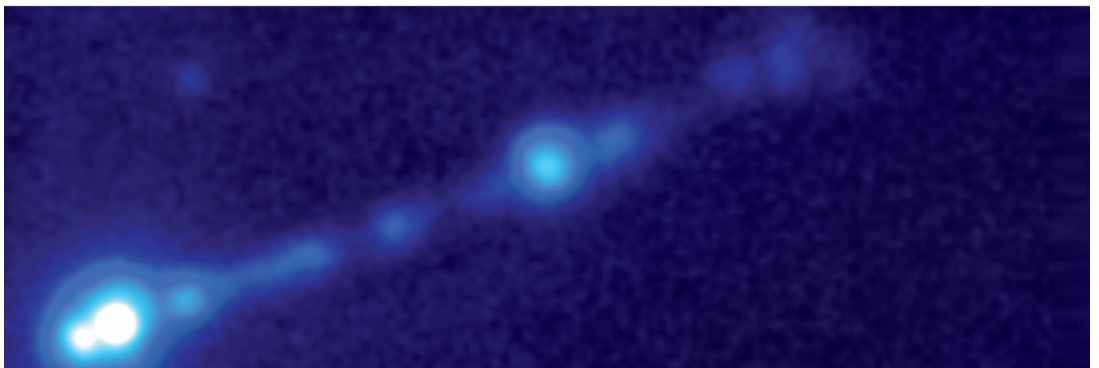
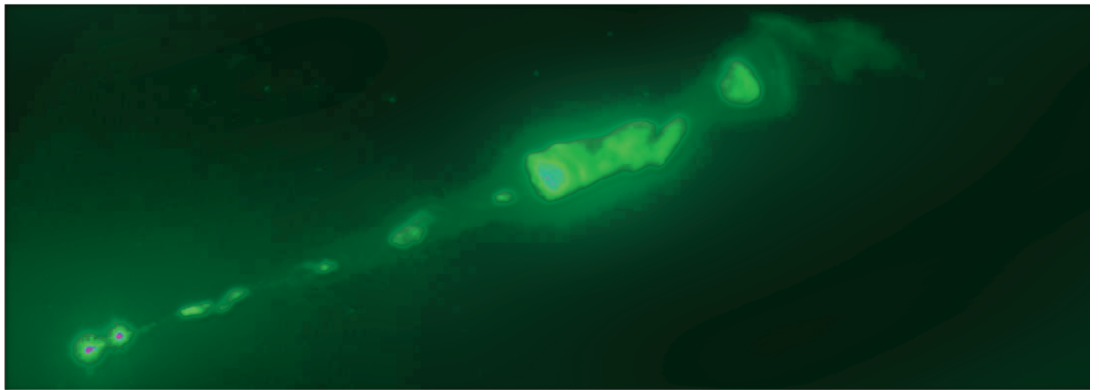
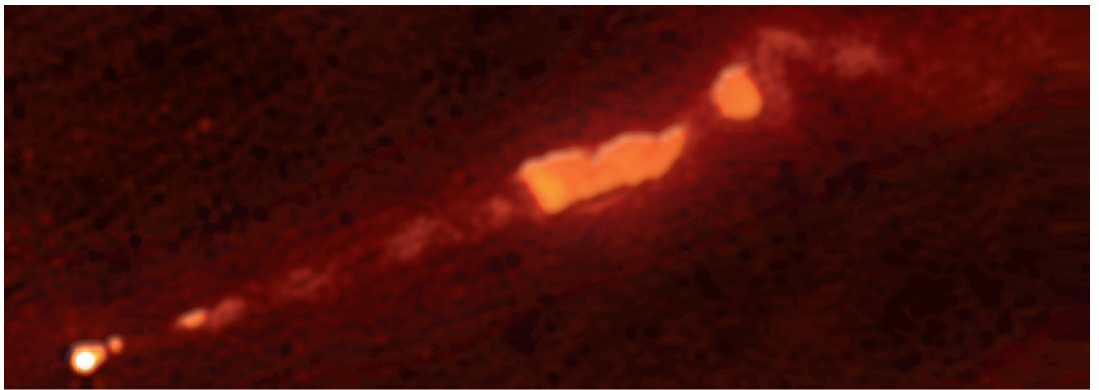


