

## Contents

---

<i>Preface</i>	xiii
<i>List of Acronyms</i>	xv
Part I Introduction	1
<b>1 An Overview of Star Formation</b>	3
1.1 Introduction	3
<b>Low-Mass Star Formation (LMSF)</b>	4
1.2 Diffuse Clouds	4
1.3 Molecular Clouds	5
1.4 Dense Prestellar Cores	6
1.5 Cold Protostellar Envelopes	8
1.6 Jets and Disk Winds	9
1.7 Protoplanetary Disks	10
<b>High-Mass Star Formation (HMSF)</b>	11
1.8 Dark Cloud to Main Sequence	11
1.9 Hot Cores	13
1.10 Compact HII Regions	14
1.11 Photodissociation Regions (PDRs)	15
1.12 Masers	16
<b>Molecular Astrophysics</b>	17
1.13 Molecular Excitation	17
1.14 Level Populations	17
1.15 Critical Densities and Excitation Temperatures	17
<b>Astrochemistry</b>	18
1.16 Gas-Phase and Grain-Surface Reactions	18
1.17 Chemical Modelling	19
<b>Observational Basics</b>	18
1.18 Antenna Temperature and Optical Depth	20

1.19	Velocity Distribution	21
1.20	Column Density, Beam Dilution, and Relative Abundance	21
1.21	Rotation Diagrams	22
1.22	Radiative Transfer Modelling	23
	Further Reading	23
Part II	Low-Mass Star Formation (LMSF)	25
<b>2</b>	<b>Two LMSFR Surveys Using IRAM and ALMA</b>	<b>27</b>
2.1	Introduction	27
2.2	IRAM COMs	27
2.3	IRAM Observations	29
2.4	COMs Correlations	32
2.5	Low-Mass YSO Chemical Model	36
2.6	COMs Formation	37
2.7	Increasing Resolution with ALMA	40
2.8	Summary	44
<b>3</b>	<b>IRAS 16293 in Ophiuchus</b>	<b>46</b>
3.1	Introduction	46
3.2	Dark Clouds and Streamers	46
3.3	Filaments and Cores	49
3.4	IRAS 16293-2422	52
3.5	A Gas Bridge	55
3.6	Deuterated Evolutionary Tracers	58
3.7	Disk–Envelope Interface	60
3.8	Disk Reservoirs	63
3.9	Centrifugal Barriers	65
3.10	Prebiotics	67
3.11	Nitriles	70
3.12	Summary	71
<b>4</b>	<b>NGC 1333 in Perseus</b>	<b>72</b>
4.1	Introduction	72
4.2	Envelope and Accretion	72
4.3	Warm Carbon-Chain Chemistry (WCCC)	75
4.4	IRAS2 and IRAS4	78
4.5	COMs Ratios	80
4.6	Comparisons	81
4.7	C <sub>2</sub> H	82
4.8	Wider Sampling	84
4.9	Summary	85

Contents		ix
<b>5</b>	<b>IRAS 15398 in Lupus</b>	88
	5.1 Introduction	88
	5.2 Nine Clouds	90
	5.3 IRAS 15398-3359 (Lupus I-1)	92
	5.4 The Bipolar Outflow	95
	5.5 H <sub>2</sub> O with ALMA	101
	5.6 Summary	102
	<b>Part III High-Mass Star Formation (HMSF)</b>	<b>105</b>
<b>6</b>	<b>Two HMSFR Surveys Using APEX and NOEMA</b>	<b>107</b>
	6.1 Introduction	107
	6.2 ATLASGAL	108
	6.3 Molecular Fingerprints with Mopra	110
	6.4 NOEMA	115
	6.5 Physical Structure	116
	6.6 Chemical Structure	119
	6.7 Comparing Timescales	121
	6.8 Summary	122
<b>7</b>	<b>Sagittarius B2(N)</b>	<b>124</b>
	7.1 Introduction	124
	7.2 Sgr B2 (N), (M), and (S)	124
	7.3 Sgr B2 (N)	126
	7.4 COMs in Sgr B2(N)	127
	7.5 Complex Isocyanides in Sgr B2 (N)	130
	7.6 Summary	133
<b>8</b>	<b>G29.96-0.02 in W43</b>	<b>134</b>
	8.1 Introduction	134
	8.2 Westerhout 43	134
	8.3 The W43 Sub-sources	135
	8.4 G29.96-0.02 #1	138
	8.5 Star Formation Efficiency (SFE)	145
	8.6 G29.96 COMs	147
	8.7 Summary	148
<b>9</b>	<b>Orion BN/KL</b>	<b>152</b>
	9.1 Introduction	152
	9.2 OMC	153
	9.3 BN/KL	155
	9.4 The Four Features	158

