storms. However, no solid study has been done on the major route of oxygen ions into and out of the inner magnetosphere. The available simulations of returning flow predict the same drift behavior for protons and oxygen ions, but the observations show clear differences (Yamauchi et al. 2005b).

2. Interdisciplinary aspect

Studies of the heavy ion budget between space and the planetary atmosphere have interdisciplinary importance as listed below.

2.1. Evolution of Earth, planets, satellites

Small differences in the atmospheric composition such as the CO_2 content are well known to make essential differences in the planetary environment. Such environmental differences cause, through the surface-atmosphere coupling, different evolutions of the entire lithosphere. In this sense, the observed ion escape is large enough to affect the planetary environment and hence the planetary evolution. In addition, the strong dependence of the oxygen outflow from the ionosphere and the richness of oxygen in the magnetosphere on the magnetospheric activity (e.g., Shelley et al. (1972); Chappell (1982 et al.); Hamilton (1988 et al.)) suggest that the planetary magnetic field plays important roles. In fact the largest escape is from the vicinity of the ionospheric cusp (e.g., Norqvist et al. 1998) where the magnetic barrier against the solar wind is the smallest. Therefore, the escape and circulation of heavy ions from the planetary atmosphere most likely have contributed to the enormous difference between the inner brother planets: Venus, Earth, and Mars.

2.2. Geochemistry of reservoir

To understand the planetary the evolution, one must also understand the entire chemical chain among the elemental species (C, N, O, S, and Na) and their reservoirs such as CO_2, SiO_2, and SO. This is still unknown. For example, the water content in the ancient Mars is, according to simple estimates, not more than one tenth of the water content in the ancient Earth. One possible solution to this discrepancy is that the reservoir could have played important roles. To find it, however, we have to know the dynamics and budget of oxygen and carbon in comparison to hydrogen at present and in the past.

2.3. Modeling of ancient Earth

Unless we know the amount and the mechanisms of the non-thermal escape, it is basically impossible to know the amounts of minor species in the ancient atmosphere. These species control the input of solar radiation to the lower atmosphere, and hence the environment of the lithosphere. Together with the chemistry aspect, this is directly related to astrobiology, i.e., the condition of emergence of life on the Earth.

2.4. Environmental issue

If the low oxygen content of Mars is caused by the non-thermal escape rather than the deposition to the reservoir or the original composition at the time of planetary formation, then the question is why we have so much oxygen

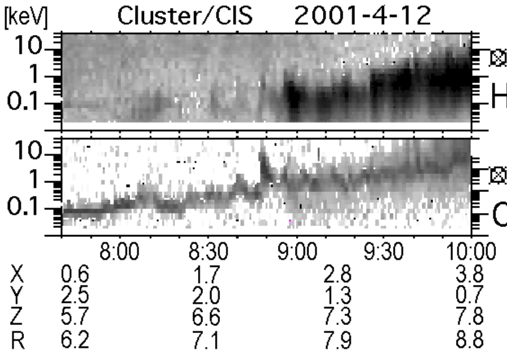

Figure 2. Energy-time spectrogram obtained by Cluster CIS instrument. [After Nilsson et al., 2004]

and water remaining on the Earth. This in turn means that the future environment of the Earth can be sensitive to small differences in the dynamics and amount of heavy ion circulation.

2.5. Planetary magnetospheric physics

The ion outflow from the ionosphere depends strongly on the magnetospheric activity. The proton-oxygen ratio and the nitrogen-oxygen ratio drastically change during magnetic storms (e.g., Hamilton (1988 et al.); Yau & Andre (1997)). Thus, the circulation of oxygen and its driving mechanism are quite different for different geomagnetic conditions. Another aspect of the heavy ions is that they are good markers of planetary origin ions in the exosphere, while one cannot distinguish the origin protons in space if they are from the solar wind or from the planetary atmosphere.

2.6. Solar wind - planetary interaction

One obvious contribution of the escaping heavy ions to the solar wind interaction with planetary exosphere is the mass-loading effect because the heavy ions are already found outside the dayside magnetopause at both the Earth (e.g., Eklund 1997 et al.) and Mars (e.g., Lundin et al. 1990). The mass-loading effect is known to strongly modify the solar wind inflow to the exosphere. In addition, the heavy ion outflow from the terrestrial ionosphere is strongest from near the cusp, indicating that the solar wind also controls the oxygen outflow. With both directions of interaction, the effect of the heavy ion outflow on the solar wind-exosphere interaction is highly non-linear (Yamauchi & Lundin 1997). Thus, the escaping heavy species affect the planetary exosphere (its environment and processes) in a complicated manner.

