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Dust in the Universe : Similarities and Differences

宇宙尘埃
——相似性和差异性

（影印版）

〔印〕斯瓦米（K. S. K. Swamy）著

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序　言

物理学是研究物质、能量以及它们之间相互作用的科学。她不仅是化学、生命、材料、信息、能源和环境等相关学科的基础，同时还是许多新兴学科和交叉学科的前沿。在科技发展日新月异和国际竞争日趋激烈的今天，物理学不仅囿于基础科学和技术应用研究的范畴，而且在社会发展与人类进步的历史进程中发挥着越来越关键的作用。

我们欣喜地看到，改革开放三十多年来，随着中国政治、经济、教育、文化等领域各项事业的持续稳定发展，我国物理学取得了跨越式的进步，做出了很多为世界瞩目的研究成果。今日的中国物理正在经历一个历史上少有的黄金时代。

在我国物理学科快速发展的背景下，近年来物理学相关书籍也呈现百花齐放的良好态势，在知识传承、学术交流、人才培养等方面发挥着无可替代的作用。从另一方面看，尽管国内各出版社相继推出了一些质量很高的物理教材和图书，但系统总结物理学各门类知识和发展，深入浅出地介绍其与现代科学技术之间的渊源，并针对不同层次的读者提供有价值的教材和研究参考，仍是我国科学传播与出版界面临的一个极富挑战性的课题。

为有力推动我国物理学研究、加快相关学科的建设与发展，特别是展现近年来中国物理学者的研究水平和成果，北京大学出版社在国家出版基金的支持下推出了《中外物理学精品书系》，试图对以上难题进行大胆的尝试和探索。该书系编委会集结了数十位来自内地和香港顶尖高校及科研院所的知名专家学者。他们都是目前该领域十分活跃的专家，确保了整套丛书的权威性和前瞻性。

这套书系内容丰富，涵盖面广，可读性强，其中既有对我国传统物理学发展的梳理和总结，也有对正在蓬勃发展的物理学前沿的全面展示；既引进和介绍了世界物理学研究的发展动态，也面向国际主流领域传播中国物理的优秀专著。可以说，《中外物理学精品书系》力图完整呈现近现代世界和中国物理

科学发展的全貌，是一部目前国内为数不多的兼具学术价值和阅读乐趣的经典物理丛书。

《中外物理学精品书系》另一个突出特点是，在把西方物理的精华要义“请进来”的同时，也将我国近现代物理的优秀成果“送出去”。物理学科在世界范围内的重要性不言而喻，引进和翻译世界物理的经典著作和前沿动态，可以满足当前国内物理教学和科研工作的迫切需求。另一方面，改革开放几十年来，我国的物理学研究取得了长足发展，一大批具有较高学术价值的著作相继问世。这套丛书首次将一些中国物理学者的优秀论著以英文版的形式直接推向国际相关研究的主流领域，使世界对中国物理学的过去和现状有更多的深入了解，不仅充分展示出中国物理学研究和积累的“硬实力”，也向世界主动传播我国科技文化领域不断创新的“软实力”，对全面提升中国科学、教育和文化领域的国际形象起到重要的促进作用。

值得一提的是，《中外物理学精品书系》还对中国近现代物理学科的经典著作进行了全面收录。20 世纪以来，中国物理界诞生了很多经典作品，但当时大都分散出版，如今很多代表性的作品已经淹没在浩瀚的图书海洋中，读者们对这些论著也都是“只闻其声，未见其真”。该书系的编者们在这方面下了很大工夫，对中国物理学科不同时期、不同分支的经典著作进行了系统的整理和收录。这项工作具有非常重要的学术意义和社会价值，不仅可以很好地保护和传承我国物理学的经典文献，充分发挥其应有的传世育人的作用，更能使广大物理学人和青年学子切身体会我国物理学研究的发展脉络和优良传统，真正领悟到老一辈科学家严谨求实、追求卓越、博大精深的治学之美。