9.5	Chemical Differentiations	161
9.6	Summary	164
Part IV Ionisation		165
<b>10</b>	<b>Two HII Surveys Using JVLA and ALMA</b>	167
10.1	Introduction	167
10.2	HII with the Jansky-VLA	167
10.3	A Second Survey: ATOMS-ALMA	172
10.4	UCHII or HCHII	173
10.5	Summary	175
<b>11</b>	<b>G24.78+0.08 in Scutum</b>	176
11.1	Introduction	176
11.2	G24.78+0.08	176
11.3	RRL Emission	181
11.4	Multiple Sub-cores	182
11.5	The A1 HCHII	183
11.6	The A1 Molecular Disk	185
11.7	Summary	187
<b>12</b>	<b>G34.26+0.15 in Aquila</b>	188
12.1	Introduction	188
12.2	G34.26+0.15	188
12.3	UCHIIs A and B	191
12.4	UCHII-C	193
12.5	The Hot Core	197
12.6	Displaced CH <sub>3</sub> CN	199
12.7	Summary	202
Part V Photodissociation		203
<b>13</b>	<b>ATLASGAL PDRs</b>	205
13.1	Introduction	205
13.2	ATLASGAL	206
13.3	Formation and Destruction of HCO/HCO <sup>+</sup>	209
13.4	Small Hydrocarbons in PDRs	211
13.5	Summary	215
<b>14</b>	<b>The Orion Bar in M42</b>	216
14.1	Introduction	216
14.2	The Orion Bar	217
14.3	PDR Ionisation	221

	Contents	xi
14.4	Molecular Dissociation	225
14.5	Inhomogeneities and Proplyds	226
14.6	Sulphur	228
14.7	Summary	234
<b>15</b>	<b>The Horsehead Nebula in Orion</b>	<b>236</b>
15.1	Introduction	236
15.2	Low-Flux Photodissociation	236
15.3	Nitrile COMs	239
15.4	Dust Extinction	243
15.5	The Warm High-Density Case	244
15.6	Sulphur	245
15.7	Summary	251
Part VI	External Galaxies	253
<b>16</b>	<b>Extragalactic Surveys: CANON and PHANGS-ALMA</b>	<b>255</b>
16.1	Introduction	255
16.2	CANON	256
16.3	Comparative Resolution	258
16.4	PHANGS-ALMA	260
16.5	Summary	266
<b>17</b>	<b>ST16 and N113 in the Large Magellanic Cloud</b>	<b>267</b>
17.1	Introduction	267
17.2	ST16	268
17.3	Column Densities	270
17.4	Comparative Abundances	273
17.5	A Rotating Envelope	275
17.6	N113	276
17.7	Low-Metallicity COMs	277
17.8	Summary	280
<b>18</b>	<b>Starburst Galaxy NGC 253</b>	<b>281</b>
18.1	Introduction	281
18.2	Super Star Clusters	282
18.3	Physical Parameters from Absorption Lines	287
18.4	Outflow Dynamics	290
18.5	Cluster Evolution Chemistry	291
18.6	The Wider Molecular Sample	292
18.7	Summary	294

<i>Appendices</i>	295
A Galactic and Extragalactic Molecules	295
B Observational and Modelling Databases	295
C Wavelength, Frequency, and Energy	296
D Generic Reaction Processes and Rates	296
E Interstellar and Circumstellar Physical Parameters	297
F Elemental Abundances	297
G Interstellar Ice Composition	298
<i>List of Research Journal Abbreviations</i>	299
<i>References</i>	301
<i>Chemical Index</i>	315
<i>Subject Index</i>	318