P071-001 Room: C501 Time: May 28 10:46-11:03

The climate evolution of Mars: behaviors of the CO2 system

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It is well known that the current Mars has an extremely cold climate. However, valley networks and the ocean hypothesis of Mars imply a warm and wet climate in the past. In order to examine the evolution of the Martian climate, it is important to know mechanisms which have determined temperature and pressure at the surface of Mars. Greenhouse effect of CO2 could have been the most important factor for the Martian environment throughout the history of Mars, because CO2 is thought to have been a principal constituent of the ancient Martian atmosphere as well as the present atmosphere. Therefore, we need to understand controlling mechanisms for the amount of CO2 in the atmosphere of Mars. We have discussed the climatic environment on Mars based both on the energy and the CO2 budgets at the surface of Mars. Polar ice caps and surface regolith are considered to be large CO2 reservoirs to exchange CO2 with the atmosphere on the present Mars (atmosphere-ice caps-regolith (AIR) system). We have constructed an energy balance climate model (EBM) for the AIR system of Mars to examine its behaviors. In this lecture, we summarize stability and possible evolution scenarios of the Martian climate system by investigating behaviors of the EBM under various conditions.

In particular, partition of CO2 between the atmosphere and the ice caps plays an important role in determining the Martian climate state. The stability of the Martian climate system is determined from competition among four feedback mechanisms in respect of the CO2 ice caps (ice albedo feedback, greenhouse feedback, freezing point feedback, and heat transport feedback). As a result, stable steady state solutions derived from the EBM under the condition of seasonal variations can be classified into four cases: (i) a solution which has residual ice caps in summer (residual-cap solution), (ii) a solution which does not have residual ice caps, but has seasonal ice caps during the winter (seasonal-cap solution), (iii) a solution which has no ice caps throughout the year (no-ice-cap solution), and (iv) a solution which has a residual cap in one pole and a seasonal ice cap in another pole. The solutions (i) and (iv) are combined into (A) residual-cap regime in which the annual mean atmospheric pressure is constant irrespective of the total amount of CO2 in the AIR system. The solutions (ii) and (iii) are combined into (B) no-residual-cap regime in which the atmospheric pressure depends on the amount of CO2 in the AIR system.

If the Martian climate was warm and wet in the past because of the strong greenhouse effect of CO2, the amount of atmospheric CO2 must have been larger than that at present. In this case, the total amount of CO2 within the whole system also should have been larger than at present and have decreased by some removal processes. If it were the case, the Martian climate could have been changed abruptly and drastically during its history from the warm no-residual-cap regime to the cold residual-cap regime due to decrease in the amount of CO2 in the AIR system. This is a climate jump during the long-term evolution (10^8 - 10^9 years) of the Martian climate. On the other hand, it is known that obliquity of Mars could have changed continually between 0 and 60 degrees on short time-scale (10^5 - 10^6 years). The obliquity variations alter the latitudinal distribution of the solar radiation. Our numerical results show that obliquity change has profound effects on the climate system of Mars. The obliquity change could cause another climate jump in the Martian climate system on short timescale. We found that the climate jump could have occurred repeatedly in short-term cycles during the Martian history due to changes in the obliquity of Mars.