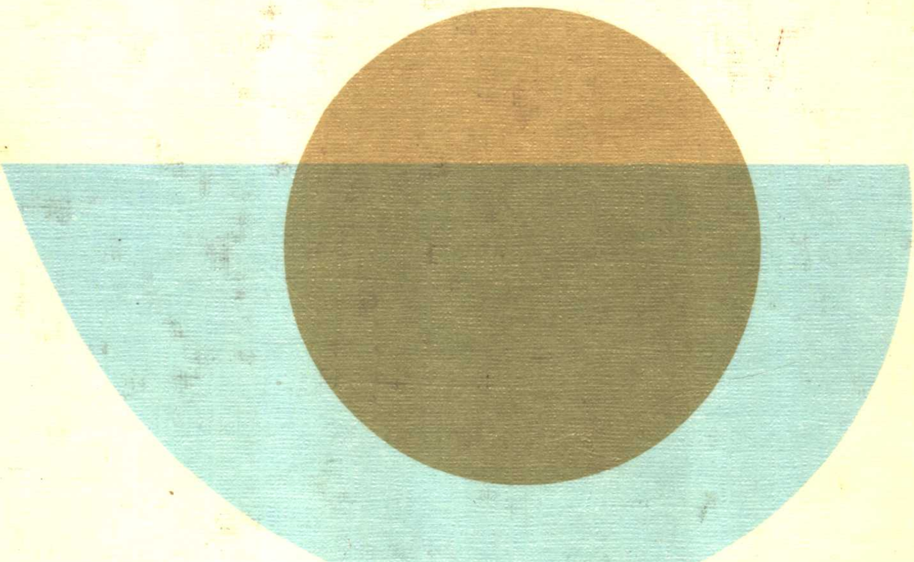
Geophysics and Astrophysics Monographs

# Physics of the Sun

Edited by P. A. Sturrock, T. E. Holzer,
D. M. Mihalas, and R. K. Ulrich

Volume II: The Solar Atmosphere



D. Reidel Publishing Company

# PHYSICS OF THE SUN

## Volume II: The Solar Atmosphere

*Edited by*

PETER A. STURROCK
*Center for Space Science and Astrophysics, Stanford University, Stanford, California, U.S.A.*

*Associate Editors:*

THOMAS E. HOLZER
*High Altitude Observatory, National Center for Atmospheric Research, Boulder, Colorado, U.S.A.*

DIMITRI M. MIHALAS
*High Altitude Observatory, National Center for Atmospheric Research, Boulder, Colorado, U.S.A.*

ROGER K. ULRICH
*Astronomy Department, University of California, Los Angeles, California, U.S.A.*

D. REIDEL PUBLISHING COMPANY

A MEMBER OF THE KLUWER ACADEMIC PUBLISHERS GROUP

DORDRECHT / BOSTON / LANCASTER / TOKYO

**Library of Congress Cataloging-in-Publication Data**

Main entry under title:

Physics of the sun.

(Geophysics and astrophysics monographs)
Includes bibliographies and index.
Contents: v. 1. The solar interior – v. 2. The solar atmosphere.
1. Sun. I. Sturrock, Peter A. (Peter Andrew). II. Series.
GB521.P48 1985 559.9'4 85-20996
ISBN 90-277-1823-7 (set)
ISBN 90-277-1860-1 (v. 1)
ISBN 90-277-1861-X (v. 2)

---

Published by D. Reidel Publishing Company,
P.O. Box 17, 3300 AA Dordrecht, Holland.

Sold and distributed in the U.S.A. and Canada
by Kluwer Academic Publishers
190 Old Derby Street, Hingham, MA 02043, U.S.A.

In all other countries, sold and distributed
by Kluwer Academic Publishers Group.
P.O. Box 322, 3300 AH Dordrecht, Holland.



Printed in the Netherlands

# PREFACE

This volume, together with its two companion volumes, originated in a study commissioned by the United States National Academy of Sciences on behalf of the National Aeronautics and Space Administration. A committee composed of Tom Holzer, Dimitri Mihalas, Roger Ulrich and myself was asked to prepare a comprehensive review of current knowledge concerning the physics of the sun. We were fortunate in being able to persuade many distinguished scientists to gather their forces for the preparation of 21 separate chapters covering not only solar physics but also relevant areas of astrophysics and solar-terrestrial relations.

