

Contents

Preface *XI*

List of Contributors *XIII*

Glossary and Acronyms *XV*

Part One Introduction 1

1 Introduction and Historical Perspective 3

Markus Böttcher, Daniel E. Harris and Henric Krawczynski

1.1 A Brief History of Jets 3

1.1.1 Synchrotron Emission as the Primary Process for Continuum Radio Sources 4

1.1.2 Occurrence/Ubiquity of Radio Jets 5

1.1.3 Origin of the Notion that SMBHs Reside in All Galactic Nuclei 6

1.1.4 Working Out of Relativistic Effects 6

1.1.5 Microquasars 6

1.2 Jets at Optical, UV, X-Rays and γ -Rays 7

1.2.1 HST Optical/UV Jets 7

1.2.2 X-Ray Jets 8

1.2.3 Jets in γ -Rays 9

1.2.4 Gamma-Ray Bursts 10

1.3 The Role of Simulations 10

1.4 Jet Composition 12

1.4.1 Options 13

1.4.2 Constraints 13

1.5 Some Things (We Think) We Know, and Some (We Know) We Don't 14

References 15

Part Two Theory Basics 17

2 Special Relativity of Jets 19

Markus Böttcher

2.1 Space-Time, Four-Vectors, and Lorentz Invariance 19

2.1.1 Interaction Thresholds 22

2.2 Lorentz Transformations 25

2.3	Relativistic Jet Diagnostics	32
2.3.1	Size Constraint from Variability	32
2.3.2	Superluminal Motion	33
2.3.3	Lorentz Factor and Viewing Angle Estimates	35
	References	38
3	Radiation Processes	39
	<i>Markus Böttcher and Anita Reimer</i>	
3.1	Radiative Transfer: Definitions	39
3.1.1	Radiative Flux, Intensity, Energy Density	40
3.1.2	The Radiative Transfer Equation	41
3.2	Nonthermal Emission Processes	43
3.2.1	Synchrotron Radiation	44
3.2.2	Compton Scattering	49
3.2.3	$\gamma\gamma$ Absorption and Pair Production	59
3.2.4	γ -Hadron Interactions	65
3.3	Electromagnetic Cascades	75
	References	79
4	Central Engines: Acceleration, Collimation and Confinement of Jets	81
	<i>Serguei Komissarov</i>	
4.1	Central Engine	81
4.1.1	Bondi Flow	81
4.1.2	Disk Accretion	83
4.1.3	The Eddington Limit	86
4.1.4	Fuel Supply	88
4.2	Magnetic Fields	90
4.2.1	Basics	90
4.2.2	Powering Magnetic Winds and Jets	92
4.2.3	The Blandford–Znajek Mechanism	96
4.3	Confinement, Collimation, and Acceleration of Jets	103
4.3.1	Acceleration in Supersonic Regime	104
4.3.2	Acceleration and Differential Collimation	105
4.3.3	Jets and Magnetic Towers	111
	References	112
Part Three Phenomenology		115
5	Observational Details: Radio	117
	<i>A.H. Bridle and M.H. Cohen</i>	
5.1	Overall Structures of Radio Sources	117
5.1.1	Terminology	120
5.2	Parsec-Scale Jets	121
5.2.1	One-Sided Jets	121
5.2.2	Two-Sided Jets	125
5.2.3	VLBI Surveys	126
5.2.4	Motions in the Jet	128

5.2.5	Relativistic Beams	130
5.2.6	Statistical Studies of Compact Jets with VLBI	133
5.2.7	Spine-Sheath Configuration	135
5.3	Kiloparsec-Scale Jets	135
5.3.1	Correlations with Extended Structure and Luminosity	135
5.3.2	The Two Jet “Flavors”	136
5.3.3	Internal Structures of Kiloparsec-Scale Radio Jets	137
5.3.4	Jet Bending on Kiloparsec Scales	140
5.4	Modeling Jet Kinematics from Radio Data	140
5.4.1	Intensity Asymmetry Modeling: Velocity-Angle Degeneracy	141
5.4.2	Polarization Asymmetry Modeling: Resolving the Degeneracy	141
5.4.3	Velocity Fields in Weak-Flavor Jets	144
5.4.4	Magnetic Field Evolution in Weak-Flavor Jets	145
5.4.5	Emissivity Evolution in Weak-Flavor Jets	146
5.4.6	Mass, Momentum and Energy Fluxes	146
5.4.7	Comparisons with Strong-Flavor Jets	147
5.5	Backflow in Bilobed FRI Sources?	148
	References	149
6	Optical, Infrared and UV Observations	153
	<i>Eric Perlman</i>	
6.1	A Historical Perspective	153
6.2	Studies of Sample Properties	156
6.3	Source Morphologies, Superluminal Motion and Variability	159
6.4	Optical and Broadband Spectra	166
6.5	Polarimetry	173
6.6	Conclusion	181
	References	182
7	Observational Details: X-Rays	185
	<i>Rita Sambruna and Daniel E. Harris</i>	
7.1	Introduction	185
7.1.1	The Dawn	185
7.1.2	The Chandra X-Ray Observatory	186
7.2	X-Ray Jets at Higher Luminosities	187
7.2.1	The First Chandra Jet	187
7.2.2	A “New” Model: IC on the Cosmic Microwave Background Photons	190
7.2.3	Challenges for the IC/CMB Model	192
7.2.4	Alternative Scenarios to the IC/CMB	193
7.2.5	Jets at High- z	194
7.3	X-Ray Jets at Lower Luminosities	196
7.3.1	Morphologies and Emission Process	196
7.3.2	A Case Study: M 87	197
7.4	X-Ray Jets at Intermediate Luminosities	201
7.4.1	Detection of X-Ray Jets in BL Lacs	201
7.5	X-Ray Emission Processes	203

