SPECTRAL IMAGING OF THE ATMOSPHERE

Volume 82

Gordon G. Shepherd

ELSEVIER

Spectral Imaging of the Atmosphere

This is Volume 82 in the
INTERNATIONAL GEOPHYSICS SERIES

A series of monographs and textbooks
Edited by RENATA DMOWSKA, JAMES R. HOLTON and H. THOMAS ROSSBY

A complete list of books in this series appears at the end of this volume

Spectral Imaging of the Atmosphere

Gordon G. Shepherd

Centre for Research in Earth and Space Science,
York University, Toronto, Canada

ACADEMIC PRESS

An Elsevier Science Imprint

Amsterdam Boston London New York Oxford Paris
San Diego San Francisco Singapore Sydney Tokyo

This book is printed on acid-free paper.

Academic Press
An Imprint of Elsevier Science
84 Theobald's Road, London WC1X 8RR, UK
http://www.academicpress.com

Academic Press
An Imprint of Elsevier Science
525 B Street, Suite 1900, San Diego, California 92101-4495, USA
http://www.academicpress.com

ISBN 0-12-639481-4

Library of Congress Catalog Number: 2002107237

A catalogue record for this book is available from the British Library

Typeset by Newgen Imaging Systems (P) Ltd., Chennai, India
Printed and bound in Great Britain by MPG Books Limited, Bodmin, Cornwall

02 03 04 05 06 07 MP 9 8 7 6 5 4 3 2 1

DEDICATED TO IRENE AND GEORGE SHEPHERD

in memory of their unfailing love and encouragement

Who has seen the Wind?
Neither you nor I:
But when the trees bow down their heads,
The wind is passing by.

Christina Rossetti (1830–1894)

“Here was the least common denominator of nature, the skeleton requirements simply, of land and sky – Saskatchewan prairie. It lay wide around the town, stretching tan to the far line of the sky, shimmering under the June sun and waiting for the unfailing visitation of wind, gentle at first, barely stroking the long grasses and giving them life; later, a long hot gusting that would lift the black topsoil and pile it in barrow pits along the roads, or in deep banks against the fences.”

“High above the prairie, platter-flat, the wind wings on, bereft and wild its lonely song. It ridges drifts and licks their ripples off; it smoothens crests, piles snow against the fences. The tinting green of Northern Lights slowly shades and fades against the prairie nights, dying here, imperceptibly reborn over there.”

Who Has Seen the Wind
W.O. Mitchell (1914–1998)

CONTENTS

PREFACE

This book is the result of a career spent talking to fellow scientists about atmospheric instruments, and working with colleagues in my own laboratory to conceive, propose, design, build, launch and operate atmospheric spectral imagers. For large space projects this has also involved international collaborations, and working closely with colleagues in industry and in government. The period of data collection is followed by data analysis, validation, software revision and the final scientific analysis, all of which leads to further understanding of the instrument. To all of the individuals involved in these activities I am indebted for the ideas shared over the years. While not all can be named, many are identified in the text but for some I wish to describe their contributions more specifically. In particular I am grateful to my M.Sc. and Ph.D. research supervisors, Donald Hunten and the late Harry Welsh respectively for starting me off in a favourable direction.

Herbert Gush and I worked in the same laboratories on our B.Sc., M.Sc. and Ph.D. degrees. We then went separate ways, he to a PDF in Pierre Jacquinot's Laboratoire Aimé Cotton, and I back to the University of Saskatchewan. Herb made me aware of what was happening in France, and made the contact that led to the visit of Robert Chabbal to Saskatoon in 1958. That visit led to the first Fabry–Perot spectrometers built there, but it was my own visit to this laboratory in 1961 where I met Ové Harang and Pierre Connes working on a field-widened Michelson interferometer that expanded my horizons much further. All of this contributed to the conceptual approach which I still follow.

In the early years at the University of Saskatchewan it was the students who built the instruments, John Nilson, Ted Turgeon, Alan Bens, Leroy Cogger, Steve Peteherych, Ken Paulson, Bill Lake, Ronald Hilliard and Harold Zwick. It was also the students there who led to the first course that I taught on this subject.