In proved necessary to divide the chapters into three separate volumes that cover three different aspects of solar physics. Volumes I and III are concerned with "The Solar Interior" and with "Astrophysics and Solar-Terrestrial Relations." This volume, devoted to "The Solar Atmosphere," covers not only the chromosphere and corona but also the principal phenomena usually referred to as "solar activity." The emphasis is on identifying and analyzing the relevant physical processes, but each chapter also contains a great deal of descriptive material.

In preparing our material, the authors and editors benefited greatly from the efforts of a number of scientists who generously agreed to review individual chapters. I wish therefore to take this opportunity to thank the the following individuals for this valuable contribution to our work: S. K. Antiochos, E. H. Avrett, J. N. Bahcall, C. A. Barnes, G. Bicknell, D. Black, M. L. Blake, P. Bodenheimer, F. H. Busse, R. C. Canfield, T. R. Carson, J. I. Castro, J. Christensen-Dalsgaard, E. C. Chupp, A. N. Cox, L. E. Cram, P. R. Demarque, L. Fisk, W. A. Fowler, D. O. Gough, L. W. Hartmann, J. W. Harvey, R. F. Howard, P. Hoyng, H. S. Hudson, G. J. Hurford, C. F. Kennel, R. A. Kopp, A. Krueger, R. M. Kulsrud, R. B. Larson, H. Leinbach, R. E. Lingenfelter, J. L. Linsky, D. B. Melrose, M. J. Mitchell, A. G. Newkirk, F. W. Perkins, R. Roble, R. T. Rood, R. Rosner, B. F. Rozsynai, S. Schneider, E. C. Shoub, B. Sonnerup, H. Spruit, R. F. Stein, M. Stix, J. Tassoul, G. Van Hoven, G. S. Vaiana, A. H. Vaughan, S. P. Worden, R. A. Wolf, and J. B. Zirker.

On behalf of the editors of this monograph, I wish to thank Dr. Richard C. Hart of the National Academy of Sciences, Dr. David Larner of Reidel Publishing Company, and Mrs. Louise Meyers of Stanford University, for the efficient and good-natured support that we received from them at various stages of the preparation of this volume.

*Stanford University, June, 1985* P. A. STURROCK

# TABLE OF CONTENTS

PREFACE xi

CHAPTER 8: Radiation Output – R. G. ATHAY 1
1. Introduction 1
2. Basic Concepts and Definitions 4
2.1. Formation of Spectra 4
2.2. Energy Balance 5
2.3. Notation 6
2.4. Escape Probability and Scattering Depth 6
2.5. Escape Coefficient 7
2.6. Creation and Destruction Probabilities 8
2.7. Thermalization and Degradation Lengths 9
2.8. Intra-Atmosphere Exchange Probability 10
2.9. The Source Function 10
2.10. The Transfer Equation 11
3. Spectral Diagnostics 14
3.1. Temperature Diagnostics 14
3.2. Density Diagnostics 16
3.3. Velocity and Magnetic Field Diagnostics 18
3.4. Abundance Diagnostics 20
4. The Role of Radiation in Determining Atmospheric Properties 22
4.1. Photosphere 22
4.2. Line Blanketing and Cooling 24
4.3. The Chromosphere 27
4.4. Characteristics of Chromosphere Radiation Loss 30
4.5. Temperature Minimum 33
4.6. The First Temperature Plateau 34
4.7. The Second Temperature Plateau 35
4.8. The Transition Region 36
4.9. The Corona 37
5. Nonradial Structure 39
5.1. Fluid Motions and Magnetic Fields 39
5.2. Photosphere and Temperature Minimum Region 40
5.3. Chromosphere and Transition Region 41
5.4. Corona 43
6. Temporal Fluctuations 44
7. Challenges for the Future 45
7.1. Radiation Diagnostics 45
7.2. Influence of Radiation on Atmospheric Properties 46
7.3. Observations 47

References 48

CHAPTER 9: Chromospheric Fine Structure – R. G. ATHAY 51
1. Introduction 51
1.1. Role of Fine Structure 51
1.2. Definition of Fine Structure and the Observational Challenge 52
2. Properties of Chromospheric Structure 54
2.1. Network and Supergranule Cells 54
2.2. Network Coarse and Fine Structure 58
2.3. Supergranule Cell Structure 60
2.4. Active Region Structure 61
3. Velocity and Magnetic Structure 61
3.1. Magnetic Structure 61
3.2. Velocity Structure 64
4. Magnetohydrodynamic Structure 65
4.1. A New Look at Fine Structure 65
4.2. Lifting Forces 66
5. Major Problems 67
5.1. Energy Balance 67
5.2. Momentum Balance 68
5.3. The Sun as a Star 68
References 68

