

Contents

<i>List of Illustrations</i>	<i>page</i> xiv
<i>List of Tables</i>	xvii
1 Basic Properties of Radiation, Atmospheres, and Oceans	1
1.1 Introduction	1
1.2 Parts of the Spectrum	1
1.2.1 Extraterrestrial Solar Irradiance	2
1.2.2 Terrestrial Infrared Irradiance	6
1.3 Radiative Interaction with Planetary Media	8
1.3.1 Feedback Processes	8
1.3.2 Types of Matter Which Affect Radiation	9
1.4 Vertical Structure of Planetary Atmospheres	10
1.4.1 Hydrostatic Equilibrium and Ideal Gas Laws	10
1.4.2 Minor Species in the Atmosphere	15
1.4.3 Optical Line-of-Sight Columns	16
1.4.4 Radiative Equilibrium and the Thermal Structure of Atmospheres	19
1.4.5 Climate Change: Radiative Forcing and Feedbacks	22
1.5 Density Structure of the Ocean	26
1.6 Vertical Structure of the Ocean	27
1.6.1 The Mixed Layer and the Deep Ocean	27
1.6.2 Seasonal Variations of Ocean Properties	29
1.6.3 Sea-Surface Temperature	30
1.6.4 Ocean Spectral Reflectance and Opacity	31
1.7 Remarks on Nomenclature, Notation, and Units	32
1.8 Summary	34
Exercises	35

vi	<i>Contents</i>	
2	Basic State Variables and the Radiative Transfer Equation	37
2.1	Introduction	37
2.2	Geometrical Optics	38
2.3	Radiative Flux or Irradiance	39
2.4	Spectral Radiance and Its Angular Moments	41
2.4.1	Relationship between Irradiance and Radiance	42
2.4.2	Average (Mean) Radiance and Energy Density	43
2.5	Some Theorems on Radiance	46
2.5.1	Radiance and Irradiance from an Extended Source	48
2.6	Perception of Brightness: Analogy with Radiance	49
2.7	The Extinction Law	50
2.7.1	Extinction = Scattering Plus Absorption	53
2.8	The Differential Equation of Radiative Transfer	56
2.9	Summary	58
	Exercises	58
3	Basic Scattering Processes	59
3.1	Introduction	59
3.2	Lorentz Theory for Radiation–Matter Interactions	61
3.2.1	Scattering and Collective Effects in a Uniform Medium	62
3.2.2	Scattering from Density Irregularities	65
3.2.3	Scattering in Random Media	66
3.2.4	First-Order and Multiple Scattering	68
3.3	Scattering from a Damped Simple Harmonic Oscillator	69
3.3.1	Case (1): Resonance Scattering and the Lorentz Profile	70
3.3.2	Conservative and Nonconservative Scattering	72
3.3.3	Natural Broadening	73
3.3.4	Pressure Broadening	74
3.3.5	Doppler Broadening	75
3.3.6	Realistic Line-Broadening Processes	77
3.3.7	Case (2): Rayleigh Scattering	78
3.4	The Scattering Phase Function	80
3.4.1	Rayleigh Scattering Phase Function	81
3.5	Mie–Debye Scattering	84
3.6	Summary	86
	Exercises	87
4	Absorption by Solid, Aqueous, and Gaseous Media	89
4.1	Introduction	89
4.2	Absorption on Surfaces, Aerosols, and within Aqueous Media	91
4.2.1	Condensed Matter	91

