REMOTE COMPOSITIONAL ANALYSIS

How do planetary scientists analyze and interpret data from telescopic and spacecraft observations of planetary surfaces? What elements, minerals, and volatiles are found on the surfaces of our Solar System's planets, moons, asteroids, and comets? This comprehensive volume answers these topical questions by providing an overview of the theory and techniques of remote compositional analysis of planetary surfaces. Bringing together eminent researchers in Solar System exploration, it describes state-of-the-art results from spectroscopic, mineralogical, and geochemical techniques used to analyze the surfaces of planets, moons, and small bodies. The book introduces the methodology and theoretical background of each technique, and presents the latest advances in space exploration, telescopic observation, and laboratory instrumentation, and major new work in theoretical studies. This engaging volume provides a comprehensive reference on planetary surface composition and mineralogy for advanced students, researchers, and professional scientists.

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REMOTE COMPOSITIONAL ANALYSIS

Techniques for Understanding Spectroscopy, Mineralogy, and Geochemistry of Planetary Surfaces

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Foreword

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So much has happened in the 25 years since the last collection of expert papers documenting principles and products of remote compositional analyses were brought together as a book! Of course, it is not that the physics and chemistry governing properties of planetary materials has changed much in a generation. However, great advances have been made during the intervening decades as new instruments were built and new spacecraft were flown across the Solar System. This is coupled with advances in information extraction techniques and instrument technology that enable the measurement of these properties with increasing detail both in the laboratory and remotely. Consequently, understanding nuances of the diagnostic properties forming the basis for compositional analyses has grown in leaps and bounds along with remarkable and expanding new data from the inner to outer Solar System, including both rocky and icy bodies with and without an atmosphere.

The 1993 book *Remote Geochemical Analyses: Elemental and Mineralogical Composition* was compiled near the end of the last millennium following a symposium bringing together planetary scientists across many disciplines. At that time, remote planetary exploration techniques were just beginning to grow in importance and impact. The impetus for bringing together information and technical background in one book was to make the scientific basis for this relatively new field readily available across a growing community. The initial discussions in *Remote Geochemical Analysis* laid the foundation for years of basic exploration of Solar System bodies in all their diversity and mystery. Subsequent expansion and maturation of remote sensing data obtained using telescopes and increasingly sophisticated exploratory spacecraft opened a wide range of data types and approaches with which to obtain information and understand the diverse and complex bodies of our Solar System.

Today, several decades later, the initial reconnaissance of the Solar System is complete. We have now looked at everything from Mercury to the Kuiper belt at least once. That has taught us there is a LOT more to learn. The path that exploration has taken has provided profound insight, awesome discoveries, and continuous inspiration. Nevertheless, it necessarily has not been a linear or complete process. We are now embarking on an era of detailed and serious exploration, that cries for in-depth knowledge of, and comparisons between, the diverse rocky, hydrated, icy, and gaseous bodies of our Solar System (including Earth) – and even planets of other star systems. Although the exploration focus and

resulting data acquired have been uneven, a plethora of fundamental questions are posed and remain unanswered regarding the composition of each planetary body we have come to know. In parallel with the quest for deeper scientific understanding, modern technology provides increasingly sophisticated instruments to measure compositional properties remotely, and such exploration tools promise many exciting decades ahead.

The chapters in this completely new *Remote Compositional Analysis: Techniques for Understanding Spectroscopy, Mineralogy, and Geochemistry of Planetary Surfaces* provide a diverse and enormously updated taste of what we know and what we have been able to learn about the composition of planetary bodies using remote sensing techniques over the last few decades. Remote compositional analysis has become a mature interdisciplinary field of science and has evolved into an indispensable component of Earth and planetary exploration.

Preface

The field of remote sensing is integral to exploration of our Solar System and encompasses results acquired from telescopic, spacecraft, and landed missions. The remote sensing techniques described in this book span a range of processes, compositions, and planetary bodies. It is a dramatically updated version of the original first edition from 1993. Since then, significant advances have occurred in space exploration, including dozens of new missions from NASA, ESA, and other space agencies around the world; substantial advances in telescopic and laboratory instrumentation, and major new work in theoretical studies have also occurred. As a result, every topic has been updated from the original book edited by C. M. Pieters and P. A. J. Englert, and new content has been added to reflect major advancements since 1993. This work sprung out of a 1988 symposium on mineral spectroscopy organized by L. M. Coyne with assistance from J. L. Bishop that was sponsored by the Division of Geochemistry of the American Chemical Society. The purpose of that symposium was to bring together an interdisciplinary, international community to foster spectral identification of minerals.

We have attempted to provide an introduction to the field of planetary surface composition and mineralogy for upper-level undergraduates, graduate students, or professional researchers just moving into this topic. This book is organized into four sections including (I) theory and laboratory measurements, (II) terrestrial field and airborne applications, (III) analysis methods, and (IV) applications to planetary surfaces. Among the types of remote sensing techniques covered are visible to infrared reflectance spectroscopy, infrared emission spectroscopy (also called thermal infrared spectroscopy), Raman spectroscopy, Mössbauer spectroscopy, Laser-Induced Breakdown Spectroscopy (LIBS), neutron spectroscopy, X-ray spectroscopy, gamma-ray spectroscopy, and radar. The basic premise of each technique, information on how to perform measurements, and example spectra of rocks, regolith, minerals, and volatiles are provided.

This book covers the minerals, elements, and molecules found on airless rocky bodies including Mercury, the Moon, and asteroids. It describes the kinds of volatiles (ices, organics, hydrated minerals) found on the surfaces of our Solar System's planets, moons, asteroids, and comets, and how they are related to volatiles on Earth. Finally, several chapters specifically focus on the composition and processes taking place on Mars, the planet most studied besides Earth.

Acknowledgments

We are grateful to the countless planetary scientists and engineers around the world who have contributed toward developing and operating the phenomenal instruments, telescopes, and spacecraft that enabled the compositional remote sensing results presented here. Obtaining these data from planets, moons, asteroids, and comets in our Solar System has required laborious efforts and diligence from large teams of people from space centers, research institutes, and universities. We appreciate the hard work of the authors who contributed state-of-the-art summaries of current topics in planetary remote sensing to this book and made it possible.

Unfortunately, two of our authors, Joshua Bandfield and Göstar Klingelhöfer, passed unexpectedly this year and we will miss them. They contributed to Chapters 15, 24, 25, and 27, where memorial statements are included.

Many others contributed to this book as well. The generous time volunteered by numerous reviewers is much appreciated. We also thank C. Gross for assistance with the cover art, L. Gründler for assistance with the index and editing, and S. Perrin for assistance with the references and editing. Finally, assistance from E. Kiddle, Z. Pruce, S. Ramamoorthy, and T. Kornak from the Cambridge University Press office and copy-editing teams is much appreciated.