CHAPTER 10: Structure, Dynamics, and Heating of the Solar Atmosphere – GERALD W. PNEUMAN and FRANK Q. ORRALL 71
1. Introduction 71
2. Basic Theory and Processes 71
3. Overall Atmospheric Structure 75
4. The Chromosphere–Corona Transition Region and the Base of the Inner Corona 77
4.1. Introduction 77
4.2. Empirical Models of the Mean Temperature Structure 78
4.3. Inhomogeneous and Dynamic Structure of the Transition Shell 80
5. Closed Coronal Regions 82
5.1. Basic Structure 82
5.2. Phenomenology of Coronal Loops 83
5.3. Quasistatic Loop Models in Energy Balance 84
5.4. Evolution and Stability 86
5.5. Systematic Flow 88
5.6. Heating 88
6. Open Coronal Regions and the Coronal Expansion into Interplanetary Space 91
6.1. Introduction 91
6.2. The Solar Wind 91
6.3. Magnetic Fields in the Solar Wind 94
6.4. Coronal Holes 96

6.5. Coronal-Interplanetary Modeling 99
7. Coronal Streamers: Gas-Magnetic Field Interactions in the Solar Corona 100
8. Coronal Activity 105
8.1. The Prominence Phenomena 105
8.1.1. Quiescent Prominences 107
8.1.2. Prominence Support 109
8.1.3. Prominence Stability: Disparition Brusques 111
8.2. Solar Flares 112
8.2.1. Two-Ribbon Flares 113
8.2.2. Compact Flares 117
8.3. Impulsive Flows 118
8.3.1. Surges 118
8.3.2. Sprays 119
8.3.3. Coronal Whips 120
8.4. Coronal Transients 120
References 125

CHAPTER 11: Physical Processes in the Solar Corona – R. ROSNER, B. C. LOW, and T. E. HOLZER 135
1. Introduction 135
2. Transport Theory 136
2.1. Fundamental Parameter Regimes 136
2.2. The 'Ideal' Problem 138
2.3. Viscosity 139
2.4. Parallel Thermal Energy Transport 140
2.5. Perpendicular Transport 144
2.6. Some Comments on Model Building 145
3. Magnetohydrodynamic Processes in the Corona 147
3.1. Equilibrium Magnetic Fields 148
3.2. Linear Stability and Nonequilibrium 153
3.3. Time-Dependent Phenomena 161
3.4. Discussion 167
4. Energy and Momentum Balance of Open and Closed Coronal Structures 169
4.1. Coronal Holes and High-Speed Streams 169
4.2. Alfvén Waves in the Lower Solar Atmosphere 169
4.3. Energy Supply to Magnetically Closed Coronal Regions 175
Acknowledgement 176
References 176

CHAPTER 12: Magnetic Energy Storage and Conversion in the Solar Atmosphere – D. S. SPICER, J. T. MARISKA and J. P. BORIS 181
1. Introduction 181
2. Fundamental Concepts 186
2.1. Magnetic Energy Generation 187
2.2. Ideal MHD Theory 189
2.3. Non-MHD Properties 192

2.4. The Concept of 'Anomalous' Resistivity 195
2.5. Global Electrodynamic Coupling 198
3. Magnetically Controlled Energy Conversion 204
3.1. Magnetic Modifications of Plasma Transport 204
3.2. Transition Region Structure and Flows 206
3.3. Channeling and Acceleration of Plasma 209
3.4. Channeling and Dissipation of MHD Waves 210
3.5. Anomalous Dissipation of Field-Aligned Currents 213
4. Magnetohydrodynamic Energy Conversion 219
4.1. Magnetic Flux Tube Emergence 219
4.2. Geometric Rearrangements 222
4.3. Reconnection and Magnetic Tearing 226
4.4. Particle Acceleration at a Neutral Sheet 235
4.5. Flare Trigger Mechanisms 236
5. Outstanding Questions 240
Acknowledgements 243
References 244

CHAPTER 13: The Acceleration and Propagation of Solar Flare Energetic Particles – M. A. FORMAN, R. RAMATY, and E. G. ZWEIBEL 249
1. Introduction 249
2. Energetic Particles in Solar Flares 250
2.1. Electromagnetic Radiations 250
2.1.1. Radio Emissions 251
2.1.2. Hard X-Rays 251
2.1.3. Gamma Rays 253
2.2. Energetic Particles 256
2.2.1. Energy Spectra and Electron-Proton Correlations 256
2.2.2. Chemical Compositions 260
2.2.3. Isotopic and Ionic Compositions 263
3. Mechanisms of Solar Flare Particle Acceleration 264
3.1. Stochastic Acceleration 264
3.2. Shock Acceleration 272
3.3. Acceleration in Direct Electric Fields 277
4. Solar Flare Particle Spectra in Interplanetary Space 280
5. Summary and Outloop 284
Acknowledgements 285
References 285

