KONRAD B. KRAUSKOPF / ARTHUR BEISER

THE PHYSICAL UNIVERSE

Sixteenth Edition

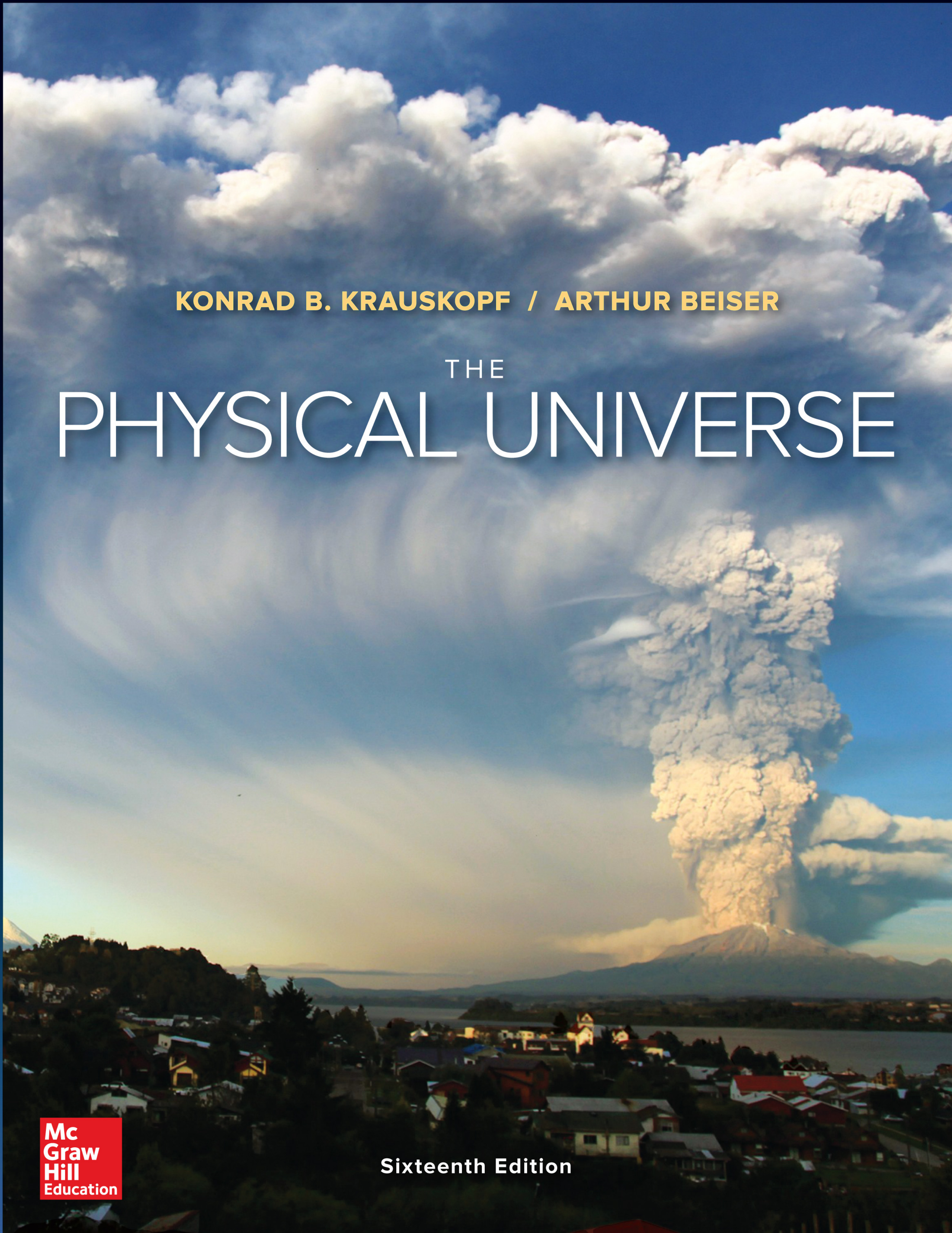

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Table 17-1 The Planets

Planet	Symbol	Mean Distance from Sun, Earth = 1[a]	Diameter, Thousands of km	Mass, Earth = 1[b]	Mean Density, Water = 1[c]	Surface Gravity, Earth = 1[d]	Escape Speed, km/s[e]	Period of Rotation on Axis	Period of Revolution around Sun	Eccentricity of Orbit[h]	Inclination of Orbit to Ecliptic[i]	Known Satellites[j]
Mercury	☿	0.39	4.9	0.055	5.4	0.38	4.3	59 days	88 days	0.21	7° 00′	0
Venus	♀	0.72	12.1	0.82	5.25	0.90	10.4	243 days[f]	225 days	0.01	3°34′	0
Earth	⊕	1.00	12.7	1.00	5.52	1.00	11.2	24 h	365 days	0.02	—	1
Mars	♂	1.52	6.8	0.11	3.93	0.38	5.0	24.5 h	687 days	0.09	1°51′	2
Jupiter	♃	5.20	143	318	1.33	2.6	60	10 h	11.9 yr	0.05	1° 8′	67
Saturn	♄	9.54	120	95	0.71	1.2	36	10 h	29.5 yr	0.06	2°29′	62
Uranus	⛢	19.2	51	15	1.27	1.1	22	16 h[g]	84 yr	0.05	0°46′	27
Neptune	♆	30.1	50	17	1.70	1.2	24	16 h	165 yr	0.01	1°46′	14

[a] *The mean earth-sun distance is called the astronomical unit, where 1 AU =* 1.496×10^8 *km.*
[b] *The earth's mass is* 5.98×10^{24} *kg.*
[c] *The density of water is* $1\ g/cm^3 = 10^3\ kg/m^3$.
[d] *The acceleration of gravity at the earth's surface is* $9.81\ m/s^2$.
[e] *Speed needed for permanent escape from the planet's gravitational field.*
[f] *Venus rotates in the opposite direction from the other planets.*
[g] *The axis of rotation of Uranus is only 8° from the plane of its orbit.*
[h] *The difference between the minimum and maximum distances from the sun divided by the average distance.*
[i] *The ecliptic is the plane of the earth's orbit.*
[j] *Probably more small ones around Jupiter, Saturn, and Uranus.*

The Physical Universe

Sixteenth Edition

Konrad B. Krauskopf
Late Professor Emeritus of Geochemistry, Stanford University

Arthur Beiser

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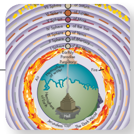
Brief Contents

	Preface	xii
1	The Scientific Method	1
2	Motion	27
3	Energy	62
4	Energy and the Future	93
5	Matter and Heat	144
6	Electricity and Magnetism	184
7	Waves	222
8	The Nucleus	262
9	The Atom	299
10	The Periodic Law	328
11	Crystals, Ions, and Solutions	360
12	Chemical Reactions	391
13	Organic Chemistry	421
14	Atmosphere and Hydrosphere	460
15	The Rock Cycle	501
16	The Evolving Earth	543
17	The Solar System	589
18	The Stars	634
19	The Universe	665
	Math Refresher	A-1
	The Elements	A-10
	Answers to Multiple-Choice Questions and Odd-Numbered Exercises	A-11
	Photo Credits	C-1
	Index	I-1

Contents

Preface xii

1 The Scientific Method 1



How Scientists Study Nature 2
- **1.1** The Scientific Method 3
- **1.2** Why Science Is Successful 5

The Solar System 6
- **1.3** A Survey of the Sky 6
- **1.4** The Ptolemaic System 8
- **1.5** The Copernican System 10
- **1.6** Kepler's Laws 11
- **1.7** Why Copernicus Was Right 14

Universal Gravitation 15
- **1.8** What Is Gravity? 15
- **1.9** Why the Earth Is Round 17
- **1.10** The Tides 18
- **1.11** The Discovery of Neptune 19

How Many of What 20
- **1.12** The SI System 21

Important Terms and Ideas 24
Multiple Choice 24
Exercises 26

2 Motion 27

Describing Motion 28
- **2.1** Speed 28
- **2.2** Vectors 31
- **2.3** Acceleration 32
- **2.4** Distance, Time, and Acceleration 34

Acceleration Due to Gravity 35
- **2.5** Free Fall 36
- **2.6** Air Resistance 40

Force and Motion 40
- **2.7** First Law of Motion 41
- **2.8** Mass 42
- **2.9** Second Law of Motion 44
- **2.10** Mass and Weight 46
- **2.11** Third Law of Motion 47

Gravitation 48
- **2.12** Circular Motion 49
- **2.13** Newton's Law of Gravity 51
- **2.14** Artificial Satellites 52

Important Terms and Ideas 55
Important Formulas 56
Multiple Choice 56
Exercises 58

