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（様式３）

博士論文の要旨

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論文題目　Comparison of grain properties in interplanetary dust from different types of parent bodies by mid-infrared spectroscopic observations with AKARI

Interplanetary dust (IPD) is a population of dust particles distributing diffusely in the interplanetary space of the Solar System. The spatial distribution of the IPD is concentrated to the inner region within a few astronomical units (au) from the Sun, and the latitudinal profile has a peak at the ecliptic plane. One of the main constituent materials is silicate and the particle size has a range from a few tens of nanometer to millimeter order.

From dynamical simulations of orbital evolutions of the IPD particles, they are thought to be blown out of the Solar System or to accrete to the Sun owing to the interaction with the solar radiation and the lifetime is significantly shorter than the age of the Solar System. Therefore, they are thought not to have survived from the formation era in the Solar System, but to be continuously supplied from asteroids and comets. Asteroids repeat to collide with each other and break into fragments, reducing sizes of themselves. As the result of this collisional cascade, asteroids provide dust particles to the interplanetary space. Comets also eject dust particles into the interplanetary space owing to the sublimation of ice and spontaneous disruptions. Since such parent bodies are primordial planetesimals formed in the proto-solar disk, it means that the IPD particles have been incorporated into the parent body in the proto-solar disk, kept inside the body during the evolution of the Solar System, and recently returned to the interplanetary space again. Therefore, IPD particles are thought to suffer from the space weathering effect much less than the surface of their parent bodies and their grain properties can give us the information on the environment in the proto-solar system.

As a tracer of such properties, I focused on the spectral features around 10 μm originating from Si-O vibration modes of silicates included in the IPD grains. The shape of the features depends on the grain properties such as mineral and chemical composition, crystallinity and crystal morphology, for examples. IPD particles scatter and absorb the sunlight in the ultraviolet { near-infrared wavelength region and the absorbed energy is re-emitted as the thermal emission in the mid-infrared wavelength region. It is the dominant diffuse source in the mid-infrared sky brightness, called the zodiacal emission. Past infrared space telescopes detected emission features in zodiacal emission spectra. However, such observations did not have high signal-to-noise ratio sufficient to identify properties of the IPD grains accurately. Moreover, differences in the grain properties of the IPD from different types of parent bodies were not discussed in these previous works, although the result in laboratory measurements of the IPD particles collected near/on the Earth suggested that the asteroidal IPD and the cometary IPD have different grain properties.

The aim of this thesis is to compare the grain properties of the IPD from different types of parent bodies in terms of spectral features seen in the zodiacal emission. I compared the zodiacal emission spectra among various directions of the sky, because the IPD has different distributions in ecliptic latitudes depending on the types of the parent bodies. According to some dynamical simulations, the asteroidal IPD locally distributes at low specific ecliptic latitudes and observed as band structures near the ecliptic plane. On the other hand, because of the variety of comets' inclinations, the cometary IPD distributes more globally than the asteroidal IPD does. Jupiter Family Comets (JFCs), which have an elliptical orbit with an inclination less than 30° and an aphelion around the Jupiter, can form the dust cloud with a broad distribution in ecliptic latitudes around the ecliptic plane. Oort Cloud Comets (OCCs), which come flying from the Oort cloud, have an isotropic distribution in inclinations and therefore, the IPD from the OCCs has an isotropic spatial distribution all over the sky. Although a substantial fraction of the total amount of the IPD is thought to be from the JFCs, it may be possible to detect any signs of the IPD from asteroids or the OCCs if observations cover the various ecliptic latitudes with a high sensitivity.

In this thesis, I analyzed mid-infrared spectroscopic data of the zodiacal emission at 74 different directions over the entire sky. The data was obtained with MIR-S channel of AKARI/IRC. This channel covers the wavelength range of 5 - 12 μm using two grisms. With a conventional reduction pipeline, the resultant spectra of two grisms were not smoothly connected owing to the inconsistency in the intensity level of their overlapping wavelength range. The cause of the inconsistency was three types of instrumental artifacts: the light scattered into pixels in the same row and column of a detector's pixel array, the light scattered at the edge of a detector after going through a small window in the aperture mask, and the ghost of the small window aperture. I have empirically examined their brightness at each position on each image and subtracted them. As the result, I successfully obtained zodiacal emission spectra with high signal-to-noise ratio. Their intensity levels at 12 μm were found to be ~10 % higher than those calculated by a zodiacal emission model based on observations of COBE/DIRBE (hereafter DIRBE zodi-model), while they were lower than those calculated by a similar model based on imaging observations using AKARI/IRC. Those inconsistencies may be caused by the inappropriate color correction factor used in the construction of both models.