CHAPTER 14: Nuclear Processes in Solar Flares – R. RAMATY 291
1. Introduction 291
2. Nuclear Reactions in Solar Flares 295
2.1. Interaction Models and Properties of the Energetic Particles 295
2.2. Neutron and 2.223 MeV Photon Production 299

2.3. Positron and 0.511 MeV Photon Production 304
2.4. Prompt De-Excitation Line Production 306
3. Implications of Gamma-Ray Observations 312
3.1. Interaction Model, Energetic Particle Spectrum, Number and Energy Content 313
3.2. Time Dependence 317
3.3. The Photospheric $^3$He Abundance 318
3.4. Beaming of the Energetic Particles 319
4. Summary 319
Acknowledgements 321
References 321

CHAPTER 15: Solar Radio Emission – MARTIN V. GOLDMAN and DEAN F. SMITH 325
1. Introduction 325
2. Observational Results 327
2.1. Type III Bursts 327
2.1.1. Ground-Based Observations (Above ~8 MHz) 327
2.1.2. Spacecraft Observations (Below 1 MHz) 331
2.1.3. Langmuir Waves and Electron Streams 334
2.2. Microwave Bursts 339
2.3. Type II Bursts 341
2.4. Moving Type IV Bursts 342
2.5. Type I Noise Storms 343
3. Theory of Type III Radio Bursts (Radio Emission from Electron Streams) 345
3.1. Overview 345
3.2. Quasilinear Theory 345
3.3. Induced Scatter Off Ions 348
3.4. Wave–Wave Effects of the Nonlinear Refractive and Self-Focusing Variety 349
3.5. Second Harmonic Emission from Langmuir Waves 351
3.6. Fundamental Emission from Langmuir Waves 354
3.7. Density Irregularities and Ion-Acoustic Waves 354
4. Radio Emission from Shock Waves and Current Sheets 355
4.1. Shock Configuration 355
4.2. Generation of Electron Streams by Shock Waves 358
4.3. Radiation Mechanisms 360
5. Radio Emission from Moving Plasmoids and Other Traps 361
5.1. Plasmoid and Other Trapping Configurations 361
5.2. Sources of Electrons in Plasmoids and Traps 364
5.3. Loss Cone and Collisional Electron Losses 366
5.4. Radiation Mechanisms 366
6. Conclusions and Recommendations 370
6.1. Type III Emissions 370
6.2. Type II Bursts 371

6.3. Moving Type IV Bursts 372
6.4. Type I Bursts 372
Acknowledgements 372
References 372
INDEX 377

CHAPTER 8

# RADIATION OUTPUT

R. G. ATHAY

## 1. Introduction

The following discussion of the Sun's radiation output is more in the nature of an essay than a review. Among the reasons for adopting such an approach are: (1) a balanced review would require more discussion than is appropriate for this volume; (2) the desired goal of the chapter is to focus attention on the nature and importance of the problems rather than describe the attempts to solve particular problems; and (3) current and rather extensive reviews already exist in such volumes as *The Solar Output and its Variations* (ed. O. R. White, 1977). *The Sun as a Star* (ed. S. Jordan, 1981), *Solar Flares* (ed. P. A. Sturrock, 1980), and *Solar Active Regions* (ed. F. Q. Orrall, 1981).

The topic of radiation output has many aspects ranging from the formalism of radiative transfer and diagnostic methods to the structure and energy balance of the solar atmosphere itself. The radiation not only carries in its spectral signature the information by which we diagnose the physical properties of the atmosphere but also a major role in determining certain of those physical properties. This chapter selects from the broad set of problems a subset that is representative of the problems currently undergoing active development. Because the selected topics are undergoing development, there are differences of opinion as to the methods and directions of development and as to the level of progress achieved.

The essay that follows is biased towards the author's point of view. Such bias is reflected in both the choice of topics and in the methods chosen to illustrate the nature of the problems.

Much work of current interest and many important historical developments are omitted from the following discussion. This is a regrettable but unavoidable restraint imposed by the conditions mentioned in the first paragraph.

