

Contents

Preface	Upwards Diffusion and the “Diffusion-Limited Escape” Concept	page xiii
PART I Principles of Planetary Atmospheres		
I The Structure of Planetary Atmospheres		
1.1 Vertical Structure of Atmospheres		
1.1.1	Atmospheric Temperature Structure: An Overview	1
1.1.2	Atmospheric Composition and Mass	3
1.1.3	Convection and Stability	6
1.2 Condensable Species on Terrestrial-Type Planets		14
1.2.1	Pure Water Atmospheres	24
1.2.2	Atmospheres with Multiple Condensable Species	24
1.2.3	Water in the Present-Day Martian Atmosphere	25
2 Energy and Radiation in Planetary Atmospheres		26
2.1 Energy Sources and Fluxes on Planets		27
2.1.1	Planetary Energy Sources	27
2.1.2	Radiation From the Sun and Other Stars	28
2.2 Planetary Energy Balance and the Greenhouse Effect		31
2.2.1	Orbits and Planetary Motion	31
2.2.2	Time-Averaged Incident Solar Flux	32
2.2.3	Albedo	32
2.2.4	Planetary Equilibrium Temperature	33
2.2.5	The Greenhouse Effect	34
2.2.6	Giant Planets, Internal Heat, and Equilibrium Temperature	36
2.3 Climate Feedbacks in the “Earth System”		37
2.3.1	Climate Sensitivity	37
2.3.2	The Emission Level and Radiative Time Constants	39
2.4 Principles of Radiation in Planetary Atmospheres		39
2.4.1	Basic Definitions and Functions in Radiative Transfer	40
2.4.2	Radiative Transfer in the Visible and Ultraviolet	42
2.4.3	Radiative Transfer in the Thermal Infrared	47
2.4.4	Level of Emission and the Meaning of “Optically Thick” and “Optically Thin”	51
2.4.5	Radiative and Radiative-Conductive Equilibrium	53
2.5 Absorption and Emission of Radiation by Atmospheric Gases		61
2.5.1	Overview of Absorption Lines	62
2.5.2	Electric and Magnetic Dipole Moments	62
2.5.3	Rotational Transitions	63
2.5.4	Vibrational Transitions	65

2.5.5	<i>Electronic Transitions</i>	66
2.5.6	<i>Collision-Induced Absorption: Giant Planets, Titan, Early Earth, and Venus</i>	67
2.5.7	<i>Line Shapes and Broadening</i>	68
2.5.8	<i>Continuum Absorption</i>	70
2.5.9	<i>Band Transmission and Weak and Strong Absorption</i>	70
2.6	Calculating Atmospheric Absorption in Climate Calculations	72
3	Essentials of Chemistry of Planetary Atmospheres	73
3.1	General Principles	73
3.1.1	<i>Essentials of Thermodynamic Chemical Equilibrium</i>	73
3.1.2	<i>Chemical Kinetics of Atmospheric Gases</i>	75
3.1.3	<i>The Importance of Free Radicals</i>	76
3.1.4	<i>Three-Body (Termolecular) Reactions</i>	77
3.1.5	<i>Temperature Dependence of Reaction Rates</i>	77
3.1.6	<i>Photolysis</i>	78
3.2	Surface Deposition	78
3.3	Earth's Stratospheric and Tropospheric Chemistry	79
3.3.1	<i>Earth's Stratospheric Chemistry</i>	79
3.3.2	<i>Earth's Tropospheric Chemistry</i>	81
3.4	CO₂ Stability on Venus and Mars	82
3.5	CO₂ and Cold Thermospheres of Venus and Mars	83
3.6	Methane and Hydrocarbons on Outer Planets and Titan	83
4	Motions in Planetary Atmospheres	85
4.1	Introductory Concepts	85
4.1.1	<i>Forces, Apparent Forces, and the Equation of Motion</i>	85
4.1.2	<i>Characteristic Force Balance Regimes in Atmospheres</i>	89
4.2	The Zonal-Mean Meridional Circulation and Thermally Driven Jet Streams	94
4.2.1	<i>The Two Types of Jet Stream: Thermally Driven and Eddy Driven</i>	94
4.2.2	<i>The Hadley Circulation and Subtropical Jets</i>	95
4.2.3	<i>Symmetric Hadley Circulation Theory</i>	96
4.2.4	<i>Asymmetric Hadley Circulations on Earth and Mars, and Monsoons</i>	100
