

## Contents

<b>1</b>	<b>Introduction</b>	<i>1</i>
<b>2</b>	<b>Solar Structure and Evolution</b>	<i>3</i>
2.1	Equations of Stellar Structure and Evolution	<i>3</i>
2.1.1	Mechanical Structure	<i>3</i>
2.1.2	Energy Conservation and Transport	<i>5</i>
2.1.2.1	Energy Transport by Radiation and Conduction	<i>5</i>
2.1.2.2	Criterion for Dynamical Instability	<i>7</i>
2.1.2.3	Energy Transport: Convection	<i>9</i>
2.1.3	Changes in Chemical Composition	<i>11</i>
2.1.3.1	Convective Mixing	<i>11</i>
2.1.3.2	Changes in Chemical Composition: Atomic Diffusion	<i>12</i>
2.1.3.3	Changes in Chemical Composition: Nuclear Reactions	<i>15</i>
2.1.3.4	Changes in Chemical Composition: Putting Everything Together	<i>16</i>
2.1.4	Full Set of Equations and Boundary Conditions	<i>17</i>
2.2	Constitutive Physics	<i>18</i>
2.2.1	Equation of State	<i>18</i>
2.2.2	Radiative Opacities	<i>21</i>
2.2.3	Nuclear Reaction Rates	<i>25</i>
2.3	Calibrating Standard Solar Models	<i>31</i>
2.3.1	Observational Constraints	<i>31</i>
2.3.1.1	Age, Mass, Radius, and Luminosity	<i>31</i>
2.3.1.2	Surface Composition	<i>32</i>
2.3.2	Adjusting the Free Parameters	<i>35</i>
2.4	Standard Solar Models	<i>36</i>
2.4.1	Previous and Future Evolution	<i>36</i>
2.4.2	The Sun Today: An Overview	<i>39</i>
2.5	Solar Neutrinos	<i>42</i>
2.6	Helioseismology	<i>48</i>
2.6.1	Overview	<i>48</i>
2.6.2	Global Structure Inversions	<i>51</i>
2.6.3	Other Constraints	<i>53</i>
2.7	Solar Abundance Problem	<i>54</i>
2.8	Uncertainties in SSMs	<i>58</i>
2.8.1	Uncertainties in SSM Inputs	<i>58</i>

2.8.1.1	Nuclear Reaction Rates	58
2.8.1.2	Microscopic Diffusion	59
2.8.1.3	Radiative Opacities	59
2.8.1.4	Solar Radius, Luminosity, and Age	59
2.8.1.5	Solar Composition	59
2.8.1.6	Equation of State	60
2.8.2	Global Uncertainties in SSMs	60
2.8.2.1	Nuclear Reaction Rates	61
2.8.2.2	Constitutive Physics	61
2.8.2.3	Element Abundances	62
2.9	Solar Models Beyond the SSM	62
2.9.1	Nonstandard Solar Physics	63
2.9.2	Nonstandard Particle Physics	65
<b>3</b>	<b>Neutrino Physics</b>	<b>69</b>
3.1	Neutrinos in the Standard Model	69
3.2	Neutrino Oscillations	75
3.3	Matter Effects	80
3.4	Neutrino Oscillation Experiments	84
3.4.1	Atmospheric Neutrinos	84
3.4.2	Long Baseline Accelerator Neutrinos	92
3.4.2.1	Long Baseline Experiments and $\theta_{13}$	97
3.4.3	Reactor Neutrinos	100
3.5	Conclusions and Open Questions	109
3.5.1	What Is the Absolute Neutrino Mass Scale?	111
3.5.2	Are Neutrinos Majorana or Dirac Particles?	120
3.5.3	What Is the Neutrino Mass Ordering and How Large Is CP- $\delta$ ?	127
3.5.4	Are There Sterile Neutrinos?	135
<b>4</b>	<b>Solar Neutrino Experiments</b>	<b>139</b>
4.1	Introduction	139
4.2	The $^{37}\text{Cl}$ Experiment	141
4.3	Kamiokande-II/III	145
4.4	The $^{71}\text{Ga}$ Experiments	153
4.5	Super-Kamiokande	162
4.6	SNO	169
4.7	Borexino	178
4.8	Summary and Open Questions	191
<b>5</b>	<b>Future Solar Neutrino Experiments</b>	<b>195</b>
5.1	SNO+	196
5.2	JUNO and LENA	199
5.3	Hyper-Kamiokande	204
5.4	DUNE	206

**References** 209

**Index** 221