

# **Physics and Chemistry of the Solar System**

---

**John S. Lewis**

Department of Planetary Sciences  
University of Arizona  
Tucson, Arizona



**Academic Press**

San Diego New York Boston London Sydney Tokyo Toronto

# Contents



## Preface ix

|  |    |
|--|----|
| Outline of Star Formation              | 30 |
| Stellar Explosions and Nucleosynthesis | 31 |
| Nuclear Cosmochronology                | 40 |

## I Introduction

|                                       |   |
|---------------------------------------|---|
| Nature and Scope of Planetary Science | 1 |
| Guide to the Literature               | 3 |

## II Astronomical Perspective

|  |    |
|--|----|
| Introduction                             | 5  |
| Distance Scales in the Universe          | 5  |
| The Big Bang                             | 8  |
| Limitations on Big Bang Nucleosynthesis  | 11 |
| Galaxy and Star Formation                | 13 |
| Structure and Classification of Galaxies | 13 |
| Classification of Stars                  | 16 |
| Stellar Evolution                        | 22 |
| Star Clusters                            | 24 |
| Stellar Origins                          | 27 |

## III General Description of the Solar System

|  |    |
|--|----|
| Introduction                           | 44 |
| The Sun                                | 44 |
| Orbits of the Planets                  | 45 |
| Properties of the Planets              | 50 |
| Mass and Angular Momentum Distribution | 53 |
| Satellites                             | 57 |
| Asteroids                              | 59 |
| Comets                                 | 61 |
| Meteors                                | 62 |
| Meteorites                             | 62 |
| Cosmic Dust                            | 64 |
| Cosmic Rays                            | 65 |
| Planetary Science in the Space Age     | 65 |
| Summary                                | 65 |

## IV The Sun and the Solar Nebula

|   |     |
|---|-----|
| Introduction                                      | 66  |
| Energy Production in the Sun                      | 66  |
| Energy Transport in the Sun                       | 68  |
| Internal Structure of the Sun                     | 71  |
| Surface of the Sun                                | 72  |
| The Chromosphere                                  | 75  |
| The Corona  | 76  |
| Discovery of the Solar Wind                       | 78  |
| Radio Wave Propagation in Space Plasmas           | 79  |
| The Solar Wind                                    | 80  |
| Chemistry of Solar Material                       | 83  |
| Ionization  | 84  |
| Dissociation and Molecule Formation               | 86  |
| Hydrogen and the Rare Gases                       | 87  |
| Oxygen, Carbon, and Nitrogen                      | 89  |
| Magnesium and Silicon                             | 91  |
| Iron  | 92  |
| Sulfur  | 93  |
| Aluminum and Calcium                              | 94  |
| Sodium and Potassium                              | 95  |
| Nickel and Cobalt                                 | 96  |
| Phosphorus and the Halogens                       | 97  |
| Geochemical Classification of the Elements        | 97  |
| The Chemistry of Rapid Accretion                  | 101 |
| Kinetic Inhibition                                | 103 |
| Mass and Density of the Solar Nebula              | 104 |
| Thermal Opacity in the Solar Nebula               | 107 |
| Dust Opacity                                      | 114 |
| Thermal Structure of the Nebula                   | 116 |
| Turbulence and Dust Sedimentation                 | 118 |
| Accretion of Rocks, Planetesimals,<br>and Planets | 120 |
| Gas Capture from the Solar Nebula                 | 122 |
| The T-Tauri Phase                                 | 124 |
| Thermal History of the Early Solar System         | 126 |

## V The Major Planets

|  |     |
|--|-----|
| Introduction   | 129 |
| Interiors of Jupiter and Saturn: Data  | 130 |
| Isothermal Interior Models of Jupiter<br>and Saturn                                    | 133 |
| Thermal Models of Jupiter and Saturn   | 136 |
| The Atmospheres of Jupiter and Saturn:<br>Observed Composition                         | 137 |
| Tropospheric Composition and Structure:<br>Theory                                      | 140 |
| Cloud Condensation in the NH <sub>3</sub> –H <sub>2</sub> O–H <sub>2</sub> S<br>System | 146 |

|  |     |
|--|-----|
| Cloud Physics on the Jovian Planets                      | 154 |
| Ion Production in the Jovian Atmosphere                  | 159 |
| Visible and Infrared Radiative Transfer                  | 161 |
| Horizontal Structure and Atmospheric<br>Circulation      | 164 |
| Photochemistry and Aeronomy                              | 177 |
| The Jovian Thermosphere                                  | 193 |
| Radiophysics and Magnetospheres of Jupiter and<br>Saturn | 194 |
| The Interiors of Uranus and Neptune                      | 206 |
| Atmospheres of Uranus and Neptune                        | 213 |
| Perspectives   | 220 |