Viewed from the perspective of the past 30 years, solar physics appears to be evolving from an essentially 'discovery mode' to what is better described as an 'understanding mode'. The discovery mode was characterized by exploratory observations in new regions of the spectrum and with new instrumental techniques for observing motions and magnetic fields. Virtually each new observing technique and each new spectral region revealed new phenomena and new aspects of previously known phenomena.

Most of the accessible spectrum has now been explored, and the rate of discovery of new phenomena appears to be slowing down. The rapid discovery of new phenomena over the past 30 years has impacted solar physics in many ways. Two of the more important

*Peter A. Sturrock (ed.), Physics of the Sun, Vol. II*, pp. 1–50.

impacts are represented on the one hand by the inescapable conclusion that the Sun is more complex than we had previously allowed ourselves to believe and, on the other hand, and perhaps more importantly, the growing conviction that we now have the potential to understand the physical processes involved in solar phenomena. These seemingly contradictory conclusions result from a newly recognized degree of order and correlation among solar phenomena that both restricts the range of plausible models and, in some cases, even suggests the nature of the model itself. It is the quest for understanding the basic physical processes and the attempts to build physical models that shape and motivate most of today's efforts in solar physics.

The effort to understand the physical processes involved in the diverse phenomena of the solar atmosphere requires that we determine the cospatial thermodynamic, velocity, and magnetic field structures together with their temporal evolution. In addition, we must be able to identify and quantify the major energy and momentum processes. Experience indicates that such a goal cannot be accomplished without a combination of precise observations coupled with careful diagnostics based on realistic physical models. For the most part, solar physics has outgrown its heyday when crude observations and zeroth-order interpretation could produce worthwhile new results.

One of the major current limitations in the study of solar phenomena is the lack of adequate spatial resolution. Abundant evidence indicates that many solar phenomena have spatial scales considerably smaller than the best resolution currently attainable. In XUV regions of the spectrum we are further limited by insufficient spectral and temporal resolution. These are engineering and resource problems and can be improved upon with new ground and space facilities such as the Solar Optical Telescope (SOT).

Increased precision in spectroscopic data must be accompanied, of course, by refined diagnostic techniques. Such refinement often requires more realistic physical models, which, in turn, are mostly likely to come from better and more complete observations. Thus, the prospect for improved diagnostics is closely coupled to the prospect for improved observations.

The diagnostic methods discussed in this chapter are based on plane-parallel models. However, considerable work has been done in multidimensional radiative transfer (cf. review by Jones and Skumanich, 1980; Rybicki, 1967; Avery and House, 1968; Jones and Skumanich, 1973; Cannon, 1973; Stenhölm, 1977), but more remains to be done, particularly in the case of diagnostics for application to data with high spatial resolution. Many of the important features of the solar atmosphere, such as magnetic flux tubes, granules, intergranular lanes, spicules and fibrils, have characteristic dimensions of an arcsec (725 km), or less. In all such features, the multidimensional structure plays an important role in determining their interaction with and their contributions to the emergent radiation field.

Parametric studies of multidimensional geometries (cf. review by Jones and Skumanich, 1980) demonstrate that photon transfer is governed primarily by the nearest 'border' (defined by optical distance). In a plane-parallel atmosphere, the nearest border is always in the vertical direction. However, in multidimensional media a discrete structure may have 'borders' in the horizontal directions that are much nearer than the borders in the vertical direction. In addition, a discrete structure may be irradiated by other nearby structures of quite different radiation properties. Thus the 'incident' radiation becomes an important factor in the problem.

Spectral diagnostics is a rather subtle art even for plane-parallel geometries. Additional and important complexities arise in multidimensional cases, and reliable diagnostics become even more subtle. The changes that occur, however, are more quantitative than qualitative. The following discussion of diagnostics for plane-parallel geometries should be regarded, therefore, as illustrative of the qualitative effects. Accurate, quantitative diagnostics of high-resolution data will very probably require the development of suitable diagnostics for multidimensional media.

One of the primary strengths of solar physics is the ability to resolve many of the structural features of the solar atmosphere. From our present perspective, it is clear that many important physical phenomena occur on scales that are a tiny fraction of the solar radius. In fact, the solar chromosphere and corona, as well as important phenomena of the photosphere, exhibit many aspects of highly localized gas dynamic and MHD phenomena, which, in turn, appear to play a fundamental, and perhaps controlling, role in determining even the large-scale physical properties of the atmosphere. This leaves solar physicists with no alternative but to attempt to achieve spatial resolution commensurate with the scale of the hydrodynamic and MHD phenomena.