温家宝总理在 2006 年中国科学技术大会上指出，“加强基础研究是提升国家创新能力、积累智力资本的重要途径，是我国跻身世界科技强国的必要条件”。中国的发展在于创新，而基础研究正是一切创新的根本和源泉。我相信，这套《中外物理学精品书系》的出版，不仅可以使所有热爱和研究物理学的人们从中获取思维的启迪、智力的挑战和阅读的乐趣，也将进一步推动其他相关基础科学更好更快地发展，为我国今后的科技创新和社会进步做出应有的贡献。

《中外物理学精品书系》编委会　主任

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2010 年 5 月于燕园

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Dust in the Universe

Similarities and Differences

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World Scientific

NEW JERSEY • LONDON • SINGAPORE • BEIJING • SHANGHAI • HONG KONG • TAIPEI • CHENNAI

Preface

We live in a dusty Universe. Dust plays an important role in the overall scenario of structure and evolution of the universe. Observations carried out with the Infrared Space Observatory showed for the first time highly complex mineralogy of the dust material and its variation among different astronomical objects in the universe, leading perhaps to a new area of astromineralogy. Extensive and high quality observations carried out using ground-based telescopes and satellites have led to phenomenal progress in our understanding of the nature and composition of dust in the universe upto redshifts $z \sim 6.4$. This shows that dust is present from almost the beginning of the Universe to the present time. The method of studying the evolution of dust is in the reverse order; starting with local universe and then moving farther in space which means going back to earlier times. Thus it seems that this is the appropriate time to summarize the present status of cosmic dust, essentially evolution of astromineralogy.

I would like to thank G. Wallerstein for impressing upon me the importance of such a book and encouraging me to take up the venture. It is a pleasure to thank Juni-ichi Watanabe and the National Astronomical Observatory of Japan for providing excellent research enviornment leading to this book. I am grateful to J.V. Narlikar for encouragement in the publication of the book. I am also thankful to Tata Institute of Fundamental Research for the use of their excellent facilities.

I am especially grateful to my colleagues H.M. Antia who helped me in various technical ways, from literature survey to digitization and S. Ramadurai for a thorough reading of the manuscript. I would also like to express my gratitude to my parents and my family for their support and encouragements. I would like to thank all the publishers and authors, who have given permission for reproduction of figures and tables. The help of

M. Shinde in the preparation of the manuscript is greatly appreciated.

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January 2005

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Contents

Chapter 1

General Introduction

Study of the dust particles in the universe is an exciting and challenging area of current astronomy. This comes from various considerations. Dust is at the centre of all important events in the universe, like star formation, distance determination etc. Dust particles influence the thermal, dynamical, ionization and chemical states of matter of the interestellar and intergalactic medium. It may be noted, about half of the elements heavier than helium is in the form of dust in the interstellar medium of our Galaxy. Dust grains are effective absorbers of radiation energy and momentum. The collisional coupling between grains and gas in dense regions around evolved stars, in molecular cloud cores and protoplanetary disks have consequences for the temperature and the dynamical evolution of the gas component. The mass loss from evolved stars, stability of molecular clouds and their fragmentation into smaller clumps etc. are directly linked to the presence of dust. Infrared observations arising due to thermal emission from dust particles probe regions of star formation. The low temperature inside clouds arising from shielding of radiation by the dust particles leads to complex chemistry between dust and atoms and molecules. The formation of molecular hydrogen takes place on the surface of grains. The dust and complex chemistry of the material present in comets appear to be the same as in these clouds. May be these are the precursors to life on earth! However due to historical reasons and also due to lack of facilities both with regard to bigger telescopes and technology, most of the studies had to be concentrated on the local universe, particularly our Galaxy and nearby ones. Even here, until recently, studies were concentrated on brighter objects. Things have improved enormously with the advent of space and new technology telescopes. It is now possible to push the limit of observations to fainter and fainter sources. Also it has been possible to study objects farther in space and hence well back in time.