<i>Contents</i>		vii
4.2.2	Aerosols	93
4.2.3	Liquids	94
4.3	Molecular Absorption in Gases	95
4.3.1	Thermal Emission and Radiation Laws	97
4.3.2	Planck's Spectral Distribution Law	100
4.3.3	Radiative Excitation Processes in Molecules	102
4.3.4	Inelastic Collisional Processes	103
4.3.5	Maintenance of Thermal Equilibrium Distributions	107
4.4	The Two-Level Atom	108
4.4.1	Microscopic Radiative Transfer Equation	108
4.4.2	Effects of Collisions on State Populations	112
4.5	Absorption in Molecular Lines and Bands	114
4.5.1	Molecular Rotation: The Rigid Rotator	116
4.5.2	Molecular Vibration and Rotation: The Vibrating Rotator	117
4.5.3	Line Strengths	119
4.6	Absorption Processes in the UV/Visible	121
4.7	Transmission in Spectrally Complex Media	125
4.7.1	Transmission in an Isolated Line	126
4.7.2	Isolated Lorentz Line	128
4.7.3	Band Models	129
4.7.4	Random Band Model	132
4.7.5	MODTRAN: A Moderate Resolution Band Model	133
4.7.6	Spectral Mapping Transformations for Homogeneous Media	136
4.8	Summary	141
	Exercises	143
5	Principles of Radiative Transfer	147
5.1	Introduction	147
5.2	Boundary Properties of Planetary Media	147
5.2.1	Thermal Emission from a Surface	148
5.2.2	Absorption by a Surface	149
5.2.3	Kirchhoff's Law for Surfaces	150
5.2.4	Surface Reflection: The BRDF	151
5.2.5	Albedo for Collimated Incidence	154
5.2.6	The Irradiance Reflectance, or Albedo: Diffuse Incidence	156
5.2.7	Analytic Reflectance Expressions	158
5.2.8	The Opposition Effect	160
5.2.9	Specular Reflection from the Surface of a Water Body	162

5.2.10	Transmission through a Slab Medium	163
5.2.11	Spherical or Bond Albedo	165
5.3	Absorption and Scattering in Planetary Media	167
5.3.1	Kirchhoff's Law for Volume Absorption and Emission	167
5.3.2	Differential Equation of Radiative Transfer	168
5.4	Solution of the Radiative Transfer Equation for Zero Scattering	170
5.4.1	Solution with Zero Scattering in Slab Geometry	173
5.4.2	Half-Range Quantities in a Slab Geometry	174
5.4.3	Formal Solution in a Slab Geometry	175
5.5	Gray Slab Medium in Local Thermodynamic Equilibrium	176
5.6	Formal Solution Including Scattering and Emission	177
5.7	Radiative Heating Rate	179
5.7.1	Generalized Gershun's Law	180
5.7.2	Warming Rate, or the Temperature Tendency	181
5.7.3	Actinic Radiation, Photolysis Rate, and Dose Rate	182
5.8	Summary	183
	Exercises	183
6	Formulation of Radiative Transfer Problems	186
6.1	Introduction	186
6.2	Separation into Diffuse and Direct (Solar) Components	186
6.2.1	Lower Boundary Conditions	188
6.2.2	Multiple Scattering	189
6.2.3	Azimuth Independence of Irradiance and Mean Radiance	190
6.2.4	Azimuthal Dependence of the Radiation Field	191
6.2.5	Spherical Shell Geometry	196
6.3	Nonstratified Media	196
6.4	Radiative Transfer in an Atmosphere–Water System	197
6.4.1	Two Stratified Media with Different Refractive Indices	199
6.5	Examples of Scattering Phase Functions	201
6.5.1	Rayleigh Scattering Phase Function	202
6.5.2	The Mie Scattering Phase Function	204
6.5.3	The Fournier–Forand Scattering Phase Function	205
6.5.4	The Petzold Scattering Phase Function	206
6.6	Scaling Transformations Useful for Anisotropic Scattering	206
6.6.1	The δ -Isotropic Approximation	208
6.6.2	Remarks on Low-Order Scaling Approximations	211
6.6.3	The δ -M Approximation: Arbitrary M	212
6.6.4	Mathematical and Physical Meaning of the Scaling	213