3 Energy 62

Work 63
- **3.1** The Meaning of Work 63
- **3.2** Power 65

Energy 67
- **3.3** Kinetic Energy 67
- **3.4** Potential Energy 69
- **3.5** Conservation of Energy 71
- **3.6** Mechanical Advantage 73
- **3.7** The Nature of Heat 75

Momentum 77
- **3.8** Linear Momentum 77
- **3.9** Rockets 79
- **3.10** Angular Momentum 80

Relativity 82
- **3.11** Special Relativity 82
- **3.12** Rest Energy 84
- **3.13** General Relativity 85

Important Terms and Ideas 87
Important Formulas 87
Multiple Choice 88
Exercises 89

4 Energy and the Future 93

The Energy Problem 95
- **4.1** Population and Prosperity 95
- **4.2** Energy Supply and Consumption 96

4.3 Climate Change 99
4.4 Carbon Dioxide and the Greenhouse Effect 102

Fossil Fuels 107
4.5 Liquid Fuels 108
4.6 Natural Gas 110
4.7 Coal 112

Alternative Sources 118
4.8 A Nuclear World? 118
4.9 Clean Energy I 121
4.10 Clean Energy II 124
4.11 Energy Storage 128
4.12 Biofuels 131

Strategies For The Future 133
4.13 Conservation 134
4.14 What Governments Must Do 136

Important Terms and Ideas 140
Multiple Choice 141
Exercises 142

5 Matter and Heat 144

Temperature and Heat 145
5.1 Temperature 146
5.2 Heat 148
5.3 Metabolic Energy 150

Fluids 152
5.4 Density 152
5.5 Pressure 153
5.6 Buoyancy 155
5.7 The Gas Laws 157

Kinetic Theory of Matter 162
5.8 Kinetic Theory of Gases 162
5.9 Molecular Motion and Temperature 163
5.10 Heat Transfer 164

Changes of State 165
5.11 Liquids and Solids 165
5.12 Evaporation and Boiling 166
5.13 Melting 167

Energy Transformations 170
5.14 Heat Engines 171
5.15 Thermodynamics 172
5.16 Fate of the Universe 175
5.17 Entropy 176

Important Terms and Ideas 177
Important Formulas 177
Multiple Choice 177
Exercises 180

6 Electricity and Magnetism 184

Electric Charge 186
6.1 Positive and Negative Charge 186
6.2 What Is Charge? 187
6.3 Coulomb's Law 189
6.4 Force on an Uncharged Object 190

Electricity and Matter 191
6.5 Matter in Bulk 191
6.6 Conductors and Insulators 191
6.7 Superconductivity 193

Electric Current 194
6.8 The Ampere 194
6.9 Potential Difference 195
6.10 Ohm's Law 198
6.11 Electric Power 200

Magnetism 202
6.12 Magnets 203
6.13 Magnetic Field 204
6.14 Oersted's Experiment 205
6.15 Electromagnets 207

Using Magnetism 208
6.16 Magnetic Force on a Current 208
6.17 Electric Motors 209
6.18 Electromagnetic Induction 210
6.19 Transformers 213

Important Terms and Ideas 216
Important Formulas 216
Multiple Choice 216
Exercises 219

7 Waves 222

Wave Motion 223
7.1 Water Waves 224
7.2 Transverse and Longitudinal Waves 225
7.3 Describing Waves 226
7.4 Standing Waves 227

Sound Waves 229
7.5 Sound 229
7.6 Doppler Effect 230
7.7 Musical Sounds 232

Electromagnetic Waves 233
7.8 Electromagnetic Waves 234
7.9 Types of EM Waves 235
7.10 Light "Rays" 238

Wave Behavior 239
7.11 Reflection 239
7.12 Refraction 239
7.13 Lenses 243
7.14 The Eye 247
7.15 Color 248
7.16 Interference 251
7.17 Diffraction 252
Important Terms and Ideas 256
Important Formulas 256
Multiple Choice 256
Exercises 259

8 The Nucleus 262

Atom And Nucleus 263
8.1 Rutherford Model of the Atom 264
8.2 Nuclear Structure 265
Radioactivity 267
8.3 Radioactive Decay 268
8.4 Half-Life 270
8.5 Radiation Hazards 271
Nuclear Energy 274
8.6 Units of Mass and Energy 274
8.7 Binding Energy 275
8.8 Binding Energy per Nucleon 276
Fission And Fusion 277
8.9 Nuclear Fission 278
8.10 How a Reactor Works 280
8.11 Reactor Accidents 283
8.12 Plutonium 285
8.13 Nuclear Fusion 286
Elementary Particles 288
8.14 Antiparticles 289
8.15 Fundamental Interactions 290
8.16 Leptons and Hadrons 292
Important Terms and Ideas 294
Multiple Choice 294
Exercises 296

9 The Atom 299

Quantum Theory of Light 300
9.1 Photoelectric Effect 301
9.2 Photons 301
9.3 What Is Light? 304
9.4 X-Rays 305
Matter Waves 306
9.5 De Broglie Waves 306
9.6 Waves of What? 307
9.7 Uncertainty Principle 308
The Hydrogen Atom 310
9.8 Atomic Spectra 310
9.9 The Bohr Model 311
9.10 Electron Waves and Orbits 313
9.11 The Laser 315
Quantum Theory of the Atom 318
9.12 Quantum Mechanics 319
9.13 Quantum Numbers 320
9.14 Exclusion Principle 322
Important Terms and Ideas 323
Important Formulas 323
Multiple Choice 323
Exercises 325

10 The Periodic Law 328

Elements and Compounds 329
10.1 Chemical Change 330
10.2 Three Classes of Matter 330
10.3 The Atomic Theory 333
The Periodic Law 334
10.4 Metals and Nonmetals 334
10.5 Chemical Activity 335
10.6 Families of Elements 336
10.7 The Periodic Table 338
10.8 Groups and Periods 338
Atomic Structure 341
10.9 Shells and Subshells 342
10.10 Explaining the Periodic Table 343
Chemical Bonds 346
10.11 Types of Bond 346
10.12 Covalent Bonding 347
10.13 Ionic Bonding 349
10.14 Ionic Compounds 350
10.15 Naming Compounds 352
10.16 Chemical Equations 352
10.17 Types of Chemical Reactions 354
Important Terms and Ideas 355
Multiple Choice 355
Exercises 357

11 Crystals, Ions, and Solutions 360

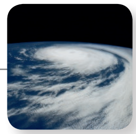
Solids 361
11.1 Ionic and Covalent Crystals 362
11.2 The Metallic Bond 364
11.3 Molecular Crystals 366
Solutions 370
11.4 Solubility 370
11.5 Polar and Nonpolar Liquids 372
11.6 Ions in Solution 374
11.7 Evidence for Dissociation 376
11.8 Water 377
11.9 Water Pollution 380
Acids and Bases 382
11.10 Acids 382
11.11 Strong and Weak Acids 383
11.12 Bases 384
11.13 The pH Scale 385
11.14 Salts 385
Important Terms and Ideas 387
Multiple Choice 387
Exercises 389

12 Chemical Reactions 391

Quantitative Chemistry 392
12.1 Phlogiston 393
12.2 Oxygen 395
12.3 The Mole 396
12.4 Formula Units 398
Chemical Energy 399
12.5 Exothermic and Endothermic Reactions 401
12.6 Chemical Energy and Stability 402
12.7 Activation Energy 405
Reaction Rates 406
12.8 Temperature and Reaction Rates 407
12.9 Other Factors 407
12.10 Chemical Equilibrium 409
12.11 Altering an Equilibrium 410
Oxidation and Reduction 411
12.12 Oxidation-Reduction Reactions 411
12.13 Electrochemical Cells 413
Important Terms and Ideas 416
Multiple Choice 416
Exercises 418

13 Organic Chemistry 421

Carbon Compounds 422
13.1 Carbon Bonds 423
13.2 Alkanes 423
13.3 Petroleum Products 424
Structures of Organic Molecules 427
13.4 Structural Formulas 427
13.5 Isomers 428
13.6 Unsaturated Hydrocarbons 430
13.7 Benzene 432
Organic Compounds 433
13.8 Hydrocarbon Groups 433
13.9 Functional Groups 434
13.10 Polymers 437
Chemistry of Life 443
13.11 Carbohydrates 443
13.12 Photosynthesis 445
13.13 Lipids 446
13.14 Proteins 447
13.15 Soil Nitrogen 449
13.16 Nucleic Acids 451
13.17 Origin of Life 452
Important Terms and Ideas 454
Multiple Choice 455
Exercises 457