Later, at York University, where this volume had its origins, I initially elicited the help of various individuals in writing the original chapters. Rick Gerson wrote the original array detector section of Chapter 4, later extended by Stoyan Sargoytchev, with a contribution from Erik Griffioen. Rudy Wiens wrote the beginning of Chapter 5, with contributions from Bob Peterson and Fadia Bahsoun-Hamade. Bill Gault wrote the orginal version of Chapter 6, little changed from its original form. Bill is the individual with whom I have had the longest association, and with whom I have shared more ideas than any other individual named. Recent course students, Jeffrey Czapla-Myers, David Babcock, Jacob Petersen and Gina Infante contributed to a revised Chapter 7 while former students John Bird and Susan McCall contributed to Chapter 8. Charlie Hersom wrote the first WINDII description with additions by Brian Solheim in Chapter 9, while Stephen Brown contributed to the ERWIN description in the same chapter. The descriptions of the new instruments, MIMI and SWIFT, in Chapter 10 were taken from material by Bill Gault and Reza Mani of York University, William Ward of the University of New Brunswick, Yves Rochon of the Meteorological Service of Canada and Neil Rowlands, Alan Scott and Gary Buttner of EMS Technologies. However, I have made many revisions in the material provided to me and take full responsibility for any misconceptions or errors that may have been introduced in the process.

My latest course students tested all of the problems; Bernard Firanski, Itamar Gabor, Craig Haley, Young-Sook Lee, Guiping Liu, Peyman Rahnama and Peter Ryan. Individual chapters, or parts of chapters, were tested on several colleagues; Ian McDade, Christian von Savigny, John Miller, Neil Rowlands, Leroy Cogger, Gonzalo Hernandez, Bill Gault, Fred Taylor, Brian Solheim, Aidan Roche, Peter Bernath, Herbert Fisher and Abas Sivjee. Again, I am responsible for the remaining deficiencies. Two others to whom I am greatly indebted for many hours of helpful discussion are Paul Hays and Raymond Roble.

Most of all, I am deeply grateful to Marianna Shepherd for her patience, encouragement and support during the many years the work was in progress.

Many of my conversations have been with graduate students, so that is the level to which this work is primarily directed; however, it is planned to be accessible to upper year undergraduates with some knowledge of optics, and the problems are designed with them in mind. It also may be used as a reference work, as the chapters need not be read in sequence, and I hope that the long accumulation of references will prove generally valuable to researchers.

I would like to thank the initial and final Senior Editors, Gioia Ghezzi and Frank Cynar, and the Production Project Manager Sutapas Bhattacharya for their consistent encouragement and support.

1

OBSERVING ATMOSPHERIC RADIATION

1.1 ATMOSPHERIC RADIATION

Winter or summer, day or night, above the Earth or on the ground, one is bathed in atmospheric radiation, comprising ultraviolet, visible and infrared light in the region of the electromagnetic spectrum, lying roughly between 30 nm and 100 μm in wavelength. The sources and processes involved in producing this radiation environment are illustrated in Figure 1.1; in this chapter they are briefly reviewed along with the framework within which this radiation is observed. The ultimate source of the observed radiation is the sun, so it is the logical place to begin. It is the brightest object in the sky, so much so that it cannot be viewed directly by eye. From its effective temperature T of 5780 K the Stefan–Boltzmann law, $E = \sigma_{SB}T^4(\sigma_{SB} = 5.67 \times 10^{-8}\ \mathrm{W\,m^{-2}\,K^{-4}})$, yields an irradiance $E = 6.33 \times 10^{7}\ \mathrm{W\,m^{-2}}$. This is the total power radiated from each square metre on the solar surface. The monochromatic solar irradiance E_λ, the irradiance as a function of wavelength λ as approximated by a black body with $T = 5780$ K is shown in Figure 1.2; this is called a spectrum. The integrated irradiance E, just introduced, is the integral over this spectrum. The spectrum of a 300 K blackbody representing the outgoing radiation from the Earth (multiplied by 10^6) is shown in the same figure; this is discussed later. For the wavelength range shown, the solar spectrum is sharply peaked, with the wavelength λ_{max} of the peak given by Wien's displacement law, $T\lambda_{max} = 2897\ \mu\mathrm{m\,K}$, or for $T = 5780$ K, $\lambda_{max} = 0.501\ \mu\mathrm{m}$, just as shown in the figure.