<i>Contents</i>		ix
6.7	Prototype Problems in Radiative Transfer Theory	214
6.7.1	Prototype Problem 1: Uniform Illumination	215
6.7.2	Prototype Problem 2: Constant Imbedded Source	216
6.7.3	Prototype Problem 3: Diffuse Reflection Problem	216
6.7.4	Boundary Conditions: Reflecting and Emitting Surface	217
6.8	Reciprocity, Duality, and Inhomogeneous Media	218
6.9	Effects of Surface Reflection on the Radiation Field	219
6.10	Integral Equation Formulation of Radiative Transfer	222
6.11	Summary	223
	Exercises	224
7	Approximate Solutions of Prototype Problems	227
7.1	Introduction	227
7.2	Separation of the Radiation Field into Orders of Scattering	228
7.2.1	The Single-Scattering Approximation	229
7.2.2	Lambda Iteration: The Multiple-Scattering Series	230
7.2.3	Single-Scattering Contribution from Ground Reflection: The Planetary Problem	232
7.2.4	Successive Orders of Scattering (SOS)	233
7.3	The Two-Stream Approximation: Isotropic Scattering	234
7.3.1	Approximate Differential Equations	234
7.3.2	The Mean Inclination: Possible Choices for $\bar{\mu}$	236
7.3.3	Prototype Problem 1: Differential Equation Approach	237
7.3.4	Imbedded Source: Prototype Problem 2	243
7.3.5	Beam Incidence: Prototype Problem 3	248
7.4	Conservative Scattering in a Finite Slab	251
7.5	Anisotropic Scattering	252
7.5.1	Two-Stream versus Eddington Approximations	252
7.5.2	The Backscattering Ratios	255
7.5.3	Two-Stream Solutions for Anisotropic Scattering	260
7.5.4	Scaling Approximations for Anisotropic Scattering	262
7.5.5	Generalized Two-Stream Equations	263
7.6	Accuracy of the Two-Stream Method	265
7.7	Final Comments on the Two-Stream Method	266
7.8	Summary	269
	Exercises	270
8	The Role of Radiation in Climate	278
8.1	Introduction	278
8.2	Irradiance and Heating Rate: Clear-Sky Conditions	280
8.2.1	Monochromatic Irradiances	281

8.2.2	Wideband Emittance Models	283
8.2.3	Narrowband Absorption Model	288
8.2.4	Band Overlap	289
8.2.5	The Diffusivity Approximation	289
8.2.6	Equations for the Heating Rate	290
8.2.7	Clear-Sky Radiative Cooling: Nonisothermal Medium	293
8.2.8	Computations of Terrestrial Cooling Rates	294
8.3	The IR Radiative Impact of Clouds and Aerosols	295
8.3.1	Heating Rate in an Idealized Cloud	296
8.3.2	Detailed Longwave Radiative Effects of Clouds	298
8.3.3	Accurate Treatment of Longwave RT Including Scattering	300
8.4	Radiative Equilibrium with Zero Visible Opacity	302
8.5	Radiative Equilibrium with Finite Visible Optical Depth	309
8.6	Radiative-Convective Equilibrium	312
8.7	The Concept of the Emission Height	315
8.8	Effects of a Spectral Window	318
8.9	Radiative Forcing	319
8.10	Climate Impact of Clouds	322
8.10.1	Longwave Effects of Water Clouds	323
8.10.2	Shortwave Effects of Water Clouds	325
8.10.3	Combined Shortwave and Longwave Effects of Clouds	328
8.11	Climate Impact of Cloud Height	331
8.12	Cloud and Aerosol Forcing	333
8.12.1	Aerosol Forcing	335
8.13	Water-Vapor Feedback	337
8.14	Effects of Carbon Dioxide Changes	338
8.15	Greenhouse Effect from Individual Gas Species	339
8.16	Summary	340
	Exercises	342
9	Accurate Numerical Solutions of Prototype Problems	347
9.1	Introduction	347
9.2	Discrete-Ordinate Method – Isotropic Scattering	347
9.2.1	Quadrature Formulas	347
9.3	Anisotropic Scattering	350
9.3.1	General Considerations	350
9.3.2	Quadrature Rule	351
9.4	Matrix Formulation of the Discrete-Ordinate Method	352
9.4.1	Two- and Four-Stream Approximations	352
9.4.2	Multistream Approximation (N Arbitrary)	353

<i>Contents</i>		xi
9.5	Matrix Eigensolutions	355
9.5.1	Two-Stream Solutions ($N = 1$)	355
9.5.2	Multistream Solutions (N Arbitrary)	356
9.5.3	Inhomogeneous Solution	357
9.5.4	General Solution	358
9.6	Source Function and Angular Distributions	359
9.7	Boundary Conditions – Removal of Ill Conditioning	360
9.8	Inhomogeneous Multilayered Media	362
9.8.1	General Solution – Boundary and Layer Interface Conditions	362
9.8.2	Source Functions and Angular Distributions	365
9.9	Correction of the Truncated Radiance Field	366
9.9.1	The Nakajima–Tanaka Correction Procedure	367
9.9.2	Computed Radiance Distributions for the Standard Problem	369
9.10	Coupled Atmosphere–Ocean Problem	370
9.10.1	Discrete-Ordinate Equations for the Atmosphere– Ocean System	370
9.10.2	Quadrature and General Solution	371
9.10.3	Boundary, Continuity, and Atmosphere–Ocean Interface Conditions	373
9.11	The Doubling–Adding and the Matrix Operator Methods	376
9.11.1	Matrix-Exponential Solution – Formal Derivation of Doubling Rules	377
9.11.2	Connection between Doubling and Discrete Ordinate Methods	378
9.11.3	Intuitive Derivation of the Doubling Rules – Adding of Dissimilar Layers	379
9.12	Other Accurate Methods	381
9.12.1	The Spherical Harmonic Method	381
9.12.2	Invariant Imbedding	381
9.12.3	Iteration Methods	382
9.12.4	The Feautrier Method	382
9.12.5	Integral Equation Approach	382
9.12.6	Monte Carlo Markov Chain Methods	383
9.13	Final Comments	384
9.14	Summary	385
	Exercises	387

