

On Atmospheric Loss of Oxygen Ions from Earth Through Magnetospheric Processes

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In Earth's environment, the observed polar outflow rate for O^+ ions, the main source of oxygen above gravitational escape energy, corresponds to the loss of $\sim 18\%$ of the present-day atmospheric oxygen over 3 billion years. However, part of this apparent loss can actually be returned to the atmosphere. Examining loss rates of four escape routes with high-altitude spacecraft observations, we show that the total oxygen loss rate inferred from current knowledge is about one order of magnitude smaller than the polar O^+ outflow rate. This disagreement suggests that there may be a substantial return flux from the magnetosphere to the low-latitude ionosphere. Then the net oxygen loss over 3 billion years drops to $\sim 2\%$ of the current atmospheric oxygen content.

Our understanding of the origin and evolution of planetary atmospheres hinges on knowing the composition, dynamics, source, and loss mechanisms operating at the present day. For example, loss processes and rates tell us how atmospheric constituents can be selectively removed and to what extent isotopic fractionation occurs. For the terrestrial planets, atmospheric loss depends not only on interaction processes at the atmosphere-surface interface but also on loss mechanisms in the upper atmosphere. In particular, the formation of an ionosphere and loss of ions due to space plasma acceleration processes can alter the evolution of an atmosphere. Earth's intrinsic magnetic field shields the upper atmosphere from direct interaction with the solar wind, and the direct escape of neutral oxygen through thermal and nonthermal processes (1), which is important for unmagnetized planets such as Venus and Mars, is small compared with the ion loss through magnetospheric processes. The intrinsic magnetic field facilitates a number of different plasma acceleration mechanisms at high latitudes where auroral processes occur. These acceleration mechanisms result in an observed outflow rate of $\sim 72 \times 10^{24} O^+$ ions s^{-1} with speeds above gravitational escape velocity averaged over the solar cycle (2). Over the course of 3 billion years (Gy), the net loss with $\sim 2.3 \times 10^{42}$ ions Gy^{-1} corresponds to $\sim 18\%$ of the present-day atmospheric oxygen content. However, the same global magnetic field that facilitates the ion acceleration

processes may also mitigate this loss by trapping the ions and returning them to the atmosphere. Here we examine the evidence for loss of terrestrial atmospheric oxygen through magnetospheric processes.

Terrestrial particles flow out primarily from the polar ionosphere (Fig. 1, label a). O^+ is one of main constituents of the polar outflows (3). There are four escape routes for terrestrial particles (Fig. 1): (i) escape of cold detached plasmaspheric particles through the magnetopause, (ii) escape of high-energy ring current/dayside plasma sheet particles through the magnetopause, (iii) escape through antisunward flow in the (nightside) plasma sheet, and (iv) escape of terrestrial ion beams through the lobe/mantle. The fourth route is added in this report on the basis of recent GEOTAIL observations of terrestrial O^+ ions flowing in the antisunward direction (hereinafter referred to as "tailward" direction) (4–6). Because global convection in the magnetosphere (7) causes ion motion from the lobe/mantle toward the plasma sheet, some of the observed O^+ beams in the near-Earth lobe/mantle will join escape routes ii or iii after being injected into the plasma sheet. However, the O^+ ions unexpectedly observed in the distant lobe/mantle will escape directly through the lobe/mantle into interplanetary space.

We estimate the net oxygen loss rate from Earth's atmosphere by determining the losses

due to the four escape routes (Fig. 1). The net oxygen loss rate could be estimated by subtracting the returning flux from the outflow flux. However, both the outflow and returning fluxes in low-latitude regions are still unknown because of the lack of comprehensive observations at the low latitudes, whereas the net outflow flux from high-latitude regions has been estimated (2, 3). First, let us investigate the O^+ loss rate due to route iv. From all data of the deep tail survey of the GEOTAIL mission (October 1993 to March 1995), we sorted out both the lobe/mantle and O^+ beam observations [see (4) for selection criteria]. During this period, the solar activity inferred from the solar radio flux at the wavelength of 10.7 cm ($F_{10.7}$; a proxy for solar extreme ultraviolet flux) was low with an average of $86.9 \times 10^{-22} J s^{-1} m^{-2} Hz^{-1}$. For tailward distances less than 150 Earth radii (R_E), both the detection probability and flux of the O^+ beams in the lobe/mantle regions decrease with increasing tailward distances, except in the 25 to 50 R_E range, where the detection probability is low because of the limited instrumental energy coverage in low energies (Fig. 2). This tendency is consistent with the picture that magnetospheric convection (7) causes injections of slow ions into the plasma sheet closer to Earth than the distant neutral line (DNL). The DNL is a region formed across the plasma sheet typically at the tailward distance of $\sim 120 R_E$, where the magnetic field lines from northern and southern lobe/mantle are reconnected. Beyond the DNL, ions in the O^+ beams will escape to interplanetary space directly from the lobe/mantle regions. The detection probability and flux are almost constant beyond 150 R_E (Fig. 2).

