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Earth's polar outflow evolution from mid-Archean to present

Kristina Kislyakova[1], Colin Johnstone[2,1], Manuel Scherf[3], Mats Holmström[4], Igor Alexeev[5], Helmut Lammer[3], Maxim Khodachenko[3,6,7], and Manuel Güdel[1]

[1]University of Vienna, Department of Astrophysics, Vienna, Austria (kristina.kislyakova@univie.ac.at)
[2]Natural History Museum, Vienna, Austria
[3]Space Research Institute, Austrian Academy of Sciences, Graz, Austria
[4]Swedish Institute of Space Physics, Kiruna, Sweden
[5]Skobeltsyn Institute of Nuclear Physics, Moscow State University, Moscow, Russia
[6]Institute of Astronomy of the Russian Academy of Sciences, Moscow, Russia
[7]Institute of Laser Physics, SB RAS, Novosibirsk, Russia

Habitable conditions on Earth developed in a tight connection to the evolution of terrestrial atmosphere which was strongly influenced by atmospheric escape. In this study, we investigated the evolution of the polar ion outflow from the Earth's open field line bundle starting from mid-Archean (three gigayears ago) and to present. We performed Direct Simulation Monte Carlo (DSMC) simulations and estimated upper limits on escape rates from the Earth's polar areas assuming the present-day composition of the atmosphere. We performed two additional simulations with lower mixing ratios of oxygen of 1% and 15% to account for the composition changes after the Great Oxydation Event (GOE).

According to our estimates, the maximum loss rates due to polar outflow was reached three gigayears ago equal to 3.3×10^{27} s^{-1} and 2.4×10^{27} s^{-1} for oxygen and nitrogen, respectively. We estimate the total maximum integrated mass loss equal to 39% and 10% of the modern atmosphere's mass, for oxygen and nitrogen, respectively. We also show that escape rates increase, if the oxygen mixing ratio is decreased (GOE simulations), which is due to reduced thermospheric cooling. According to these results, the main factors that governed the polar outflow in the considered time period are the evolution of the XUV radiation of the Sun and the atmosphere's composition. The evolution of the Earth's magnetic field plays a less important role. We conclude that although the atmosphere that has a present-day composition can survive the escape due to polar outflow from 3 gigayears ago and later, a higher level of CO_2 between 3.0 and 2.0 Ga is likely necessary to reduce the escape.