4.2.5	<i>Hadley Circulations on Venus and Titan</i>	101
4.2.6	<i>Mean Meridional Circulation and Planetary Habitability</i>	101
4.3	Eddy-Driven Jet Streams and Planetary Waves	102
4.3.1	<i>Vorticity</i>	102
4.3.2	<i>Jet Forcing by Stirring or Friction</i>	103
4.3.3	<i>Planetary Waves</i>	106
4.3.4	<i>Effects of Vertical Variation</i>	108
4.3.5	<i>Planetary Wave Instability</i>	111
4.3.6	<i>Eddy-Driven Jets on the Outer Planets: Shallow Layer Atmospheres</i>	113
4.3.7	<i>Eddy-Driven Jets on the Outer Planets: Deep Atmospheres</i>	113
4.3.8	<i>A Shallow Atmosphere Model Coupled to the Deep Interior of Outer Planets</i>	114
4.3.9	<i>Ice Giants: Uranus and Neptune</i>	115
4.4	Buoyancy Waves and Thermal Tides	115
4.4.1	<i>Mechanism and Properties of Buoyancy Waves</i>	115
4.4.2	<i>Wave Generation, Breaking, and Impact on the Zonal Mean Flow</i>	117
4.4.3	<i>Atmospheric Tides</i>	120
4.5	Superrotation	123
4.6	Transport by Eddy-Driven Circulations	125
4.6.1	<i>The Brewer-Dobson Circulation and Mesospheric Circulation</i>	125
4.6.2	<i>Implications of Large-Scale Overturning Circulations for Atmospheric Evolution</i>	126
4.7	Atmospheric Dynamics and Habitability: Future Prospects	127

5 Escape of Atmospheres to Space	129
5.1 Historical Background to Atmospheric Escape	130
5.2 Overview of Atmospheric Escape Mechanisms	131
5.2.1 Thermal Escape Overview	131
5.2.2 Suprathermal (or Nonthermal) Escape, in Brief	134
5.2.3 Impact Erosion, in Brief	134
5.2.4 The Upper Limit of Diffusion-Limited Escape, in Brief	135
5.3 Breakdown of the Barometric Law	135
5.4 The Exobase or “Critical Level”	136
5.5 Escape Velocity	137
5.6 Jeans’ Thermal Escape of Hydrogen	138
5.6.1 Concept and Mathematical Derivation	138
5.6.2 Effusion Velocity	141
5.7 Suprathermal (Nonthermal) Escape of Hydrogen	141
5.8 Upwards Diffusion and the “Diffusion-Limited Escape” Concept	143
5.8.1 Molecular Diffusion	143
5.8.2 Eddy Diffusion	144
5.8.3 Diffusion-Limited Escape of Hydrogen	145
5.8.4 Application of Diffusion-Limited Hydrogen Escape to Earth’s Atmosphere	146
5.9 Diffusion-Limited Hydrogen Escape Applied to Mars, Titan, and Venus	148
5.9.1 Mars	148
5.9.2 Titan	149
5.9.3 Venus	149
5.10 Hydrodynamic Escape	150
5.10.1 Conditions for Hydrodynamic Escape	150
5.10.2 Energy-Limited Escape	155
5.10.3 Density-Limited Hydrodynamic Escape	157
5.10.4 Maximum Molecular Mass Carried Away in Hydrodynamic Escape	158
5.11 Mass Fractionation by Hydrodynamic Escape	161
5.11.1 Fractionation Theory	161
5.11.2 Applications of Mass Fractionation in Hydrodynamic Escape: Noble Gas Isotopes	162
5.12 Impact Erosion of Planetary Atmospheres	165
5.13 Summary of the Fundamental Nature of Atmospheric Escape	166
PART II Evolution of the Earth’s Atmosphere	169
6 Formation of Earth’s Atmosphere and Oceans	171
6.1 Planetary Formation	171
6.1.1 Formation of Stars and Protoplanetary Disks	171
6.1.2 The Planetesimal Hypothesis	172
6.1.3 Planetary Migration: When Did the Gas and Dust Disappear?	175
6.2 Volatile Delivery to the Terrestrial Planets	175
6.2.1 The Equilibrium Condensation Model	175
6.2.2 Modern Accretion Models	177
6.2.3 D/H Ratios and their Implications for Water Sources	179
6.3 Meteorites: Clues to the Early Solar System	181
6.4 The Implications of the Abundances of Noble Gases and Other Elements	183