Edited by M. Boettcher, D. E. Harris,  
and H. Krawczynski

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# Relativistic Jets from Active Galactic Nuclei





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Active Galactic Nuclei**

*Edited by  
Markus Böttcher,  
Daniel E. Harris, and  
Henric Krawczynski*

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and Henric Krawczynski*



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## 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 $\gamma$ -Rays 7

##### 1.2.1 HST Optical/UV Jets 7

##### 1.2.2 X-Ray Jets 8

##### 1.2.3 Jets in $\gamma$ -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
<b>3</b>	<b>Radiation Processes</b>	<b>39</b>
	<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	$\gamma$ -Hadron Interactions	65
3.3	Electromagnetic Cascades	75
	References	79
<b>4</b>	<b>Central Engines: Acceleration, Collimation and Confinement of Jets</b>	<b>81</b>
	<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
<b>Part Three Phenomenology</b>		<b>115</b>
<b>5</b>	<b>Observational Details: Radio</b>	<b>117</b>
	<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 FR I Sources?	148
	References	149
<b>6</b>	<b>Optical, Infrared and UV Observations</b>	<b>153</b>
	<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
<b>7</b>	<b>Observational Details: X-Rays</b>	<b>185</b>
	<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 $\Gamma$	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
<b>8</b>	<b>Unresolved Emission from the Core: Observations and Models</b>	<b>215</b>
	<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
<b>Part Four Crucial Aspects under Investigation 245</b>		
<b>9</b>	<b>Particle Acceleration in Turbulent Magnetohydrodynamic Shocks</b>	<b>247</b>
	<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

<b>10</b>	<b>Simulations of Jets from Active Galactic Nuclei and Gamma-Ray Bursts</b>	<b>297</b>
	<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
<b>11</b>	<b>Jet Structure, Collimation and Stability: Recent Results from Analytical Models and Simulations</b>	<b>341</b>
	<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
<b>12</b>	<b>Jets and AGN Feedback</b>	<b>369</b>
	<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
<b>13</b>	<b>Summary and Outlook</b>	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
	<b>Appendix A Physical and Astrophysical Constants</b>	401
	<i>Markus Böttcher, Daniel E. Harris and Henric Krawczynski</i>	
	<b>Index</b>	403

## Preface

The idea of writing a text book on extragalactic jets was initially beset by many doubts. Why produce a book on a subject that is only poorly understood at best? Most text books are the result of several years teaching a course on a relatively stable field of endeavor, but our understanding of jets is still evolving rapidly. Furthermore, the subject matter is very broad, ranging from cutting edge simulations, to relativistic MHD, and of course observations at the limits of our best instruments. We asked ourselves, is it worth our time to pursue this project? Yet in the end, we cast aside these doubts and convened a group of experts who each agreed to contribute a chapter. The reader of this book will see that although we do not know with certainty what jets are made of and how they are launched, accelerated and collimated, there is a vast body of observational evidence which has already been confronted with a wide range of theoretical models. Thus, although the theory of jets is beset with uncertainties, it is highly constrained at the same time. This book gives an overview of a mature and rich field in which key observational and theoretical breakthroughs as well as paradigm shifts can happen at any time.

The book is intended to be used by graduate students, teachers, and researchers who are interested in active galactic nuclei (AGN) and their relativistic outflows. The introductory chapters covering aspects of special relativity and radiation processes may be of interest to a broader audience, e.g., graduate students working in the fields of radio astronomy or high-energy astrophysics. Some of the more advanced chapters of this book will also be of interest to researchers in the field, as they give up-to-date reviews of the rapidly evolving subject matter.

