

Contents

Continuum Processes in X-Ray and γ -Ray Astronomy

M.S. Longair

1	Introduction	1
2	Continuum Radiation Processes from Hot and Relativistic Plasmas	2
3	Basic Radiation Concepts	4
3.1	The radiation of an accelerated charged particle – J.J. Thomson’s treatment	5
3.2	Thomson scattering	8
3.3	Radiation of an accelerated electron – improved version .	13
3.4	A useful relativistic invariant	15
3.5	Parseval’s theorem and the spectral distribution of the radiation of an accelerated electron	16
4	Bremsstrahlung	17
4.1	Encounters between charged particles	17
4.2	The spectrum and energy loss rate of bremsstrahlung . .	19
4.3	Non-relativistic and thermal bremsstrahlung	22
4.4	Non-relativistic and relativistic bremsstrahlung losses . .	24
5	Hot Gas in Clusters of Galaxies	27
5.1	The properties of rich clusters of galaxies	27
5.2	Hot gas in clusters of galaxies and isothermal gas spheres	28
5.3	X-ray observations of hot gas in clusters of galaxies	32
5.4	Cooling flows in clusters of galaxies	34
5.5	The Sunyaev–Zeldovich effect in hot intra-cluster gas . . .	36
5.6	The X-ray thermal bremsstrahlung of hot intergalactic gas	38
5.7	The origin of the hard X-ray background	40
6	Synchrotron Radiation	43
6.1	Motion of an electron in a uniform, static magnetic field .	44
6.2	The total energy loss rate	45
6.3	Non-relativistic gyroradiation and cyclotron radiation . .	47
6.4	The spectral distribution of radiation from a single electron – physical arguments	51
6.5	The spectrum of synchrotron radiation – improved version	55

6.6	The synchrotron radiation of a power law distribution of electron energies	57
6.7	Why is synchrotron radiation taken so seriously?	58
6.8	Synchrotron self-absorption	61
6.9	Distortions of injection spectra of the electrons	64
6.10	The energetics of sources of synchrotron radiation	68
7	Inverse Compton Scattering	73
8	Synchro-Compton Radiation and the Inverse Compton Catastrophe	79
9	γ -Ray Processes, Photon–Photon Interactions and the Compactness Parameter	84
9.1	Electron–positron annihilation	85
9.2	Photon–photon collisions	87
9.3	The compactness parameter	88
10	Relativistic Beaming	89
11	The Acceleration of Charged Particles	97
	References	106

Atomic Physics of Hot Plasmas

R. Mewe

1	Introduction	109
I	X-Ray Spectral Modeling of Hot Plasmas	110
2	Radiation Processes and Plasma Models	110
3	Spectral Modeling of Optically Thin Plasmas	113
3.1	General scheme	113
3.2	Spectral fitting with SPEX	113
4	Coronal Model	115
4.1	Deviations from the coronal CIE model approximation . .	117
II	Ionization and Recombination in a Coronal Plasma	125
5	Ionization Balance	125
5.1	Accuracy of atomic physics for the ionization balance . .	126
5.2	Update of the ionization balance by improved calculations for the rate coefficients	127
6	Rate Coefficients for Ionization	128
6.1	Collisional ionization	128
7	Rate Coefficients for Recombination	135
7.1	Radiative recombination; the Milne equation	137

7.2	Dielectronic recombination	141
III	Formation of X-Ray Spectra in a Coronal Plasma	145
8	Line Radiation	146
8.1	Excitation processes	148
8.2	Radiative transitions	157
9	Continuum Radiation	162
IV	Diagnostics of Plasma Parameters	166
10	Electron Temperature	166
11	Elemental Abundances	167
12	Ionization Balance in NEI	167
13	Electron Density	167
14	Differential Emission Measure	170
15	Diagnostics of Satellite Lines	172
15.1	Dielectronic recombination (DR) satellite intensity	173
15.2	Inner-shell excitation (IE)	174
15.3	Inner-shell ionization (II)	175
15.4	Diagnostics	175
16	Comparison of Calculated Spectra and Accuracy	181
17	Summary	182
	References	182

The X-Ray Spectral Properties of Photoionized Plasmas and Transient Plasmas

D.A. Liedahl

1	Introduction	189
2	Comptonization	193
2.1	Energy transfer in a single Compton scatter	195
2.2	The Compton y parameter	198
2.3	The Kompaneets equation	201
2.4	Compton heating and cooling	208
2.5	The Compton temperature	210
3	Spectroscopy of X-Ray Photoionized Plasmas	212
3.1	X-ray nebulae	213
3.2	The ionization parameter: overionization in the nebula . .	214
3.3	Differential emission measure distributions	219
3.4	Radiative recombination continua	221