6.4.1 Atmophiles, Geochemical Volatiles, and Refractory Elements	183
6.4.2 Noble Gases	184
6.4.3 Early Degassing	186
6.5 Impact Degassing, Co-accretion of Atmospheres, and Ingassing	188
6.5.1 Laboratory Evidence for Impact Degassing	188

6.5.2 Formation of Steam and Reducing Atmospheres During Accretion	188
6.5.3 Ingassing	189
6.6 Moon Formation and its Implications for Earth's Volatile History	191
6.6.1 The Giant Impact Hypothesis	191
6.6.2 The Post-Impact Atmosphere and Loss of Volatiles	191
6.7 "Late Heavy Bombardment": Causes and Consequences	192
6.8. The Early Atmosphere: the Effect of Planetary Differentiation and Rotation Rate	195
6.8.1 Core Formation and its Effect on Atmospheric Chemistry	195
6.8.2 Day Length, the Lunar Orbit, and the Early Steam Atmosphere	196
7 Volcanic Outgassing and Mantle Redox Evolution	198
7.1 Historical Context: Strongly and Weakly Reduced Atmospheres	198
7.2 Volcanic Outgassing and Metamorphic Degassing of Major Volatile Species	200
7.2.1 Mechanisms of Volcanic Outgassing	200
7.2.2 Outgassing and Metamorphic Degassing of CO_2	202
7.2.3 Subaerial Outgassing of H_2O , SO_2 , H_2S , and N_2	203
7.3 Oxidation State of the Mantle	205
7.3.1 Oxidation State of the Present Upper Mantle	205
7.3.2 How the Mantle Became Oxidized	206
7.4 Release of Reduced Gases From Subaerial Volcanism	208
7.5 Reduced Gases Released From Submarine Volcanism and Hydrothermal Systems	210
7.5.1 H_2S and H_2	210
7.5.2 CH_4	211
7.6 Past Rates of Volcanic Outgassing	212
7.7 Summary	213
8 Atmospheric and Global Redox Balance	215
8.1 Principles of Redox Balance	216
8.2 H_2 Budget of the Prebiotic Atmosphere: Approximate Solution	216
8.3 Rigorous Treatment of Atmospheric Redox Balance	218
8.4 Global Redox Budget of the Early Earth	221
8.5 Organic Carbon Burial and the Carbon Isotope Record	223
8.6 Redox Indicators for Changes in Atmospheric Oxidation State	227
8.6.1 Holland's f -Value Analysis	227
8.6.2 The Catling and Claire K_{OXY} Parameter	230
9 The Prebiotic and Early Postbiotic Atmosphere	231
9.1 N_2 and CO_2 Concentrations in the Primitive Atmosphere	231
9.2 Prebiotic O_2 Concentrations	232
9.2.1 Dependence of O_2 on CO_2	233
9.2.2 Dependence of O_2 on H_2	235
9.2.3 Effect of Higher UV Fluxes on O_2 and O_3	236
9.3 Prebiotic Synthesis of Organic Compounds in Weakly Reduced Atmospheres	237
9.3.1 Synthesis of RNA Building Blocks: H_2CO and HCN	238
9.3.2 CO as a Prebiotic Compound	239
9.4 When Did Life Originate?	240
9.4.1 Evidence from Microfossils and Stromatolites	240
9.4.2 Carbon Isotopic Evidence for Early Life	243
9.4.3 Molecular Biomarkers	244
9.5 The Molecular Phylogenetic Record of Life	244
9.6 Early Anaerobic Metabolisms and Their Effect on the Atmosphere	246
9.6.1 Heterotrophy and Fermentation	247

9.6.2	<i>Methanogenesis</i>	247
9.6.3	<i>Sulfur Metabolism and Sulfate Reduction</i>	248
9.6.4	<i>Nitrogen Fixation and Nitrate Respiration</i>	249
9.6.5	<i>Anoxygenic Photosynthesis</i>	250
9.7	Detailed Modeling of H₂-Based Ecosystems	251
9.7.1	<i>Atmosphere–Ocean Gas Exchange: the Stagnant Film Model</i>	252
9.7.2	<i>Models of H₂-Based Archean Ecosystems</i>	252
9.8	Comparing With the Carbon Isotope Record	255
10	The Rise of Oxygen and Ozone in Earth’s Atmosphere	257
10.1	<i>Co-evolution of Life and Oxygen: an Overview</i>	257