14 Atmosphere and Hydrosphere 460

The Atmosphere 461
14.1 Regions of the Atmosphere 461
14.2 Atmospheric Moisture 464
14.3 Clouds 466
Weather 470
14.4 Atmospheric Energy 470
14.5 The Seasons 473
14.6 Winds 474
14.7 General Circulation of the Atmosphere 475
14.8 Middle-Latitude Weather Systems 478
Climate 486
14.9 Tropical Climates 486
14.10 Middle- and High-Latitude Climates 486
14.11 Climate Change 487
The Hydrosphere 490
14.12 Ocean Basins 491
14.13 Ocean Currents 493

Important Terms and Ideas 495
Multiple Choice 496
Exercises 498

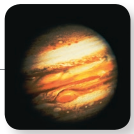
15 The Rock Cycle 501

Rocks 503
15.1 Composition of the Crust 503
15.2 Minerals 504
15.3 Igneous Rocks 506
15.4 Sedimentary Rocks 507
15.5 Metamorphic Rocks 509
Within the Earth 511
15.6 Earthquakes 511
15.7 Structure of the Earth 513
15.8 The Earth's Interior 518
15.9 Geomagnetism 520
Erosion 520
15.10 Weathering 521
15.11 Stream Erosion 522
15.12 Glaciers 525
15.13 Groundwater 526
15.14 Sedimentation 527
Vulcanism 531
15.15 Volcanoes 531
15.16 Intrusive Rocks 535
15.17 The Rock Cycle 537
Important Terms and Ideas 538
Multiple Choice 538
Exercises 540

16 The Evolving Earth 543

Tectonic Movement 545
16.1 Types of Deformation 545
16.2 Mountain Building 546
16.3 Continental Drift 547
Plate Tectonics 550
16.4 Lithosphere and Asthenosphere 551
16.5 The Ocean Floors 551
16.6 Ocean-Floor Spreading 553
16.7 Plate Tectonics 554
Methods of Historical Geology 561
16.8 Principle of Uniform Change 561
16.9 Rock Formations 564
16.10 Radiometric Dating 565
16.11 Fossils 567
16.12 Geologic Time 568
Earth History 570
16.13 Precambrian Time 571
16.14 The Paleozoic Era 572
16.15 Coal and Petroleum 574
16.16 The Mesozoic Era 576
16.17 The Cenozoic Era 579
16.18 Human History 581
Important Terms and Ideas 584
Multiple Choice 585
Exercises 587

17 The Solar System 589



The Family of the Sun 590
17.1 The Solar System 591
17.2 Comets 594
17.3 Meteors 595
The Inner Planets 600
17.4 Mercury 600
17.5 Venus 601
17.6 Mars 604
17.7 Is There Life on Mars? 606
17.8 Asteroids 608
The Outer Planets 611
17.9 Jupiter 611
17.10 Saturn 614
17.11 Uranus, Neptune, Pluto, and More 617
The Moon 620
17.12 Phases of the Moon 621
17.13 Eclipses 622
17.14 Lunar Surface and Interior 624
17.15 Evolution of the Lunar Landscape 627
17.16 Origin of the Moon 628
Important Terms and Ideas 629
Multiple Choice 630
Exercises 632

18 The Stars 634

Tools of Astronomy 635
18.1 The Telescope 636
18.2 The Spectrometer 637
18.3 Spectrum Analysis 639
The Sun 640
18.4 Properties of the Sun 641
18.5 The Aurora 643
18.6 Sunspots 644
18.7 Solar Energy 646

The Stars 648
18.8 Stellar Distances 648
18.9 Variable Stars 649
18.10 Stellar Motions 650
18.11 Stellar Properties 651

Life Histories of the Stars 652
18.12 H-R Diagram 652
18.13 Stellar Evolution 654
18.14 Supernovas 656
18.15 Pulsars 657
18.16 Black Holes 658

Important Terms and Ideas 661
Multiple Choice 661
Exercises 663

19 The Universe 665

Galaxies 666
19.1 The Milky Way 666
19.2 Stellar Populations 669
19.3 Radio Astronomy 670
19.4 Galaxies 671
19.5 Cosmic Rays 675

The Expanding Universe 677
19.6 Red Shifts 677
19.7 Quasars 679

Evolution of The Universe 680
19.8 Dating the Universe 681
19.9 After the Big Bang 682
19.10 Origin of the Solar System 687

Extraterrestrial Life 688
19.11 Exoplanets 689
19.12 Interstellar Travel 690
19.13 Interstellar Communication 691

Important Terms and Ideas 693
Multiple Choice 694
Exercises 696

Math Refresher A-1
The Elements A-10
Answers to Multiple-Choice Questions and Odd-Numbered Exercises A-11
Photo Credits C-1
Index I-1

Preface

Creating Informed Citizens

The aim of *The Physical Universe* is to present, as simply and clearly as possible, the essentials of physics, chemistry, earth science, and astronomy to students whose main interests lie elsewhere.

Because of the scope of these sciences and because we assume minimal preparation on the part of the reader, our choice of topics and how far to develop them had to be limited. The emphasis throughout is on the basic concepts of each discipline. We also try to show how scientists approach problems and why science is a never-ending quest rather than a fixed set of facts.

The book concentrates on those aspects of the physical sciences most relevant to a nonscientist who wants to understand how the universe works and to know something about the connections between science and everyday life. We hope to equip readers to appreciate major developments in science as they arrive and to be able to act as informed citizens on matters that involve science and public policy. In particular, there are serious questions today concerning energy supply and use and the contribution of carbon dioxide emissions to the climate changes that are under way. Debates on these questions require a certain amount of scientific literacy, which this book is intended to provide, in order that sensible choices be made that will determine the welfare of generations to come. Past choices have not always benefited our planet and its inhabitants: it is up to us to see that future choices do. There is little time left to make some of these choices, as Chapter 4 makes clear, and there is no Planet B to fall back on if we make the wrong ones.

Scope and Organization

There are many possible ways to organize a book of this kind. We chose the one that provides the most logical progression of ideas, so that each new subject builds on the ones that came before.

Our first concern in *The Physical Universe* is the scientific method, using as illustration the steps that led to today's picture of the universe and the earth's place in it. Next we consider motion and the influences that affect moving bodies. Gravity, energy, and momentum are examined, and the theory of relativity is introduced. Then we examine the many issues associated with the energy that today's world consumes in ever-increasing amounts and the accompanying environmental consequences. Matter in its three states now draws our attention, and we pursue this theme from the kinetic-molecular model to the laws of thermodynamics and the significance of entropy. A grounding in electricity and magnetism follows, and then an exploration of wave phenomena that includes the electromagnetic theory of light. We go on from there to the atomic nucleus and elementary particles, followed by a discussion of the quantum theories of light and of matter that lead to the modern view of atomic structure.

The transition from physics to chemistry is made via the periodic table. A look at chemical bonds and how they act to hold together molecules, solids, and liquids is followed by a survey of chemical reactions, organic chemistry, and the chemistry of life.

Our concern next shifts to the planet on which we live, and we begin by inquiring into the oceans of air and water that cover it. From there we proceed to the materials of the earth, to its ever-evolving crust, and to its no-longer-mysterious interior. After a survey of the main events in the earth's geological history (with a look at those of its biological history) we go on to what we know about our nearest neighbors in space—planets and satellites, asteroids, meteoroids, and comets.

Now the sun, the monarch of the solar system and the provider of nearly all our energy, claims our notice. We go on to broaden our astronomical sights to include the other stars, both individually and as members of the immense assemblies called galaxies. The evolution of the universe starting from the big bang is the last major subject, and we end with the origin of the earth and the likelihood that other inhabited planets exist in the universe and how we might communicate with them.

Website

A website (www.mhhe.com/Krauskopf) has been established that contains additional material of various kinds such as an instructor's manual, PowerPoint lectures, test bank, more worked examples, sidebars, and biographies.

Mathematical Level

The physical sciences are quantitative, which has both advantages and disadvantages. On the plus side, the use of mathematics allows many concepts to be put in the form of clear, definite statements that can be carried further by reasoning and whose predictions can be tested objectively. Less welcome is the discomfort many of us feel when faced with mathematical discussions.

The mathematical level of *The Physical Universe* follows Albert Einstein's prescription for physical theories: "Everything should be as simple as possible, but not simpler." A modest amount of mathematics enables the book to show how science makes sense of the natural world and how its findings led to the technological world of today. In general, the more complicated material supplements rather than dominates the presentation, and full mastery is not needed to understand the rest of the book. The basic algebra needed is reviewed in the Math Refresher. Powers-of-ten notation for small and large numbers is carefully explained there. This section is self-contained and can provide all the math background needed.

How much mathematics is appropriate for a given classroom is for each instructor to decide. To this end, a section is included in the Instructor's Manual that lists the slightly more difficult computational material in the text. This material can be covered as wished or omitted without affecting the continuity or conceptual coverage of a course.

