# 非磁化惑星からの大気イオン流出に関する多種イオンＭＨＤシミュレーション

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# Multi-ion MHD simulation of plasma structure and ion escape from the unmagnetized planets

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Recently, a number of MHD and hybrid simulation results have been published to study the escape mechanism of planetary ions from upper atmospheres of unmagnetized planets. It should be pointed out that these results are not yet in a total harmony with each other. An obvious reason for this discrepancy is that the MHD and hybrid simulations often use different boundary conditions particularly at the bottom of the ionosphere (or at the exospheric base) because of the necessity from the computer resources for the case of hybrid simulations. Since the total escape flux depends on the supply of ions across the exospheric base, the boundary conditions at the exospheric base are a critical issue for the hybrid simulations adopting the exospheric base at the lower boundary. Another source for discrepancy is the fact that the hybrid simulation can take account of electric field asymmetry around the planet due to different ion (and electron) masses, but the MHD simulations can not. A puzzle related to this point is that there have been opposite simulation results for the y-asymmetry in the escaping ion flow even for hybrid simulations (the y-axis is defined to be parallel to the -VxB direction, where V and B are the solar wind velocity and the IMF). A closer look at the opposing results shows that the asymmetry results from different altitudes for different simulations. In some cases, ions escape from the upper ionosphere preferentially on the +y hemisphere by ion pick-up processes (Chanteur et al., 2003). In other cases, ions escape from the lower ionosphere preferentially on the -y hemisphere (Kallio et al., 2002).

In order to find a key to solve these discrepancies, we have recently developed a multi-ion dynamics MHD code, which combines the good points of both the ordinary MHD and hybrid simulations codes. In our code, dynamics of different ion species (treated as fluids) are solved independently using independent continuity, momentum, and energy equations for each ion species. (Note that most of the past multi-ion MHD simulations assumed that all ion species have a common velocity based on a single momentum equation). Therefore, the E+VxB term (which vanishes for ordinary MHD) does not vanish for each ion species in our code, and the asymmetric electric field produced around the planet naturally arises in our code just as in the hybrid code simulations. On the other hand, since our code requires less computer resources than hybrid simulations, it can treat the ionospheric boundary conditions more rigorously.

We here discuss the results of our new simulation codes. Main conclusions are:

(1) The pick-up ions produced in the magnetosheath and in the upper ionosphere are accelerated towards the +y hemisphere just as in the case of hybrid simulations. However, these pick-up ions are a minor component of the total escape flux.

(2) The three-ray structure of escaping ions, as found in our previous MHD simulations, remains to be found in our new code. The difference is that the structure now has a y-asymmetry: the peak of escape flux is shifted towards -y direction, which is consistent with Kallio et al.(2002) (and not consistent with Chanteur et al.(2003)). These rays are produced at relatively low altitudes at the terminator so that possibly they have not been treated properly by hybrid simulations.

(3) The MPB (Magnetic Pile-up Boundary), discovered at Mars, cannot be reproduced by our code even though we have adopted most recent chemical reaction rates including electron impact ionization and charge exchange processes. We note that there have been several simulation reports which claim that the MPB has been reproduced by their codes. However, if we take a closer look at their results, the claimed boundaries have certain characteristics not consistent with observations. The real mechanism of the MPB formation remains to be studied with a need for new theoretical considerations.