The need in solar physics to pursue detailed, precise observations and to seek refined diagnostic methods beyond those normally used in astrophysics may appear to those uninitiated in solar physics as perhaps a loss of perspective or as a hindrance to rapid progress. However, without such details much of solar physics would merely stagnate on a shaky framework of unanswered questions, unsolved problems, and uncertain conclusions. It was the pursuit of unexplained details in line profiles by a number of workers following the pioneering work of Jeffries and Thomas (1958) that led to a workable formulation of non-LTE methods in radiative transfer. Subsequent refinements and additions to non-LTE diagnostics and their applications to solar and stellar problems have profoundly altered the conclusions derived from analysis of line profiles.

Similarly, it was the pursuit of details in solar magnetograph data by several workers that led finally to the conclusion that solar magnetic fields are mostly confined to small flux tubes with diameters of a fraction of an arcsecond, which is much below the resolution limit of the magnetographs. This surprising conclusion has totally reshaped the interpretation of solar magnetic field phenomena.

These are but two of many examples in solar physics where careful observations and careful attention to theoretical detail have overturned previous concepts and replaced them with radically new ones. The process is by no means complete. We are still forced to rely heavily on primitive concepts that are known to be inadequate or incorrect, but which represent the best we can do at the time. Diagnostic methods for velocity and magnetic fields are particular cases in point.

In the following discussion, it is necessary to omit much of the detail referred to above. The reader should bear in mind, however, that it is just these details in both observation and theory that provide the basis for progress.

Section 2 deals with some concepts and definitions in radiative transfer that are useful for subsequent discussion. Those already familiar with radiative transfer theory may wish to skip this rather elementary discussion. Section 3 discusses diagnostic methods and associated problems. Section 4 considers the role of radiation in determining the thermodynamic properties of the atmosphere. Sections 5 and 6 deal briefly with certain aspects of the nonradial structure of the atmosphere and the temporal fluctuations of the radiation output. These topics are discussed in broader context in other chapters of this volume. Finally, Section 7 contains some comments on future expectations and needs in solar physics.

## 2. Basic Concepts and Definitions

### 2.1. Formation of Spectra

With but few exceptions, quantitative studies of the Sun are dependent upon the interpretation of spectroscopic data. Whether such data are collected at radio, visual, or X-ray wavelengths, their interpretation rests upon our ability, first, to identify the process by which the radiation is produced, second, to interpret the radiation in terms of local plasma conditions at the place of origin, and, third, to organize the different plasma regimes observed at different wavelengths in proper relationship to each other.

To illustrate the problems involved in each of these steps, we consider a spectrum giving specific intensity $I_\lambda$ as a function of wavelength. We represent the functional dependence of the spectrum in the symbolic form:

$$I_\lambda(r_i, S_i, \varphi_{\lambda i}, \kappa_{0i}, \Delta z_i, \Delta\lambda, \Delta\theta, \Delta t),$$

where $r_i$ denotes the different radiation processes (usually two or more, such as line and continuum), $S_i$ denotes the source function for photons of species $i$, $\varphi_{\lambda i}$ is the absorption profile, $\kappa_{0i}$ is the absorption coefficient, $\Delta z_i$ denotes the spread in the line-of-sight distance within which the observed radiation originates and $\Delta\lambda$, $\Delta\theta$, and $\Delta t$, respectively, are spectral, spatial, and temporal resolution. The latter three quantities are instrumental parameters and, within limitations, are set by the observer. On the other hand, the five quantities $r_i$, $S_i$, $\kappa_{0i}$, $\varphi_{\lambda i}$, and $\Delta z_i$ are determined by the solar atmosphere, and these are the five quantities that convey most of the information about the atmosphere.

Even under optimum conditions for $\Delta\theta$ and $\Delta\lambda$, the radiation intensity $I_\lambda$ at a given value of $\lambda$ arises from a spread in distance that is often larger than the characteristic lengths for changes in thermodynamic, fluid dynamic, and magnetic field variables. This has the consequence that a given $I_\lambda$ cannot be unambiguously associated with specific values of such variables as temperature, fluid velocity, and magnetic fidle strength. Instead, one must interpret $I_\lambda$ in terms of a model atmosphere in which both the local plasma parameters and their gradients are given. To accomplish this, it is necessary to consider values of $I_\lambda$ over a number of different wavelengths with different representative values of $\Delta z$.