xii	<i>Contents</i>	
10	Shortwave Radiative Transfer in the Atmosphere and Ocean	389
10.1	Introduction	389
10.2	Solar Radiation	391
10.2.1	Modeling UV Transmission into the Ocean	392
10.2.2	Measured and Computed UV Irradiance in the Ocean	393
10.2.3	Impact of Ozone Depletion on Primary Production in the Ocean	395
10.2.4	Interaction of Solar Radiation with Snow and Ice	395
10.3	Modeling of Shortwave Radiative Effects in the Atmosphere	397
10.3.1	Gaseous Absorption and Penetration Depth	397
10.3.2	Solar Warming Rates Due to Ozone, Aerosols, and Clouds	402
10.3.3	Computation of Photolysis Rates	404
10.3.4	UV Transmission: Relation to Ozone Abundance	405
10.3.5	UV Transmission and Dose Rates at the Earth's Surface	407
10.3.6	Measured and Computed UV Irradiance – Derivation of Ozone Abundance and Cloud Effects	409
10.4	Modeling of Shortwave Radiation in the Ocean	411
10.4.1	Attenuation in the Ocean: Apparent Optical Properties (AOPs)	411
10.4.2	Two-Stream Model Appropriate for Deep Water	411
10.5	AccuRT: An RT Model for Coupled Atmosphere–Water Systems	413
10.5.1	Introduction	413
10.5.2	Notation	415
10.5.3	User Interface – Input/Output	415
10.5.4	Inherent Optical Properties (IOPs)	417
10.5.5	Spectral Averaging of Absorption Coefficients	430
10.5.6	Solving the Radiative Transfer Problem	430
10.5.7	Summary of AccuRT	434
10.6	Ocean Color – Simultaneous Marine and Aerosol Retrieval	434
10.6.1	Introduction	434
10.6.2	Methodology	435
10.6.3	Neural Network Training	437
10.6.4	Retrieved Atmospheric and Marine Parameters	438
10.6.5	Summary of OC-SMART Algorithm	439
10.7	Bidirectional Dependence of the Water-Leaving Radiance	441
10.7.1	Importance of the Anisotropy	441
10.7.2	Configuration of BRDF Measurements	441
10.7.3	Computation of the Anisotropy Factor	443
10.7.4	Radiance Anisotropy – the Q Factor	444

<i>Contents</i>		xiii
10.7.5	Radiative Transfer Simulations of the Q Factor	445
10.7.6	Summary of Water BRDF Issues	450
10.8	Retrieving Water IOP Profiles from Measured AOP Profiles	451
10.8.1	Background and Status of Knowledge	451
10.8.2	Inverting IOPs from AOPs	452
10.8.3	IOP Inversion Algorithm	453
10.8.4	Summary of Water AOP \rightarrow IOP Inversion Algorithm	456
10.9	Modeled versus Measured BRDFs: The Sunlint Problem	456
10.9.1	Description of the Sunlint Problem	456
10.9.2	Solution of the Sunlint Problem	458
10.9.3	Retrieval of Slope Variances, Wind Direction, and Aerosol Optical Depth	461
10.9.4	Summary of Sunlint Study	462
10.10	Overall Summary	463
	Exercises	465
<i>Appendix A</i> Nomenclature: Glossary of Symbols		473
<i>Appendix B</i> Physical Constants		481
<i>Appendix C</i> Ocean Optics Nomenclature		482
<i>Appendix D</i> Reflectance and Transmittance at an Interface		485
<i>Appendices E through U can be downloaded from</i> www.cambridge.org/stamnes or www.rtatmocn.com .		
	<i>References</i>	491
	<i>Index</i>	509