

Contents

Some Milestones up to the Beginning of the Space Age	xiii
Chapter 1 The Elements in the Solar System	1
1.1 Introduction	1
1.2 Abundances of the Elements	6
1.2.1 Sources for the Solar System Composition	9
1.2.2 Elemental Abundance Scales	13
1.2.3 Sun's Photospheric Composition	14
1.2.4 Elemental Abundances in Carbonaceous CI-Chondrites	17
1.2.5 Comparison of Meteoritic and Solar Abundances	17
1.2.6 D, ³ He, Li, Be and B	19
1.3 Solar System Elemental Abundances	23
1.4 Trends in Solar System Elemental Abundances and Origins	24
1.4.1 Elemental Abundance Trends	24
Further Reading	31
References	31
Chapter 2 Meteorites	34
2.1 Introduction	34
2.2 Meteorite Classification	36
2.2.1 Oxygen Isotopes	39
2.2.2 Meteorite Falls and Finds	45

Chemistry of the Solar System

By Katharina Lodders and Bruce Fegley, Jr.

© K. Lodders and B. Fegley, Jr. 2011

Published by the Royal Society of Chemistry, www.rsc.org

2.3	Chondrites	50
2.3.1	Chondrules	56
2.3.2	Petrologic Types of Chondrites	63
2.3.3	Ordinary Chondrites	68
2.3.4	Enstatite Chondrites	73
2.3.5	R and K Chondrite Groups	74
2.3.6	Carbonaceous Chondrites	75
2.3.7	Hydrous Silicates and Salts: The Case of CI Chondrites	79
2.4	Iron Meteorites	93
2.5	Stony-iron Meteorites	103
2.6	Achondrites	105
2.6.1	Acapulcoites and Lodranites	105
2.6.2	Brachinites	106
2.6.3	Winonaites	106
2.6.4	Angrites	107
2.6.5	Aubrites	107
2.6.6	Ureilites	108
2.6.7	Eucrites, Howardites and Diogenites	108
2.6.8	SNC Meteorites and Lunar Meteorites	109
2.7	Meteorite Home Worlds	111
	Further Reading and Resources	112
	References	112
Chapter 3	The Solar Nebula	116
3.1	Introduction	116
3.2	Stages of Solar System Formation	119
3.2.1	Interstellar Medium and Presolar Grains	119
3.2.2	Interstellar Molecular Cloud Collapse and Solar Nebula Formation	124
3.3	Chemical Zones in the Solar Nebula	134
3.4	Cosmochemical Classification of the Elements	137
3.4.1	Condensation Temperatures	138
3.5	Solar System Timescales	158
3.5.1	Chronometers with Long-lived Radioactivities	160
3.5.2	Short-lived Radioactivities	172
3.6	An Early Solar System Timeline	176
	Further Reading and Resources	178
	References	179
Chapter 4	The Bodies in the Inner Solar System	184
4.1	Introduction	184
4.2	Physical and Chemical Properties	185

4.2.1	Physical Properties	185
4.2.2	Chemical Properties	199
4.2.3	The Earth's Moon	229
4.2.4	Comparison of Planetary Compositions	243
4.3	Accretion Scenarios	246
4.3.1	Rock, Ice and Gas	246
4.3.2	Accretion Models	250
4.4	Atmospheres and Surfaces of Venus and Mars	260
4.4.1	Overview	260
4.4.2	Surface Composition and Chemistry	277
4.5	Origin and Evolution of Terrestrial Planet Atmospheres	284
4.6	Extrasolar Terrestrial Planets	293
	Further Reading	294
	References	294
Chapter 5	Terrestrial Atmospheric Chemistry	298
5.1	Introduction	298
5.2	Basic Definitions	298
5.2.1	Mixing Ratio	298
5.2.2	Column Abundance	299
5.2.3	Hydrostatic Equilibrium, Scale Height and Barometric Equation	303
5.2.4	Top of the Atmosphere	305
5.2.5	Eddy Diffusion Coefficient	306
5.3	Major Features of Earth's Atmosphere	307
5.3.1	Troposphere	308
5.3.2	Tropopause and Stratosphere	310
5.3.3	Stratopause and Mesosphere	311
5.3.4	Thermosphere, Exosphere and Ionosphere	311
5.4	Atmospheric Composition	312
5.5	Tropospheric Chemistry	315
5.5.1	OH Radical and Oxidation Reactions	315
5.5.2	Tropospheric Ozone	317
5.5.3	Carbon Monoxide	319
5.5.4	Methane	320
5.6	Stratospheric Chemistry	323
5.6.1	Ozone	323
5.6.2	History of the Discovery of the Ozone Layer	324
5.6.3	Ozone Abundance Measurements	328
5.6.4	Chapman Cycle	328
5.6.5	Catalytic Cycles for Ozone Destruction	329
5.6.6	Hydrogen Oxide (HO _x) Catalytic Cycles	330
5.6.7	Nitrogen Oxide (NO _x) Catalytic Cycles	332

5.6.8	Halogen Oxide (ClO_x , BrO_x , IO_x) Catalytic Cycles	333
5.6.9	Antarctic Ozone Hole	338
5.6.10	Oxygen Isotopic Fractionations in Ozone	340
5.7	Mesospheric and Thermospheric Chemistry	340
5.8	Ionospheric Chemistry	342
	Further Reading	343
Chapter 6	The Greenhouse Effect and Biogeochemical Cycles on Earth	345
6.1	Introduction	345
6.2	Greenhouse Effect and Greenhouse Gases	345
6.2.1	Solar Energy Received by the Earth	345
6.2.2	Budget for the Incoming Solar Flux	346
6.2.3	Budget for Earth's Outgoing Flux	346
6.2.4	Greenhouse Effect	349
6.2.5	Heat Absorbing or Greenhouse Gases	349
6.3	Biogeochemical Cycles	351
6.3.1	Earth's Geochemical Reservoirs	351
6.3.2	Carbon Cycle	361
6.3.3	Nitrogen Cycle	371
6.3.4	Sulfur Cycle	379
6.3.5	Phosphorus and Halogen Cycles	384
	Further Reading	390
Chapter 7	The Outer Solar System	391
7.1	Introduction	391
7.2	The Giant Planets	391
7.2.1	Overview	391
7.2.2	Jupiter and Saturn: The Gas-rich Giant Planets	393
7.2.3	Uranus and Neptune: The Gas-poor Giant Planets	405
7.2.4	Photochemistry on the Giant Planets	409
7.3	Satellites and Rings of the Giant Planets	419
7.3.1	Galilean Satellites	426
7.3.2	Titan	427
7.4	Dwarf Planets	431
	Further Reading	433
	References	433
Appendix A	Table of Abundances of Nuclides in the Solar System	435

Appendix B	Table of Average Element Concentrations in Major Chondritic Meteorite Groups	444
Appendix C	Review of Chemical Kinetics	448
	C.1 Unimolecular Reactions	449
	C.2 Bimolecular or Two-body Reactions	451
	C.3 Termolecular or Three-body Reactions	452
	Further Reading	453
Subject Index		454