## VI Pluto and the Icy Satellites of the Outer Planets

|  |     |
|--|-----|
| Introduction   | 222 |
| Surfaces of Icy Satellites                           | 223 |
| Eclipse Radiometry                                   | 226 |
| Surface Temperatures                                 | 227 |
| Surface Morphology of the Galilean Satellites        | 229 |
| Density and Composition of Icy Satellites            | 234 |
| Internal Thermal Structure of Galilean<br>Satellites | 237 |
| Dynamical Interactions of the Galilean<br>Satellites | 241 |
| Thermal and Tectonic Evolution of Icy<br>Satellites  | 243 |
| Minor Satellites of Jupiter                          | 246 |
| Planetary Rings                                      | 247 |
| Titan  | 257 |
| The Intermediate-Sized Saturnian Satellites          | 260 |
| Minor Satellites of Saturn                           | 264 |
| Satellites of Uranus                                 | 265 |
| Satellites of Neptune                                | 270 |
| The Pluto–Charon System                              | 274 |
| The Neptune–Pluto Resonance                          | 276 |
| Spacecraft Exploration                               | 276 |

## VII Comets and Meteors

|  |     |
|--|-----|
| Historical Perspectives                            | 278 |
| The Nature of Comets                               | 279 |
| Cometary Orbits                                    | 281 |
| Heating by Passing Stars                           | 285 |
| Evaporation and Nongravitational Forces            | 286 |
| The Nucleus and Coma of P/Halley                   | 287 |
| Chemistry and Photochemistry of Water              | 288 |
| Further Chemical Processes in the Coma<br>and Tail | 291 |

|                                     |     |
|-------------------------------------|-----|
| Behavior of Small Particles         | 292 |
| Dynamical Behavior of Dust in Space | 293 |
| Meteors                             | 295 |
| Cometary Fireballs                  | 301 |
| Cometary Impacts on Jupiter         | 302 |

## VIII Meteorites and Asteroids

|   |     |
|---|-----|
| Introduction  | 304 |
| Introduction to Meteorites                            | 304 |
| Meteorite Orbits                                      | 307 |
| Phenomena of Fall                                     | 308 |
| Physical Properties of Meteorites                     | 311 |
| Meteorite Minerals                                    | 314 |
| Composition of Chondrites                             | 316 |
| Composition of Achondrites                            | 321 |
| Composition of Stony-Irons                            | 323 |
| Composition of Irons                                  | 323 |
| Isotopic Composition of Meteorites                    | 325 |
| Genetic Relationships between Meteorite Classes       | 333 |
| Introduction to Asteroids                             | 334 |
| Asteroid Orbits                                       | 336 |
| Stability of Trojan Orbits                            | 337 |
| Sizes, Shapes, and Albedos of Asteroids               | 339 |
| Masses and Densities of Asteroids                     | 340 |
| Photometry and Spectroscopy of Asteroids              | 342 |
| Thermal Evolution of Asteroids                        | 347 |
| Dynamical Evolution of the Asteroid Belt              | 351 |
| Relationships among Asteroids, Meteorites, and Comets | 354 |
| Asteroid Resources                                    | 357 |

|  |     |
|--|-----|
| Lunar Rock Types                                 | 383 |
| Lunar Minerals                                   | 383 |
| Lunar Elemental Abundance Patterns               | 385 |
| Geology of the Moon                              | 385 |
| Geophysics of the Moon                           | 386 |
| History of the Earth–Moon System                 | 390 |
| Origin and Internal Evolution of the Moon        | 391 |
| Solar Wind Interaction with the Moon and Mercury | 392 |
| The Planet Mercury                               | 393 |
| Motions of Mercury                               | 394 |
| Composition and Structure of Mercury             | 395 |
| Noncrater Geology of Mercury                     | 395 |
| Geophysics of Mercury                            | 398 |
| Atmospheres of Mercury and the Moon              | 400 |
| Polar Deposits on Mercury and the Moon           | 401 |
| Unfinished Business                              | 404 |

