CONTENTS

CHAPTER 1

RADIATION OF HOT GASES

(thermal and non-thermal)

J. RICHTER

1. INTRODUCTION 1
   - 1.1. General remarks 1
   - 1.2. Physical state of a plasma 2
   - 1.3. Spectroscopic plasma diagnostics 3
   - 1.4. Outline of this chapter 4

2. INTENSITY AND RADIATION FIELD 5
   - 2.1. Intensity 5
   - 2.2. Radiation density 7
   - 2.3. Radiation flux 8

3. EQUILIBRIUM RELATIONS 9
   - 3.1. General remarks 9
   - 3.2. Planck's radiation law 10
   - 3.3. Kirchhoff's law of radiation 11
   - 3.4. Velocity distribution and kinetic temperatures 13
   - 3.5. The Boltzmann formula 14
   - 3.6. The Saha equation 15
   - 3.7. The equation of state 16
   - 3.8. Lowering of the ionization energy 16
   - 3.9. Calculation of particle densities in equilibrium 18
   - 3.10. Calculation of partition functions 20

4. ABSORPTION AND EMISSION OF SPECTRAL LINES 20
   - 4.1. Transition probabilities 20
   - 4.2. Determination of transition probabilities 22
   - 4.3. Absorption coefficient of spectra lines 25
   - 4.4. The emission coefficient of spectral lines 27

5. CONTINUOUS EMISSION AND ABSORPTION 28
   - 5.1. General remarks 28
   - 5.2. The process of photo-ionization 29
   - 5.3. Absorption and emission coefficient of the bound-free radiation 32

5.4. Approximation formulas for hydrogen-like ions 35
5.5. The ξ-factor of Biberman 36
5.6. The advance of series limits 37
5.7. The continuum of negative ions 39
5.8. The free-free continuum 40

6. Deviations from thermodynamic equilibrium 42
6.1. Models of the plasma state 42
6.2. Interaction processes in a plasma 43
6.3. Local thermodynamic equilibrium (LTE) 45
6.4. Partial local thermodynamic equilibrium 49
6.5. The corona model 51

7. Radiation intensity emitted from a plasma 53
7.1. The equation of radiative transfer 53
7.2. Radiation transfer in an LTE and in a collision-dominated plasma . . . 55
7.3. The curve of growth for a homogeneous layer 56
7.4. Extinction and scattering 59
7.5. Radiative transfer including scattering 60

Selected bibliography on radiation of hot gases and atomic and molecular spectra . 62

References 63

Chapter 2

INTERPRETATION OF LINE BROADENING AND LINE SHIFT

G. TRAVING

1. Introductory remarks 66

2. Mathematical foundations and classical theories 67
2.1. Formulation of the problem 67
2.2. The radiation damping 68
2.3. The correlation function 70
2.4. Dopplerbroadening 72
2.5. Pressure broadening, general considerations 74
2.6. The impact theory 76
2.7. The static theory, nearest neighbour approximation 81
2.8. The static theory, Van der Waals' interaction 82
2.9. The static theory, $p = 2$, the Holtsmark distribution 83
2.10. The electric field distribution for interacting charges 85
2.11. The field distribution in dense plasma 87

3. Quantum theory of line broadening 89
3.1. The autocorrelation function $\phi(s)$ 89
3.2. The semi-classical approach 90
3.3. Interaction representation and the one level atom 93

3.4. Quantum mechanical approach 94
3.5. The collision approximation 97
3.6. Broadening due to electron collisions 99

4. SPECIAL APPLICATIONS 101
4.1. Hydrogen lines 101
4.2. The broadening of HeI and other lines by charged perturbers 113
4.3. The broadening by neutral perturbers 120

5. THE VOIGT FUNCTION $H(\alpha, v)$ 127

References 131

CHAPTER 3

EVALUATION OF PLASMA PARAMETERS

W. LOCHTE-HOLTGREVEN

1. INTRODUCTION 135
1.1. Discussion of some general plasma properties 136
1.2. Pressure and concentration gradients within plasmas 143
1.3. Time for establishment of L.T.E.; transient plasmas 146

2. HOMOGENEOUS, OPTICALLY THIN L.T.E. PLASMAS 148
2.1. The solution of Saha's equation 149
2.2. The determination of the electron density 157
2.3. The determination of temperature 166
2.4. Experimental proof for establishment of L.T.E. 183

3. INHOMOGENEOUS, OPTICALLY THIN L.T.E. PLASMAS 184
3.1. Cylindrical symmetry of light sources. Abel's inversion 184

4. NON-L.T.E. OPTICALLY THIN PLASMAS 186
4.1. Determination of T_e from absolute and relative line intensities 186
4.2. Determination of T_e from second order Stark effect 187
4.3. Evaluation of norm temperatures 188

