

Contents

1	Order in the Chemical Elements	1
1.1	An Early Start	1
1.2	Ideas in the Far East	2
1.3	Alchemy	2
1.4	Lavoisier and the Beginning of the Modern Era	3
1.5	Wenzel and Richter: Quantitative Chemistry	4
1.6	Proust and Gay-Lussac Versus Berthollet: 1800–1808	5
1.7	Berthollet Was Both Right and Wrong	6
1.8	Dalton and the Revival of the Atomic Theory	9
1.9	Higgins and an Unjustified Claim for Priority	13
1.10	If You Dislike a Theory, Reinvent it Under Another Name	14
1.11	Avogadro: A Superb Insight, Perfect Timing, but Rejected	16
1.12	Prout and the Name of the Game: Numerology	17
1.13	Berzelius and the End of Prout's Atomic Hypothesis	21
1.14	Petit and Dulong's Law and Fading Hopes	22
1.15	Thomson 1821: Prout Is Nevertheless Right	23
1.16	Berzelius and the Realisation that Imaginary Substances Are Not Chemical Elements	27
1.17	Dumas 1828	27
1.18	Gaudin 1833 and the Correct But Ignored Explanation	29
1.19	Marignac and the Quest for Accurate Numerical Values	30
1.20	Stas and Regrets for Earlier Thoughts	30
1.21	Whewell: Philosophy a Bit Too Early	32
1.22	How to Classify the Elements?	32
1.23	The 1860 Karlsruhe Conference: The Fog Lifts	33
1.24	Early Attempts to Classify the Elements	34
1.25	Newlands Rediscovered the Octave Law	37
1.26	Odling 1864	38

1.27	Mendeleev 1869 and Meyer 1864–1870	39
1.28	Loschmidt and the Value of the Avogadro Number	47
1.29	Meyer 1888: A Historical Perspective	48
1.30	Certain Elements Are Not Forever	48
1.31	Philosophy of a Discoverer When No Theory Is Yet Available.	49
1.32	Is the Atomic Weight Variable?	50
1.33	Moseley: At Long Last, an Accurate Table	52
1.34	The Theory Behind Moseley's Discovery	55
1.35	The Last Element to Be Discovered	55
1.36	Aston and the Discovery of Isotopes	55
1.37	A Solution to a Long-Standing Problem	57
1.38	Is the Periodicity of the Chemical Elements Really So Obvious?	59
2	Preparing the Ground for Delving into the Stars	61
2.1	The Long Road to Deciphering the Composition of the Stars	61
2.2	Why the Sodium D Line Appears Everywhere	64
2.3	The Concept of Equilibrium: Pictet and Prévost	65
2.4	Beyond the Visible Light.	69
2.5	Stewart, the Forgotten Discoverer	73
2.6	Kirchhoff's Law	76
2.7	A Modern Physical Explanation for the Reversal Phenomenon.	80
2.8	Could the Coincidence Be Fortuitous?	81
2.9	The Priority Debate.	81
2.10	The Radiation Law	81
2.11	Stewart in Retrospect	83
2.12	Who Discovered the Source of the D_2 Lines?	84
2.13	Kelvin and the Reversal Phenomenon	86
2.14	Kirchhoff's Rebuttal	89
2.15	Huggins' Particular View: How Stellar Spectroscopy Came into Being.	90
2.16	Lockyer 1887: The Chemical Composition of the Sun	91
2.17	More Creditors?	97
2.18	An Unimaginable but True Story: No Life on the Sun	98
2.19	Final Comments on the Kirchhoff Saga.	101
2.20	Epilogue	103
2.21	The Late Kirchhoff Grilled by His Compatriots	104
2.22	A Mathematical Proof (if Needed): Hilbert	106
2.23	The French View	106
2.24	One Can Never Foresee the Future	107
2.25	Getting the Black Body Function: Maxwell	107