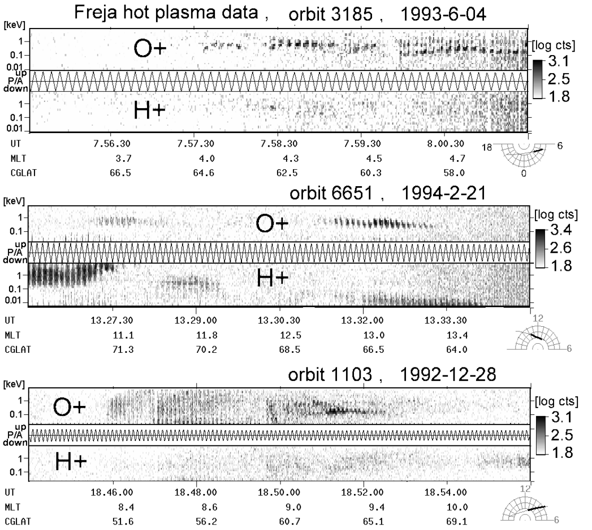

Figure 3. Energy-time spectrograms for heavy ions and protons observed by Freja at about 1700 km altitude [after Yamauchi et al., 2005a].

2.7. Basic plasma microphysics

The heavy ions have larger gyroradii than the proton gyroradius. This means that the kinetic effect becomes dominant for heavy ions while the protons follow the fluid dynamics, at sites such as the magnetopause and the plasma sheet near the tail neutral region. The different species of ions mean different resonant frequencies, which are sometimes essential to instabilities that is critical to large-scale phenomena. In this way the dynamic variation of the heavy ion content in the exosphere may play essential roles in the exospheric dynamics through microphysics.

3. Topics to study

Thus, understanding the dynamics and circulation of the essential elements such as oxygen, carbon, nitrogen, sodium, and sulfur in space in the Terrestrial/planetary exosphere has cross-disciplinary importance. However, the circulation of oxygen and other essential elements between planet and space has barely been studied, partly because no plasma instrument for keV range energy in earlier missions could separate O+ and N+, and only few could separate O+ and H+. The route, amount, and mechanism of the heavy ion circulation are not understood at all except some heating mechanisms and subsequent escapes at low altitudes for the terrestrial case (e.g., Moore et al. 1999). Even the total amount of oxygen ions that returns back to the Earth is still unknown, so is the energization mechanism that causes the non-thermal oxygen escape from the Mars.

Under this circumstance, we have to find out:

- Heavy ion escape: its route, amount, and related mechanism;
- Fate of escaped ions: destination, proportion, and dynamic variation;
- Return flow: budget, circulation path, and its driving mechanism;
- Active roles of these heavy ions to the space plasma and exospheric environment;
- Coupling to its reservoirs (atmosphere and surface);
- Roles of solar UV, solar wind (or planetary convection), planetary (or satellite) magnetic field, and its atmosphere.
- Variability of oxygen circulation at different planets.

Study should be in comparison to protons to understand the circulation of planetary protons because it by itself cannot be distinguished from solar wind origin.

4. Request for future missions

The lack of knowledge is partly because the oxygen loss rate from a planet by the thermal escape (assumed until 15 years ago) is much lower than the actual values, and partly because we do not have proper missions to study the heavy ion circulation. For example, none of the present and planned Mars mission by ESA or NASA has proper plasma instrumentation (particles + magnetic field + waves) to address this problem. Therefore, we do need missions that can properly study the heavy ion circulation. Full understanding of heavy ion circulation and its roles requires comparable examinations between different solar system bodies (Mars, Venus, comets, satellites of Giant planets) in a systematic manner.

This is not very difficult because the technology for mass-resolving energy spectroscopy is available for both three-axis stabilized spacecraft (< 3 kg) and spinning spacecraft (< 2 kg) although extra mass is required to resolve C, N, and O (or O_2 and CO_2). The heavy ion measurements can easily be included in any solar system mission including planetology missions.

Candidate missions that should include heavy ion measurement are:

- Comparative planetary science (both plasma and subsurface) missions;
- Exo/astrobiology missions to study the habitable or prebiotic conditions;
- Missions to small-bodies, which could continuously supply oxygen and other heavy ions;
- Multi-spacecraft missions for small-scale physics.

To understand the dynamical change of the circulation, however, we also need a simultaneous monitoring of the solar wind conditions (or planetary wind conditions for satellites of giant planets). With modern nano-satellite technology (e.g., Yamauchi et al. 2002), it is feasible to have such a sub-satellite in the planetary mission to provide minimum plasma information with a reasonable budget (Barabash 2004 et al.).

5. Conclusion

Since the amount of the heavy ion escape is large enough to affect the planetary evolution, the dynamics and circulation of the heavy ions in space has cross-disciplinary importance, e.g., for plasma physics, atmospheric science, planetology, astrobiology, and environmental issue. To understand the circulation of the heavy ions around the planetary exospheres, we have to first measure the flux and the energy distribution of the heavy ion flow at various places in the planetary exosphere for different external/internal conditions. This task is not as difficult as it sounds because measuring heavy ions can easily be done in any solar system mission including the planetology missions.

For fruitful understanding, it is recommended to have at least one sub-satellite that can monitor the incoming plasma flow (e.g., solar wind) while the main spacecraft measures the heavy ions, because the heavy ion circulation is expected to be very dynamic depending on the incoming plasma flow condition. In addition to planetary missions, we also need a dedicated terrestrial mission to study the oxygen circulation between the Earth and space.

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