# EXPLORATION OF THE SOLAR SYSTEM BY INFRARED REMOTE SENSING

This book describes all aspects of the theory, instrumental techniques, and observational results of the remote sensing of objects in our Solar System through studies of infrared radiation. Fully revised since publication of the first edition in 1992, it now incorporates the latest technologies, new mission results, and scientific discoveries. It also includes a fully up-dated list of references to reflect the advances made in this field during the past ten years.

The theories of radiative transfer, molecular spectroscopy, and atmospheric physics are first combined to show how it is possible to calculate the infrared spectra of model planetary atmospheres. Next the authors describe the instrumental techniques, in order to assess the effect of real instruments on the measurement of the emerging radiation field. Finally, techniques that allow the retrieval of atmospheric and surface parameters from observations are examined. There are plenty of examples from ground-based and space observations that demonstrate the methods of finding temperatures, gas compositions, and certain parameters of the solid surface. All planets from Mercury to Pluto, many of their satellites, asteroids, and comets are discussed.

The presentation will appeal to advanced students and professional planetary science researchers, although some chapters are of wider interest. The authors have drawn on their extensive experience at the NASA–Goddard Space Flight Center to produce a definitive account of what can be learned from infrared studies of our planetary system.

RUDOLF HANEL worked at the Goddard Space Flight Center for 31 years where he served as Principal Investigator on missions around Earth (Tiros, Nimbus), Mars (Mariner 9), and the outer planets (Voyagers 1 and 2). During this time he published over 100 scientific papers and book chapters, and was the recipient of numerous prestigious awards including the G. P. Kuiper Award of the Planetary Division of the American Astronomical Society.

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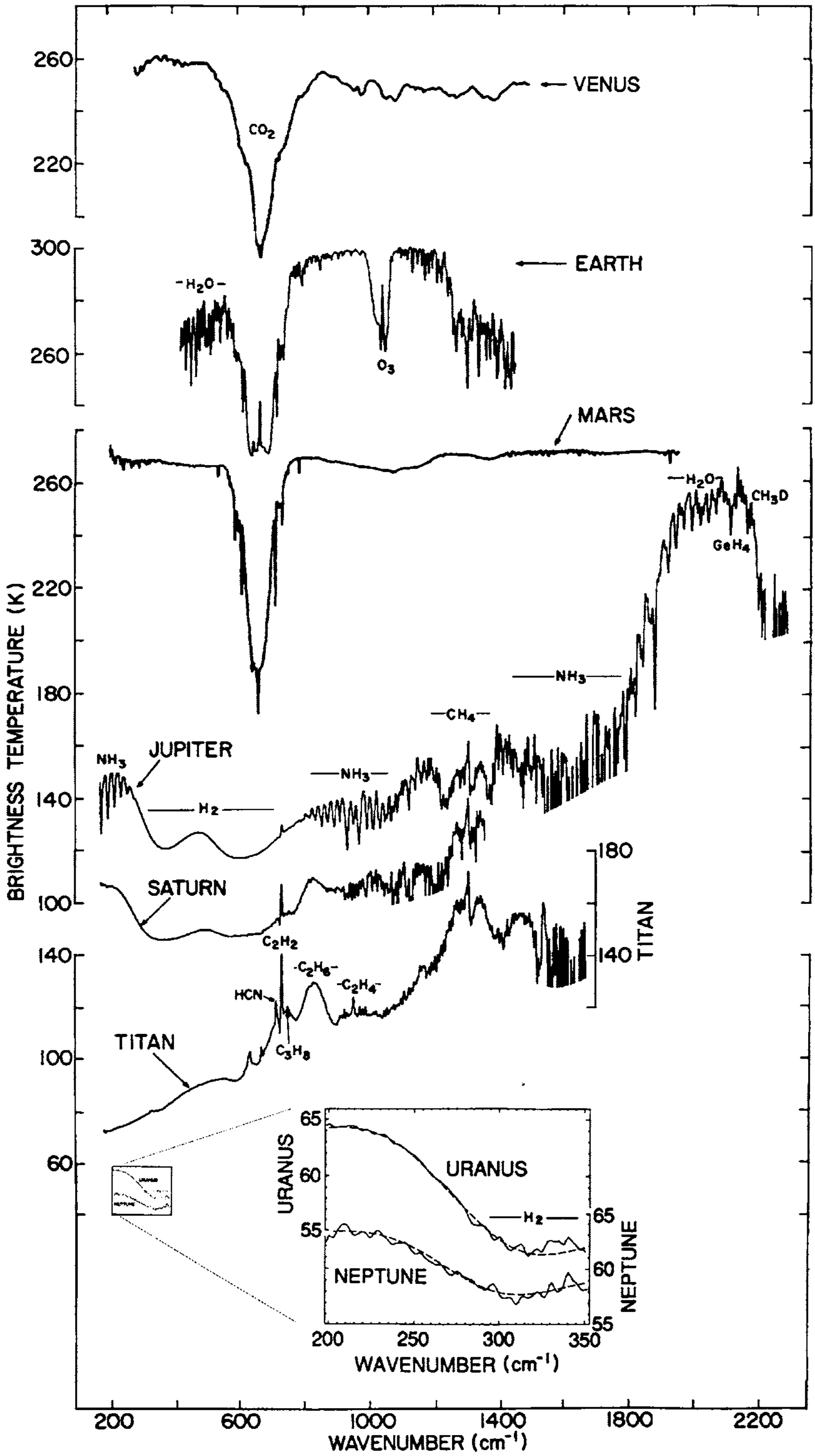
DONALD JENNINGS has worked at the Goddard Space Flight Center since 1977 in the area of infrared spectroscopy; developing and using a variety of spectrometers to study atmospheres of planets, the Sun, and stars. His research has ranged from examining molecules in the laboratory to measuring the infrared glow of the Space Shuttle and he is presently Instrument Scientist for the Composite Infrared Spectrometer on the Cassini mission to Saturn.