7.5.1	Challenges for Synchrotron Models	204
7.5.2	Estimating Synchrotron Parameters	204
7.5.3	Synchrotron Self-Compton Emission	205
7.5.4	IC Emission from Photons Originating in Other Components	206
7.5.5	IC/CMB Emission from Jets with Large Γ	206
7.5.6	Estimating IC/CMB Parameters	207
7.6	Summary, Conclusions, Future Work	208
7.6.1	The Nature of Offsets and Spectral Progressions	209
7.6.2	The Nature of Knots	209
7.6.3	Future Possibilities	210
	References	211
8	Unresolved Emission from the Core: Observations and Models	215
	<i>Henric Krawczynski, Markus Böttcher and Anita Reimer</i>	
8.1	Introduction	215
8.2	Emission from Various Nonjet Components	216
8.3	Emission from the Inner Jet	218
8.3.1	Blazars	218
8.3.2	Blazar Models	220
8.3.3	Blazar Multiwavelength Observations	234
8.4	Conclusions and Outlook	239
	References	240
Part Four	Particle Acceleration in Turbulent Magnetohydrodynamic Shocks	245
9	Particle Acceleration in Turbulent Magnetohydrodynamic Shocks	247
	<i>Matthew G. Baring</i>	
9.1	Introduction	247
9.2	Electromagnetic Turbulence in Jet Shocks	248
9.3	Structure of Relativistic Shocks	250
9.3.1	Relativistic Thermal Gases	253
9.3.2	Hydrodynamic Jump Conditions	256
9.3.3	MHD Rankine–Hugoniot Conditions	260
9.4	The Character of Diffusive Acceleration in Relativistic Shocks	268
9.4.1	The Principle of the Fermi Mechanism	269
9.4.2	Diffusive Acceleration in Parallel, Relativistic Shocks	272
9.4.3	Diffusive Acceleration in Oblique, Relativistic Shocks	277
9.4.4	Shock Drift Acceleration	282
9.4.5	Acceleration Time Scales	284
9.4.6	Nonlinear Acceleration Effects	288
9.5	Acceleration by Magnetic Reconnection	290
9.6	Outstanding Questions	291
	References	293

10	Simulations of Jets from Active Galactic Nuclei and Gamma-Ray Bursts	297
	<i>Miguel A. Aloy and Petar Mimica</i>	
10.1	Governing Equations	298
10.2	Numerical Algorithms	300
10.2.1	Specific Numerical Methods for MHD	301
10.3	Basic Numerical Modeling	303
10.3.1	Jet Stability	304
10.3.2	Nonlinear Jet Dynamics	308
10.3.3	GRB Jets	317
10.4	Numerics Confront Observations: Emission from Synthetic Jets	321
10.4.1	Radiative Processes and Relativistic Effects	321
10.4.2	Classification of Algorithms for Computing the Jet Emission	322
10.4.3	Applications	325
10.5	Summary and Outlook	331
	References	332
11	Jet Structure, Collimation and Stability: Recent Results from Analytical Models and Simulations	341
	<i>Rony Keppens and Zakaria Meliani</i>	
11.1	Exact Models for Collimated Jets	341
11.1.1	Concepts for Curved Space-Time	342
11.1.2	General Relativistic Magnetohydrodynamics	343
11.1.3	3 + 1 for Schwarzschild Black Hole Surroundings	344
11.1.4	Self-Similar Models: Classical to General Relativistic MHD	347
11.1.5	Models for Jets from Rotating Black Holes	349
11.2	Numerical Findings on Propagation, Deceleration, Collimation	351
11.2.1	Entrainment and Deceleration	352
11.2.2	Fanaroff–Riley I/II and HYMORS: ISM Influences	353
11.2.3	Jet Composition and EOS	355
11.2.4	Magnetic Field Topologies	356
11.3	Two-Component Jets: a Recurring Paradigm	358
11.3.1	Observational and Theoretical Arguments	358
11.3.2	Aspects Deduced from Modern Simulations	360
11.4	Stability Studies for Radially Structured Jets	360
11.4.1	Spine-Sheath Models	360
11.4.2	Two-Component Jets and FRI/II Classification	362
11.5	Further Challenges for Modern Simulations	364
	References	366
12	Jets and AGN Feedback	369
	<i>Christopher S. Reynolds</i>	
12.1	Introduction	369
12.2	Galaxy Formation and Two Classic Problems	371
12.2.1	Cosmological Background	371
12.2.2	The Overcooling Problem	374

12.2.3	The Cooling Flow Problem	376
12.3	Jet-ICM Interactions in Galaxy Clusters	379
12.3.1	Theoretical Expectations	379
12.3.2	Jet-Blown Cavities	382
12.3.3	Shocks and Sound Waves	385
12.4	Thermal Conduction, MHD Instabilities, and an Alternative View of AGN Feedback	389
12.4.1	The Near Impossibility of a Stable Hydrostatic Equilibrium	391
12.4.2	MHD Models of Cluster Cooling Cores and an Alternative Role for AGN	392
	References	393
13	Summary and Outlook	395
	<i>Markus Böttcher, Daniel E. Harris and Henric Krawczynski</i>	
13.1	The Core: Insights into the Processes of Jet Formation, Acceleration, and Collimation	395
13.2	Large-Scale Jets: Insights into Their Structure and Make-Up and Their Impact on Their Hosts	397
13.3	Theory and Simulations	398
	Appendix A Physical and Astrophysical Constants	401
	<i>Markus Böttcher, Daniel E. Harris and Henric Krawczynski</i>	
	Index	403