3.5	Spectral signatures of recombination kinetics	224
3.6	Density diagnostics in X-ray photoionized plasmas	229
3.7	Fluorescent K-shell emission	234
3.8	Dielectronic recombination in X-ray photoionized plasmas	243
4	Transient Phases of Ionization Disequilibrium	248
4.1	Equilibration time and ionization time	250
4.2	A two-stage system	251
4.3	A three-stage system	252
4.4	Metastable energy levels in rapidly ionizing plasmas	254
4.5	A worked example: transient ionization of oxygen	258
	References	266

X-Ray Spectroscopic Observations with ASCA and BeppoSAX

J.S. Kaastra

1	Introduction	269
1.1	X-ray spectroscopy	269
1.2	The ASCA and BeppoSAX missions	270
1.3	The most prominent spectral features observable with ASCA and BeppoSAX	272
2	A Few Notes on Spectral Data Fitting	274
2.1	Introduction	274
2.2	Data binning	274
2.3	Model binning	275
2.4	Calibration uncertainties	275
2.5	Spectral deconvolution	275
2.6	Statistics	276
2.7	Low count rates	277
2.8	Data presentation	278
2.9	Plasma models	278
3	Stellar Coronae	279
3.1	Introduction	279
3.2	Differential emission measure distribution techniques	280
3.3	Temperature structure	280
3.4	Abundances	283

	3.5	Flares	284
	3.6	Stellar evolution	285
4		Hot Stars	285
	4.1	Introduction	285
	4.2	Normal O and B stars	285
	4.3	Luminous blue variables	286
	4.4	Wolf-Rayet stars	286
5		Protostars and T Tauri Stars	287
	5.1	Introduction	287
	5.2	X-ray emission from protostars	287
	5.3	X-ray emission from T Tauri stars	288
6		Cataclysmic Variables	289
	6.1	Introduction	289
	6.2	Non-magnetic cataclysmic variables	289
	6.3	Intermediate polars	290
	6.4	Polars	292
7		High-Mass X-Ray Binaries	293
	7.1	Introduction	293
	7.2	Vela X-1	293
	7.3	Cyg X-3	295
	7.4	Cen X-3	296
	7.5	SS 433	296
	7.6	Other cases	297
8		Low-Mass X-Ray Binaries	298
	8.1	Introduction	298
	8.2	4U 1626-67	298
	8.3	Cir X-1	299
9		Supernova Remnants	301
	9.1	Introduction	301
	9.2	Oxygen-rich remnants: Cas A	303
	9.3	Young type Ia remnants	304
	9.4	Old shell-like remnants	305
	9.5	Synchrotron X-ray emission from SNRs	307
	9.6	Crab-like remnants	307
	9.7	Center-filled thermal remnants	308
	9.8	Jets interacting with SNRs	308

9.9	Isolated pulsars	309
9.10	The Magellanic Cloud SNRs	310
9.11	Supernova explosions in distant galaxies	311
10	Extended X-Ray Emission from Normal Galaxies	311
10.1	The galactic ridge	311
10.2	The galactic center	311
10.3	X-ray emission from other normal galaxies	314
11	Seyfert 1 Galaxies	315
11.1	The iron line	315
11.2	Warm absorbers	319
11.3	The power law component	320
11.4	Soft components	321
11.5	Low-luminosity AGN	322
11.6	Broad-line radio galaxies	322
12	Seyfert 2 Galaxies	323
12.1	Introduction	323
12.2	NGC 1068	323
12.3	NGC 6552	324
12.4	NGC 4945	325
12.5	NGC 1808	326
12.6	Other cases	326
12.7	Intermediate cases: narrow-line emission galaxies and others	326
13	Quasars	328
13.1	Radio-quiet quasars	328
13.2	Radio-loud quasars	330
13.3	Type 2 quasars	331
13.4	BL Lac objects	331
14	Clusters of Galaxies	331
14.1	Temperature distribution of the hot medium	332
14.2	The cooling flow and the central temperature distribution	333
14.3	Mass distribution	335
14.4	Groups of galaxies	336
14.5	Cluster mergers and dynamical evolution	336
14.6	Optical-depth effects	337
14.7	The quest for the Hubble constant	338
14.8	Abundances in nearby clusters	338