A further consequence of the inability to assign a unique value of $z$ to $I_\lambda$ is that the average value, $\langle z \rangle$, may depend upon the particular parameter extracted from $I_\lambda$. For example, there is no *a priori* reason for the value of $\langle z \rangle$ associated with a temperature inferred from the source function to correspond to that value of $\langle z \rangle$ associated with a fluid velocity inferred from $\varphi_\lambda$. Also, the value of $\langle z \rangle$ associated with a fluid velocity may be quite different from the $\langle z \rangle$ associated with a magnetic field intensity, even though both are inferred from $\varphi_\lambda$.

The preceding comments illustrate the inherent difficulty of properly organizing the plasma variables in terms of relative values of $z$. This, however, is only part of the problem. An equally, and perhaps more, difficult problem is in the complicated transport of photons through the atmosphere and the consequent complexity of the information content in $I_\lambda$. Although all of the photons in $I_\lambda$ can be represented as being emitted within the range $\Delta z$, it does not follow that the photon energy in $I_\lambda$ is extracted from the interval energy within $\Delta z$. In fact, much, and perhaps most, of the photon energy within $\Delta z$ may simply be a result of photons diffusing through the atmosphere, i.e. scattering. Scattering photons often react passively with the local plasma with no essential communication between the photon and the internal energy of the plasma. An electron raised to a higher level through absorption of a photon merely returns to its original level and re-emits the photon.

In addition to photons diffusing in depth, they diffuse in wavelength. Thus, photon energy at wavelength $\lambda$ contributing to $I_\lambda$ may have originated at a depth far removed from $\Delta z$ and at a wavelength quite different from $\lambda$. What this means in a practical sense is that of the total photons in $I_\lambda$ only a fraction, say, $\rho I_\lambda$ are produced within the depth internal $\Delta z$ and it is only this fraction that is strongly coupled to the thermodynamic state of the plasma within $\Delta z$. In many cases of interest in solar physics, $\rho$ is very small and must be determined carefully. This requires accurate solutions of the radiative transfer equations.

As difficult as it is to diagnose properly the solar spectrum, such diagnoses provide the primary means of probing the physical state of the atmosphere. It is essential, therefore, that we understand the complexities of the problem in order that we treat it with proper care.

Studies of the Sun, of course, often utilize the resolved structure on the solar disk and at the limb to aid in determining the relative locations of different solar features and different plasma regimes. Features that are high in the atmosphere, for example, are usually more readily visible at the limb whereas features that are low in the atmosphere tend to be obscured at the limb. Similarly, limb brightening or darkening gives a relatively unambiguous indication of the sign of the intensity gradient. Even such rudimentary knowledge provides a strong and useful supplement to the spectroscopic data.

## 2.2. Energy Balance

Radiation from the Sun not only provides the primary means for diagnosing the solar atmosphere; it plays a major role in determining the physical state of the atmosphere. In the photosphere, radiation provides both the main source of energy and the main loss of energy. Higher in the atmosphere, in the chromosphere and corona, the plasma is heated to high temperature by nonradiative sources and, in turn, eventually loses almost all of this energy as radiation. The fraction lost in the solar wind and in energetic particles may dominate in the outer corona and in such places as coronal holes, but, as a global average, the radiation losses dominate.

The problem of ascertaining the magnitude of the radiation terms in the local energy balance is no different, in essence, from that of performing the diagnostics for the thermodynamic variables. In both cases one needs to determine from the total photon ensemble the fraction of the energy that is produced locally. However, whereas the diagnostics might be performed with only a small subset of the spectrum, the energy balance requires an examination of all relevant parts of the spectrum. In some cases, it is not clear *a priori* just which spectral features are most relevant. For this reason, relatively less progress has been made with the energy balance problem. In the photosphere and low chromosphere, we still rely on approximate treatments of questionable validity even though the thermodynamic structure in these layers is known better than in the higher layers. The techniques for solving these problems with higher accuracy are known, but the sheer magnitude of the problem is intimidating.

## 2.3. Notation

Extended discussions of spectral diagnostics are given in such texts as Thomas (1965), Jeffries (1968), Athay (1972), and Mihalas (1978). Here we review only certain aspects of the problems that are particularly germane to the present discussion. For the most part, the emphasis will be on concepts rather than the formal mathematics of the problem, which are beyond the intended scope of this chapter. This may tend to convey a false illusion of simplicity since we will avoid the harsh reality of dealing with quantitative solutions.

