

Contents

1	Instruments for a Revolution	1
1.1	Solar Mysteries	1
1.2	<i>Yohkoh</i> Detects Unrest on an Awesome Scale	7
1.3	<i>Ulysses</i> Moves into Unexplored Territory	11
1.4	<i>Wind</i> Investigates the Sun's Varying Input to Earth	16
1.5	The Sun Does Not Set for <i>SOHO</i>	20
1.6	<i>ACE</i> Measures the Composition of High-Energy Particles Bombarding Earth	28
1.7	<i>TRACE</i> Focuses on Fine Details of the High-Temperature Gas	30
1.8	High-Energy Solar Outbursts Observed with <i>RHESSI</i>	34
1.9	Hinode Observes How Varying Magnetic Fields Heat the Corona and Power Explosive Outbursts There	37
1.10	<i>STEREO</i> Observes Coronal Mass Ejections in Three Dimensions from the Sun to Earth	44
1.11	Summary Highlights: Modern Solar Space Missions	46
2	Discovering Space	51
2.1	Space Is Not Empty	51
2.1.1	Auroras and Geomagnetic Storms from the Sun	51
2.1.2	The Main Ingredients of the Sun	53
2.1.3	The Hot Solar Atmosphere	55
2.1.4	Discovery of the Solar Wind	61
2.2	Touching the Unseen	64
2.2.1	The First Direct Measurements of the Solar Wind	64
2.2.2	Properties of the Solar Wind at Earth's Orbit	66
2.3	Cosmic Rays	68
2.4	Pervasive Solar Magnetism	72
2.4.1	Magnetic Fields in the Photosphere	72
2.4.2	The 11-Year Magnetic Activity Cycle	75
2.4.3	Magnetic Fields in the Corona	77
2.4.4	Interplanetary Magnetic Fields	80

2.5	X-rays from the Sun	83
2.6	Solar Outbursts Send Energetic Radiation and Particles into Space	89
2.6.1	Solar Flares	89
2.6.2	Erupting Prominences	91
2.6.3	Coronal Mass Ejections	93
2.7	Summary Highlights: Discovery of Space	94
2.8	Key Events in the Discovery of Space	97
3	Exploring Unseen Depths of the Sun	105
3.1	What Makes the Sun Shine?	105
3.1.1	The Sun's Size, Mass, and Temperature	105
3.1.2	Nuclear Reactions in the Sun's Central Regions	106
3.1.3	Solving the Solar Neutrino Problem	110
3.2	How the Energy Gets Out	116
3.3	Taking the Sun's Pulse	122
3.4	Looking Within the Sun	128
3.5	How the Sun Rotates Inside	131
3.6	Waves in the Sun's Core	135
3.7	Internal Flows	137
3.7.1	Early Work and New Methods	137
3.7.2	Poleward Flows	139
3.7.3	Zonal Flow Bands	139
3.7.4	Internal Changes Over the 11-year Cycle of Magnetic Activity	141
3.8	Three-Dimensional Views of Sunspots and Active Regions	142
3.8.1	Looking Beneath Sunspots	142
3.8.2	Swirling Flows Beneath Active Regions	143
3.8.3	Detecting Active Regions on the Far Side of the Sun	144
3.9	The Solar Dynamo	146
3.10	Summary Highlights: Exploring the Inside of the Sun	150
3.11	Key Events in the Understanding of the Internal Constitution of the Sun	152
4	Solving the Sun's Heating Crisis	161
4.1	Mysterious Heat	161
4.2	Wave Heating	164
4.3	Heating Coronal Loops in Active Regions	170
4.4	Heating the "Quiet" Corona	177
4.4.1	Heat from Jets, Bright Points, Blinkers, Explosive Events, and Interacting, Non-Flaring Loops	177
4.4.2	Nanoflares	182
4.4.3	The Magnetic Carpet	183
4.5	How Hot Is a Coronal Hole?	186
4.6	Summary Highlights: The Sun's Heating Crisis	188
4.7	Key Events in Coronal Heating	190

