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学位(専攻分野)	博士(理学)
学位記番号	総研大甲第 1664 号
学位授与の日付	平成26年3月20日
学位授与の要件	物理科学研究科　宇宙科学専攻 学位規則第6条第1項該当
学位論文題目	A new cosmic dust distribution model inside the Earth's orbit based on IKAROS-ALADDIN results
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論文内容の要旨
Summary of thesis contents

IKAROS-ALADDIN 観測データに基づいた 地球軌道より内側の宇宙塵分布モデル
A new cosmic dust distribution model inside the Earth's orbit based on IKAROS-ALADDIN results

This dissertation investigates a new modeling of cosmic dust distribution inside the Earth's orbit mainly based on in-situ dust measurement data by the Arrayed Large-Area Dust Detectors in INterplanetary space (ALADDIN) onboard the Interplanetary Kite-craft Accelerated by Radiation of the Sun (IKAROS). In addition to the modeling work, laboratory calibration experiments with the ALADDIN flight-spare were conducted with hypervelocity microparticle accelerators and a nanosecond pulsed laser. Furthermore, analysis and reduction of the measurement data from the ALADDIN are also presented as part of the dissertation.

Recent optical observation results suggest that orbital trapping of 10–100's-μm-sized dust particles by planets' mean motion resonances (MMRs) and dust-dust collisions are key roles in sculpting morphology of debris disks in exo-planetary systems. As is the case with extrasolar planetary systems, dust disks in our Solar System, i.e., zodiacal dust cloud and Edgeworth-Kuiper belt, are also predicted to have the characteristic morphology governed by the dust-planet MMRs and the dust-dust collisions. In order to establish a general reference model for debris disks in planetary systems, some dust distribution models in the Solar System have been developed and validated mainly from optical observation results. However, optical observation faces difficulty in revealing fine structures of the dust disk such as local size distribution, attributed to fundamental characteristics of the optical observations such as physical complexity of visible light scattering and thermal infrared emission of dust particles, which are superimposed brightness from various sized dust particles that exist in an observer's line of sight. Moreover, optical observations from the vicinity of the Earth are not suited to investigate the inner planetary region than the Earth's orbit because of the sunlight interference. In order to uniquely determine the size distribution and investigate the fine structure within dust disks, in-situ dust impact detection along the trajectory of spacecraft is a more promising option. Nevertheless, the dust distribution inside the Earth's orbit has not been well investigated even by in-situ detection until now, because of the lack of sufficient flight opportunities. Furthermore, all the past in-situ

dust detectors have had only too small sensor areas to measure sparse distribution of the 10–100's-μm-sized dust particles, which are likely to be trapped in the planets' MMRs.

In these situations, the large-area in-situ dust detector based on PVDF named ALADDIN has been developed for IKAROS mission, in order to reveal the dust distribution between 0.7–1 AU. This study contributes to reveal and to model the size distribution and the fine structure of dust distribution, especially focusing on ≥10-μm-sized dust particles inside the Earth's orbit mainly by using measurement data of the IKAROS-ALADDIN during its 16 months orbiting around the Sun from 0.7 to 1 AU.

This thesis presents results of laboratory calibration of the ALADDIN flight spare with three types of experiments: hypervelocity (> 1 km/s) microparticle impacts at the 2 MV Van de Graaff dust accelerator, hypervelocity (> 1 km/s) 100's-μm-sized particle impacts with the two-stage light gas gun, and laser irradiation with the nano-second pulsed Nd:YAG laser. Considering the characteristics of analog signal processing of the ALADDIN's detector electronics, A modified signal acquisition system and signal analysis method, which utilizes signals measured at intermediate points of the analog circuits were developed. As the results of these calibration methods, it was verified that the detection size range of the dust particles onto the ALADDIN corresponds to 3–37 μm at the average impact velocity of 20 km/s at 1 AU heliocentric distance while representative dust density is 2.0 g/cm^3.

In addition to the laboratory calibration experiments focusing on the ALADDIN's analog signal, the ALADDIN measurement data were analyzed and reduced, by investigating the digital circuit characteristics of the ALADDIN electronics, multi-flagged features of some obtained data, and possible thermal degradation of the PVDF sensors. Based on the signal sampling rate of the analog-to-digital converter inside the digital electronics, sampling probabilities were calculated for a given amplitude of analog signal. Thus, it was found that impact events showing ≥4 V of measured signal amplitude, which are thought to be generated by impacts of ~30-μm or larger dust particles at 20 km/s, can be straightforwardly interpreted with the probabilistic sampling effect. A large portion of the ALADDIN space data have indicated multi-flagged features, which show more than one channels are flagged despite being caused by a single dust impact. These multi-flagged events have recorded appropriate event rate as dust impact frequency in the interplanetary space. From its reproductive experiment on the ground and careful analysis of the flagged signal pattern, 733 high-confidence dust impact data at ≥4 V signal were determined on the ALADDIN's 20-μm-thick large sensors, among all the transmitted ~4500 data obtained during 16-month measurement in the Earth-Venus region. In order to estimate the size of the detected dust particles at each IKAROS position of heliocentric distance, the in-flight thermal degradation of PVDF sensitivity were investigated through both static pressure and impact experiments of the heated large PVDF sensor. As the result, the possible thermal degradation of the ALADDIN PVDF seems not to affect significantly on the detectable size of impacting dust particles. Consequently, a total amount of such large dust particles detected by the ALADDIN measurement is more than 10 times of that of the past in- situ dust detectors. Thus, the applicability of the ALADDIN to measuring ≥10-μm-sized dust particles inside the Earth's orbit was verified. The dust particles in this size range correspond to the dust particles observed by optical observations and also the dominant-sized dust in the characteristic dust distribution governed by the planets' MMRs.