2.26	Attempts to Obtain Kirchhoff's Function	108
2.27	Getting the Integral of an Unknown Function First	109
2.28	A Black Body Does Not Necessarily Look Black	114
2.29	Buried in the Finer Details	114
2.30	Rayleigh: Give Classical Physics a Chance	116
2.31	Jeans: No Way of Saving the Classical Picture	116
2.32	Classical Physics is Ruled Out for Microscopic Phenomena	117
2.33	The Photoelectric Effect: A Further Success for the Quantum Theory	118
2.34	Are the Positions of the Fraunhofer Lines Random?	119
2.35	The Structure of the Atom: Only Complete Solutions Are Acceptable	122
2.36	Einstein: An Explicit Expression for the Kirchhoff Law	125
2.37	A Physical Note	128
2.38	Not All Are Quick to Accept	128
2.39	New Elements in the Sun	129
3	Probing the Stars from Afar	133
3.1	Spectral Classification and Abundance Uniformity	133
3.2	Stellar Correlations: The HR Diagram	135
3.3	Stellar Abundance Uniformity: Before the Revolution	136
3.4	The Revolution	138
3.5	First Attempts to Derive the Shape of the Fraunhofer Lines	142
3.6	Confirmation, and by Whom!	143
3.7	Finding the Abundances: The Curve of Growth	146
3.8	The Theory Gradually Improves	147
3.9	Conceptual Problems with Uniform Composition	149
4	Is Physics the Same Everywhere?	151
4.1	Are the Laws of Physics Universally Valid?	151
4.2	The Connection Between the Micro and the Mega Cosmos	152
4.3	The Possible Variability of the Gravitational Constant	158
4.4	Modern Attitude and Hypotheses	159
4.5	What Does Nature Say? The Oklo Phenomenon	160
4.6	α Variability in the Distant Past?	162
4.7	Present Day Laboratory Tests	166
4.8	Upper Limits for the Variability of the Gravitational Constant	167
4.9	No Detectable Variability in the Physical Constants (So Far?)	168

5	Towards the Bottom of the Nuclear Binding Energy	169
5.1	The Light at the End of the Tunnel.	170
5.2	Stellar Energy Balance	174
5.3	The Birth of Nuclear Astrophysics	176
5.4	How to Jump from H to He	177
5.5	The Discovery of the Neutron	178
5.6	The Return of Atkinson	179
5.7	Weizsäcker: A Good Idea, but the Wrong Calculation.	180
5.8	The Answers Are in Bethe's Bible	181
5.9	Hans Bethe and the First Calculation of the pp Reaction.	182
5.10	Hans Bethe and the CN Cycle	187
5.11	Schatzman 1951: From White Dwarfs to Main Sequence.	190
5.12	Salpeter 1952: So It Should Be	191
5.13	The Discovery of the ${}^3\text{He} + {}^4\text{He}$ Reaction: A New Branch	193
5.14	Where is the pp Reaction Crucial?	194
6	The Composition–Age–Velocity Connection	195
6.1	The Stars are Never at Rest	196
6.2	The Discovery of the Doppler Effect.	197
6.3	The Doppler Effect at the Service of Astrophysics	198
6.4	Reality is More Intricate	200
6.5	Unintentional Evidence from Other Galaxies	206
6.6	Doubts.	207
6.7	Oort	209
6.8	The Enigma of the Nebulae	209
6.9	The Great Debate	210
6.10	Fornax and Sculptor Provide Hints	213
6.11	Not all Variables are Alike	214
6.12	Star Clusters as the Rosetta Stone of Stellar Evolution	215
6.13	Baade: Stellar Populations	217
6.14	The Details are Important	222
6.15	Dispersing the Fog Around the Variable Stars	223
6.16	It is the Chemical Elements: First Signs	225
6.17	Confirmation: It is the Chemical Elements.	227
6.18	Theoretical Understanding of Stellar Populations	232
6.19	Early Successful and Failed Attempts to Explain the Red Giants.	232
6.20	Who is Right?	235
6.21	Hoyle & Lyttleton and Schönberg & Chandrasekhar (1942).	236
6.22	Gamow Acquiesces: 1945	239
6.23	When Do Stars Expand and When Do They Contract	241
6.24	Failures in Modelling Red Giants	241

