Study of ion loss mechanisms from ancient Mars with a focus on effects of the global intrinsic magnetic field

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Past observations on Mars suggested a warm and wet environment approximately four billion years ago. Such a warm climate requires the greenhouse effect of a thick atmosphere, but Mars has only a thin (~0.007 bar) CO_2 atmosphere today. A major problem in understanding climate evolution at Mars is determining processes that have played an important role in the removal of the atmosphere over time. Ion loss caused by interactions between the solar wind and the upper atmosphere is one of the candidate processes. Mars was exposed to intense solar X-ray and extreme ultraviolet (XUV) flux and strong solar wind during a younger, more active phase of the Sun. Intense solar activity during the early period may enhance ion loss by several orders of magnitude. The crustal remnant magnetic fields on Mars suggest existence of a global intrinsic magnetic field on ancient Mars. A global intrinsic magnetic field affects magnetic configuration around the planet and thus ion loss, but the detailed effects are still unclear.

We investigated processes and rates of ion loss from ancient Mars with a focus on effects of the existence and strength of an intrinsic magnetic field based on multispecies magnetohydrodynamics (MHD) simulations. We conducted simulations under the two different (extreme and moderate) solar conditions and the different strength of the intrinsic magnetic field. The extreme solar conditions were that the solar XUV flux was 100 times higher than the present value, and the solar wind number density, the velocity, and the interplanetary magnetic field (IMF) strength were 1000 cm^{-3}, 2000 km s^{-1}, and 60 nT, respectively. The moderate solar conditions were that the solar XUV flux was 10 times higher, and the solar wind number density, the velocity, and the IMF strength were 70 cm^{-3}, 700 km s^{-1}, and 6.58 nT, respectively. The intrinsic magnetic field was assumed to be a dipole field and northward at the equator.

Under extreme solar conditions, existence of a dipole field strongly affects molecular ion escape by the cusp outflow. The effect depends on the dipole field strength. In the overpressure cases where the solar wind dynamic pressure exceeds the dipolar magnetic pressure, the cusp outflow is enhanced, and the loss rates of molecular ions are increased by a factor of ~6. In the non-overpressure cases where the dipolar magnetic pressure is higher than the solar wind dynamic pressure, however, the loss rates are strongly suppressed by two orders of magnitude. The mass-loading of O^+ on the extended oxygen corona contributes to a certain part of the total O^+ loss. Therefore, the effects of the dipole field are less pronounced on the O^+ loss rate.

Under moderate solar conditions, the effects are similar but partly different. The loss rates of molecular ions are increased in the overpressure cases. However, only the O_2^+ loss rate is increased even in the non-overpressure case. In this case, the main escape process is the O_2^+-rich polar outflow instead of the cusp outflow. The polar outflow is driven by relatively strong pressure gradient in the polar ionosphere caused by the thinner corona and higher magnetopause. The O^+ loss rate is decreased with the dipole field strength. The mass-loading process is weaker and more sensitive to change in altitude of the magnetopause. This is because the density and the scale height of the corona is small due to the weaker

solar XUV flux.

The study reveals that effects of an intrinsic magnetic field on ion loss depend on the pressure balance between the solar wind dynamic pressure and the magnetic pressure of the intrinsic magnetic field. The effects are also affected by properties of the oxygen corona that is mainly determined by the solar XUV flux.

Keywords: ancient Mars, atmospheric escape, multispecies MHD simulation, intrinsic magnetic field