New To This Edition

The entire book was brought up to date and new material was added where appropriate. The discussions of various topics and the explanations in a number of examples were modified for greater clarity. Nearly a thousand changes were made, including the following:

- There are 123 new photographs, and new or revised drawings throughout the text.
- Section 1.12 has a new subsection on converting units and the subsection on significant figures was revised.
- Sections 2.4, 2.5, and 2.9 example solutions were elaborated for better understanding of how to deal with accelerated motion. In Section 2.14 the sidebar on space junk was updated.

- Section 3.10 has a new biography of Emmy Noether, who discovered the significance of conservation principles.
- Chapter 4, whose 14 sections consider every aspect of the energy problem (including population pressures, energy supply, climate change, pros and cons of energy sources, and strategies to protect the environment), was almost entirely rewritten with greater coverage and updated information.
- Section 6.11, sidebar The Grid was updated and Example 6.8 was revised. In Section 6.16 the sidebar on maglev trains was updated.
- Section 7.10, the sidebar Ultraviolet and the Skin was revised.
- Section 8.5, the discussion of the hazards of medical x-rays was updated. In Sections 8.9–8.11 the material on nuclear weapons, nuclear reactors, nuclear wastes, and reactor accidents was revised and updated. In Section 8.16 the sidebar on new accelerators was updated.
- Section 10.10 now introduces the concept of ionization energy with a figure showing the ionization energies of the elements. In Section 10.14 the discussion of polyatomic ions was revised. In Section 10.16 how to balance a chemical equation is shown in more detail than before. Section 10.17 on types of chemical reactions is new.
- Section 11.2 has a revised sidebar on buckyballs, nanotubes, and graphene. Sections 11.8 and 11.9 on freshwater supply and pollution were revised and updated. Section 11.11 now considers the acidification of the oceans.
- Section 12.5 now includes information on nitrogen oxides in the atmosphere and Section 12.6 has a new table of chemical bond energies.
- Section 13.3 has a revised sidebar on oil spills. Sections 13.12 on photosynthesis and 13.13 on lipids were both revised. In Section 13.15 the sidebar on cooking was revised. Sections 13.16 and 13.17 have additional material on DNA and on its connection with the origin of life.
- Section 14.1 has updates on atmospheric ozone and on smog. Section 14.11 has been revised with more information on the Little Ice Age.
- Sections 16.12–16.16 on earth history were revised and include new information on the dinosaurs. Section 16.18 on human history and on the future of life on the earth was expanded and updated.
- Chapter 17 on the solar system incorporates the latest information on its members and on the space missions that were involved in the research.
- Section 18.1 on telescopes (including those in space) and Section 18.14 on supernovas were both updated.
- Section 19.3 on radio astronomy was revised. Section 19.4 has a new biography of Vera Rubin whose work helped establish the existence of the mysterious dark matter that is responsible for most of the mass of the universe. Section 19.9 on the early history of the universe was revised and now includes descriptions of cosmic inflation and gravitational waves. Section 19.11 on exoplanets was updated.

The Learning System

A variety of aids are provided in *The Physical Universe* to help the reader master the text.

Chapter Opener An outline provides a preview of major topics, showing at a glance what the chapter covers. Notable findings and ideas the chapter introduces are listed in order by section.

Illustrations Almost 800 illustrations, both line drawings and photographs, are full partners to the text and provide a visual pathway to understanding scientific observations and principles for students unaccustomed to abstract argument.

Worked Examples A full grasp of physical and chemical ideas includes an ability to solve problems based on these ideas. Some students, although able to follow the discussions in the book, nevertheless may have trouble putting their knowledge to use in this way. To help them, detailed solutions of typical problems are provided that show how to apply formulas and equations to real-world situations. Besides the worked examples, answers and outline solutions for half the end-of-chapter exercises are given at the end of the text. Thinking through the model solutions should bring the unsolved even-numbered problems within reach. In addition to its role in reinforcing the understanding of physical and chemical ideas, solving problems can provide great pleasure, and it would be a shame to miss out on this pleasure. The worked examples in the text are not limited to problems—nearly half of them show how basic ideas can be used to answer serious questions that do not involve calculations.

Bringing Science to Life

Biographies Brief biographies of major figures in the development of the physical sciences appear where appropriate throughout the text. The biographies provide human and historical perspectives by attaching faces and stories to milestones in these sciences.

Sidebars These are brief accounts of topics related to the main text. A sidebar may provide additional information on a particular subject, comment on its significance, describe its applications, consider its historical background, or present recent findings. Twenty new ones have been added for this edition.

End-of-Chapter Features

Important Terms and Ideas Important terms introduced in the chapter are listed together with their meanings, which serves as a chapter summary. A list of the **Important Formulas** needed to solve problems based on the chapter material is also given where appropriate.

Exercises An average of over a hundred exercises on all levels of difficulty follow each chapter. They are of three kinds, multiple choice, questions, and problems:

- **Multiple Choice** An average chapter has 41 Multiple-Choice exercises (with answers at the back of the book) that act as a quick, painless check on understanding. Correct answers provide reinforcement and encouragement; incorrect ones identify areas of weakness.
- **Exercises** Exercises consist of both questions and problems arranged according to the corresponding text section. Each group begins with questions and goes on to problems. Some of the questions are meant to find out how well the reader has understood the chapter material. Others ask the reader to apply what he or she has learned to new situations. Answers to the odd-numbered questions are given at the back of the book. The physics and chemistry chapters include problems that range from quite easy to moderately challenging. The ability to work out such problems signifies a real understanding of these subjects. Outline solutions (not just answers) for the odd-numbered problems are given at the back of the book.

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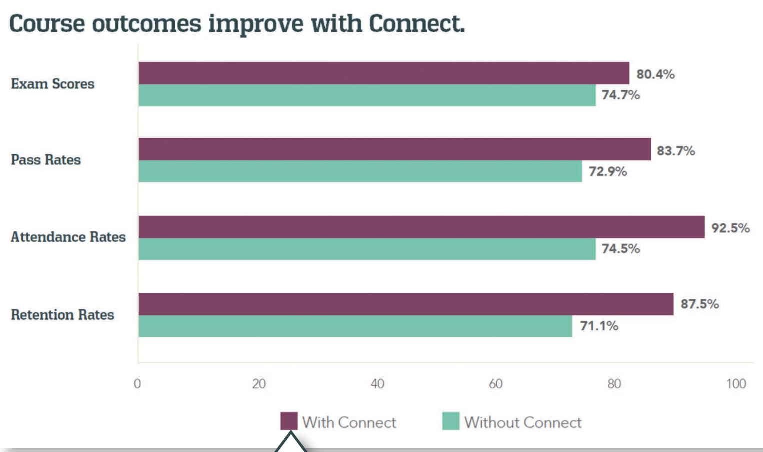

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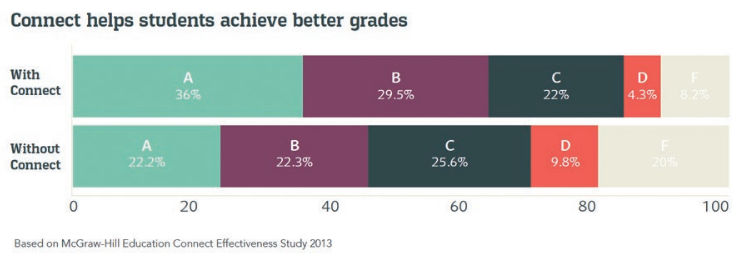

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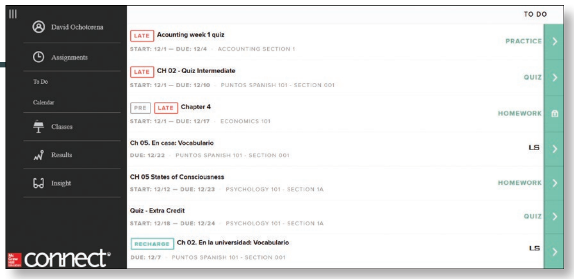

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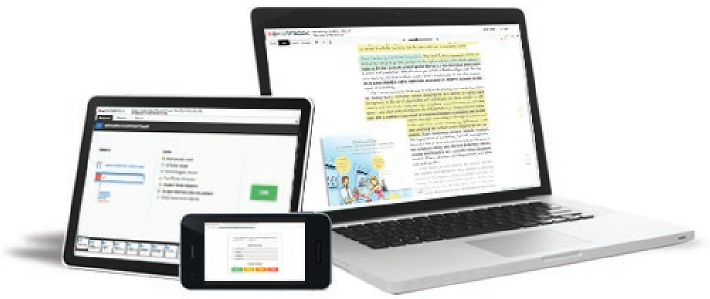

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Student Study Guide

Another helpful resource can be found in *The Physical Universe* Student Study Guide. With this study guide, students will maximize their use of *The Physical Universe* text package. It supplements the text with additional, self-directed activities and complements the text by focusing on the important concepts, theories, facts, and processes presented by the authors. The Student Study Guide ISBN 125968346X can be customized to your course and is available through McGraw-Hill Create™. Questions and Interactive Problems from the Student Study Guide are also assignable in Connect in an auto-gradable format.