We divided the O^+ beam data set into three subsets in terms of the tailward distance: 0 to 75, 75 to 150, and 150 to 210 R_E . If we assume that the magnetotail is circular in cross section with a radius of 20 R_E (8), we can estimate the loss rate of O^+ ions through the entire magnetotail due to escape route iv with these values (Table 1). The escape rate in regions beyond 150 R_E , 0.59×10^{24} ions s^{-1} , gives the lower limit of the loss rate of O^+ ions due to route iv, and the actual rate should be between rates in the middle and distant tails, $(0.59 \text{ to } 1.6) \times 10^{24}$

Table 1. Oxygen escape rate due to lobe/mantle beams.

Data set*	Tailward distance† (R_E)	O^+ flux ($cm^{-2} s^{-1}$)	Detection probability (%)	Escape rate‡ (s^{-1})
All distances	0–210	2.1×10^4	13	1.4×10^{24}
Near Earth	0–75	3.7×10^4	9.5	1.8×10^{24}
Middle	75–150	2.1×10^4	14.4	1.6×10^{24}
Distant	150–210	1.5×10^4	7.6	0.59×10^{24}

*Plasma data were sorted by distance from Earth. †Tailward distance from Earth is calculated with a correction of 4° aberration because of Earth's revolution around the sun. ‡Magnetotail radius of 20 R_E is adopted for estimation of the escape rate.

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ions s^{-1} , because the middle tail observations can contain regions beyond DNL. Thus, the O^+ loss rate through route iv is on the order of 10^{24} ions s^{-1} . In the near-Earth tail, the rate is about three times larger than that in the distant tail. The results indicate that the O^+ supply rate from the lobe/mantle to the plasma sheet is also on the order of 10^{24} ions s^{-1} . These rates may increase with increasing solar activity, because O^+ populations in the polar outflow (2) and the outer ring current (9) are known to increase with solar activity.

As for escape route iii, there are two major transport processes of terrestrial ions to beyond the DNL: the tailward transport of lobe/mantle-originating ions through the DNL and the tailward ejection of a helical magnetic field structure called a plasmoid (10) (Fig. 1A) generated by magnetic field reconnection in the near-Earth plasma sheet. The O^+ loss due to the former process should be less than the O^+ supply rate from the lobe/mantle to the plasma sheet throughout the magnetotail, i.e., $\sim 10^{24}$ ions s^{-1} . As for the latter process accompanied with plasmoids, there has been no statistical report of thermal O^+ population in the plasma sheet or in plasmoids beyond the DNL. For a rough estimate of the loss rate, however, we use the O^+ density ($\sim 0.02 \text{ cm}^{-3}$) observed in tail-

ward distances of 10 to $23 R_E$ for a low solar activity period (11) and statistical properties of the plasmoids (10) such as the occurrence frequency $\sim 8.5 \text{ day}^{-1}$ and average volume $\sim 10 R_E$ by $40 R_E$ by $10 R_E$. Assuming that plasmoids have included the O^+ ions in the near-Earth regions and brought them to the distant tail, the resultant O^+ loss rate due to plasmoids is $\sim 2.0 \times 10^{24}$ ions s^{-1} .

As for escape routes i and ii, we refer to O^+ observations in the dayside magnetosheath. A statistical study of O^+ ions in the energy range of 0.1 to 17 keV shows that the occurrence frequency of O^+ leakage is 10 to 20% of the time and the average O^+ density is less than 10^{-2} cm^{-3} (12). To get the upper limit of the O^+ loss rate due to the leakage, we assume that the O^+ ions are leaking with a typical jet velocity (250 km s^{-1}) (13) in the boundary layer extending over the whole dayside magnetopause (180° longitudinal range: $10\pi R_E$) with a radial thickness of $1 R_E$. Then the resultant O^+ loss due to routes i and ii at this energy range is $\sim 1.3 \times 10^{24}$ ions s^{-1} for 20% occurrence frequency. As for the O^+ escape rate above 17 keV, we do not have enough statistical information yet, but high-energy O^+ bursts observed in the dayside magnetosheath coinciding with pressure pulses in the solar wind have much

smaller fluxes than those of route iv (14). Thus, the upper limit of the total O^+ loss rate from Earth through all four routes is $\sim 5 \times 10^{24}$ ions s^{-1} during low solar activity periods.