14.9	Abundances in distant clusters	339
14.10	Abundance gradients	339
	References	340

Future X-Ray Spectroscopy Missions

F. Paerels

1	Introduction	347
2	Resolving Powers of Interest in Astrophysical X-Ray Spectroscopy	348
2.1	Ionization stage spectroscopy	348
2.2	Excitation mechanism	348
2.3	Density diagnostics	349
2.4	Satellite line spectroscopy	351
2.5	Radiative recombination continuum spectroscopy	352
2.6	Thermal Doppler broadening	353
2.7	Compton scattering effects	353
2.8	Raman scattering	354
2.9	Fluorescence spectroscopy	355
2.10	EXAFS spectroscopy	358
2.11	Radial-velocity spectroscopy	359
3	X-Ray Astrophysical Spectrometers	360
3.1	Diffraction spectrometers	361
3.2	Non-diffractive spectrometers	366
3.3	Comparison with astrophysically significant resolving powers	367
3.4	The Rowland circle	369
4	The High Resolution X-Ray Spectrometers on <i>AXAF</i>	373
4.1	Introduction	373
4.2	The high energy transmission grating spectrometer	375
4.3	The diffraction efficiency of an X-ray transmission grating	382
4.4	The low energy transmission grating spectrometer	387
4.5	In Von Laue and Debye's footsteps: scattering by random fluctuations in the properties of a transmission grating	390
5	The Reflection Grating Spectrometers on <i>XMM</i>	397
5.1	Introduction	397

5.2	Properties of reflection gratings, and design of a grazing-incidence reflection grating spectrometer . . .	398
5.3	Implementation of the design, and actual performance of the RGS	404
5.4	Examples	409
6	The Objective Crystal Spectrometer on <i>Spectrum X</i> / γ	412
7	The Microcalorimeter Experiment on <i>ASTRO-E</i>	415
7.1	Introduction	415
7.2	Thermodynamic fluctuations	416
7.3	An alternative derivation	423
7.4	The microcalorimeter on <i>ASTRO-E</i>	428
8	The 21st Century	429
	References	432

New Developments in X-Ray Optics

R. Willingale

1	Introduction	435
1.1	What is or are X-ray optics?	435
1.2	The fundamental interaction utilised in X-ray optics . . .	435
1.3	The challenge of X-ray optics in astronomy	436
2	X-Ray Dispersion Theory	436
2.1	The classical electromagnetic theory	436
2.2	The origin of dispersion – optical constants for X rays . .	438
2.3	The Kramers–Kronig relations – measuring and calculating the refraction index for X rays	442
2.4	EXAFs	444
3	The Reflection of X Rays	444
3.1	Fresnel reflection	444
3.2	Reflection from multi-layers	446
3.3	Reflection from crystals	448
3.4	Reflection and transmission gratings	449
3.5	Scattering from surface roughness	450
4	Geometries for X-Ray Optics	452
4.1	The geometric theory of imaging	452
4.2	Grazing-incidence telescopes; Wolter type I and II and Kirkpatrick-Baez systems	455
4.3	Grating and crystal spectrometers	457

5	X-Ray Telescopes and Spectrometers	457
5.1	Optimization of the design	457
5.2	Types of primary X-ray mirror	458
5.3	Mirror coatings	463
5.4	<i>AXAF</i> and <i>XMM</i>	463
5.5	Assessing the performance of X-ray telescopes	467
5.6	Future X-ray astronomy missions	469
	References	474

Instrumentation for X-Ray Spectroscopy

G.W. Fraser

1	Introduction	477
2	Astrophysical X-Ray Spectra as Measurable Objects	478
2.1	The primary energy band: 0.1–10 keV	478
2.2	The EUV band	481
2.3	The hard X-ray band: 10–100 keV	482
3	The Ideal Spectrometer	483
4	Wavelength Dispersive Spectrometers	485
4.1	Operating principles	485
4.2	Transmission grating spectrometers: examples from <i>AXAF</i>	487
4.3	Reflection gratings	487
4.4	Disadvantages of gratings: novel developments	490
4.5	Bragg crystal spectrometers	490
5	Energy Dispersive Spectroscopy: Basic Principles	492
6	Cryogenic Detectors	497
6.1	Superconducting tunnel junctions (STJs)	499
6.2	Microcalorimeters	503
	References	508

Name Index	511
-----------------------------	------------

Subject Index	519
--------------------------------	------------

Object Index	527
-------------------------------	------------

X-Ray Spectroscopy in Astrophysics

Lectures Held at the Astrophysics School X Organized
by the European Astrophysics Doctoral Network (EADN)
in Amsterdam, The Netherlands, September
22–October 3, 1997

Paradijs, J. van; Bleeker, J.A.M. (Eds.)

1999, XV, 532 p., Hardcover

ISBN: 978-3-540-65548-0