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Arthur Beiser

Meet the Authors

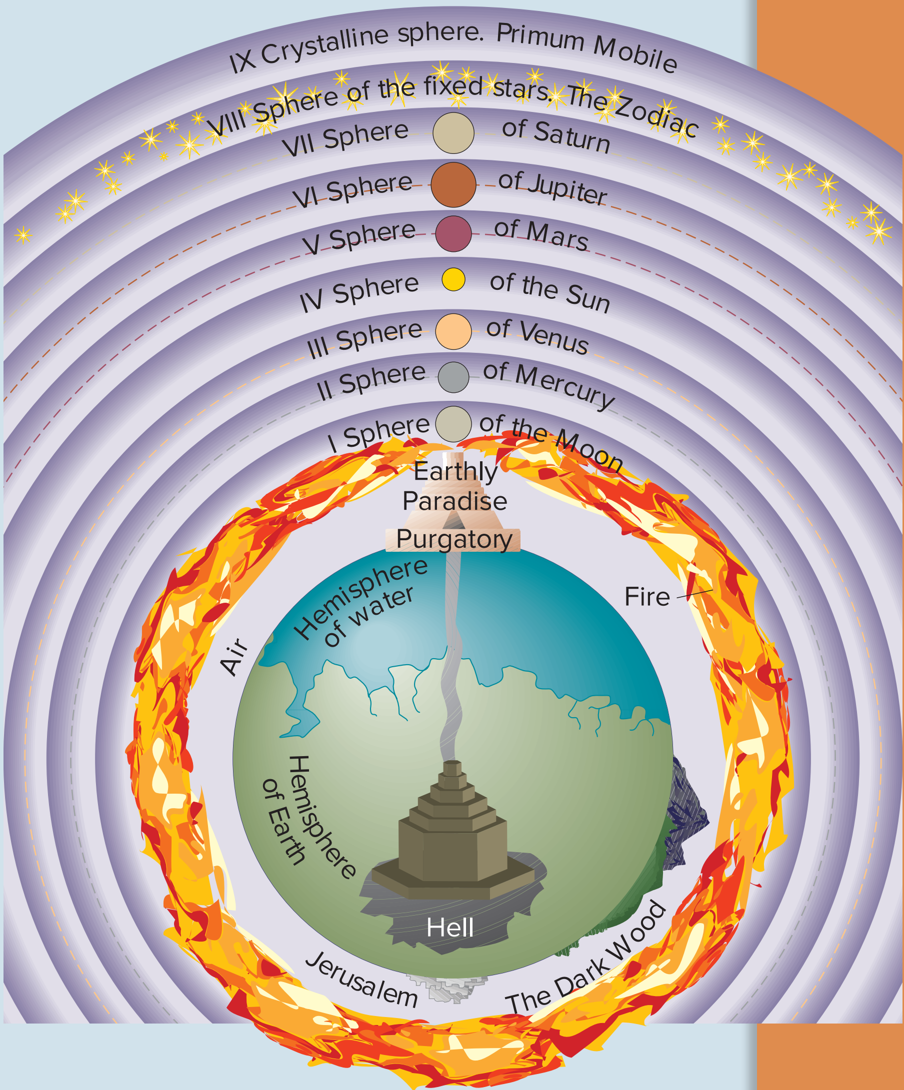
Konrad B. Krauskopf was born and raised in Madison, Wisconsin, and earned a B.S. in chemistry from University of Wisconsin in 1931. He then earned a Ph.D. in chemistry at the University of California in Berkeley. When the Great Depression made jobs in chemistry scarce, Professor Krauskopf decided to study geology, which had long fascinated him. Through additional graduate work at Stanford University, he earned a second Ph.D. and eventually a position on the Stanford faculty. He remained at Stanford until his retirement in 1976. During his tenure, Professor Krauskopf also worked at various times with the U.S. Geological Survey, served with the U.S. Army in occupied Japan, and traveled to Norway, France, and Germany on sabbatical leaves. His research interests included field work on granites and metamorphic rocks and laboratory study on applications of chemistry to geologic problems, especially the formation of ore deposits. In later years, Professor Krauskopf spent time working with various government agencies on the problem of radioactive waste disposal. Professor Krauskopf passed away on May 8, 2003.

Arthur Beiser, a native of New York City, received B.S., M.S., and Ph.D. degrees in physics from New York University, where he later served as Associate Professor of Physics. He then was a Senior Research Scientist at the Lamont Geological Observatory of Columbia University. His research interests were chiefly in cosmic rays and in magnetohydrodynamics as applied to geophysics and astrophysics. In addition to theoretical work, he participated in a cosmic-ray expedition to an Alaskan peak and directed a search for magnetohydrodynamic waves from space in various Pacific locations. A Fellow of The Explorers Club, Dr. Beiser was the first chairman of its Committee on Space Exploration. He is the author or coauthor of 36 books, mostly college texts on physics and mathematics, 14 of which have been translated into a total of 27 languages. Two of his books are on sailing, *The Proper Yacht* and *The Sailor's World.* Figure 13-21 is a photograph of Dr. Beiser at the helm of his 58-ft sloop; he and his wife Germaine have sailed over 150,000 miles, including two Atlantic crossings and a rounding of Cape Horn. Germaine Beiser, who has degrees in physics from the Massachusetts Institute of Technology and New York University, is the author or coauthor of seven books on various aspects of physics and has contributed to *The Physical Universe.* For a number of years she was the editor of a cruising guide to the Adriatic Sea.

CHAPTER

1

The Scientific Method



Medieval picture of the universe.

CHAPTER OUTLINE AND GOALS

Your chief goal in reading each section should be to understand the important findings and ideas indicated (•) below.

How Scientists Study Nature

1.1 ***The Scientific Method***
Four Steps
- What the scientific method is.
- The difference between a law and a theory.
- The role of models in science.

1.2 ***Why Science Is Successful***
Science Is a Living Body of Knowledge, Not a Set of Frozen Ideas
- Why the scientific method is so successful in understanding the natural world.

The Solar System

1.3 ***A Survey of the Sky***
Everything Seems to Circle the North Star
- Why Polaris seems almost stationary in the sky.
- How to distinguish planets from stars without a telescope.

1.4 ***The Ptolemaic System***
The Earth as the Center of the Universe
- How the ptolemaic system explains the astronomical universe.

1.5 ***The Copernican System***
A Spinning Earth That Circles the Sun
- How the copernican system explains the astronomical system.

1.6 ***Kepler's Laws***
How the Planets Actually Move
- The significance of Kepler's laws.

1.7 ***Why Copernicus Was Right***
Evidence Was Needed That Supported His Model While Contradicting Ptolemy's Model
- How parallax decides which system provides the best explanation for what we see.

Universal Gravitation

1.8 ***What Is Gravity?***
A Fundamental Force
- Why gravity is a fundamental force.

1.9 ***Why the Earth Is Round***
The Big Squeeze
- What keeps the earth from being a perfect sphere.

1.10 ***The Tides***
Up and Down Twice a Day
- The origin of the tides.
- The difference between spring and neap tides and how it comes about.

1.11 ***The Discovery of Neptune***
Another Triumph for the Law of Gravity
- The role of the scientific method in finding a hitherto unknown planet.

How Many of What

1.12 ***The SI System***
All Scientists Use These Units
- How to go from one system of units to another.
- The use of metric prefixes for small and large quantities.
- What significant figures are and how to calculate with them.

All of us belong to two worlds, the world of people and the world of nature. As members of the world of people, we take an interest in human events of the past and present and find such matters as politics and economics worth knowing about. As members of the world of nature, we also owe ourselves some knowledge of the sciences that seek to understand this world. It is not idle curiosity to ask why the sun shines, why the sky is blue, how old the earth is, why things fall down. These are serious questions, and to know their answers adds an important dimension to our personal lives.

We are made of atoms linked together into molecules, and we live on a planet circling a star—the sun—that is a member of one of the many galaxies of stars in the universe. It is the purpose of this book to survey what physics, chemistry, geology, and astronomy have to tell us about atoms and molecules, stars and galaxies, and everything in between. No single volume can cover all that is significant in this vast span, but the basic ideas of each science can be summarized along with the raw material of observation and reasoning that led to them.

Like any other voyage into the unknown, the exploration of nature is an adventure. This book records that adventure and contains many tales of wonder and discovery. The search for knowledge is far from over, with no end of exciting things still to be found. What some of these things might be and where they are being looked for are part of the story in the chapters to come.