10.2	Controls on O₂ Levels	260
10.2.1	<i>Redox Budgeting for the Modern O₂-Rich System</i>	260
10.2.2	<i>The “Net” Source Flux of O₂</i>	261
10.2.3	<i>The O₂ Sink Fluxes</i>	263
10.2.4	<i>Generalized History of Atmosphere–Ocean Redox</i>	265
10.3	Evidence for a Paleoproterozoic Rise of O₂	266
10.3.1	<i>Continental Indicators: Paleosols, Detrital Grains, and Redbeds</i>	266
10.3.2	<i>Banded Iron Formations</i>	267
10.3.3	<i>Concentration of Redox-Sensitive Elements and the Rise of Oxygen</i>	269
10.3.4	<i>Iron Speciation: Ocean Anoxia or Euxinia, and the Rise of Oxygen</i>	270
10.4	Mass-Dependent Stable Isotope Records and the Rise of Oxygen	272
10.4.1	<i>Carbon Isotopes</i>	272
10.4.2	<i>Sulfur Isotopes</i>	273
10.4.3	<i>Nitrogen Isotopes</i>	274
10.4.4	<i>Transition Metal (Iron, Chromium, and Molybdenum) and Non-Metal Isotopes (Selenium)</i>	275
10.5	Mass-Independent Fractionation of Sulfur Isotopes and the Rise of Oxygen	276
10.6	When Did Oxygenic Photosynthesis Appear?	279
10.6.1	<i>Geochemical Evidence for O₂ Before the Great Oxidation Event</i>	279
10.6.2	<i>Fossil and Biomarker Evidence for O₂ Before the Great Oxidation Event</i>	281
10.7	Explaining the Rise of O₂	281
10.7.1	<i>General Conditions for an Anoxic Versus Oxic Atmosphere</i>	281
10.7.2	<i>Hypotheses for an Increasing Flux of O₂</i>	284
10.7.3	<i>Hypotheses for a Decreasing Sink of O₂</i>	284
10.8	Atmospheric Chemistry of the Great Oxidation Event	289
10.8.1	<i>A Great Collapse of Methane</i>	289
10.8.2	<i>The Formation of a Stratospheric Ozone Shield</i>	291
10.8.3	<i>Did the Rise of O₂ Affect Atmospheric N₂ Levels?</i>	291
10.9	The Neoproterozoic Oxidation Event (NOE) or Second Rise of Oxygen	292
10.9.1	<i>Evidence for Neoproterozoic Oxygenation</i>	292
10.9.2	<i>What Caused the Second Rise of Oxygen?</i>	294
10.10	Phanerozoic Evolution of Atmospheric O₂	296
10.11	O₂ and Advanced Life in the Cosmos	297
11	Long-Term Climate Evolution	299
11.1	Solar Evolution	299
11.2	Implications for Planetary Surface Temperatures: Sagan and Mullen’s Model	301
11.3	Geological Constraints on Archean and Hadean Surface Temperatures	302
11.3.1	<i>Glacial Constraints on Surface Temperature</i>	302
11.3.2	<i>Isotopic Constraints on Surface Temperature</i>	303
11.4	Solving the Faint Young Sun Problem with CO₂	304
11.4.1	<i>The Carbonate–Silicate Cycle</i>	304
11.4.2	<i>Feedbacks in the Carbonate–Silicate Cycle and a Possible Solution to the Faint Young Sun Problem</i>	306

11.4.3	<i>Geochemical Constraints on Past CO₂ Concentrations</i>	307
11.5	Clouds and the Faint Young Sun Problem	310
11.6	Effect of Reducing Gases on Archean Climate	310
11.6.1	<i>Methane and Climate: Greenhouse and Anti-Greenhouse Effects</i>	311
11.6.2	<i>Fractal Organic Haze and UV Shielding of Ammonia</i>	313
11.6.3	<i>Effect of H₂ on Archean Climate</i>	314
11.7	The Gaia Hypothesis	315
11.8	N₂, Barometric Pressure, and Climate	315
11.9	The Warm and Stable Mid-Proterozoic Climate	316
11.9.1	<i>Greenhouse Warming by CH₄</i>	316
11.9.2	<i>Greenhouse Warming by N₂O</i>	318
11.10	The Neoproterozoic “Snowball Earth” Episodes	318
11.10.1	<i>Geologic Evidence for Snowball Earth</i>	318
11.10.2	<i>Alternative Models to Explain Low-Latitude Glaciation</i>	319
11.10.3	<i>Triggering a Snowball Earth</i>	321
11.10.4	<i>Recovery from Snowball Earth</i>	322
