

Contents

1	Radio Astronomical Fundamentals	1
1.1	On the Role of Radio Astronomy in Astrophysics	1
1.2	The Radio Window	3
1.3	Discoveries in Radio Astronomy	5
1.3.1	A Selected List of Facilities	6
1.4	Some Basic Definitions	7
1.5	Radiative Transfer	10
1.6	Black Body Radiation and the Brightness Temperature	13
1.7	Emissivity and Reflectivities of Surfaces	18
1.8	The Nyquist Theorem and the Noise Temperature	19
	Problems	20
	References	23
2	Electromagnetic Wave Propagation Fundamentals	25
2.1	Maxwell's Equations	25
2.2	Plane Waves in Nonconducting Media	26
2.3	Wave Packets and the Group Velocity	30
2.4	Plane Waves in Conducting Media	32
2.5	The Dispersion Measure of a Tenuous Plasma	33
	Problems	37
	References	39
3	Wave Polarization	41
3.1	Vector Waves	41
3.2	The Poincaré Sphere and the Stokes Parameters	46
3.3	Quasi-monochromatic Plane Waves	50
3.4	The Stokes Parameters for Quasi-monochromatic Waves	51
3.5	Faraday Rotation	52
	Problems	57
	References	59

4	Signal Processing and Receivers: Theory	61
4.1	Signal Processing and Stationary Stochastic Processes	61
4.1.1	Probability Density, Expectation Values and Ergodicity	61
4.1.2	Autocorrelation and Power Spectrum	63
4.1.3	Linear Systems	66
4.1.4	Filters	68
4.1.5	Digitization and Sampling	68
4.1.6	Gaussian Random Variables	71
4.1.7	Square Law Detectors	72
4.1.8	Receiver Calibration Procedure	73
4.2	Limiting Receiver Sensitivity	74
4.2.1	Noise Uncertainties Due to Random Processes	76
4.2.2	The Minimum Noise for a Coherent System	78
4.2.3	Receiver Stability	79
	Problems	85
	References	89
5	Practical Receiver Systems	91
5.1	Historical Introduction	91
5.1.1	Incoherent Radiometers	91
5.1.2	Coherent Radiometers	91
5.1.3	Bolometer Radiometers	92
5.1.4	The Noise Equivalent Power of a Bolometer	94
5.1.5	Currently Used Bolometer Systems	95
5.2	Coherent Receivers	98
5.2.1	Basic Components: Passive Devices	98
5.2.2	Basic Components: Active Devices	99
5.2.3	Semiconductor Junctions	105
5.2.4	Practical HEMT Devices	107
5.2.5	Superconducting Mixers	109
5.2.6	Hot Electron Bolometers	111
5.3	Summary of the Coherent Front Ends Presently in Use	113
5.3.1	Single Pixel Receiver Systems	113
5.3.2	Multibeam Systems	114
5.4	Back Ends: Correlation Receivers, Polarimeters and Spectrometers	115
5.4.1	Correlation Receivers and Polarimeters	115
5.4.2	Spectrometers	118
5.4.3	Fourier and Autocorrelation Spectrometers	119
5.4.4	Pulsar Back Ends	130
	Problems	132
	References	134