I estimated a continuum spectrum at each direction of the sky on the basis of the DIRBE zodi-model. By dividing the zodiacal emission spectrum obtained at each direction by the corresponding continuum, I derived observed/continuum spectra at all 74 pointing directions. I detected excess emission at 9 - 12 μm in all the observed/continuum spectra. They exhibit some sharp peaks significantly beyond the error range. Such detailed shapes have been revealed for the first time thanks to the IRC's high sensitivity and the accurate subtractions of instrumental artifacts. I discussed the shapes of the emission features at all directions from a mineralogical point of view. First, I averaged the observed/continuum spectra in all observed directions and compared with absorption coefficients of candidate minerals. This enables us to understand grain properties typical for all over the sky. These typical properties represent the grain properties of the IPD from the JFCs, because the IPD from the JFCs (i.e., the smooth cloud) accounts for the significantly largest fraction of the total IPD. In the averaged spectra, I found main peaks around 9.60 and 10.65 μm caused by small grains of enstatite, and sub-peaks around 10.15 and 11.85 μm which are mainly contributed by small grains of forsterite, in addition to a composite peak from enstatite and forsterite at 11.30 μm. It indicates that the IPD from the JFCs includes small crystalline grains and is enstatite-rich. In order to reproduce the wavelength position of the enstatite peak shifted from 9.2 μm to 9.6 μm and the suppressed enstatite peak at 11.6 μm, enstatite grains included in the IPD from the JFCs may have extreme crystal morphologies like whisker- or platelet-shapes.

Secondly, I compared the feature shapes among different pointing directions, in order to compare grain properties among the IPD originating from different types of parent bodies. To investigate the influence of the asteroidal IPD on feature shapes, I compared feature shapes among directions with different brightness contribution levels of the asteroidal dust bands. The contribution was denoted by A and calculated on the basis of the IPD's density distribution in the DIRBE zodi-model. On the other hand, the contribution of the IPD from the OCCs could not be calculated quantitatively because of the lack of an accurate model prediction of the density distribution including the isotropic component composed of the IPD from the OCCs. Instead, I compared feature shapes among directions with different absolute values of ecliptic latitudes, $|\beta_{Earth}|$, in order to investigate the influence of the IPD from the OCCs. I averaged the observed/continuum spectra in A - or $|\beta_{Earth}|$ - bins and compared the feature shapes.

As the most simple parameter of the feature shape, I calculated the equivalent width of the whole excess emission (EW_{whole}), which means the strength of excess above the continuum integrated in the 8 - 12 μm. EW_{whole} showed a clear positive correlation with $|\beta_{Earth}|$. It indicates the increase in the fraction of small grains at the higher ecliptic latitudes, because absorption coefficients of small grains (~1 μm) show more significant peaks than those of larger grains (> 10 μm). This result is consistent with previous works and can be explained by the collisional cascade during the accretion of IPD particles. On the other hand, a weak negative correlation between EW_{whole} and A was found. It means that the size distribution of the asteroidal IPD is biased to relatively larger grains owing to grains in the middle of the collisional cascade from asteroids.

The high signal-to-noise ratio of AKARI spectra enabled us to investigate more detailed feature shape for the first time. I defined 3 parameters for the quantitative investigation: an equivalent width ratio in 10.0 - 10.5 μm and 9.0 - 9.5 μm ($EW_{10.0\text{-}10.5}/EW_{9.0\text{-}9.5}$), a wavelength shift of a peak excess due to crystalline silicates ($\Delta\lambda_{peak}$) and an equivalent width ratio of peak excess due to crystalline silicates (EW_{fo}/EW_{en}). $EW_{10.0\text{-}10.5}/EW_{9.0\text{-}9.5}$ and EW_{fo}/EW_{en} were found to show a weak positive and negative correlation with A, respectively. A possible qualitative interpretation is the contribution of a smooth excess around 10 μm due to phyillosilicate minerals in the asteroidal IPD. Since phyillosilicate is a hydrated mineral, this implies the evidence of the aqueous alteration in the asteroidal IPD. From the negative $|\beta_{Earth}|$-dependence of $EW_{10.0\text{-}10.5}/EW_{9.0\text{-}9.5}$, the IPD from the OCCs was found to have a lower olivine/(olivine+pyroxene) ratio in amorphous grains than that of the IPD from the JFCs. In addition, the negative correlation between $|\beta_{Earth}|$ and $\Delta\lambda_{peak}$ in the peak around 11.34 μm can be interpreted as evidence that the enstatite sub-peak at 11.1 μm is enhanced relative to the forsterite main peak around 11.25 μm at higher $|\beta_{Earth}|$. This enhancement indicates a lower forsterite/(forsterite+ enstatite) ratio of the IPD from the OCCs compared with that of the IPD from the JFCs. It was consistent with the result of the negative correlation of EW_{fo}/EW_{en} with $|\beta_{Earth}|$.