6.25	A Byproduct: The First Inhomogeneous Solar Model	242
6.26	The Giants: Alternative Solutions?	244
6.27	Inhomogeneous Models: Comparison with Observation	245
6.28	The Key Is Again Provided by the Globular Clusters	248
6.29	Observations of Globular Clusters.	249
6.30	Galaxy Collisions and Composition Differences	250
6.31	Observations of Galaxy Collisions	251
6.32	Unifying Chemical Element Synthesis and Galaxy Formation	253
6.33	Can Alternative Theories Work?	256
6.34	Spitzer and Schwarzschild (1953)	257
6.35	Successes.	260
6.36	Salpeter and the Invention of the Initial Mass Function: Stellar Birth Statistics	260
6.37	Stars Are Born Homogeneous: 1956	262
6.38	The Vatican Meeting 1957.	263
6.39	Further Evidence for Enrichment During Collapse	265
6.40	Direct Observational Evidence for Mixing in Stars	266
6.41	The Stellar Onion Model	268
6.42	Are the Derived Abundances Correct?	269
6.43	Complicated Reality	270
7	Big and Little Bangs.	277
7.1	Paving the Way to the Big Bang	277
7.2	The Synthesis Must Have Been Explosive	279
7.3	Questions About the Validity of Equilibrium	280
7.4	Hoyle 1946: The Key Is in the Stars	281
7.5	What Do the Numbers Imply?	283
7.6	The Discovery of the Expanding Universe: Theory	283
7.7	The K-Term	287
7.8	Discovering the Recession of the Nebulae	287
7.9	First Attempts to Confirm the de Sitter Model	288
7.10	Criticism from Astronomers	296
7.11	Understanding the Recessional Velocities	296
7.12	Why Did Hubble Not Believe in an Expanding Universe?	299
7.13	The Exploding Universe	301
7.14	A Rival Theory: The Elements Form in Stars.	303
7.15	Statistical Equilibrium at Zero Temperature	304
7.16	The $\alpha\beta\gamma$ Paper	306
7.17	An Opposing Theory: The Cosmological Steady State.	310
7.18	Inventive but Not Really New	311
7.19	Problems with the $\alpha\beta\gamma$ Theory	314
7.20	Why Not Breakup (Top-Down) Rather Than Buildup (Bottom-Up)?	318

7.21	The BBC Debate and the Invention of a Sensational Buzzword	320
7.22	Hayashi: Fixing the Initial State	321
7.23	Cold Big Bang?	323
7.24	The Early 1950s	324
7.25	Alpher, Follin, and Herman Correct the Theory	325
7.26	B ² FH 1957: An Attempt at a Global Picture	325
7.27	Hoyle and Tayler 1964: This Is no Retreat	326
7.28	The Cosmic Microwave Background Radiation	328
7.29	Peebles (1966): Getting the Helium Abundance Right.	333
7.30	Wagoner, Fowler, and Hoyle: Light Element Indicators.	334
7.31	Stars Cannot Do it All.	336
7.32	Breaking a Symmetry: A Remaining Question	338
7.33	The Present Day Picture: Most of the Universe Is Dark	339
8	How Nature Overcomes Its Own Barriers	341
8.1	Unsuccessful Attempts to Overcome the {A = 8 Barrier}	341
8.2	Pursuing the Structure of the Carbon Nucleus	344
8.3	The Structure of the ¹² C Nucleus	347
8.4	A Digression to ⁸ Be.	348
8.5	Back to New Developments in the Structure of ¹² C	349
8.6	The Last Word ⁸ Be Is Unstable	354
8.7	Öpik's Suggested Solution: The Triple Alpha Process.	354
8.8	More Information About ¹² C	356
8.9	Salpeter: The Solution Is Two Plus One	357
8.10	Between Salpeter and Hoyle 1952–1954	360
8.11	The Kellogg Laboratory Group Phase I.	361
8.12	The New Experiment	362
8.13	Hoyle: We Must Have Carbon in Our Universe!	362
8.14	The Kellogg Laboratory Group Phase II	364
8.15	Salpeter 1957: Completing the Job	366
8.16	When Is the Energy Released?	369
8.17	More Resonances in ¹² C	369
8.18	Carbon Structure Is Half the Story: The ¹² C + α \rightarrow ¹⁶ O + γ Reaction.	370
8.19	Present Day Perspective: Theory.	373
8.20	The C/O Ratio Today: Observations and What They Imply	374
8.21	The Structure of ¹² C and the α Model: Retrospect	375
8.22	Some Recent Developments.	375
8.23	Philosophy: The Anthropic Principle.	376
9	Beyond Carbon	377
9.1	Post-Helium Burning.	377