6	Fundamentals of Antenna Theory	137
6.1	Electromagnetic Potentials	137
6.2	Green's Function for the Wave Equation	139
6.3	The Hertz Dipole	143
6.4	The Reciprocity Theorem	148
6.5	Arrays of Dipoles	148
6.6	Radiation Fields of Filled Antennas	152
6.6.1	Two Dimensional Far Field	152
6.6.2	Three Dimensional Far Field	154
6.6.3	Circular Apertures	157
6.6.4	Antenna Grading Related to Power Patterns	159
6.7	Summary	161
	Problems	162
	References	164
7	Practical Aspects of Filled Aperture Antennas	165
7.1	Descriptive Antenna Parameters	165
7.1.1	The Power Pattern $P(\vartheta, \varphi)$	165
7.1.2	The Main Beam Solid Angle	166
7.1.3	Effective Area	168
7.1.4	Antenna Temperature	172
7.2	Primary Feeds	174
7.2.1	Prime Focus Feeds: Dipole and Reflector	175
7.2.2	Horn Feeds Used Today	175
7.3	Reflector Systems	177
7.3.1	Antenna Blockage	179
7.3.2	Field of View	181
7.4	Antenna Tolerance Theory	183
7.5	The Practical Design of Parabolic Reflectors	188
7.5.1	General Considerations	188
7.5.2	Specific Antennas	190
7.6	Summary	194
	Problems	195
	References	197
8	Single Dish Observational Methods	199
8.1	The Earth's Atmosphere	199
8.2	Calibration Procedures	204
8.2.1	General	204
8.2.2	Compact Sources	205
8.2.3	Extended Sources	207
8.2.4	Extremely Extended Sources	208
8.2.5	Calibration of Meter Wavelength Instruments	208
8.2.6	Calibration of Centimeter Wavelength Telescopes	209

8.2.7	Calibration of mm and sub-mm Wavelength Telescopes for Heterodyne Systems	209
8.2.8	Bolometer Calibrations	213
8.3	Continuum Observing Strategies	213
8.3.1	Point Sources	213
8.3.2	Imaging of Extended Continuum Sources	215
8.4	Additional Requirements for Spectral Line Observations	217
8.4.1	Radial Velocity Settings	217
8.4.2	Stability of the Frequency Bandpass	219
8.4.3	Instrumental Frequency Baselines	219
8.4.4	The Effect of Stray Radiation	222
8.4.5	Spectral Line Observing Strategies	224
8.5	Pulsar Observing Strategies	226
8.6	Source Confusion	227
8.6.1	Introduction	227
8.6.2	Spectral Line Confusion	230
	Problems	230
	References	235
9	Interferometers and Aperture Synthesis	237
9.1	The Quest for Higher Angular Resolution	237
9.2	Basic Principles	240
9.2.1	Historical Development	242
9.3	Responses of Interferometers	244
9.3.1	Finite Bandwidth	244
9.3.2	Source Size and Minimum Spacing	246
9.3.3	Bandwidth and Beam Narrowing	246
9.4	Hardware Requirements	247
9.4.1	Local Oscillators and Instrumental Effects	247
9.4.2	Multibeam Systems and Focal Plane Arrays	248
9.4.3	Coordinate Systems for Interferometry	250
9.5	Very Long Baseline Interferometry	253
9.6	Interferometers in Astrometry and Geodesy	256
9.7	Sensitivity	259
9.8	Observing Strategies	260
9.8.1	Basic Procedures	260
9.8.2	Dynamic Range and Image Fidelity	261
9.8.3	Observing Procedures	262
9.9	Spatial Filtering and Interferometry	264
9.10	Data Processing	265
9.10.1	Gridding uv Data	265
9.10.2	Principal Solution, Dirty Map and Dirty Beam	266
9.11	Aperture Synthesis	270
9.11.1	Improving Visibility Functions	272
9.11.2	Multi-antenna Array Calibrations	273