ROBERT SAMUELSON was a research scientist at the Goddard Space Flight Center for 39 years and is presently a research associate with the Astronomy Department at the University of Maryland. His specialities include radiative transfer in scattering atmospheres and the interpretation of radiometric and spectroscopic data from ground-based and space-borne infrared instruments. He is a co-investigator for the Cassini Orbiter infrared spectrometer and the Huygens Probe aerosol collector/pyrolizer experiment.




Examples of infrared spectra of the planets (except Mercury and Pluto) and of Titan recorded by Michelson interferometers on Venera, Nimbus, Mariner 9, and Voyager.

# EXPLORATION OF THE SOLAR SYSTEM BY INFRARED REMOTE SENSING

Second edition

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# Contents

# Introduction to first edition

The advent of spaceflight has ushered in a new era of Solar System exploration. Man has walked on the Moon and returned with soil samples. Instrumented probes have descended through the atmospheres of Venus and Mars. The Mariner, Pioneer, Venera, Viking, and Voyager space flight programs have provided opportunities to study the planets from Mercury to Neptune and most of the satellites. Remote sensing investigations have been conducted with unprecedented spatial and spectral resolutions, permitting detailed examinations of atmospheres and surfaces. Even for the Earth, space-borne observations, obtained with global coverage and high spatial, spectral, and temporal resolutions, have revolutionized weather forcasting, climate research, and the exploration of natural resources.

The collective study of the various atmospheres and surfaces in the Solar System constitutes the field of comparative planetology. Wide ranges in surface gravity, solar flux, internal heat, obliquity, rotation rate, mass, and composition provide a broad spectrum of boundary conditions for atmospheric systems. Analyses of data within this context lead to an understanding of physical processes applicable to all planets. Once the general physical principles are identified, the evolution of planetary systems can be explored.

Some of the data needed to address the broader questions have already been collected. Infrared spectra, images, and many other types of data are available in varying amounts for Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, Neptune, and many of their satellites. It is now appropriate to review and assess the techniques used in obtaining the existing information. This will not only provide a summary of our present capabilities, but will also suggest ways of extending our knowledge to better address the issues of comparative planetology and Solar System evolution.