HOW SCIENTISTS STUDY NATURE

Every scientist dreams of lighting up some dark corner of the natural world—or, almost as good, of finding a dark corner where none had been suspected. The most careful observations, the most elaborate calculations will not be fruitful unless the right questions are asked. Here is where creative imagination enters science, which is why many of the greatest scientific advances have been made by young, nimble minds.

Scientists study nature in a variety of ways. Some approaches are quite direct: a geologist takes a rock sample to a laboratory and, by inspection and analysis, finds out what it is made of and how and when it was probably formed. Other approaches are indirect: nobody has ever visited the center of the earth or ever will, but by combining a lot of thought with clues from different sources, a geologist can say with near certainty that the earth has a core of molten iron.

No matter what the approaches to particular problems may be, however, the work scientists do always fits into a certain pattern of steps. This pattern, a general scheme for gaining reliable information about the universe, has become known as the **scientific method.** The scientific method is the most powerful lens we have with which to examine the natural world.

1.1 The Scientific Method

Four Steps

We can think of the scientific method in terms of four steps: (1) formulating a problem, (2) observation and experiment, (3) interpreting the data, and (4) testing the interpretation by further observation and experiment to check its predictions. These steps are often carried out by different scientists, sometimes many years apart and not always in this order. Whatever way it is carried out, though, the scientific method is not a mechanical process but a human activity that needs creative thinking in all its steps. Looking at the natural world is at the heart of the scientific method, because the results of observation and experiment serve not only as the foundations on which scientists build their ideas but also as the means by which these ideas are checked (Fig. 1-1).

1. **Formulating a problem** may mean no more than choosing a certain field to work in, but more often a scientist has in mind some specific idea he or she wishes to investigate. In many cases formulating a problem and interpreting the data overlap. The scientist has a speculation, perhaps only a hunch, perhaps a fully developed **hypothesis,** about some aspect of nature but cannot come to a definite conclusion without further study.
2. **Observation and experiment** are carried out with great care. Facts about nature are the building blocks of science and the ultimate test of its results. This

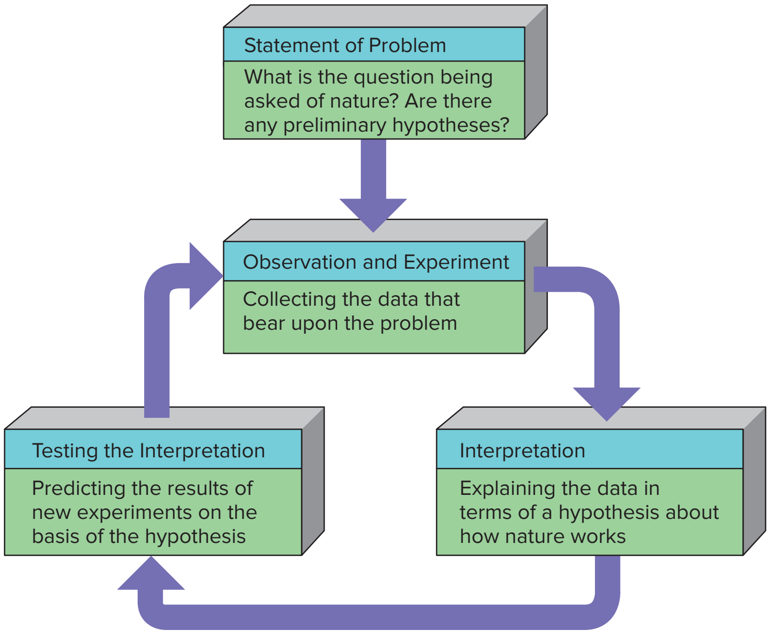


Figure 1-1 The scientific method. No hypothesis is ever final because future data may show that it is incorrect or incomplete. Unless it turns out to be wrong, a hypothesis never leaves the loop of experiment, interpretation, testing. Of course, the more times the hypothesis goes around the loop successfully, the more likely it is to be a valid interpretation of nature. Experiment and hypothesis thus evolve together, with experiment having the final word. Although a hypothesis may occur to a scientist as he or she studies experimental results, often the hypothesis comes first and relevant data are sought afterward to test it.

Finding the Royal Road

Hermann von Helmholtz, a nineteenth-century German physicist and biologist, summed up his experience of scientific research in these words: "I would compare myself to a mountain climber who, not knowing the way, ascends slowly and toilsomely and is often compelled to retrace his steps because his progress is blocked; who, sometimes by reasoning and sometimes by accident, hits upon signs of a fresh path, which leads him a little farther; and who, finally, when he has reached his goal, discovers to his annoyance a royal road which he might have followed if he had been clever enough to find the right starting point at the beginning."

Experiment Is the Test

A master of several sciences, Michael Faraday is best remembered for his discoveries in electricity and magnetism (see biography in Sec. 6.18). This statement appears in the entry for March 19, 1849 in his laboratory notebook: "Nothing is too wonderful to be true if it be consistent with the laws of nature, and . . . experiment is the best test of such consistency."

Faraday was a Fellow of Britain's Royal Society, which was founded in 1660 to promote the use of observation and experiment to study the natural world. The oldest scientific organization in the world, the Royal Society has as its motto *Nullus in Verba*—Latin for "Take nobody's word for it." On its 350th anniversary, the Royal Society held a celebration of "the joy and vitality of science, its importance to society and culture, and its role in shaping who we are and who we will become."

insistence on accurate, objective data is what sets science apart from other modes of intellectual endeavor.

3. **Interpretation** may lead to a general rule or **law** to which the data seem to conform. Or it may lead to a **theory,** which is a more ambitious attempt to account for what has been found in terms of how nature works. In any case, the interpretation must be able to cover new data obtained under different circumstances. As put forward orginally, a scientific interpretation is usually called a hypothesis.
4. **Testing the interpretation** involves making new observations or performing new experiments to see whether the interpretation correctly predicts the results. If the results agree with the predictions, the scientist is clearly on the right track. The new data may well lead to refinements of the original idea, which in turn must be checked, and so on indefinitely.

The Laws of Nature The laws of a country tell its citizens how they are supposed to behave. Different countries have different laws, and even in one country laws are changed from time to time. Furthermore, though he or she may be caught and punished for doing so, anybody can break any law at any time.

The laws of nature are different. Everything in the universe, from atoms to galaxies of stars, behaves in certain regular ways, and these regularities are the laws of nature. To be considered a law of nature, a given regularity must hold everywhere at all times within its range of applicability.

The laws of nature are worth knowing for two reasons apart from satisfying our curiosity about how the universe works. First, we can use them to predict phenomena not yet discovered. Thus Isaac Newton's law of gravity was applied over a century ago to apparent irregularities in the motion of the planet Uranus, then the farthest known planet from the sun. Calculations not only showed that another, more distant planet should exist but also indicated where in the sky to look for it. Astronomers who looked there found a new planet, which was named Neptune.

Second, the laws of nature can give us an idea of what goes on in places we cannot examine directly. We will never visit the sun's interior (much too hot) or the interior of an atom (much too small), but we know a lot about both regions. The evidence is indirect but persuasive.

Theories A **law** tells us *what;* a **theory** tells us *why.* A theory explains why certain events take place and, if they obey a particular law, how that law originates in terms of broader considerations. For example, Albert Einstein's general theory of relativity interprets gravity as a distortion in the properties of space and time around a body of matter. This theory not only accounts for Newton's law of gravity but goes further, including the prediction—later confirmed—that light should be affected by gravity.

As the French mathematician Henri Poincaré once remarked, "Science is built with facts just as a house is built with bricks, but a collection of facts is not a science any more than a pile of bricks is a house."

Models It may not be easy to get a firm intellectual grip on some aspect of nature. Therefore a **model**—a simplified version of reality—is often part of a hypothesis or theory. In developing the law of gravity, Newton considered the earth to be perfectly round, even though it is actually more like a grapefruit than like a billiard ball. Newton regarded the path of the earth around the sun as an oval called an **ellipse,** but the actual orbit has wiggles no ellipse ever had. By choosing a sphere as a model for the earth and an ellipse as a model for its orbit, Newton isolated the most important features of the earth and its path and used them to arrive at the law of gravity.

If Newton had started with a more realistic model—a somewhat squashed earth moving somewhat irregularly around the sun—he probably would have made little progress. Once he had formulated the law of gravity, Newton was then able to explain how the spinning of the earth causes it to become distorted into the shape of a grapefruit and how the attractions of the other planets cause the earth's orbit to differ from a perfect ellipse.

Theory

In science a *theory* is a fully developed logical structure based on general principles that ties together a variety of observations and experimental findings and permits as-yet-unknown phenomena and connections to be predicted. A theory may be more or less speculative when proposed, but the point is that it is a large-scale framework of ideas and relationships.

