

## Contents

<i>Preface</i>	<i>page</i> ix
<b>1 Energy in planetary processes and the First Law of Thermodynamics</b>	<b>1</b>
1.1 Some necessary definitions	2
1.2 Conservation of energy and different manifestations of energy	4
1.3 Mechanical energy. An introduction to dissipative and non-dissipative transformations	4
1.4 Expansion work. Introduction to equations of state	13
1.5 Isothermal and adiabatic processes. Dissipative vs. non-dissipative transformations redux	23
1.6 Elastic energy	24
1.7 Two complementary descriptions of nature: macroscopic and microscopic	26
1.8 Energy associated with electric and magnetic fields	27
1.9 Thermal energy and heat capacity	35
1.10 The First Law of Thermodynamics	39
1.11 Independent variables and material properties	40
1.12 Some applications of the First Law of Thermodynamics	41
1.13 Enthalpy associated with chemical reactions	49
1.14 Internal energy and the relationship between macroscopic thermodynamics and the microscopic world	55
1.15 An overview of the properties of matter and equations of state	64
Exercises for Chapter 1	67
<b>2 Energy sources in planetary bodies</b>	<b>70</b>
2.1 Planetary heat flows	71
2.2 Dissipation of gravitational potential energy	73
2.3 Gravitational binding energy	75
2.4 Accretion	78
2.5 Contraction	89
2.6 Differentiation	96
2.7 Tidal dissipation of mechanical energy	103
2.8 Dissipation of electrical energy	112
2.9 Radioactive heating	116
Exercises for Chapter 2	120
<b>3 Energy transfer processes in planetary bodies</b>	<b>122</b>
3.1 Transport processes	124
3.2 Heat transport by diffusion	126
3.3 Heat diffusion and cooling of planetary bodies	137

3.4	Convection as a heat engine	141
3.5	Planetary adiabats	145
3.6	Heat advection	148
3.7	Convection as a heat transport mechanism	153
3.8	Parametrization of convection in planetary interiors	165
3.9	Convection and cooling of solid planetary interiors	173
	Exercises for Chapter 3	178
<b>4</b>	<b>The Second Law of Thermodynamics and thermodynamic potentials</b>	<b>181</b>
4.1	An intuitive approach to entropy	181
4.2	The entropy postulate and the Second Law of Thermodynamics	183
4.3	The First Law of Thermodynamics revisited	185
4.4	Entropy generation and energy dissipation	186
4.5	Planetary convection and Carnot cycles	189
4.6	A microscopic view of entropy	196
4.7	The Third Law of Thermodynamics	206
4.8	Thermodynamic potentials	209
4.9	Gibbs free energy	223
	Exercises for Chapter 4	227
<b>5</b>	<b>Chemical equilibrium. Using composition as a thermodynamic variable</b>	<b>229</b>
5.1	Chemical equilibrium	229
5.2	Equilibrium among pure chemical species	238
5.3	Phases of variable composition: chemical potential revisited	245
5.4	Partial molar properties	248
5.5	Generalized equilibrium condition. Activity and the equilibrium constant	253
5.6	Introduction to solution theory: ideal solutions	258
5.7	The geometric view of activity and Gibbs free energy of mixing	265
5.8	More complex ideal activity–composition relationships	266
5.9	Non-ideal solutions	274
	Exercises for Chapter 5	285
<b>6</b>	<b>Phase equilibrium and phase diagrams</b>	<b>287</b>
6.1	The foundations of phase equilibrium	287
6.2	Analysis of phase equilibrium among phases of fixed composition	295
6.3	Phase diagrams in open systems	315
6.4	Equilibrium among phases of variable composition	325
6.5	Chemical equilibrium at first-order phase transitions	326
6.6	Discontinuous phase transitions in phases of variable composition	330
	Exercises for Chapter 6	347
<b>7</b>	<b>Critical phase transitions</b>	<b>349</b>
7.1	An intuitive approach to critical phase transitions	349
7.2	Location of the critical mixing point	355
7.3	Calculation of non-dimensional solvi	359
7.4	Order–disorder phase transitions in crystalline solids	361

7.5	Analogies with other phase transitions	369
7.6	Landau theory of phase transitions	372
	Exercises for Chapter 7	384
<b>8</b>	<b>Equations of state for solids and the internal structure of terrestrial planets</b>	<b>386</b>
8.1	An introduction to equations of state for solids	386
8.2	Macroscopic equations of state	388
8.3	Isothermal equations of state from interatomic potentials: the Born–Mie EOS	405
8.4	Thermal pressure	407
	Exercises for Chapter 8	419
<b>9</b>	<b>Thermodynamics of planetary volatiles</b>	<b>420</b>
9.1	Fugacity and standard state fugacity	420
9.2	Liquid–vapor equilibrium. Critical phase transitions redux	428
9.3	The principle of corresponding states	440
9.4	Equations of state for real fluids at $P$ – $T$ conditions typical of the crusts and upper mantles of the terrestrial planets	442
9.5	Calculation of fugacity in fluid phases	450
9.6	Speciation in multicomponent volatile phases	459
9.7	Fluids at the conditions of giant planet interiors	473
	Exercises for Chapter 9	475
<b>10</b>	<b>Melting in planetary bodies</b>	<b>477</b>
10.1	Principles of melting	477
10.2	Melting point depression. Eutectics, cotectics and peritectics	481
10.3	Partitioning of trace components between solids and melts	484
10.4	The effect of “impurities” on melting temperature	487
10.5	Melting in planetary interiors	494
10.6	Decompression melting	494
10.7	Open system melting	512
10.8	The nature of solid–melt equilibrium in icy satellites	517
	Exercises for Chapter 10	521
<b>11</b>	<b>Dilute solutions</b>	<b>522</b>
11.1	Some properties of dilute solutions	522
11.2	Effects of dilute solutes on the properties of the solvent	529
11.3	Electrolyte dissociation	540
11.4	Thermodynamic formulation of electrolyte solutions	544
11.5	Speciation in ionic solutions. Iron solubility in ocean water as an example	554
11.6	Activity coefficients in electrolyte solutions	562
	Exercises for Chapter 11	575
<b>12</b>	<b>Non-equilibrium thermodynamics and rates of natural processes</b>	<b>577</b>
12.1	Non-equilibrium thermodynamics	577
12.2	Chemical diffusion	581

12.3	Rate of chemical reactions	592
12.4	Controls on rate constants	609
12.5	An introduction to kinetics of heterogeneous processes	611
	Exercises for Chapter 12	615
<b>13</b>	<b>Topics in atmospheric thermodynamics and radiative energy transfer</b>	<b>616</b>
13.1	Gravitational binding of planetary atmospheres	616
13.2	Equilibrium thermodynamics in a gravitational field	620
13.3	Radiative energy transfer	625
	Exercises for Chapter 13	643
<b>14</b>	<b>Thermodynamics of life</b>	<b>645</b>
14.1	Chemical evolution of post-nebular atmospheres	645
14.2	Thermodynamics of metabolic processes	657
14.3	Speculations about extraterrestrial life	665
14.4	Entropy and life	668
	Exercise for Chapter 14	669
	<i>Appendix 1 Physical constants and other useful numbers and conversion factors</i>	671
	<i>Appendix 2 Derivation of thermodynamic identities</i>	672
	<i>References</i>	675
	<i>Index</i>	690