We decided to limit the book to relativistic jets from AGN. Although jets from microquasars may share much the same physics as our AGN jets, we felt that we could not treat the subject matter of galactic binaries adequately given the constraints of the project. We also decided not to deal with jets from gamma-ray bursts mainly because we felt that while again the underlying physics may be similar, there are so few observables available that jet models for GRB are difficult to disprove by observation. Stellar jets are another subject we decided to exclude since they are not believed to be relativistic.

We thank the staff at Wiley for their patience and assistance. We are very grateful to E. Mandel (SAO) who kindly wrote the scripts to facilitate construction of the index.

September 2011

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## Glossary and Acronyms

AMR	Adaptive Mesh Refinement
AMRVAC	Adaptive Mesh Refinement Versatile Advection Code
ATCA	Australian Telescope Compact Array
BLR	Broad-Line Region (as seen in AGN spectra)
BeppoSAX	A small X-ray satellite launched in 1996
Big blue bump (BBB)	A spectral feature of some AGN thought to arise from the accretion disk
CJF	Caltech–Jodrell Bank Flat Spectrum VLBI Survey
CSO	Compact Symmetric Object (describing a small radio source)
CSS	Compact Steep Spectrum (describing a small radio source)
Chandra	One of NASA’s “Great Observatories”; for X-ray imaging and spectroscopy
EBL	Extragalactic Background Light
EVLA	Extended Very Large Array. The upgraded workhorse of radio astronomy in New Mexico
Fermi	A NASA mission for MeV and GeV observations, a.k.a. FGST: Fermi Gamma-Ray Space Telescope
FIDO	Fiducial observer
FSRQ	Flat-Spectrum Radio Quasar
Faraday rotation	The rotation of the angle of the linear polarization during propagation through a magnetized plasma
GEMS	Gravity and Extreme Magnetism SMEX
GMVA	Global Millimeter VLBI Array
GPS	Gigahertz-peaked spectrum. A radio source with peak flux density in the GHz range
GRB	Gamma-ray burst
HALCA	Highly Advanced Laboratory for Communications and Astronomy
HBL	High-frequency (peaked) BL Lac object

H.E.S.S.	High-Energy Spectroscopic System. A GeV/TeV gamma-ray observatory in Namibia (a.k.a. HESS)
HETE II	High-Energy Transient Explorer II
HST	Hubble Space Telescope
HYMORS	Hybrid Morphology (Radio) Source. Usually one side is like FRI, the other FR II
High-Polarization Quasar	Quasar with a high degree of optical polarization (HPQ)
IGM	Intergalactic medium
ISM	Interstellar medium
IXO	International X-ray Observatory
LDQ	Lobe-Dominated Quasar (radio morphology)
LOFAR	Low-Frequency Array for Radio Astronomy
MAGIC	A GeV/TeV gamma-ray observatory in the Canary Islands
MERLIN	Multielement Radio-Linked Interferometer
MOJAVE	Monitoring of Jets of AGN with VLBI Experiments
NLR	Narrow-line region
OSSE	Oriented Scintillation Spectrometer Experiment
OVV	Optically Violent Variable
PARAMESH	Parallel Adaptive Mesh Refinement
Poynting Flux	Energy flux carried by electromagnetic fields, $S = \left(\frac{1}{\mu_0}\right) \mathbf{E} \times \mathbf{B}$ (in SI units)
RHD	Relativistic hydrodynamics
RMHD	Relativistic magnetohydrodynamics
RRFID	Radio Reference Frame Image Database
SED	Spectral energy distribution
SKA	Square Kilometer Array
SSA	Synchrotron self-absorption
SSC	Synchrotron self-Compton (emission)
TANAMI	Tracking Active Galactic Nuclei with Austral Milliarc-second Interferometry
UHECR	Ultra-high-energy cosmic ray
VCS1	VLBA Calibrator Survey No. 1
VERITAS	Very Energetic Radiation Imaging Telescope Array System. A GeV/TeV gamma-ray observatory in Arizona
VIPS	VLBA Imaging and Polarimetry Survey
VLA	Very Large Array. Twenty-seven element radio interferometer in New Mexico
VLBA	Very Long Baseline Array
VLBI	Very Long Baseline Interferometry
VSOP	VLBI Space Observatory Program
ZAMO	Zero Angular Momentum Observer