To people ignorant of science, a theory is a suggestion, a proposal, what in science is called a hypothesis. For instance, believers in creationism, the unsupported notion that all living things simultaneously appeared on earth a few thousand years ago, scorn Darwin's theory of evolution (see Sec. 16.8) as "just a theory" despite the wealth of evidence in its favor and its bedrock position in modern biology. In fact, few aspects of our knowledge of the natural world are as solidly established as the theory of evolution.

1.2 Why Science Is Successful

Science Is a Living Body of Knowledge, Not a Set of Frozen Ideas

What has made science such a powerful tool for investigating nature is the constant testing and retesting of its findings. As a result, science is a living body of information and not a collection of dogmas. The laws and theories of science are not necessarily the final word on a subject: they are valid only as long as no contrary evidence comes to light. If such contrary evidence does turn up, the law or theory must be modified or even discarded. To rock the boat is part of the game; to overturn it is one way to win. Thus science is a self-correcting search for better understanding of the natural world, a search with no end in sight.

Scientists are open about the details of their work, so that others can follow their thinking and repeat their experiments and observations. Nothing is accepted on anybody's word alone, or because it is part of a religious or political doctrine. "Common sense" is not a valid argument, either; if common sense were a reliable guide, we would not need science. What counts are definite measurements and clear reasoning, not vague notions that vary from person to person.

The power of the scientific approach is shown not only by its success in understanding the natural world but also by the success of the technology based on science. It is hard to think of any aspect of life today untouched in some way by science. The synthetic clothing we wear, the medicines that lengthen our lives, the cars and airplanes we travel in, the telephone, Internet, radio, and television by which we communicate—all are ultimately the products of a certain way of thinking. Curiosity and imagination are part of that way of thinking, but the most important part is that nothing is ever taken for granted but is always subject to test and change.

Evolution

In the past, scientists were sometimes punished for daring to make their own interpretations of what they saw. Galileo, the first modern scientist (see his biography in Sec. 2.5), was forced by the Roman Catholic Church in 1633 under threat of torture to deny that the earth moves about the sun. Even today, attempts are being made to compel the teaching of religious beliefs—for instance, the story of the Creation as given in the Bible—under the name of science. But "creation science" is a contradiction in terms. Science follows where evidence leads, whereas the essence of creationism is that it is a fixed doctrine with no basis in observation. The scientific method has been the means of liberating the world from ignorance and superstition. To discard this method in favor of taking at face value every word in the Bible is to replace the inquiring mind with a closed mind.

Those who wish to believe that the entire universe came into being in 6 days a few thousand years ago are free to do so. What is not proper is for certain politicians (whom Galileo would recognize if he were alive today) to try to turn back the intellectual clock and compel such matters of faith to be taught in schools alongside

Degrees of Doubt

Although in principle everything in science is open to question, in practice many ideas are not really in doubt. The earth is certainly round, for instance, and the planets certainly revolve around the sun. Even though the earth is not a perfect sphere and the planetary orbits are not perfect ellipses, the basic models will always be valid.

Other beliefs are less firm. An example is the current picture of the future of the universe. Quite convincing data suggest that the universe has been expanding since its start in a "big bang" about 13.8 billion years ago. What about the future? It seems likely from the latest measurements that the expansion will continue forever, but this conclusion is still tentative and is under active study by astronomers today.

What the Constitution Says

The founders of the United States of America insisted on the separation of church and state, a separation that is part of the Constitution. What happens in countries with no such separation, in the past and in the present, testifies to the wisdom of the founders.

In 1987 the U.S. Supreme Court ruled that teaching creationism in the public schools is illegal because it is a purely religious doctrine. In response, the believers in creationism changed its name to "intelligent design" without specifying who the designer was or how the design was put into effect. Their sole argument is that life is too complex and diverse to be explained by evolution, when in fact this is precisely what evolution does with overwhelming success. Nevertheless, attempts have continued to be made to include intelligent design in science classes in public schools. All such attempts have been ruled illegal by the courts.

or even in place of scientific concepts, such as evolution (see Sec. 16.8), that have abundant support in the world around us. To anyone with an open mind, the evidence that the universe and its inhabitants have developed over time and continue to do so is overwhelming, as we shall see in later chapters. Nothing stands still. The ongoing evolution of living things is central to biology; the ongoing evolution of the earth is central to geology; the ongoing evolution of the universe is central to astronomy.

Advocates of creationism (or "intelligent design") assert that evolution is an atheistic concept. Yet religious leaders of almost all faiths see no conflict between evolution and religious belief. According to Cardinal Paul Poupard, head of the Roman Catholic Church's Pontifical Council for Culture, "we . . . know the dangers of a religion that severs its links with reason and becomes prey to fundamentalism. The faithful have the obligation to listen to that which secular modern science has to offer."

THE SOLAR SYSTEM

Each day the sun rises in the east, sweeps across the sky, and sets in the west. The moon, planets, and most stars do the same. These heavenly bodies also move relative to one another, though more slowly.

There are two ways to explain the general east-to-west motion. The most obvious is that the earth is stationary and all that we see in the sky revolves around it. The other possibility is that the earth itself turns once a day, so that the heavenly bodies only appear to circle it. How the second alternative came to be seen as correct and how this finding led to the discovery of the law of gravity are important chapters in the history of the scientific method.

1.3 A Survey of the Sky

Everything Seems to Circle the North Star

One star in the northern sky seems barely to move at all. This is the North Star, or **Polaris,** long used as a guide by travelers because of its nearly unchanging position. Stars near Polaris do not rise or set but instead move around it in circles (Fig. 1-2). These circles carry the stars under Polaris from west to east and over it from east to west. Farther from Polaris the circles get larger and larger, until eventually they dip below the horizon. Sun, moon, and stars rise and set because their circles lie partly below the horizon. Thus, to an observer north of the equator, the whole sky appears to revolve once a day about this otherwise ordinary star.

Why does Polaris occupy such a central position? The earth rotates once a day on its axis, and Polaris happens by chance to lie almost directly over the North Pole. As the earth turns, everything else around it seems to be moving. Except for their

Figure 1-2 Time exposure of stars in the northern sky. The trail of Polaris is the bright arc slightly to the left of the center of the larger arcs. The dome in the foreground houses one of the many telescopes on the summit of Mauna Kea, Hawaii. This location is favored by astronomers because observing conditions are excellent there. The lights of cars that moved during the exposure are responsible for the yellow traces near the dome.

circular motion around Polaris, the stars appear fixed in their positions with respect to one another. Stars of the Big Dipper move halfway around Polaris between every sunset and sunrise, but the shape of the Dipper itself remains unaltered. (Actually, as discussed later, the stars *do* change their relative positions, but the stars are so far away that these changes are not easy to detect.)

Constellations Easily recognized groups of stars, like those that form the Big Dipper, are called **constellations** (Fig. 1-3). Near the Big Dipper is the less conspicuous Little Dipper with Polaris at the end of its handle. On the other side of Polaris from the Big Dipper are Cepheus and the W-shaped Cassiopeia, named,

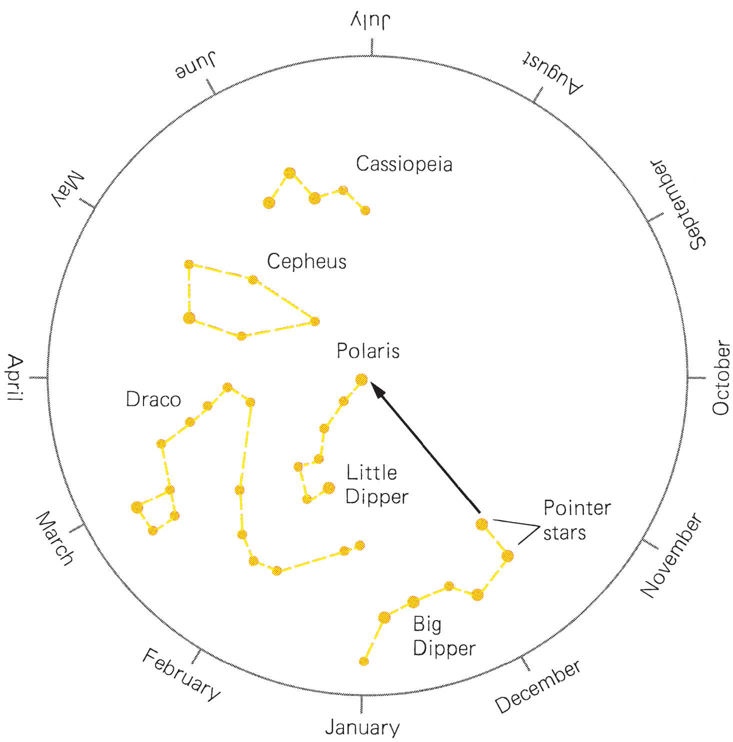


Figure 1-3 Constellations near Polaris as they appear in the early evening to an observer who faces north with the figure turned so that the current month is at the bottom. Polaris is located on an imaginary line drawn through the two "pointer" stars at the end of the bowl of the Big Dipper. The brighter stars are shown larger in size.