9.2	Change of Modus Operandi: Neutrino Losses	
	Take Control	377
9.3	Neutrino Losses	378
9.4	The Paper B2FH.	380
9.5	The Rise and Fall of the α Process	382
9.6	The Equilibrium e -Process	387
9.7	Problems with the Grand Picture of B2FH.	388
9.8	Carbon Burning	391
9.9	Neon, Oxygen, and Silicon Burning	393
9.10	The Modern State of the Art: Nuclear Networks.	396
10	Which Star Becomes Which Supernova?	397
10.1	SN Type Ia	397
10.2	SN Types Ib and Ic, and II	398
11	Between Two Extreme Nuclear Models	403
11.1	Nuclear Theory Before Nuclear Physics	404
11.2	Rutherford's Nuclear Model.	407
11.3	Isotopic Abundances	409
11.4	Challenging Rutherford: The Right Explanation for the Wrong Experiment	410
11.5	Gamow Enters the Game	412
11.6	Signs of Non-Smoothness in Nuclear Properties	415
11.7	The Elimination of the Nuclear Electrons	416
11.8	More Signs of the Individual Particle Behavior of Nuclei	418
11.9	Elsasser and Guggenheimer	419
11.10	Fermi	421
11.11	Bohr's Declaration Against the Independent Particle Model	424
11.12	Support in Question: The Breit-Wigner Formula	425
11.13	Domination of the Compound Model	426
11.14	Elsasser Does Not Back Down	429
11.15	From Cosmic Abundances to Nuclear Structure	429
11.16	Enlightenment Occurs Twice	434
11.17	The Final Vindication: From Three Remains One.	436
11.18	How Nature Teases Physicists and Astrophysicists	440
11.19	A Chemist's Attempt: Linus Pauling.	441
11.20	What Nuclei Can Exist: The Binding Energy Formula	442
11.21	Unstable Elements	446
11.22	Unstable Elements Below Lead	447
11.23	The Elements Above Lead.	448
11.24	Why Are There Only 92 Chemical Elements?	449

12	Synthesis of the Heavier-than-Iron Elements	451
12.1	Introduction	451
12.2	Salient Features of the Abundance Curve for HTI Nuclei	452
12.3	Overcoming the Coulomb Barrier: Neutron Processes	452
12.4	Neutron Absorption by Heavy Elements	457
12.4.1	The Available Time, Timescales, and Capture Processes	461
12.4.2	The β Parabola	466
12.5	Steady State Versus Transient Neutron Capture	467
12.5.1	The Steady State Assumption	467
12.5.2	Non-Steady State Options	469
12.6	Classification of Heavy Nuclei	471
12.7	Viable Stellar Neutron Sources	472
12.8	The Nuclear Physics of the ^{13}C Neutron Source	476
12.8.1	The Nuclear Physics of the ^{22}Ne Neutron Source	482
12.9	Where Does the Reaction Take Place?	491
12.10	Carbon Stars: Where the HTI Nuclei are Synthesized	492
12.10.1	The Rosetta Stone?	495
12.11	The Stellar Asymptotic Giant Branch Phase	497
12.11.1	Towards the AGB Phase of Stellar Evolution	497
12.12	The Helium Flash: Does it or Does it Not Mix	498
12.13	Core Helium Burning	507
12.14	Two Burning Shells	507
12.15	Why Cigar Burning is Unstable in Stars	508
12.16	Two Types of Mixing, but Do They Mix?	511
12.17	The End of the AGB Phase and Planetary Nebulae	512
12.17.1	Mass Loss	512
12.18	What Becomes of a Star After the AGB Phase?	515
12.19	The Mass Limit	517
12.20	Comparison with Observation: But What to Compare?	518
12.20.1	Is There Mixing or Not?	520
12.21	Consequences of Complexity: Each Computer Code has its Solution	521
12.22	Variations with the Metallicity	522
12.23	Astrophysical Problems Affecting the <i>s</i> -Process Theory	523
13	A Process in Search of an Environment: The <i>r</i>-Process	527
13.1	The <i>r</i> -Process: A High Neutron Flux for a Short Time	527
13.2	<i>r</i> -Process Signatures in the Solar System Abundance Curve	540
13.3	<i>r</i> -Process Elements in the Sun	541
13.4	Some Characteristics of the Process	543
13.5	Site-Free High-Temperature <i>r</i> -Process Models	545

