

論文 / 著書情報
Article / Book Information

題目(和文)	原始惑星系円盤から惑星に至る揮発性・半揮発性物質の継承のモデル化
Title(English)	Modeling the inheritance of volatiles and semi-volatiles from protoplanetary disks to planets
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出典(和文)	学位:博士(理学), 学位授与機関:東京科学大学, 報告番号:甲第220号, 授与年月日:2025年3月26日, 学位の種別:課程博士, 審査員:奥住 聡,井田 茂,中本 泰史,佐藤 文衛,癸生川 陽子,黒川 宏之
Citation(English)	Degree:Doctor (Science), Conferring organization: Institute of Science Tokyo, Report number:甲第220号, Conferred date:2025/3/26, Degree Type:Course doctor, Examiner:,,,,,
学位種別(和文)	博士論文
Category(English)	Doctoral Thesis
種別(和文)	論文要旨
Type(English)	Summary

論文要旨

THESIS SUMMARY

系・コース： Department of, Graduate major in	地球惑星科学系 地球惑星科学	系 コース	申請学位 (専攻分野)： Academic Degree Requested	博士 Doctor of	(理学)
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要旨 (英文 800 語程度)

Thesis Summary (approx.800 English Words)

Through direct exploration of solar system bodies and observations of exoplanets using current-generation telescopes, we have gained not only physical information, such as the size and mass of planets, but also chemical insights, including the abundances of atoms and molecules that compose them. The composition of these planets reflects the properties of the dust and gas in the protoplanetary disk as well as the history of their transport processes within the disk and the chemical evolution that occurs within the planets.

Understanding the transport and inheritance processes of elements from disks to planets is crucial for advancing planet formation theory, which has traditionally focused on the mass evolution of dust.

The volatile elements that contribute to the diverse composition of protoplanetary disks, driven by dust transport processes, provide critical insights into the formation location and timing of celestial bodies. For instance, the C/O ratio in exoplanet atmospheres reflects the proportions of major volatile molecules such as H₂O, CO₂, and CO in the disk gas. A low C/O ratio in a planetary atmosphere suggests that the planet likely formed in the inner disk ($r < 3$ au), where it could acquire a significant amount of H₂O vapor. While such constraints can be strengthened by examining various elemental ratios, research on other volatile elements, including nitrogen and sulfur, remains limited. In this thesis, we aim to elucidate the inheritance process of volatile elements, including nitrogen and sulfur, from the disk to the planet. Furthermore, we seek to uncover when, where, and with what types of building blocks the observed planetary compositions were formed.

We first developed a theoretical model to investigate the transport processes of nitrogen in the disk and its impact on the nitrogen abundance of forming planets. A significant fraction of the cosmic nitrogen budget, accounting for tens of percent, remains attributed to unknown components. Recent detections of semi-volatile ammonium salts in comets and molecular clouds suggest these salts as potential candidates.

Our model incorporates the transport of nitrogen by ammonium salts in addition to the volatile N₂ and NH₃, which have traditionally been considered the main nitrogen carriers in disks. The results show that, under plausible disk parameters, ammonium salts can increase the nitrogen abundance in disk gas to several times the solar value. This enrichment is subsequently inherited by the planetary atmosphere forming in the inner region of the disk. In the solar system, Jupiter's atmosphere exhibits a nitrogen abundance enriched to three times the solar value. Our model suggests that nitrogen transport via ammonium salts could provide a plausible explanation for this enrichment.

Then, we performed calculations of disk material transport and, based on these results, developed a series of theoretical models to calculate the atmospheric structures of planets and predict their transmission spectra.

The disk model incorporates semi-volatile ammonium salts in addition to volatile ices, using cometary compositions as a reference. This model tracks the evolution of C, O, N, and S abundances in the disk. Our findings reveal that the dissociation of NH₄SH near the water snow line increases the nitrogen and sulfur abundances in the disk gas to more than twice the solar value. Notably, the disk gas inside the water snow line exhibits a high N/H, S/H, and O/H ratio and a low C/O ratio, driven by the dissociation of salts and the sublimation of H₂O ice. In the atmospheres of planets that inherit this composition, nitrogen- and sulfur-containing molecules such as NH₃, H₂S, NO, SO₂, and NS become dominant. Our predictions indicate that transmission spectra will feature prominent signatures of NH₃, H₂S, and SO₂. These results suggest that the transport of elements via ammonium salts may explain the detection of SO₂ in short-period exoplanets by JWST. In particular, we found that ammonium salts would play a crucial role in the transport and inheritance of volatile elements in WASP-107b, a warm Neptune where nitrogen and sulfur are simultaneously enriched.

Our disk model is based on the composition of comets; however, it remains uncertain whether this composition is universal in actual disks, and there are limited observational constraints on the ice composition in disks. To

address this, we developed a model to predict the scattered light spectrum of disk ice, aiming to identify the distribution of disk ice through observations. By comparing the optical depth in various bands where ice exhibits absorption features, as predicted by our model, with observational data, it becomes possible to estimate the ice composition of the disk. Applying our model to observations of HD 100546, we found that a model containing 3-20 wt% water ice reproduces the observations within the margin of error for $r < 50$ au.

Our model, which explores the inheritance of volatile elements from the disk to the planet, demonstrates that the observed spectrum of a planetary atmosphere is closely linked to the planet's formation location and timing. This model can be tested through future observations of planet-embedded disks. With further development, the model will enable us to better constrain the origin of planets, including their formation positions and times, based on their compositions.

備考：論文要旨は、和文 2000 字と英文 300 語を 1 部ずつ提出するか、もしくは英文 800 語を 1 部提出してください。

Note: Thesis Summary should be submitted in either a copy of 2000 Japanese Characters and 300 Words (English) or 1 copy of 800 Words (English).

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