Aa-012 Room: C310 Time: June 6 11:03-11:21

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 ~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 is either a significant return flux from the magnetosphere to the low-latitude ionosphere or unknown loss process(es) of oxygen ions. In the former case, an intrinsic magnetic field may help a planet to keep its atmosphere.

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 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 non-thermal processes, which is important for unmagnetized planets such as Venus and Mars, is small compared to 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 ~72x10^24 O+ ions/s with speeds above gravitational escape velocity averaged over the solar cycle. Over the course of 3 billion years, the net loss corresponds to ~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.

In this paper, we examine loss rate of terrestrial atmospheric oxygen through magnetospheric processes by examining loss rates of four escape routes with high-altitude spacecraft observations. The estimated O+ loss rate is almost one order of magnitude smaller than the polar O+ outflow rate. This disagreement suggests that there is either a significant return flux from the magnetosphere to the low-latitude ionosphere or unknown loss process(es) of oxygen ions. In the former case, the net loss can be less than 2 % of atmospheric oxygen has been lost over 3 Gy. It might indicate that the existence of a substantial intrinsic magnetic field can help a planet to keep its atmosphere. Alternatively in the latter case, a candidate of the unknown loss mechanism(s) may be 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 is the charge exchange loss of ring current ions 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.