Atmospheric recycling of planets embedded in a protoplanetary disk: the suppression by buoyancy barrier

*Hiroyuki Kurokawa[1], Takayuki Tanigawa[2]

1. Earth-Life Science Institute, Tokyo Institute of Technology, 2. National Institute of Technology, Ichinoseki College

The ubiquity of super-Earths in exoplanetary systems poses a problem for the planet formation theory: they are expected to become gas giants through the runaway accretion of disk gas within the lifetime of protoplanetary disks. Rapid recycling of the envelope gas of planets embedded in a protoplanetary disk has been proposed to delay the cooling and following accretion of disk gas. However, the topography of the recycling flow has been shown to differ between previous studies of the flow past a planet in a disk: some studies have found efficient recycling, whereas others have found that the recycling is limited in the upper part of the planetary envelope.

We conducted a detailed comparison between isothermal and non-isothermal 3D hydrodynamical simulations of the gas flow past a planet by using Athena++ hydrodynamical simulation code and investigated the effect of radiative cooling on the recycling flow. Radiative cooling was implemented by the β cooling model.

We observed the pattern of recycling flow: fluid entered the Bondi sphere at high latitudes and leaves through the midplane regions, which is consistent with previous studies. The topography of inflow and outflow is the other way around when disk gas rotates in sub-Keplerian. Whereas the isothermal simulations showed complete recycling where streamlines are connected to the planetary core, the non-isothermal simulations showed limited recycling; at the inner part of the planetary envelope, streamlines are circular. We found that the buoyancy force induced by the entropy difference between the atmosphere (low entropy) and disk gas (high entropy) suppresses the recycling. Though our models adopted the simple β cooling, the mechanism of the buoyancy barrier is useful to understand the difference between the previous studies.

Our results suggested that, once the atmosphere starts cooling, the buoyancy barrier prevents the high-entropy disk gas from intruding the cooled atmosphere, leading further cooling of the atmosphere and runaway gas accretion onto the core. Nevertheless, the interaction of the recycling flow with accreting dusts may delay the growth of super-Earth cores and help to explain the ubiquity of super-Earths in extrasolar planetary systems.

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