9.12	Advanced Image Improvement Methods	273
9.12.1	Self-Calibration	273
9.12.2	The CLEAN Process	274
9.12.3	The Maximum Entropy Deconvolution Method (MEM)	275
9.13	Calibrations and Corrections for Low Frequency Measurements	276
9.14	Calibrations and Corrections for High Frequency Measurements	277
9.15	Present Day Facilities	279
9.16	Summary	283
	Problems	283
	References	287
10	Emission Mechanisms of Continuous Radiation	289
10.1	The Nature of Radio Sources	289
10.2	Black Body Radiation from Astronomical Objects	291
10.3	Dust Emission	292
10.4	Radiation from Accelerated Electrons	296
10.5	The Frequency Distribution of Bremsstrahlung for an Individual Encounter	297
10.6	The Radiation of an Ionized Gas Cloud	301
10.7	Nonthermal Radiation Mechanisms	305
10.8	Review of the Lorentz Transformation	306
10.9	The Synchrotron Radiation of a Single Electron	309
10.9.1	The Total Power Radiated	310
10.9.2	The Angular Distribution of Radiation	311
10.9.3	The Frequency Distribution of the Emission	312
10.10	The Spectrum and Polarization of Synchrotron Radiation	314
10.11	The Spectral Distribution of Synchrotron Radiation from an Ensemble of Electrons	317
10.11.1	Homogeneous Magnetic Field	320
10.11.2	Random Magnetic Field	322
10.12	Energy Requirements of Synchrotron Sources	323
10.13	Low-Energy Cut-Offs in Nonthermal Sources	325
10.14	Inverse Compton Scattering	326
10.14.1	The Sunyaev-Zeldovich Effect	326
10.14.2	Energy Loss from High-Brightness Sources	328
	Problems	329
	References	331
11	Some Examples of Thermal and Nonthermal Radio Sources	333
11.1	The Quiet Sun	333
11.2	Radio Radiation from Other Solar System Objects	337
11.3	Spatially Extended Radio Radiation	338
11.4	Measurements of the Cosmic Microwave Background Radiation	339

11.5	Models Based on CMB Data	343
11.6	Radio Radiation from H II Regions	344
11.6.1	Thermal Continuum	344
11.6.2	Radio Radiation from Ionized Stellar Winds	346
11.7	Supernovae and Supernova Remnants	347
11.8	The Hydrodynamic Evolution of Supernova Remnants	349
11.8.1	The Free-Expansion Phase	350
11.8.2	The Second Phase: Adiabatic Expansion	352
11.8.3	The Third Phase: Snowplow Expansion	357
11.9	The Radio Evolution of Older Supernova Remnants	357
11.10	Pulsars	360
11.10.1	Detection and Source Nature	360
11.10.2	Distance Estimates and Galactic Distribution	362
11.10.3	Intensity Spectrum and Pulse Morphology	364
11.10.4	Pulsar Timing	367
11.10.5	Rotational Slowdown and Magnetic Moment	369
11.10.6	Binary Pulsars	372
11.10.7	Millisecond Pulsars	374
11.10.8	Pulsars as Gravitational Wave Detectors	376
11.10.9	Radio Emission Mechanism	377
11.11	Extragalactic Sources	378
11.11.1	Relativistic Effects and Time Variability	379
11.11.2	Radio Galaxies: Cygnus A	382
11.11.3	An Example of the Sunyaev-Zeldovich Effect: Clusters of Galaxies	383
11.11.4	Gravitational Lensing	384
Problems	.....	385
References	.....	388
12	Spectral Line Fundamentals	393
12.1	Radio Spectroscopy	393
12.2	The Einstein Coefficients	393
12.3	Radiative Transfer with Einstein Coefficients	395
12.4	Dipole Transition Probabilities	398
12.5	A Solution of the Rate Equation	400
Problems	.....	402
References	.....	404
13	Line Radiation from Atoms	405
13.1	The 21 cm Line of Neutral Hydrogen	406
13.2	The Zeeman Effect	409
13.3	Spin Temperatures	410
13.4	Emission and Absorption Lines	412
13.4.1	The Influence of Beam Filling Factors and Source Geometry	413
13.5	The Physical State of the Diffuse Interstellar Gas	416