Let us now reconsider the oxygen loss from the terrestrial atmosphere. Observations of polar outflows by the DE-1 satellite showed that the O^+ outflow rate from the polar region above the invariant latitude of 56° at energies of 0.01 to 17 keV is $\sim 43 \times 10^{24}$ ions s^{-1} for the low solar activity period of $F_{10.7} = 86.9 \times 10^{-22} \text{ J s}^{-1} \text{ m}^{-2} \text{ Hz}^{-1}$, if averaged over all geomagnetic activity levels (2). (This value is a little smaller than the average over a solar cycle mentioned above.) This rate is almost one order of magnitude higher than the O^+ loss rate estimated from the four routes. One possibility to explain the gap is that there exists a substantial return flux on the order of 10^{25} ions s^{-1} from the magnetosphere back into the low-latitude ionosphere, because more than 90% of observed O^+ outflows had energies less than 1 keV (2) and many of them will be trapped in the near-Earth magnetosphere within DNL. This implies that the O^+ outflow rate from the polar ionosphere, which corresponds to the

Fig. 1. Atmospheric escape from Earth is illustrated schematically in two ways. (A) Three-dimensional cutaway of Earth's magnetosphere. (B) A flow chart of plasma for each plasma regime in the magnetosphere. In (A) and (B), colors represent different plasma regimes, black arrows display escape routes of terrestrial particles, and red arrows indicate returning particles as precipitation into the ionosphere. Escape rate can be obtained by a - b or by i + ii + iii + iv. Route iv was discovered by GEOTAIL observations.

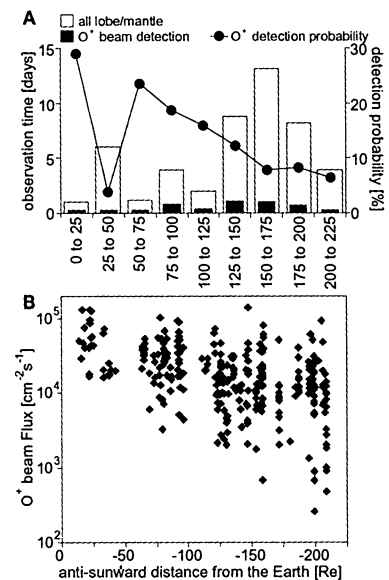
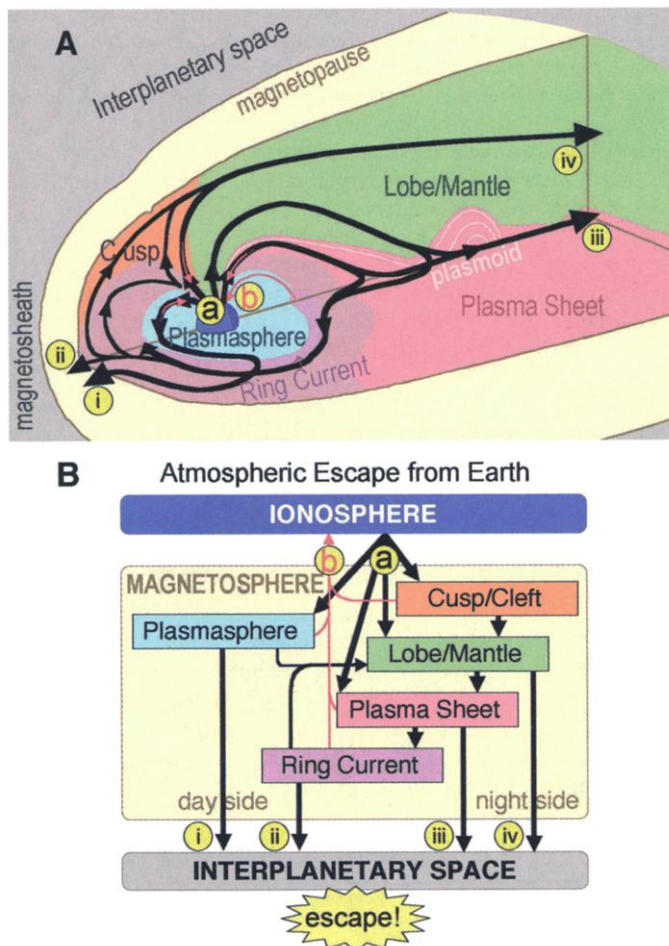


Fig. 2. GEOTAIL observations in the lobe/mantle region during the low solar activity period of October 1993 to March 1995. (A) Solid circles show the detection probability of O^+ beams obtained by dividing total observation time of O^+ beams (black bars) by that of lobe/mantle region (shaded bars) in each range of antisunward distance from Earth. (B) O^+ beam flux per square centimeter is plotted against antisunward distance in R_E . Each flux value is derived from partial moment calculation of the O^+ distribution function (4) and typically contains $\sim 13\%$ of a probable error. This error is smaller than the statistical deviation of data points.