13.6	A Site-Free High-Density r -Process Scenario	546
13.7	The Multi-Event r -Process Model	547
13.8	The Basic Problem: Lack of Nuclear Data—An Example . . .	548
13.8.1	The Nuclear Binding Energy	551
13.9	Neutron Absorption Data	556
13.10	Where Could the r -Process Operate? Suggested Sites	557
13.10.1	Neutron Star Mergers	557
13.10.2	r -Process in Neutrino Winds	561
13.10.3	Neutron Captures in Exploding He- or C-Rich Layers	564
13.10.4	The r -Process in the Decompression of Cold Neutron Star Matter	565
13.11	What Can We Learn from the r -Process Abundances	566
13.12	The So-Called Mo Anomaly	566
13.13	The Xe Anomaly and a Revolution	569
13.14	Determining the Abundance of HTI Elements in Stars	572
13.15	Neutron Capture During the Early Evolutionary Phases of the Galaxy	574
13.16	Are r -Process Elements in Metal-Poor Stars Solar Abundance Compatible?	576
13.17	The Galactic History of Neutron-Capture Elements	577
13.18	Solar System Nucleo-Cosmochronology	578
13.19	The p -Process	580
13.19.1	Spallation	584
13.20	Astrophysically Relevant Progress Expected in Nuclear Physics	586
13.20.1	Nuclear Ground State Properties	586
13.20.2	Peculiarities of High N/Z Ratios: Halo Nuclei	587
13.20.3	Chaos?	588
13.20.4	Are the Magic Numbers Universal?	590
13.20.5	More Than One Ground State	591
13.20.6	Half-Lives Against β -Decay	592
13.20.7	Clustering in Neutron-Rich Nuclei	592
13.20.8	And Yet There Is Life in the Old α Model	594
13.21	No Further Neutron Build-up: The Fission Barrier	596
13.22	Some Reflections on Present Day Nuclear Physics	597
14	The Elusive First Stars	599
14.1	The Need for Population III	599
14.2	Cosmic Timetable: When Did It Happen?	600
14.3	Some General Properties Expected of Population III	601
14.4	Ideas Leading to Population III: Why Do We Need them?	602
14.5	Alternative Ideas	604

14.6	Can a Non-Standard Big Bang Do the Job?	612
14.7	Why Do Stars Form?	613
14.8	Thermal Stability	620
14.9	Primordial Cooling and the Hydrogen Molecule	623
14.10	Must the First Star Have Been Massive?	625
14.11	How Stars Form Today	626
14.12	The Virial Theorem in Clusters of Galaxies	627
14.13	Dark Matter in Galaxies. Tracers of a Larger Mass.	636
14.14	Guesses about What Dark Matter Is Made of?	640
14.15	The Role of Dark Matter in Structure formation.	642
14.16	Almost Seeing the Beginning	645
14.17	When Did the First Stars Form?	646
14.18	Where Are the First Heavy Elements Expected to Have Been Synthesized?	646
14.19	What Has Been Found So Far?	650
14.20	The Most Massive Stars Known Today	652
14.21	The Intriguing Abundance of Lithium in Metal-Poor Stars	654
14.22	The First Direct Age Measurement of a Star	657
14.23	The Tale of G77-61: What an Old Star Can Tell Us	660
14.24	Metal-Rich Stars: A Star Loaded with Puzzles	663
14.25	How Pristine Can Stars Be?	667
14.26	Open Questions	668
Author Index		671