5. L.T.E. PLASMAS ALMOST, BUT NOT QUITE OPTICALLY THIN 189
5.1. Determination of the temperature from the velocity of sound 189
5.2. Determination of density from the refractivity of the plasma 190

6. NON-L.T.E. PLASMAS, NOT OPTICALLY THIN 198
6.1. Measurement of the plasma pressure and the plasma density 198
6.2. Plasma density obtained from absorption of electro-magnetic radiation . . 199
6.3. Measurement of the plasma density from corpuscular probe beams and from tracer methods 200
6.4. Plasma density from the curve of growth 201

References 210

CHAPTER 4

EVALUATION OF PLASMA PARAMETERS IN OPTICALLY THICK PLASMAS

H. ZWICKER

1. INTRODUCTION 214

2. INFLUENCE OF REABSORPTION IN HOMOGENEOUS PLASMAS 215
2.1. Collisional radiative plasma models 215
2.2. Collision-dominated plasmas 220

3. REABSORPTION IN DIAGNOSTICS OF HOMOGENEOUS PLASMAS 224
3.1. Line profile 224
3.2. Infra-red measurements 225

4. THE INFLUENCE OF REABSORPTION IN INHOMOGENEOUS PLASMA COLUMNS HAVING LOCAL THERMAL EQUILIBRIUM 230

5. DIAGNOSTIC METHODS FOR INHOMOGENEOUS PLASMA COLUMNS WHICH ARE OPTICALLY NOT THIN 240
5.1. Determination of temperature 240
5.2. Determination of electron density 244
5.3. Determination of the line shape in self-reversed lines 246

References 248

CHAPTER 5

QUANTITATIVE SPECTROSCOPY AND SPECTRAL PHOTOMETRY

W. LOCHTE-HOLTGREVEN and J. RICHTER

1. DETECTION AND MEASUREMENT OF LIGHT 250
1.1. The photographic layer 250
1.2. Photo-electric detectors 266

2. SPECTRAL SEPARATION 279
2.1. Filters 279
2.2. Spectrographs and monochromators 283
2.3. The interferometer of Fabry and Perot 296

3. INTENSITY AND WAVELENGTHS STANDARDS 303
3.1. The primary intensity standard: blackbody radiation 303
3.2. Secondary standards 303
3.3. Synchrotron radiation 311
3.4. Other possibilities for intensity calibration especially in the ultraviolet spectral region 312
3.5. Wavelengths standards 313

4. MEASUREMENT OF INTENSITIES AND OF WAVELENGTHS 315
4.1. Photographic measurement of relative intensities 315

4.2. Photo-electric measurement of relative intensities 318
4.3. Relative intensities of lines being superposed to some continuous background 322
4.4. Photographic measurement of absolute intensities 323
4.5. The apparatus profile and the correction of line profiles 325
4.6. Measurement of wavelengths 328

5. SHORT TIME SPECTROSCOPY 330
5.1. Fast shutters for cameras 330
5.2. Fast shutters for spectrographs 333
5.3. Time resolved photographic spectra 335
5.4. Photo-electric recording of spectra 338
5.5. Image intensification 339

References 342

CHAPTER 6

VACUUM ULTRAVIOLET SPECTROSCOPY

R. LINCKE

1. INTRODUCTION 347

2. TRANSMISSION AND REFLECTION OPTICS 349
2.1. Transmission of solids. Windows, lenses and prisms 350
2.2. Transmission of thin films. Filters and windows 351
2.3. Transmission of gases. Narrow-band filters 354
2.4. High reflectance coatings 354
2.5. Reflection filters 357
2.6. Gratings 357

3. SPECTROGRAPHS AND MONOCHROMATORS 360
3.1. Prism spectrographs 361
3.2. Grating spectrographs and monochromators 366
3.3. Time-resolving spectrographs 368

4. DETECTORS 369
4.1. Spectroscopic films and plates 371
4.2. Photomultipliers with windows 373
4.3. Fluorescence-sensitized photomultipliers 375
4.4. Metal-coated fluorescent screens 380
4.5. Open photomultipliers 382
4.6. Ionization chambers and photon counters 387
4.7. Thermopiles 389

5. LIGHT SOURCES 391

6. MEASUREMENT OF SPECTRAL INTENSITIES 394
6.1. Basic considerations 395
6.2. Calibration based on detectors with known response 397