I assumed that the JFCs were formed only in an outer region like > 15 au in the proto-solar disk while the OCCs could be formed also in a more inner region like 4 - 15 au, as predicted by the Nice model. Since the grain properties of the IPD reflect the dust properties in the forming region of the parent bodies, obtained grain properties of the IPD from the JFCs show the dust properties in the outer region of the proto-solar disk. It means crystalline silicates were included in the dust particles in such cold region, although the interstellar dust is known as amorphous and silicate crystals can be formed only in a hot region like < 1 au from the Sun. This indicates any radial mixing process has occurred and annealed or re-condensed dust has been transported outward. Three hypotheses have been proposed to explain the radial mixing: turbulence mixing model, X-wind model, and the transportation by radiation pressure. I also found the differences of the mineral composition between the IPD from the JFCs and the OCCs, which imply the differences of the mineral composition among dust at different radial distances in the proto-solar disk. My findings may become useful to identify which radial mixing model is more reliable, if radial dependence of the mineral composition will be available in each model.

Form8・Separate Sheet
（様式８・別紙）

Results of the doctoral thesis screening

博士論文審査結果

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Title
論文題目　Comparison of grain properties in interplanetary dust from different types of parent bodies by mid-infrared spectroscopic observations with AKARI

あかり中間赤外線分光観測による異なる母天体起源の惑星間塵の性質比較

出願者は、赤外線天文衛星「あかり」のスリット分光観測で得られた中間赤外スペクトルデータを解析して、惑星間塵（IPD：Inter-Planetary Dust）の空間分布と母天体との関係を明らかにした。本研究は、出願者が観測装置に由来する迷光・散乱光を分析して除去することにより、高い拡散光感度をもつ「あかり」の分光観測の性能を十分に発揮することに成功することで、初めて得られた成果である。これにより、原始太陽系円盤の環境を知る上での手がかりとなることが期待されてきた IPD について、主要成分とされる木星族彗星（JFCs）起源のものに加えて、オールト雲彗星（OCCs）起源のもの、小惑星起源のダストバンドが、これら母天体によって空間分布が異なることを初めて示した。

本研究では、まず全天に分布する 74 方向の「あかり」中間赤外分光データを解析し、得られた観測スペクトルデータから迷光・散乱光を除去し、次いで DIRBE 黄道光モデルを用いて見積もった連続光スペクトルに対する比を求めた。得られたスペクトルから、惑星間塵の平均的性質として、複数の鋭いピークが見られることからミクロンサイズの結晶質シリケートが豊富に含まれること、および Enstatite（Mg-end 結晶質 Pyroxene）の放射が強く見られることを明らかにした。なお、そのピーク波長が本来の 9.2 μm からシフトした 9.6 μm 付近に見られることから、Enstatite が特異な形状（縦長等）を有することも示唆している。

続いて母天体の相違による惑星間塵の性質の違いを調べるために、8－12 μm バンド全体での超過成分等価幅 EW_{whole} と、鉱物組成比の指標（9 μm /10 μm 強度比、ピーク波長シフト $\Delta\lambda$ peak、Fo/En 比）を定義した。これらの指標と DIRBE モデルから計算したダストバンド寄与率 A との関係を調べたところ、非結晶質と結晶質との間で弱い逆相関が見られることを示した。このことは、ダストバンドの惑星間塵には含水鉱物（層状シリケイト）が存在する可能性を示唆している。また黄緯 β による違いを調べたところ、非結晶質の Olivine/Pyroxene 比に強い負の相関が見られ、結晶質のものも弱いながら同様であった。これは、高い黄緯で卓越する OCCs 起源惑星間塵は、JFCs 起源のそれよりも低い Olivine/Pyroxene 比を示すことを意味している。

さらにこれらの結果を踏まえて、母天体の形成領域について巨大惑星移動説（Nice モデル）に基づいて考察した。それによると、JFCs は元来 15AU より外側で形成された一方で、OCCs の形成は数 AU の内側までを含む広範な領域で行われたとされる。本研究により、JFC 起源 IPD は結晶質を含む、即ち過去に局所加熱または Radial Mixing が起きて

いたことが示唆される。一方 OCC 起源の IPD は JFC 起源のそれよりも低い Olivine/Pyroxene 比を示すことから、原始太陽系円盤内で鉱物組成比が日心距離依存性を示していたことが示唆される。

また本研究の結果は、今後予定される「はやぶさ 2」探査 C 型小惑星サンプルとの比較による小惑星内部の性質調査や、さらに将来の OCC 起源 IPD の空間分布調査（黄道面脱出ミッション)、太陽系外原始惑星円盤の動径方向移動の観測などに、大いに寄与することが期待できるものである。この他にも、本研究は様々な示唆に富んでいる。例えば、鉱物組成の定量性（物質量の比率等）は依然として困難であるが、ピーク波長位置・幅を再現できる吸収係数モデルの整備が望まれる。今後、原始惑星系の Radial Mixing 進化モデルに化学進化を考慮することで、原始惑星系で起こった物理過程の制限が可能になることが期待される。

審査会においては、約 1 時間半の公開講演、質疑応答、その後の審査委員全員との非公開質疑を通し、出願者が観測データの解析・解釈のために専門家との議論や情報整理等、本論文の取りまとめを主体的に進めたことが確認された。審査委員会は全員一致で本論文が博士学位論文に相応しい優れたものであると認めたことから、合格と判定する。