11.10.5	<i>Survival of the Photosynthetic Biota: the Thin-Ice Model and Narrow Waterbelt State</i>	323
11.11	Phanerozoic Climate Variations	325
PART III Atmospheres and Climates on Other Worlds		327
12	Mars	329
12.1	Introduction to Mars	329
12.1.1	<i>Overview of Mars</i>	329
12.1.2	<i>The Geologic Timescale for Mars</i>	332
12.1.3	<i>The Basis of our Knowledge: Spacecraft Data and Martian Meteorites</i>	333
12.2	The Present-Day Atmosphere and Climate of Mars	335
12.2.1	<i>Composition and Thickness of the Present Atmosphere</i>	335
12.2.2	<i>Climate and Meteorology</i>	336
12.2.3	<i>Atmospheric Chemistry</i>	338
12.2.4	<i>The Escape of H, O, C, and N</i>	340
12.3	Volatile Inventory: Present and Past	342
12.3.1	<i>The Present-Day Volatile Inventories</i>	342
12.3.2	<i>Past Volatile Inventory</i>	345
12.3.3	<i>Noachian and Pre-Noachian Atmospheric Escape: Theory and Evidence</i>	349
12.4	Evidence for Past Climate Change and Different Atmospheres	351
12.4.1	<i>Geomorphic Evidence of Possible Water Flow</i>	351
12.4.2	<i>Mineralogy and Sedimentology</i>	355
12.5	Explaining the Early Climate of Mars	360
12.5.1	<i>The Faint Young Sun Problem</i>	360
12.5.2	<i>Mechanisms for Producing Early Climates Conducive to Fluvial Erosion</i>	361
12.6	Effect of Orbital Change on Past Martian Climate	366
12.7	Wind Modification of the Surface	367
12.8	Unanswered Questions of Mars’ Astrobiology and Atmospheric Evolution	368
13	Evolution of Venus’ Atmosphere	370
13.1	Current State of Venus’ Atmosphere	370
13.1.1	<i>Atmospheric Temperature and Composition: the Concept of “Excess Volatiles”</i>	370
13.1.2	<i>Cloud Composition and Photochemistry</i>	373
13.1.3	<i>Atmospheric Circulation</i>	375
13.2	The Solid Planet: Is Plate Tectonics Active on Venus?	376
13.3	Formation of Venus’ Atmosphere: Wet or Dry?	378

13.4 The Runaway Greenhouse	379
13.4.1 <i>The Classical Runaway Greenhouse</i>	379
13.4.2 <i>A Simple Approximation to the Outgoing Infrared Flux from a Runaway Greenhouse Atmosphere</i>	381
13.4.3 <i>More Rigorous Limits on Outgoing Infrared Radiation from Gray Atmospheres</i>	382
13.4.4 <i>Radiation Limits from Non-Gray Models</i>	384
13.4.5 <i>Evolution of Venus' Atmosphere: the "Moist Greenhouse"</i>	387
13.5 Stability of Venus' Present Atmosphere	389
13.6 Implications for Earth and Earth-Like Planets	390
13.6.1 <i>Can CO₂ Cause a Runaway Greenhouse on Earth?</i>	390
13.6.2 <i>Future Evolution of Earth's Climate</i>	391
14 Giant Planets and their Satellites	393
14.1 Giant Planets	393
14.1.1 <i>Current Atmospheres</i>	393
14.1.2 <i>Thermal Evolution of Giant Planets and their Atmospheres</i>	395
14.1.3 <i>Thermal (Hydrodynamic) Escape on Hot Giant Exoplanets</i>	396
14.2 Tenuous Atmospheres on Icy Worlds	397
14.2.1 <i>Overview of Outer Satellite Atmospheres</i>	397
14.2.2 <i>Tenuous Volcanic or Cryovolcanic Atmospheres</i>	399
14.2.3 <i>Tenuous O₂-Rich and CO₂-Rich Atmospheres</i>	400
14.2.4 <i>The Nitrogen Atmospheres of Triton and Pluto</i>	401
14.3 The Dense Atmosphere on Titan versus the Barren Galilean Satellites	404
14.4 Titan	405
14.4.1 <i>Overview</i>	405
14.4.2 <i>Titan's Atmosphere: Structure, Climate, Chemistry, and Methane Cycle</i>	407
14.4.3 <i>Atmospheric Escape</i>	415
14.4.4 <i>Origin and Evolution of Titan's Atmosphere</i>	417