Remote sensing is an interdisciplinary task. Theories of radiative transfer, molecular quantum mechanics, atmospheric physics, photochemistry, and planetary geology overlap with the design of advanced instrumentation, complex data processing, and a wide range of analysis methods. The purpose of this book is to bring many of these disciplines together with emphasis on the acquisition and interpretation of thermal infrared data. We address the advanced student and active researcher in the field. It is our intent to examine the basic principles in some depth. To meet this goal we strive to develop a consistent and essentially self-contained review. It is necessary to be highly selective in choosing illustrative cases because the development of each is fairly complex.

Although some *in situ* measurements have been made, planetary investigations have largely been restricted to remote sensing of emitted and reflected radiation. Planets emit most of their thermal radiation in the middle and far infrared while reflected sunlight dominates their visible and near infrared spectra. Planetary spectra, recorded from orbiting or fly-by spacecraft, make it possible to simultaneously obtain good horizontal and vertical resolutions of both atmospheric composition and thermal structure. These quantities and their gradients lead to a description of energetic and dynamical processes characteristic of each atmosphere. High resolution images at visible and infrared wavelengths display cloud patterns, which manifest this dynamical activity and provide highly complementary information to the spectral data. Ground-based astronomy has contributed additional information, with the significant advantage of providing observations over relatively long time spans.

Emitted and reflected radiation fields can be regarded as coded descriptions of planetary atmospheres and surfaces. Radiative transfer theory provides a means of transforming the codes into intelligible terms. This approach requires an understanding of electromagnetic radiation and its interaction with matter. Chapters 1 through 3 are directed towards these ends. A review of Maxwell's equations, wave propagation, polarization, reflection, refraction, and the Planck function is undertaken in Chapter 1. In Chapter 2 the equation of radiative transfer is derived in a form suitable for remote sensing from space, and various solutions of the transfer equation are obtained. In Chapter 3 we examine the interaction of radiation with matter. Quantum mechanical concepts, the principles of vibrational and rotational spectra, and other tools necessary to understand planetary spectra are developed. Investigation of matter in condensed phases – solid surfaces, ice crystals, and liquid droplets – requires an understanding of the emission and reflection of radiation at surfaces characterized by a complex index of refraction and such topics as the Mie theory.

With the tools developed in Chapters 1 through 3, it is possible to construct models of the emission and reflection of gas layers over a solid surface. Such models, with increasing complexity, including scattering, are the subject of Chapter 4. However, it is impossible to separate a study of planetary systems by remote sensing from the instruments which record the data. Inferences of atmospheric and surface parameters require the analysis of observed spectra, which have been subjected to modifications characteristic of the instruments used. In Chapter 5 we consider concepts of remote sensing instruments. The discussion of certain principles and techniques is supplemented with specific examples of instruments, such as the Thematic Mapper and the Voyager infrared spectrometer. Special attention is given to radiometric calibration. Examination of scientific objectives and instrumental techniques leads to a discussion of trade-offs between spatial and spectral resolution, signal-to-noise ratio, data rate, and other parameters.

In Chapter 6 we consider instrumental effects, such as spectral resolution and signal-to-noise ratio, and discuss data from the terrestrial and the giant planets in a qualitative manner. In Chapter 7 we examine methods for interpreting spectroscopic and radiometric data produced by real instruments in terms of physical properties of atmospheres and surfaces. Emphasis is placed on the retrieval of thermal structure, gas composition and cloud properties of the atmospheres, and thermal properties and texture of surfaces. Limitations on the information content inherent in measured quantities are assessed.

In Chapter 8 we associate measured quantities with the underlying physical processes. The connection between thermal equilibrium and the vertical temperature profile is investigated. Dynamical regimes are explored with emphasis on wind fields and circulations. Certain aspects of Solar System composition, internal heat sources, and the concept of global energy balance are discussed in the context of planetary evolution.

In Appendix 1 we list some of the properties of vectors and mathematical functions used in the text. Important physical constants are listed in Appendix 2. The most important planetary and satellite parameters, such as dimensions and composition, are summarized in Appendix 3.