The spectra of Figure 1.2 are misleading in terms of the energy distribution because λ is inversely proportional to the photon energy; for this reason it is often preferable to present the spectrum as a function of $(1/\lambda)$, which is the number of waves per unit length, called the wavenumber, σ. In fact it is more complicated than this because wavelengths are normally what is measured, in air, while spectroscopists prefer a universal standard, and so define wavenumbers as in vacuum. The correct conversion thus involves the index of refraction of air, but this minor complication is ignored throughout this work. The spectra of Figure 1.2 are shown as a function of wavenumber in $\mathrm{cm^{-1}}$ in Figure 1.3. On this scale the Earth's

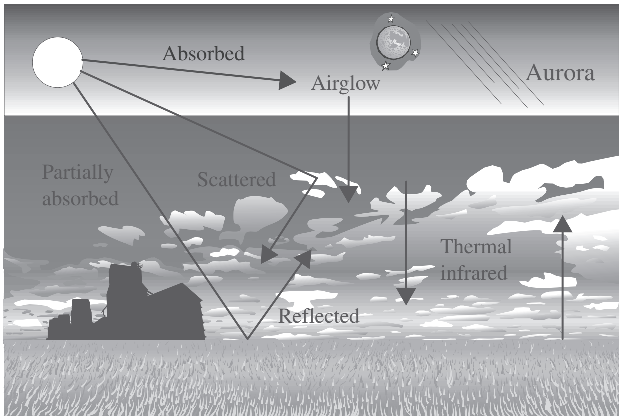

Figure 1.1. Illustrating sky radiation observable through spectral imaging.

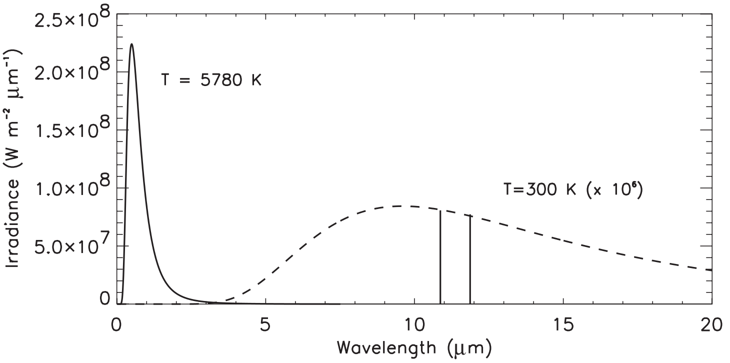

Figure 1.2. The monochromatic irradiance of a 5780 K black body, representative of the sun, and a 300 K black body, representative of the Earth, with the latter multiplied by 10^6. The vertical lines are separated by 1 μm; the interval is centred at 11.37 μm.

spectrum becomes narrow and the solar spectrum is broad which, as noted, reflects more correctly the energy distributions involved.

The monochromatic irradiances shown in Figure 1.2 and Figure 1.3 must specify the spectral interval over which the irradiance corresponds. In Figure 1.2 the interval used is 1 μm, so that the irradiance units are W m^{-2} μm^{-1}. For illustration, a spectral interval of 1 μm centred at 11.37 μm is shown in Figure 1.2, which means that the corresponding value of 7.8×10^7 W m^{-2} is radiated over this wavelength interval. For Figure 1.3 the spectral interval used is 1 cm^{-1}, and for clarity the units are shown as W m^{-2}(cm^{-1})$^{-1}$. While the author's objective is to use SI (System International) units, based on MKS, throughout, the use of cm^{-1} for spectroscopy is so deeply rooted it cannot normally be avoided, even in this work. Because most spectral imaging instruments use photon detectors it is often