13.6	Differential Velocity Fields and the Shape of Spectral Lines	418
13.7	The Velocity Field in the Interstellar Galactic Gas	420
13.8	Extragalactic Neutral Hydrogen	424
13.8.1	Virial Masses	426
13.8.2	The Tully-Fisher Relation	428
13.9	Cosmological Neutral Hydrogen	430
Problems	.....	433
References	.....	436
14	Radio Recombination Lines	439
14.1	Emission Nebulae	439
14.2	Photoionization Structure of Gaseous Nebulae	440
14.2.1	Pure Hydrogen Nebulae	440
14.2.2	Hydrogen and Helium Nebulae	443
14.2.3	Actual HII Regions	445
14.3	Rydberg Atoms	446
14.4	Line Intensities Under LTE Conditions	448
14.5	Line Intensities When LTE Conditions Do Not Apply	450
14.5.1	Collisional Broadening	455
14.6	The Interpretation of Radio Recombination Line Observations	456
14.6.1	Anomalous Cases	458
14.7	Recombination Lines from Other Elements	458
Problems	.....	459
References	.....	462
15	Overview of Molecular Basics	465
15.1	Basic Concepts	465
15.2	Rotational Spectra of Diatomic Molecules	467
15.2.1	Hyperfine Structure in Linear Molecules	470
15.3	Vibrational Transitions	471
15.4	Line Intensities of Linear Molecules	473
15.4.1	Total Column Densities of CO Under LTE Conditions	475
15.5	Symmetric Top Molecules	479
15.5.1	Energy Levels	479
15.5.2	Spin Statistics	480
15.5.3	Hyperfine Structure	481
15.5.4	Line Intensities and Column Densities	484
15.6	Asymmetric Top Molecules	486
15.6.1	Energy Levels	486
15.6.2	Spin Statistics and Selection Rules	486
15.6.3	Line Intensities and Column Densities	487
15.6.4	Electronic Angular Momentum	491
15.6.5	Molecules with Hindered Motions	493
Problems	.....	494
References	.....	496

16	Molecules in Interstellar Space	499
16.1	Introduction	500
16.1.1	History	500
16.2	Molecular Excitation	504
16.2.1	Excitation of a Two-Level System	504
16.2.2	Maser Emission Processes in One Dimension	506
16.2.3	Non-LTE Excitation of Molecules	512
16.3	Models of Radiative Transfer	515
16.3.1	The Large Velocity Gradient Model	515
16.4	Spectral Lines as Diagnostic Tools	521
16.4.1	Kinetic Temperatures	521
16.4.2	Linewidths, Radial Motions and Intensity Distributions	522
16.4.3	Rotation Diagrams and the Total Column Densities of Species	523
16.4.4	Determination of H ₂ Densities	525
16.4.5	Estimates of H ₂ Column Densities from CO Line Data	526
16.4.6	Masses of Molecular Clouds from Measurements of ¹² C ¹⁶ O	527
16.4.7	The Correlation of CO and H ₂ Column Densities	528
16.4.8	Mass Estimates and Cloud Stability	531
16.4.9	Signatures of Cloud Collapse	533
16.5	A Simplified Classification of Clouds	534
16.6	Chemistry	536
16.6.1	Observational Results	536
16.6.2	Ion-Molecule Chemistry	539
16.6.3	Neutral-Neutral Chemistry	543
16.6.4	Grain Chemistry	543
16.6.5	Models of Photon Dominated Regions	544
16.6.6	Searches for New Molecules	546
16.6.7	Searches for Precursors of Life	549
	Problems	550
	References	553
A	Some Useful Vector Relations and Fourier Transforms	557
	References	561
B	The Van Vleck Clipping Correction: One Bit Quantization	563
C	Conventional Derivation of Square Law Detector Response and Receiver Noise	567
C.1	Square-Law Detector	567
C.2	Limiting Receiver Sensitivity	570
	References	574

D	The Reciprocity Theorem	575
E	Filled Aperture Antennas	579
E.1	The Radiation Field of Localized Sources	579
F	The Hankel Transform	583
	Reference	584
G	Lists of Calibration Radio Sources	585
	References	588
H	The Mutual Coherence Function and van Cittert-Zernike Theorem	589
H.1	The Mutual Coherence Function	589
H.2	The Coherence Function of Extended Sources: The van Cittert-Zernike Theorem	590
	Reference	594
Index	.....	595