We assume that the reader is familiar with the definitions of the customary parameters of radiative transfer, including the following:

$I_\nu$ = specific intensity
$J_\nu$ = mean intensity over angle
$H_\nu$ = net outward flux
$\mu$ = $\cos\theta$, $\theta$ measured from the normal
$\tau_\nu$ = optical depth
$\Phi_\nu$ = absorption profile normalized so that $\int_{-\infty}^{\infty} \Phi_\nu \, d\nu = 1$
$\varphi_\nu$ = $M_0 \Phi_\nu$ = absorption profile normalized to unity at $\nu = \nu_0$
$\Psi_\nu$ = emission profile normalized so that $\int_{-\infty}^{\infty} \Psi_\nu \, d\nu = 1$
$S_\nu$ = source function
$B_\nu$ = Planck function.

In addition, we wish to make use of a number of concepts that are best discussed in terms of other quantities, which we now define.

## 2.4. Escape probability and scattering depth

We define the single-step escape probability, $P_e$, for a photon ensemble at depth $\tau_0$ ($\nu = \nu_0$) and between frequencies $\nu_1$ and $\nu_2$ as

$$P_e = \int_{\nu_1}^{\nu_2} \int_0^1 \Psi_\nu \exp(-\tau_\nu/\mu) \, d\mu \, d\nu, \tag{2.1}$$

i.e. escape means the arrival of a photon at $\tau = 0$. Since $\Psi_\nu$ is normalized such that $\int_{-\infty}^{\infty} \Psi_\nu \, d\nu = 1$, $P_e$ is the average probability that a photon is emitted in the interval $\nu_1$ to $\nu_2$ and reaches the surface $\tau_0 = 0$ without interacting with the gas by scattering or absorption.

The context in which we shall use $P_e$ is illustrated through the integral form of the transfer equation. The specific intensity at the surface $\tau_0 = 0$ due to radiation between $\tau_0 = 0$ and a finite value $\tau_0$ is given by

$$I_\nu(0) = \int_0^{\tau_0} S_\nu \exp(-\tau_\nu/\mu) \frac{\mathrm{d}\tau_\nu}{\mu} . \tag{2.2}$$

After multiplying by $\mu$ and averaging over $\mu$, we obtain

$$H_\nu(0) = \int_0^{\tau_0} S_\nu M_0 \int_0^1 \Phi_\nu \exp(-\tau_\nu/\mu)\, \mathrm{d}\mu\, \mathrm{d}\tau. \tag{2.3}$$

We next integrate over frequency, assuming $S_\nu \Phi_\nu = S\Psi_\nu$, where $S$ is independent of frequency, and obtain

$$H(0) = \int_0^{\tau_0} SP_e M_0 \, \mathrm{d}\tau_0. \tag{2.4}$$

Thus, $P_e M_0 S$ gives the contribution to $H(0)$ of photons emitted in the optical depth interval between $\tau_0$ and $\tau_0 + \mathrm{d}\tau_0$.

Note that $P_e$ is a function only of $\tau_0$, $\Psi_\nu$ and $\varphi_\nu$ and can be evaluated as a function of $\tau_0$ without solving the transfer equation. Near the surface in an optically thick atmosphere $P_e$ approaches 1/2.

Since $P_e$ is defined as the average probability of reaching $\tau_0 = 0$ in a single step, we define a scattering depth, $N$, by setting

$$NP_e = 1/2. \tag{2.5}$$

Note that $N$ approaches unity at the surface $\tau_0 = 0$. The dependence of $N$ on $\tau_0$ varies with the form of $\Phi_\nu$ and $\Psi_\nu$. For $\Psi_\nu = \Phi_\nu = \text{const}$, $N \propto E_2(\tau_0)$, where $E_2$ is the second exponential integral, and for a Gaussian $\Phi_\nu$, $N \propto \tau_0(\ln \tau_0)^{1/2}$. As defined, $N$ is the average number of photon emissions required in order for one photon at $\tau_0$ to reach the surface $\tau_0 = 0$ by direct flight. In the following, we will sometimes use $N$ rather than $\tau_0$ as a depth variable as a matter of convenience.

## 2.5. Escape coefficient

We now define an escape coefficient (sometimes called the net radiative bracket, Thomas (1961)) that is different from the escape probability and therefore useful in a different context. The equation of radiative transfer

$$\mu \frac{\mathrm{d}I_\nu}{\mathrm{d}\tau_\nu} = I_\nu - S_\nu \tag{2.6}$$

can be averaged over angle to give

$$\frac{\mathrm{d}H_\nu}{\mathrm{d}\tau_\nu} = J_\nu - S_\nu \tag{2.7}$$