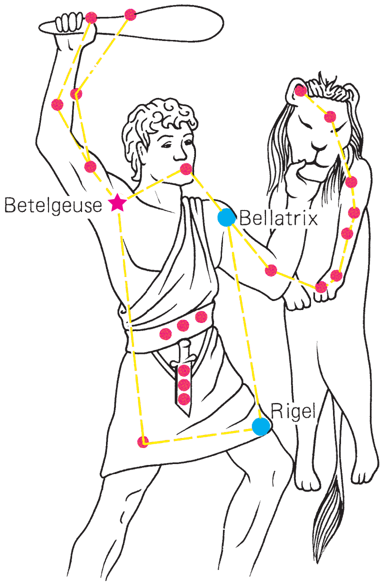


Figure 1-4 Orion, the mighty hunter. Betelgeuse is a bright red star, and Bellatrix and Rigel are bright blue stars. Stars that seem near one another in the sky may actually be far apart in space. The three stars in Orion's belt, for instance, are in reality at very different distances from us.

respectively, for an ancient king and queen of Ethiopia. Next to Cepheus is Draco, which means dragon.

Elsewhere in the sky are dozens of other constellations that represent animals, heroes, and beautiful women. An especially easy one to recognize on winter evenings in the northern hemisphere is Orion, the mighty hunter of legend. Orion has four stars, three of them quite bright, at the corners of a warped rectangle with a belt of three stars in line across its middle (Fig. 1-4). Except for the Dippers, a lot of imagination is needed to connect a given star pattern with its corresponding figure, but the constellations nevertheless are useful as convenient labels for regions of the sky.

Sun and Moon In their daily east-west crossing of the sky, the sun and moon move more slowly than the stars and so appear to drift eastward relative to the constellations. In the same way, a person on a train traveling west who walks toward the rear car is moving east relative to the train although still moving west relative to the ground. In the sky, the apparent eastward motion is most easily observed for the moon. If the moon is seen near a bright star on one evening, by the next evening it will be some distance east of that star, and on later nights it will be farther and farther to the east. In about 4 weeks the moon drifts eastward completely around the sky and returns to its starting point.

The sun's relative motion is less easy to follow because we cannot observe directly which stars it is near. But if we note which constellations appear where the sun has just set, we can estimate the sun's location among the stars and follow it from day to day. We find that the sun drifts eastward more slowly than the moon, so slowly that the day-to-day change is scarcely noticeable. Because of the sun's motion each constellation appears to rise about 4 min earlier each night, and so, after a few weeks or months, the appearance of the night sky becomes quite different from what it was when we started our observations.

By the time the sun has migrated eastward completely around the sky, a year has gone by. In fact, the **year** is defined as the time needed for the sun to make such an apparent circuit of the stars.

Planets Five other celestial objects visible to the naked eye also shift their positions with respect to the stars. These objects, which themselves resemble stars, are **planets** (Greek for "wanderer") and are named for the Roman gods Mercury, Venus, Mars, Jupiter, and Saturn. Like the sun and moon, the planets shift their positions so slowly that their day-to-day motion is hard to detect. Unlike the sun, they move in complex paths. In general, each planet drifts eastward among the stars, but its relative speed varies and at times the planet even reverses its relative direction to head westward briefly. Thus the path of a planet appears to consist of loops that recur regularly, as in Fig. 1-5.

1.4 The Ptolemaic System

The Earth as the Center of the Universe

Although the philosophers of ancient Greece knew that the apparent daily rotation of the sky could be explained by a rotation of the earth, most of them preferred to

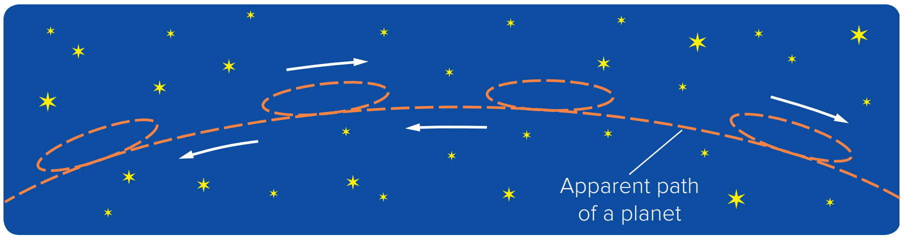


Figure 1-5 Apparent path of a planet in the sky looking south from the northern hemisphere of the earth. The planets seem to move eastward relative to the stars most of the time, but at intervals they reverse their motion and briefly move westward.

regard the earth as stationary. The scheme most widely accepted was originally the work of Hipparchus. Ptolemy of Alexandria (Fig. 1-6) later included Hipparchus's ideas into his *Almagest,* a survey of astronomy that was to be the standard reference on the subject for over a thousand years. This model of the universe became known as the **ptolemaic system.**

The model was intricate and ingenious (Fig. 1-7). Our earth stands at the center, motionless, with everything else in the universe moving about it either in circles or in combinations of circles. (To the Greeks, the circle was the only "perfect" curve, hence the only possible path for a celestial object.) The fixed stars are embedded in a huge crystal sphere that makes a little more than a complete turn around the earth each day. Inside the crystal sphere is the sun, which moves around the earth exactly once a day. The difference in speed between sun and stars is just enough so that the sun appears to move eastward past the stars, returning to a given point among them once a year. Near the earth in a small orbit is the moon, revolving more slowly than the sun. The planets Venus and Mercury come between moon and sun, the other planets between sun and stars.

To account for irregularities in the motions of the planets, Ptolemy imagined that each planet moves in a small circle about a point that in turn follows a large circle about the earth. By a combination of these circular motions a planet travels in a series of loops. Since we observe these loops edgewise, it appears to us as if the planets move with variable speeds and sometimes even reverse their directions of motion in the sky.

From observations made by himself and by others, Ptolemy calculated the speed of each celestial object in its assumed orbit. Using these speeds he could then figure out the location in the sky of any object at any time, past or future. These calculated positions checked fairly well, though not perfectly, with positions that had been recorded centuries earlier, and the predictions also agreed at first with observations

Figure 1-6 Ptolemy (A.D. 100–170).

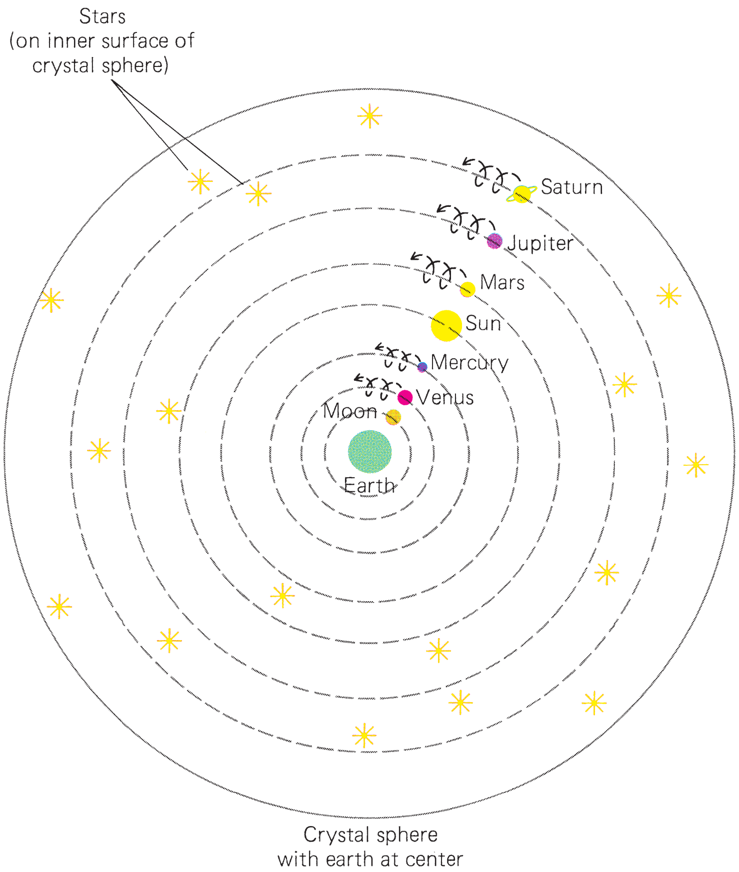


Figure 1-7 The ptolemaic system, showing the assumed arrangement of the members of the solar system within the celestial sphere. Each planet is supposed to travel around the earth in a series of loops, while the orbits of the sun and moon are circular. Only the planets known in Ptolemy's time are shown. The stars are all supposed to be at the same distance from the earth.