Nature and composition of dust in the Galaxy have come from many kinds of observations such as extinction, scattering and polarization of starlight, infrared continuum emission, spectral features in the infrared region, interstellar depletion of elements, presence of isotopic anomalies in meteorites etc. These studies have been carried out on different kinds of objects such as diffuse and dense clouds, Reflection nebulae, star forming regions, HII regions, circumstellar shells of stars, meteorites, interplanetary dust particles etc. High resolution spectral observations in the infrared region have given enormous information about the composition of dust particles. All these studies have shown that dust particles are mainly made up of crystalline and amorphous silicates and of carbonaceous material in some form. The near and mid-infrared spectra of many sources are dominated by strong emission features at 3.3, 6.2, 7.7, 8.6 and 11.3μm. These are collectively known as unidentified infrared (UIR) bands. However it is suggestive that they could arise from the large sized molecules containing about 50 to 100 atoms, such as Polycyclic Aromatic Hydrocarbon (PAHs). However no specific molecule has been identified and it is further complicated by the fact that emission arises not from a single molecule but from a host of molecules. However the carrier appears to be aromatic in character. In view of this, We prefer to use the term "Aromatic Unidentified Infrared Bands" (AUIBs) to describe this generic spectrum. The grains inside molecular clouds are heavily processed with a mantle of various ices. Nature of the dust is also dependent on the radiation field present in the environment.

The major supply of dust comes from circumstellar shell of evolved stars such as oxygen-rich and carbon-rich stars producing silicate type and carbonaceous type of materials respectively. Stellar winds eject these dust particles into interstellar medium. These particles cycle several times through dense and diffuse clouds which could modify their original composition. The chemical and physical structure of dust grains are also modified by a host of processes including UV photon irradiation, gas-phase chemistry, accretion and grain surface reactions, cosmic ray bombardment and destruction by shock waves generated by supernova explosion etc. Therefore the nature and chemical composition of grains in the Galaxy is a function of the environment and quite complicated.

An understanding of the chemical complexity of the grain material in Galaxy is crucial for an understanding of the chemical state of dust in extragalactic systems and in the universe. It may be noted that the conditions existing in astrophysical objects are diverse and extreme. The temperature, particle density and radiation field can vary over a wide range of values. Therefore the success of the study of dust grains in the Galaxy and in extragalactic systems is critically dependent upon laboratory studies of dust carried out under astrophysical conditions. Extensive laboratory studies carried out with dust analogues have helped enormously our understanding of the chemical composition of dust in various locations. Since the laws of physics and chemistry are the same throughout we can extend the studies of local environment to the universe.

Other galaxies in the universe can have various shapes defined as spirals (our Galaxy), ellipticals etc. which themselves form clusters and superclusters. Dust is present, as we have seen above, not only within the galaxies but in the intergalactic and intracluster media as well. One major difference of course is that chemical composition of the gaseous material in the past is not the same as that of the Galaxy. The earliest heavy elements could not have been created until after the first stars and the first supernova, roughly at redshift $z \sim 6$. This could in principle have an effect on the nature of dust present in these objects. Dust condenses out of the gaseous material. This is the processed material inside stars due to nucleosynthetic processes. The processed gaseous material inside the star is returned to the interstellar medium which enriches the original material. The stars formed out of the new material will be richer in heavier elements compared to the previous generation of stars. Once the dust is formed within the galaxies it can be expelled to extragalactic space by several processes like galactic wind, explosions etc. The modification of the material has been going on through such a cycle over the age of the universe.

As mentioned earlier, dust manifests in different ways. However detailed nature of the dust can be determined from objects which are close by. As one goes out to larger and larger distances objects become fainter and fainter. Therefore one can estimate only some gross property of the grains. This situation should improve in future with the availability of bigger telescopes and sensitive detectors. However at the present time, Quasars, the highly redshifted objects are well suited for this study at large distances as they are very bright. At the present time they have traced the state of the universe upto redshift of $z \sim 6$.

In the succeeding chapters we would like to elaborate on some of these aspects. We will first present some of the Laboratory studies relating to the nature of dust, like silicates, carbonaceous materials etc. This will then be followed by the available information on the nature and composition of