14.4.5 <i>Life on Titan: "Weird Life" or Liquid Water Life</i>	420
14.5 The Exoplanet Context for Outer Planets and their Satellites	421
15 Exoplanets: Habitability and Characterization	422
15.1 The Circumstellar Habitable Zone	422
15.1.1 <i>Requirements for Life: the Importance of Liquid Water</i>	422
15.1.2 <i>Historical Treatment of the Habitable Zone</i>	423
15.1.3 <i>Modern Limits on the Habitable Zone Around the Sun</i>	424
15.1.4 <i>Empirical Estimates of Habitable Zone Boundaries</i>	426
15.1.5 <i>Habitable Zones Around Other Main Sequence Stars</i>	427
15.1.6 <i>Other Concepts of the Habitable Zone</i>	431
15.1.7 <i>The Galactic Habitable Zone</i>	432
15.2 Finding Planets Around Other Stars	432
15.2.1 <i>The Astrometric Method</i>	433
15.2.2 <i>The Radial Velocity Method</i>	433
15.2.3 <i>The Transit Method and Results from NASA's Kepler Mission</i>	434
15.2.4 <i>Gravitational Microlensing</i>	436
15.2.5 <i>Direct Detection Methods: Terrestrial Planet Finder (TPF) and Darwin</i>	437
15.3 Characterizing Exoplanet Atmospheres and Surfaces	438
15.3.1 <i>The Near Term: Transit Spectra of Planets Around Low-Mass Stars</i>	438
15.3.2 <i>The Future: Direct Detection of Habitable Planets</i>	440
15.4 Interpretation of Possible Biosignatures	444
15.4.1 <i>The Criterion of Extreme Thermodynamic Disequilibrium</i>	444
15.4.2 <i>Classification of Biosignature Gases</i>	446
15.4.3 <i>Is O₂ by Itself a Reliable Biosignature?</i>	446
15.5 Parting Thoughts	448

Appendix A: One-Dimensional Climate Model	449
A.1 Numerical Method	449
A.2 Calculation of Radiative Fluxes	450
A.3 Treatment of Water Vapor	452
A.4 Treatment of Clouds	454
Appendix B: Photochemical Models	455
B.1 Photochemical Model Equations	455
B.2 Finite Differencing the Model Equations	456
B.3 Solving the System of Ordinary Differential Equations (ODEs)	457
B.4 Boundary Conditions	458
B.5 Including Particles	459
B.6 Setting up the Chemical Production and Loss Matrices	460
B.7 Long- and Short-Lived Species and Ill-Conditioned Matrices	460
B.8 Rainout, Lightning, and Photolysis	461
Appendix C: Atomic States and Term Symbols	463
Bibliography	467
Index	562
Color plate section between pages 298–299	
12.1 Introduction to Mars	
12.1.1 Overview of Mars	
12.1.2 The Galactic Record of Mars	
12.1.3 The Basis of Surface-Induced Weathering and Weathering Products	
12.1.4 The Present-Day Environment and Climate of Mars	
12.1.5 Evidence and Theories of the Fainter-Young Sun	
12.1.6 The Atmosphere	
12.2 Volcanoes, Glaciers, and Flows	
12.2.1 The Present-Day Liquid Flow	
12.2.2 Heat Transport	
12.2.3 The Fainter-Young Sun	
12.2.4 Evolution of the Atmosphere	
12.2.5 Evidence for Early Climate of Mars	
12.2.6 The Greenhouse Problem	
12.2.7 Evidence for Early Climate Conditions in Flows	
12.2.8 Evidence for Climate Changes on Two Planets	
12.2.9 Wind Erosion of the Surface	
12.2.10 Unknown Questions of the Past and Future	
12.3 Evolution of Venus' Atmosphere	
12.3.1 Current State of Venus' Atmosphere	
12.3.2 Composition and Abundance of the Concentrations of Gases	
12.3.3 Cloud Composition and Precipitation	
12.3.4 Atmospheric Circulation	
12.3.5 The Solid Planes to Plate Tectonics Active on Venus	
12.3.6 Formation of Venus' Atmosphere: Wet or Dry?	
12.4 Future	
12.4.1 The Future of Mars	
12.4.2 The Future of Venus	
12.4.3 The Future of the Earth	