6.3. Calibrations based on standard radiation sources 400
6.4. Calibration of spectroscopic films 408

7. Applications 410
7.1. Emission spectroscopy 410
7.2. Absorption spectroscopy 413

References 419

Chapter 7

X-RAY DIAGNOSTICS OF PLASMAS

P. BOGEN

1. Introduction 424

A. X-ray emission from plasmas 426
2. Ionization of a plasma 426
3. Line radiation 428
4. Continuum radiation 429
5. Line broadening 432
6. Hard X-rays 433

B. X-ray sources 433
7. Plasma sources 433
8. Non-thermal X-rays sources 436

C. Radiation detectors 437
9. Photographic emulsions 437
10. Windowless photomultipliers 439
11. Scintillator-photomultiplier combinations 441
12. Gas counters 443
13. Semiconductor detectors 443
14. Pulse height analysis 444

D. Filters 445
15. Absorption filters 445
16. Reflection filters 450

E. Spectrometers 451
17. Grating spectrometers 451
18. Crystal spectrometers 455
19. Comparison between grating and crystal spectrometers 459
20. Experimental arrangement of spectrometer and light source 460
21. Apparatus function 462
22. Scattered light 463

F. Calibration 464
23. General discussion 464

24. Wavelength calibration 467
25. Possible intensity standards 467
26. Absolute calibration of detectors 470
27. Transmission of spectrometers 471
28. Geometrical factors 473

References 474

CHAPTER 8

MICROWAVE DIAGNOSTIC TECHNIQUES

H. HERMANSDORFER

1. INTRODUCTION 478

2. DISPERSION RELATIONS 479
2.1. Cold plasma 480
2.2. Collisions 487
2.3. Hot plasma 490

3. TRANSMISSION PATH MODELS 493
3.1. W.K.B. approximation 493
3.2. Uniform plasma slab with sharp boundaries 494
3.3. Inhomogeneous plasma slab — wave optics approach 496
3.4. Plasma columns 498
3.5. Diffraction considerations 498

4. DIFFERENT MEASURING PRINCIPLES 500
4.1. Forward transmission 500
4.2. Reflection 503
4.3. Refraction 506
4.4. Cross modulation 507

5. EXPERIMENTAL ARRANGEMENTS 507
5.1. Free-space arrrangements 507
5.2. Guided propagation 509
5.3. Probes 510
5.4. Resonators 512

6. THERMAL MICROWAVE RADIATION 517

7. ELECTRON DENSITY FLUCTUATIONS 521
7.1. Ray optic scattering 521
7.2. Combination scattering 521
7.3. Collective radiation 524

8. COHERENT PHASE BRIDGE INTERFEROMETERS 525
8.1. Principles of operation 525
8.2. Detection 527

8.3. Modulation techniques 530
8.4. Interferometer circuitry 535
8.5. Polarization techniques 537

9. RADIOMETERS 538
9.1. Baseband and superheterodyne receivers 539
9.2. Dicke radiometers 540
9.3. Correlation radiometry 540
9.4. Microwave frequency selection 541

References 541

CHAPTER 9

THE LASER AS A TOOL FOR PLASMA DIAGNOSTICS

H. J. KUNZE

A. PLASMA DIAGNOSTICS BY LIGHT SCATTERING
1. Theory of light scattering by plasmas 550
1.1. Scattering of radiation by a single free electron (Thomson scattering) . 551
1.2. Limits of the Thomson scattering theory 556
1.3. Scattering of radiation by a bound electron 558
1.4. Scattering of radiation by a fully ionized plasma 558
1.5. Scattering of radiation by a partially ionized plasma 571
2. Application of light scattering 572
2.1. Choice of the scattering angle 572
2.2. Considerations on the required light source 574
2.3. Inherent experimental limitations of this diagnostic method 576
2.4. Experimental arrangements 579
2.5. Calibration methods 586
2.6. Influence of the laser on the plasma 589
2.7. Technical remarks 591

B. FARADAY ROTATION IN THE VISIBLE AND INFRARED REGION
3. Theoretical considerations 597
4. Experiments 599

C. APPLICATION OF LASERS TO PLASMA INTERFEROMETRY
5. The laser, a new light source for interferometric, schlieren and shadowgraph techniques 603
6. The laser interferometer 606

References 611

CHAPTER 10

MEASUREMENT OF MAGNETIC FIELDS IN PLASMAS

W. BÖTTICHER

1. INTRODUCTION 617

2. PROBE MEASUREMENTS 618
2.1. Inductive probes 618
2.2. Galvano-magnetic probes 637
2.3. Interactions of probe and plasma 643

3. SPECTROSCOPIC METHODS 649
3.1. The Faraday effect 650
3.2. The Zeeman effect 650

4. DETERMINATION OF CURRENT DENSITY AND MAGNETIC PRESSURE 663
References 665

CHAPTER 11

ELECTRICAL PROBES

L. SCHOTT

1. INTRODUCTION 668

2. SINGLE PROBES 670
2.1. The probe characteristic 670
2.2. Spherical and cylindrical probes 675
2.3. Limitations and improvements of low pressure theory 681
2.4. Determination of the plasma properties 694
2.5. Special single probe arrangements 699
2.6. Probe construction 703