loss of $\sim 18\%$ of current atmospheric oxygen during 3 Gy, does not represent the net atmospheric oxygen loss from Earth. In other words, the net loss can be one order of magnitude smaller than the polar outflow rate; i.e., less than 2% of atmospheric oxygen has been lost over 3 Gy. The result also suggests that the current oxygen loss rate from Earth is almost one order smaller than that from Mars (30×10^{24} ions s^{-1}) (15) and Venus (50×10^{24} ions s^{-1}) (16). It might indicate that the existence of a substantial intrinsic magnetic field can help a planet to keep its atmosphere. Alternatively, the resultant one order difference between estimates of the polar outflow and the four routes might indicate the existence of unknown loss processes for terrestrial oxygen. One possibility is the escape of cold O^+ ions at energies below 50 eV either to the magnetosheath or

through the plasma sheet, which are difficult to observe in the magnetosphere without spacecraft potential control. Another candidate may be the charge exchange loss of ring current ions (17) that become dominated by O^+ during magnetic storm periods. For further understanding, systematic ion-composition measurements in the magnetosheath and the plasma sheet as well as quantitative investigation of ring current loss mechanisms are needed.

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Quantum Mechanical Actuation of Microelectromechanical Systems by the Casimir Force

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The Casimir force is the attraction between uncharged metallic surfaces as a result of quantum mechanical vacuum fluctuations of the electromagnetic field. We demonstrate the Casimir effect in microelectromechanical systems using a micromachined torsional device. Attraction between a polysilicon plate and a spherical metallic surface results in a torque that rotates the plate about two thin torsional rods. The dependence of the rotation angle on the separation between the surfaces is in agreement with calculations of the Casimir force. Our results show that quantum electrodynamical effects play a significant role in such microelectromechanical systems when the separation between components is in the nanometer range.

Microelectromechanical systems (MEMS) are movable structures fabricated on a semiconductor wafer through the use of integrated circuits technology (1) and have become a key technology in the production of sensors and actuators. So far, the smallest separations between surfaces of micromachined components are typically on the order of micrometers, and the operation of MEMS is well described by classical mechanics. As further miniaturization takes place, quantum effects may become significant in device design and operation (2). The Casimir effect (3–7), for example, is the attractive force between two uncharged conducting surfaces, arising from quantum fluctuations of the electromagnetic field. According to quantum theory, electro-

magnetic fields fluctuate and therefore can never be exactly zero. This gives rise to a finite zero point energy even when there are no photons in the field. In the presence of two perfectly conducting plates, the electromagnetic field must satisfy the boundary conditions. The zero point energy density of the electromagnetic field between the conducting plates is lower than in free space. As a result, there is a net attractive force per unit area between the plates, given by (3)

$$F_c = -\frac{\pi^2 \hbar c}{240} \frac{1}{z^4} \quad (1)$$

where c is the speed of light, $\hbar$ is Planck constant/ 2π , and z is the separation between the plates. When the separation between the surfaces decreases, the Casimir pressure increases rapidly, reaching about 1 atmosphere at $z \sim 10$ nm. Sparnaay (8) performed the first measurement that showed evidence for the Casimir force, but experimental uncer-

tainties were too large for a quantitative verification of the effect. Recently, the Casimir force was accurately measured with the use of a torsional pendulum (9) and an atomic force microscope (10, 11). In both cases, one of the surfaces was chosen to be spherical to avoid the problem of keeping two flat surfaces parallel. According to the proximity force theorem (12, 13), this geometry modifies the Casimir force to

$$F_{cs} = -\frac{\pi^3 \hbar c}{360} R \frac{1}{z^3} \quad (2)$$

where R is the radius of the spherical surface. These experiments generated renewed theoretical interest in the Casimir force, in particular the corrections due to nonideal experimental conditions such as surface roughness and finite conductivity (14–19).

We demonstrate the actuation of a micromachined torsional device by the Casimir force. Our device consists of a 3.5- μm -thick, 500- μm^2 heavily doped polysilicon plate freely suspended on two of its opposite sides by thin torsional rods (Fig. 1A). The other ends of the torsional rods are anchored to the substrate by support posts (Fig. 1B). Two fixed polysilicon electrodes (not visible in Fig. 1A) are located symmetrically underneath the plate, one on each side of the torsional rod. Each electrode is half the size of the top plate. There is a 2- μm gap between the top plate and the fixed electrodes created by etching a SiO_2 sacrificial layer. The top plate is thus free to rotate about the torsional rods in response to an external torque.

To detect rotation of the plate, we measure the capacitance between the top plate and the bottom electrodes. In the absence of an external torque, the capacitances of the top plate to each electrode are almost equal. When an external torque tilts the top plate, one of the capacitances increases and the other one de-

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