## **Part One Introduction**



# 1

## Introduction and Historical Perspective

*Markus Böttcher, Daniel E. Harris, and Henric Krawczynski*

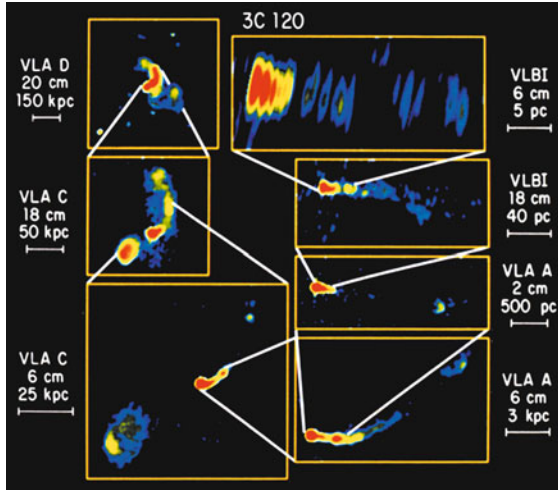
Definition: In this book, the term “relativistic jet” designates highly collimated outflows from supermassive black holes, or in more general terms from a “central engine” in the centers of active galactic nuclei. The jets transport energy and momentum from the central engine to remote locations. In some sources, energy and momentum are dissipated in hot spots hundreds of kiloparsec away from the galactic nucleus and in radio lobes which surround the jets and the hot spot complexes.

### 1.1

#### A Brief History of Jets

Jets are collimated outflows associated with supermassive black holes (SMBH) in the nuclei of some types of active galactic nuclei (AGN). The first recorded observation of a jet was in 1918 within the elliptical galaxy M 87 in the Virgo cluster: “A curious straight ray lies in a gap in the nebulosity in p.a.  $20^\circ$ , apparently connected with the nucleus by a thin line of matter. The ray is brightest at its inner end, which is  $11''$  from the nucleus” [1]. At that time, the extended feature was a mere curiosity and its nature was not understood. It was not until well after World War II, when technical improvements provided for increasingly better angular resolutions and lower noise receivers, that it was demonstrated that many galaxies exhibited extended radio emission consisting of a nuclear component, jets, hot spot complexes, and radio lobes. Implementation of radio interferometry developed quickly during the same period. In particular, so-called Very Long Baseline Interferometers (VLBI) showed that there were compact high-temperature radio cores in AGN.

According to our current understanding, jets originate in the vicinity of a SMBH (with several million to several billion solar masses) located at the center of the AGN. The jets are powered by these black holes and possibly by their associated accretion disks, and the jets themselves transport energy, momentum, and angular momentum over vast distances [2–4], from the “tiny” black hole of radius  $r = 10^{-4} M_{\text{BH}}/10^9 M_{\odot}$  pc to radio hot spots, hot spot complexes and lobes which may be up to a megaparsec or more away. Thus the study of jets must encompass a



**Figure 1.1** This montage of radio observations of 3C 120 demonstrates the range of physical sizes (projected of course), the knotty behavior (common to most jets), and quite pronounced bending (not a universal property of jets). “Knotty” is a somewhat poorly defined description, but essentially means that jets usually have regions of high brightness interspersed with low-brightness segments: often so low that these segments are not de-

tected. The apparent bending of a jet does not mean it bends that much in 3D since if the jet is coming towards us a physically small bend may be sharply amplified in projection. This figure is a “false-color” version with red indicating the highest brightness and blue the lowest. It first appeared in Harris, Mossman, and Walker [5]; reproduced with permission from the National Radio Astronomy Observatory.

range of scales covering a factor of  $10^{10}$ ! Some sense of this vast range of scales is provided by Figure 1.1.