5	Winds Across the Void	197
5.1	The Fullness of Space	197
5.2	The Two Solar Winds	201
5.3	Where Do the Sun's Winds Come From?	205
5.3.1	Source Regions of the Solar Winds Near Solar Activity Minimum	205
5.3.2	Source Regions of the Solar Winds Near Solar Activity Maximum	211
5.3.3	Fast Wind Sources in Coronal Holes	214
5.4	Getting Up to Speed	217
5.5	Riding the Waves	224
5.6	Magnetic Connections	226
5.6.1	Flowing Wide Open	226
5.6.2	Unexpected Behavior	228
5.7	Ingredients of the Sun's Winds	231
5.7.1	Different Sources, Varying Ionization	232
5.7.2	Shocking Times	233
5.7.3	Pick-Ups Near and Far	234
5.7.4	Super-Hot and Undemocratic	236
5.8	Edge of the Solar System	236
5.9	Summary Highlights: The Sun's Expanding Corona	240
5.10	Key Events in Studies of the Solar Wind	243
6	Our Violent Sun	253
6.1	Solar Outbursts of Awesome Power	253
6.2	Flare Ribbons	259
6.3	X-Ray Flares	261
6.3.1	Soft X-Rays and Hard X-Rays from Solar Flares	261
6.3.2	A Model of Flaring X-Ray Emission	267
6.4	White-Light Flares	269
6.5	Gamma Rays from Solar Flares	271
6.6	Solar Radio Bursts	276
6.7	Filaments Lift Off, Prominences Erupt	282
6.8	Coronal Mass Ejections	287
6.8.1	Coronagraph Observations of Coronal Mass Ejections	287
6.8.2	Physical Properties of Coronal Mass Ejections	289
6.9	After the Blast	296
6.9.1	Solar Flares Excite Coronal Loop Oscillations	296
6.9.2	Sunquakes	298
6.9.3	Coronal Dimming After Coronal Mass Ejections	299
6.9.4	Large Flares Excite Global Waves	299
6.10	Explaining Why Solar Outbursts Happen	301
6.10.1	What We Do Not Know About Solar Outbursts	301
6.10.2	Magnetic Reconnection During Solar Flares	303
6.10.3	Extension of Magnetic Reconnection to Coronal Mass Ejections	309
6.10.4	Flares, Avalanches, and Earthquakes	313

6.10.5	All Twisted Up	314
6.11	Summary Highlights: Solar Flares, Erupting Prominences, and Coronal Mass Ejections	320
6.12	Key Events in Understanding Solar Outbursts	324
7	Space Weather	337
7.1	The Space Weather Concept	337
7.2	Forecasting Space Weather	342
7.3	Solar Energetic Particles	345
7.3.1	Energetic Particles Accelerated by Solar Flares or Coronal Mass Ejection Shocks	345
7.3.2	Interplanetary Coronal Mass Ejections, Interplanetary Shocks, and Magnetic Clouds	349
7.3.3	Observations of Solar Energetic Particles with Contemporary Spacecraft	352
7.3.4	Two Classes of Solar Energetic Particles	353
7.4	Impacting Planet Earth	356
7.4.1	Our Protective Magnetic Cocoon	356
7.4.2	Earth's Magnetic Storms	359
7.4.3	The Auroras – Cosmic Neon Signs	362
7.4.4	High-Flying Humans at Risk	364
7.4.5	Failing to Communicate	365
7.4.6	Satellites in Danger	366
7.4.7	Varying Solar Radiation and Earth's Changing Atmosphere	367
7.5	Sun – Climate	369
7.5.1	An Inconstant Sun	370
7.5.2	Solar Variability and Climate Change Over the Past 1,000 Years	374
7.5.3	The Earth's Rising Fever	377
7.5.4	Climate Change Over Millions and Billions of Years	381
7.6	Summary Highlights: Space Weather	386
7.7	Key Events in the Discovery of Solar-Terrestrial Interactions	391
Appendix		407
I.	Solar Space Missions	407
II.	Heliopause Heliography	408
III.	Space Weather	409
IV.	Solar Observatories and Groups	409
V.	Virtual Observatories	409
VI.	Educational	409
VII.	NASA	410
References		411
Author Index		523
Subject Index		533