3. DOUBLE PROBES 705
3.1. Basic equations 705
3.2. The double probe characteristic 706
3.3. Evaluation of plasma parameters 708

4. PROBES UNDER COMPLICATED PLASMA CONDITIONS 711
4.1. High pressure 711
4.2. Magnetic fields 716

5. TIME RESOLUTION OF PROBES 722

6. CONCLUSIONS 724

References 725

CHAPTER 12

LANGMUIR PROBES ON SPACECRAFT

R. L. F. BOYD

1. INTRODUCTION 732
1.1. Historical 732
1.2. Special features of the spacecraft use of probes 733
1.3. Scope of this chapter 733

2. Space plasmas 734

3. The role of the spacecraft 739
3.1. The current return problem 739
3.2. The spacecraft equilibrium potential 742
3.3. Photo-electric emission currents 744
3.4. Magnetic field effects 745
3.5. Contact potentials 748
3.6. Vehicle gassing 749
3.7. Interference from other equipment 750
3.8. Ram and wake effects 753
3.9. The constraint of the data rate 757

4. Electron probes 758
4.1. Plane electron probes 759
4.2. Cylindrical electron probes 765
4.3. Spherical electron probes 766
4.4. Other geometries 767

5. Ion probes 768
5.1. Plane ion probes 768
5.2. Spherical ion probes 769

6. General conclusions 773

References 775

Chapter 13

MASS SPECTROMETRY OF PLASMAS

H. W. DRAWIN

1. Introduction 777

2. Exploitation of mass spectra 778

3. Particle extraction 780
3.1. Extraction of neutral particles 781
3.2. Ion extraction from plasmas without external magnetic fields 782
3.3. Ion extraction from plasmas in external magnetic fields 791

4. Particle detection 795
4.1. Ion detection 795
4.2. Detection of neutral particles 812

5. Information obtainable from mass-spectrometric measurements. Some plasma-physical applications 821
5.1. Flames 821
5.2. Glow discharges 823

5.3. Sparks 827
5.4. Shock waves 827
5.5. Plasma probing by fast particle beams 830
5.6. Measurement of neutral particle flux 832
5.7. Measurement of impurity levels 835
5.8. Measurement of the state of ionization – verification of ionization formulas 835

Acknowledgements 836

References 836

CHAPTER 14

COLLISION AND TRANSPORT CROSS-SECTIONS

H. W. DRAWIN

1. INTRODUCTION 842

2. EXCITATION 844
2.1. Electronic excitation from ground states 844
2.2. Excitation transfer collisions 849
2.3. Electronic excitation of sublevels l of excited states m 855

3. IONISATION 856

4. RECOMBINATION 858

5. SCATTERING OF ELECTRONS BY HEAVY PARTICLES 860
5.1. Momentum transfer cross-sections for electron-ion encounters $\langle\sigma_{ei}\rangle$ . . . 860
5.2. Scattering of electrons by neutral particles 862

6. TRANSPORT COEFFICIENTS AND TRANSPORT CROSS-SECTIONS 866
6.1. Evaluation of transport cross-sections $\langle\sigma_{0e}\rangle$ and $\langle\sigma_{ei}\rangle$ 870
6.2. Evaluation of transport cross-sections $\langle\sigma_{00}\rangle$, $\langle\sigma_{10}\rangle$ and $\langle\sigma_{11}\rangle$ 872

References 873

CHAPTER 15

EVALUATION OF ELECTRICAL CONDUCTIVITY, HEAT CONDUCTIVITY AND VISCOSITY OF PLASMAS

H. W. DRAWIN

1. ELECTRICAL CONDUCTIVITY 877
1.1. Differential floating potential method 878
1.2. The I–U and U–d characteristic method 879
1.3. Magnetic probe method 880
1.4. High-frequency measurement of d.c. plasma conductivity 884
1.5. Electrodeless impedance measurement 885
1.6. Evaluation of the Elenbaas-Heller differential equation 885

2. Heat conductivity 888
2.1. Discharges in the stationary state ($\partial/\partial t = 0$) 890
2.2. Heat flux potential method 892
2.3. Plasma decay method ($\partial/\partial t \neq 0$) 892

3. Viscosity 895
3.1. Measurement of $\rho(r, Z)$ 895
3.2. Measurement of $u(r, Z)$ 896
3.3. Ultrasonic method 898

References 898

Author index 901

Subject index 924