It is not yet known what jets are made of and which of the components (atoms, protons, electrons, positrons, Poynting flux) carries the dominant fraction of the jet energy and momentum. In a similar fashion, it is not firmly established how jets form and accelerate and what collimates them over vast distances.

### 1.1.1

#### Synchrotron Emission as the Primary Process for Continuum Radio Sources

During the 1950s, a fascinating interplay between theory and observation led to key advances in our understanding of the nature of continuum radio sources. When discrete cosmic radio sources were first observed, the general notion was to interpret them as radio stars since it was already known that the Sun produced radio waves. Thus as early as 1950, Alfvén and Herlofson [6] suggested that the radio emission of the object Cygnus A (which we know call a radio galaxy) could be interpreted as synchrotron radiation from cosmic ray electrons gyrating in a star’s magnetic field. A few years later, Shklovsky [7] championed the idea that both the radio emission and the optical light from the diffuse component of the Crab Nebula – a supernova remnant in our Galaxy, were segments of the same synchrotron

spectrum. With detections of optical linear polarization from both the Crab Nebula and from the jet in M 87 [8], the community was quickly convinced that synchrotron radiation was the primary emission mechanism for the ever-increasing number of continuum radio sources. Theorists were soon publishing plausible physical parameters for synchrotron models for the radio and optical nonthermal emissions, for example Burbidge [9] for the AGN M 87 in the nearby Virgo galaxy cluster.

### 1.1.2

#### Occurrence/Ubiquity of Radio Jets

The discovery of radio emission from extragalactic jets began with the identification by [10] of “a star of about thirteenth magnitude and a faint wisp or jet” near the accurate radio positions of two bright components of 3C 273 derived from a lunar occultation observation [11]. Schmidt’s identification of 3C 273B and the measurement of a cosmological redshift of  $z = 0.158$ , which implied an extragalactic origin, famously marks the start of the quasar “industry”.

His identification of 3C 273A with the tip of the “faint wisp or jet” also marks the start of a radio jet industry that grew more slowly. The next step came when the work in [12] showed that a compact extranuclear radio component in 3C 274 coincided with the brightest knot in the optical jet of the object M 87, but it was not until the one-mile and five-kilometer interferometers at Cambridge began systematic high-resolution studies of 3C sources that further radio jets were found in the low-power plumed source 3C 66B [13] and in the higher-power “classical double” 3C 219 [14]. Radio jets were soon recognized in images taken with the Westerbork Synthesis Radio Telescope of other low-power radio galaxies: B0844+319 and 3C 129 [15] and retrospectively in 3C 449 [16] and 3C 83.1 [17].

The first example of an AGN radio jet remaining well collimated and evidently stable over several hundred kiloparsecs was found in the giant radio galaxy NGC 6251 [18]. These early discoveries showed that the jet phenomenon ran the gamut of radio powers and structure types, but it remained unclear whether the sources with detected radio jets were in some sense exceptional. That question was answered when the Very Large Array (VLA) came into operation in the late 1970s. Radio jets were soon found in radio-loud AGN of all known sizes and powers, including Seyfert, classical radio galaxies, and quasars. The VLA was able to show the *ubiquity* of radio jets because its 27-element design provided the sensitivity to detect weak jets in only brief observations, the dynamic range to do so in the presence of bright unresolved emission from the AGN, and the angular resolution to separate jets convincingly from other extended radio emission. This allowed simple but well-defined quantitative criteria to be applied for identifying a linear radio feature as a “jet” [19, 20].

The mass and luminosity range of objects known to generate relativistic jets was also extended to include the galactic “microquasars”, for example SS 433 [21] and 1E140.7-2942 [22].