Throughout the book we adopt the International System (SI), with the basic units of meter, kilogram, second, ampere, mole, and kinetic temperature (kelvin). However, we make exceptions in deference to common usage. For example, in atmospheric physics and specifically in meteorology the bar and millibar are firmly entrenched in the literature as units of pressure; we retain these here. The corresponding SI unit, the pascal (newton per square meter, or N $m^{-2}$), which equals $10^{-5}$ bar, is only slowly gaining acceptance in the planetary literature.

The SI unit of intensity, the candela, is defined (1985) as the luminous intensity in a given direction of a source that emits at $540 \times 10^{12}$ hertz (Hz) and has a radiant intensity in that direction of 1/683 watt per steradian (W $sr^{-1}$). Although the candela should be a convenient unit in the discussion of radiative processes, it is not used in planetary astronomy or in the field of remote sensing. Hence we follow tradition and express the spectrally integrated intensity in W $cm^{-2}$ $s^{-1}$; the spectral intensity itself is then expressed in W $cm^{-2}$ $sr^{-1}/cm^{-1}$ (we prefer to retain this explicit expression rather than use the equivalent term W $cm^{-1}$ $sr^{-1}$). The term spectral radiance is synonymous with specific or spectral intensity.

Another exception concerns the units of wavenumber and wavelength. Radio astronomy is a rather modern branch of science and has easily adopted the SI (e.g., flux in W m$^{-2}$), while spectroscopy is an old discipline of physics. The roots of spectroscopy lie deep in the nineteenth century, when the Gaussian system ruled with the centimeter as the unit of length. The common spectroscopic unit of wavenumber is, therefore, cm$^{-1}$; wavelength is usually measured in $\mu$m. We follow that tradition.

In writing this book the authors gained from numerous discussions with many colleagues and friends. Several have made specific comments on the manuscript. We would like to acknowledge contributions from W. Bandeen, G. Birnbaum, R. Born, M. Flasar, P. Gierasch, G. Hunt, T. Kostiuk, V. Kunde, J. Mangus, J. Mather, J. Pearl, and D. Reuter. J. Guerber and L. Mayo helped with computer programming. We also appreciate the encouragement and patience of the editor S. Mitton and his staff at Cambridge University Press.

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We also thank the authors for making this material available.

# Introduction to second edition

Since the first edition of this book appeared in print, infrared observations have been responsible for a number of significant new results from many objects in the Solar System. Besides highly sophisticated ground-based measurements, instruments on space probes such as Galileo, Mars Global Surveyor, Vega, Giotto, Phobos-2, the Infrared Space Observatory, and others have produced new data leading to interesting conclusions. Even the spectacular impact of comet Shoemaker–Levy 9 yielded unique information on the atmosphere of Jupiter as well as on the structure of comets. More refined analyses of older data sets have also contributed new insight.

Clearly, an identical reprint of the first edition would have been out of date. To bring the book up to the present state of the art it was necessary to incorporate the latest results. Although discussion of the Solar System bodies has been broadened by including Pluto, comets, and asteroids, the basic format and structure of the book has been preserved. The first four chapters, dealing primarily with fundamental aspects, radiative transfer theory, molecular physics, and modeling of atmospheric spectra, have not been affected by new information. Only minor changes have been made to the text, in some cases to correct errors, in others to clarify certain points. The latest results have been added primarily to Chapters 5 through 9. Some new instrumental techniques needed to be included. More recent information on atmospheric composition and structure had to be compared to older results. Although the Galileo probe data are *in situ* measurements, the composition of the Jovian atmosphere cannot be treated without referring to them. Therefore, we made an exception and included results from the helium-to-hydrogen detector and the mass spectrometer along with the remote sensing information. A new chapter (7) dealing with trans-Neptunian objects and asteroids has been inserted. In some cases, the treatment of earlier work was shortened to make room for interesting newer findings.

We are grateful to Dr Heidi Hammel and her colleagues at the Massachusetts Institute of Technology, who have used the first edition as part of a course. They have pointed out errors, misprints, and several areas where changes might benefit the reader. We thank also other reviewers for their suggestions. Again, we would like to thank authors, editors, and publishers for permission to use recently published figures. We also appreciate the support and patience of S. Mitton and his staff at Cambridge University Press.

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