The number density calculated with part of the reduced ALADDIN data in the Earth's trailing region was compared with the existing standard dust flux model (Grün flux) at 1 AU heliocentric distance, which was established on the in-situ measurement at the vicinity of the Earth. It was found that there was a clear discrepancy between them, which should be caused by the dust-Earth MMRs and the dust-dust collisions. In order to reproduce the observed azimuthal discrepancy, a new dust distribution model was developed by combining the existing MMRs- only model and the collision-only model. The new model has an ability to simultaneously handle the effect of the dust-planet MMRs and the dust-dust collisions for the dust distribution modeling in the interplanetary space. As the result, the newly developed model demonstrates a better estimate than the past MMRs-only model or the collision-only models for azimuthal variation of the dust number density at 1 AU heliocentric distance observed by the ALADDIN. In the future, this model calculation will be expanded to the Venus orbit for interpreting the ALADDIN data measured around its closest approach to Venus, and then a new comprehensive view of the cosmic dust distribution between the two planet-MMRs regions by the Earth and Venus can be achieved.

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博士論文の審査結果の要旨

Summary of the results of the doctoral thesis screening

IKAROS-ALADDIN観測データに基づいた
地球軌道より内側の宇宙塵分布モデル
A new cosmic dust distribution model inside the Earth's orbit
based on IKAROS-ALADDIN results

本研究は、太陽光セイル小型実証ミッション「IKAROS」探査機 の大面積膜材に搭載された、宇宙探査史上最高の空間分解能を持ち、日本で初めて設計・開発・校正・運用されたダスト計測器である「ALADDIN」のデータ解析を通じて、地球および金星近傍の大型ダストの分布構造について、従来の理論モデルや光学観測で予見されていた値を世界で初めて実証し、それらに独自のダスト分布モデルで意味づけをしようとしたものである。特に、以下の３項目について学術成果をあげている。

(1) PVDFダスト計測器への大型ダスト衝突の校正曲線の導出

個別の地上試験装置だけでは校正が困難なダストの衝突速度・サイズ領域に対して、複数の衝突試験装置と短パルスレーザーを組み合わせることで、統合的な校正曲線を描くことに成功した。これにより、 PVDFダスト計測器の宇宙実測データを適切に解釈できるようにした。その結果、ALADDINが10ミクロンオーダーのダストの超高速衝突を検出するのに適した計測器であることを証明した。

(2) ALADDINの全検出信号から信頼性の高い大型ダスト衝突信号の識別・抽出

ALADDINの検出感度限界はミクロンオーダーのダスト衝突にあるが、一部センサの回路上の不具合、他機器動作時の同期ノイズ、日心距離が短いことによる熱劣化、小型探査機ゆえの厳しいリソースに起因する信号回路および探査機 CPU とのインターフェイス上の制約など、真のダスト衝突信号を識別・抽出する際に考慮すべき課題も多い。本研究ではこれらを一つ一つ吟味し、4000個以上の信号から有効データを約2700個、さらに今回の科学目標である大型ダストの分布構造の解明に資する高品質データを700個以上、識別することに成功した。過去の探査機より一桁以上統計的に信頼性が高いダストフラックスの算出を可能にした。

(3) ダスト・惑星間の平均運動共鳴及びダスト相互衝突を同時に考慮した、新しいダスト分布モデルの開発

ALADDINの計測結果に基づき、地球近傍の実測データから外挿されていた従来のダスト分布標準モデルが、内惑星領域および地球軌道上の位相方向に対して過小評価となっていることを示した。その原因は地球と金星でのダスト・惑星間の平均運動共鳴およびダスト相互衝突が未検討である故との仮定に立ち、両者を同時に考慮する独自のダスト分布モデルを提案した。その結果、ALADDINが地球・金星の周太陽ダストバンドとバンド内のギャップ領域を実測したことを実証するとともに、濃集領域とギャップ領域の比率の計算結果を、平均運動共鳴モデル単体よりも、実測により近づけられるようになった。

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深宇宙空間でのダスト計測研究自体は、宇宙探査の歴史とほぼ同じ長さを持つ、伝統ある宇宙科学分野のテーマである。しかし ALADDIN 以前の太陽系内ダスト分布構造の研究においては、光学観測による散乱光の積分値か、小口径ゆえに小さなダストサイズのダストを少数しか検出できず、不確定性の高い計測器による実測しか依拠すべきデータがなかった。ALADDIN の登場と本研究の成果により、惑星との平均運動共鳴など、軌道力学的影響を受けやすい大きなダストの分布構造を初めて実測し、研究できるようになった。上記三項目の研究成果は、こうした ALADDIN による科学成果の創出に不可欠であり、出願者はその全てで主要な役割を担った。また今後も地球、金星周辺の独自ダスト分布モデルを独自に発展させることにより、太陽系外の惑星系のデブリディスクに埋もれた未知の惑星の発見や質量推定に、ダスト分布比率の観測が新規のプローブとなりうる道を開くものでもある。
さらに今回の校正実験やデータ解析の成果をもとに ALADDIN を改良すれば、JAXA で検討中の木星圏ソーラー電力セイルによる、外惑星領域ダスト分布の計測にも応用できる。以上から、本研究は、太陽系科学、天文学、宇宙工学をカバーする学際研究に貢献しうる、学術的価値の高い研究であると評価する。