## X The Terrestrial Planets: Mars, Venus, and Earth

|  |     |
|--|-----|
| Introduction   | 406 |
| Mars   | 407 |
| Motions of Mars  | 408 |
| Density and Figure of Mars                             | 408 |
| Geophysical Data on Mars                               | 410 |
| Gravity and Tectonics of Mars                          | 411 |
| Geology of Mars  | 411 |
| Surface Composition                                    | 424 |
| Viking Lander Investigations                           | 427 |
| The Shergottite, Nakhelite, and Chassignite Meteorites | 429 |
| Atmospheric Structure                                  | 430 |
| Atmospheric Circulation                                | 431 |
| Atmospheric Composition                                | 432 |
| Photochemical Stability and Atmospheric Escape         | 435 |
| Explosive Blowoff                                      | 440 |
| Origin and Evolution of the Atmosphere                 | 440 |
| Organic Matter and the Origin of Life                  | 443 |
| Venus  | 445 |
| Motions and Dynamics of Venus                          | 446 |
| Geophysical Data on Venus                              | 447 |
| Geology of Venus                                       | 448 |
| Venus: Atmospheric Structure and Motions               | 454 |
| Venus: Atmospheric Composition                         | 456 |
| Venus: Atmosphere–Lithosphere Interactions             | 459 |
| Venus: Photochemistry and Aeronomy                     | 462 |
| Venus: Atmospheric Escape                              | 465 |
| Venus: Planetary Evolution                             | 468 |
| Earth  | 468 |

## IX The Airless Rocky Bodies: Io, Phobos, Deimos, the Moon, and Mercury

|  |     |
|--|-----|
| Introduction                                       | 361 |
| Orbits and Physical Structure of Phobos and Deimos | 363 |
| Io: General Properties                             | 365 |
| Io: Surface Processes                              | 366 |
| Io: Internal Energy Sources                        | 366 |
| Io: Geology  | 370 |
| Io: Atmospheric and Volcanic Gases                 | 372 |
| Io: Escape and the Plasma Torus                    | 374 |
| Io: Genetic Relationships                          | 374 |
| Impact Cratering                                   | 374 |
| Motions of the Moon                                | 380 |
| Physical Properties of the Moon                    | 381 |
| Composition of the Moon                            | 382 |

|   |     |
|---|-----|
| Earth: Motions                            | 469 |
| Earth: Internal Structure                 | 470 |
| Earth: Magnetic Field and Magnetosphere   | 472 |
| Earth: Surface Geology                    | 472 |
| Earth: Early Geological History           | 475 |
| Earth: Biological History                 | 476 |
| Earth: Geochemistry and Petrology         | 480 |
| Weathering in the Rock Cycle              | 483 |
| Earth: Atmospheric Composition and Cycles | 485 |
| Radiocarbon Dating                        | 489 |
| Photochemistry and Aeronomy               | 490 |
| Escape and Infall                         | 492 |
| Polar Ice, Glaciation, and Ice Ages       | 494 |
| Life: Origins                             | 495 |
| Life: Stability and the Biosphere         | 500 |

## XI Planets and Life about Other Stars

|  |     |
|--|-----|
| Introduction                                 | 502 |
| Chemical and Physical Prerequisites of Life  | 502 |
| The Stellar Environment                      | 505 |
| The Search for Planets of Other Stars        | 506 |
| The Search for Extraterrestrial Intelligence | 508 |

## XII Future Prospects

|                             |     |
|-----------------------------|-----|
| Introduction                | 510 |
| Mercury                     | 512 |
| Venus                       | 512 |
| Earth's Moon                | 512 |
| Mars                        | 513 |
| Asteroids                   | 514 |
| Jupiter                     | 514 |
| Saturn, Uranus, and Neptune | 514 |
| Pluto                       | 515 |
| Comets                      | 515 |
| Beyond the Solar System     | 515 |

## Appendix I: Equilibrium

### Thermodynamics 519

|                                       |     |
|---------------------------------------|-----|
| Heat and Work                         | 519 |
| Adiabatic Processes and Entropy       | 520 |
| Useful Work and the Gibbs Free Energy | 521 |
| Chemical Equilibrium                  | 521 |
| Exact and Complete Differentials      | 522 |
| The Maxwell Relations                 | 523 |

## Appendix II: Absorption and Emission of Radiation by Quantum Oscillators 524

## Appendix III: Exploration of the Solar System 527

## Appendix IV: Basic Physical Constants 532

## Suggested Readings

|   |     |
|---|-----|
| Introduction  | 533 |
| Chapter I. Introduction   | 533 |
| Chapter II. Astronomical Perspective  | 533 |
| Chapter III. General Description of the Solar System                            | 534 |
| Chapter IV. The Sun and the Solar Nebula  | 534 |
| Chapter V. The Major Planets  | 534 |
| Chapter VI. Pluto and the Icy Satellites of the Outer Planets                   | 535 |
| Chapter VII. Comets and Meteors   | 535 |
| Chapter VIII. Meteorites and Asteroids  | 535 |
| Chapter IX. The Airless Rocky Bodies: Io, Phobos, Deimos, the Moon, and Mercury | 535 |
| Chapter X. The Terrestrial Planets: Mars, Venus, and Earth                      | 536 |
| Chapter XI. Planets and Life about Other Stars                                  | 536 |
| Chapter XII. Future Prospects   | 537 |

## Index 538