## 1.1.3

**Origin of the Notion that SMBHs Reside in All Galactic Nuclei**

It was not long after the realization that radio galaxies (which roughly account for  $\approx 1\%$  of all galaxies, and favor massive ellipticals) produce jets, which transmit prodigious amounts of power out of the central region, that it was also understood that jets had to be coupled with processes involving a black hole of high mass, that is, more than a million solar masses [23]. The two available sources of energy to power jets and thus hot spots and lobes are potential energy (in the gravitational field of a SMBH) and rotation of the SMBH itself. Furthermore, the role of AGN in influencing galaxy formation and evolution was recognized quite early (e.g., [24]). As other developments established a relationship between the properties of galaxies and the masses of their black holes [25, 26], a great deal of effort was expended on trying to ascertain why some galaxies and quasars are radio-loud, whereas others are radio-quiet (“quiet” is a relative term, which indicates a bimodality in the distribution of the ratio of radio intensity to optical intensity rather than a complete absence of radio emission).

## 1.1.4

**Working Out of Relativistic Effects**

Perhaps the most important development after the realization that jets carry power over vast distances and that the emission we see is nonthermal came from Very Long Baseline Interferometry (VLBI), see Section 5.2. After primitive radio interferometry demonstrated the basic source structure of extragalactic radio sources [27], astronomers developed VLBI techniques in which phase information was sacrificed in order to obtain baselines which were too long to be coherently connected. Thus the order of the day was to develop more stable atomic clocks and more reliable and higher-density magnetic tape drives so as to record wider bandwidths. Since almost all radio sources have emission on both sides of the nucleus, but a majority of bright jets are on one side only (Section 5.2.1), the notion of “Doppler boosting” became the established paradigm. As the VLBI data improved, it became apparent that individual emission regions at the parsec scale could be tracked and had apparent proper motions larger than the velocity of light. This effect was quickly explained as a bulk relativistic motion of an emitting plasma moving close to our line-of-sight (Section 5.2.5). Most of the salient relativistic effects pertaining to jets were worked out in Konigl’s thesis [28].

## 1.1.5

**Microquasars**

“Microquasars” is a term applied to those galactic X-ray binary systems that have been found to eject luminous material, which appears to be moving at a considerable fraction of the speed of light. In one case (SS 433) the material traces out a helical path and emission lines of ionized common elements have been found in

the optical and X-ray spectra. A detailed precessing jet model provides an accurate value of the velocity:  $0.26c$ . In addition to the spectral lines, there is a continuous spectrum of synchrotron emission so VLBI techniques have augmented the optical and X-ray study of line emission with direct imaging of the twin jets.

No line emission has been observed for any other galactic microquasar, nor for any extra galactic jet, large or small. Although many researchers have attempted to demonstrate that microquasar jets and AGN jets are basically the same (physical) phenomenon, there are significant differences. Chief among these is the difference in velocity of ejection. While some microquasars have features believed to be moving at  $0.8$  or  $0.9c$ , we always see both sides of the jet whereas for AGN jets, Doppler boosting often enhances the approaching jet and the receding jet is below detection thresholds.

The study of X-ray binaries and their jets has led to a vast amount of published literature and the classification of many aspects of their behavior. In this book, we will not attempt to deal with these jets as such, but refer to them from time to time if relevant. Interested readers can consult [29].

## 1.2

### Jets at Optical, UV, X-Rays and $\gamma$ -Rays

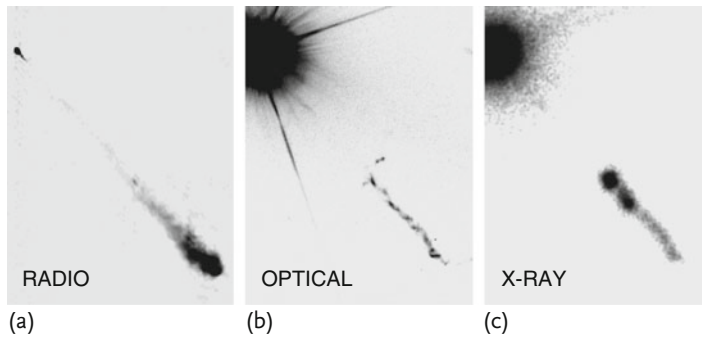
At the higher frequencies, the synchrotron  $E^2$  half-lives are on the order of several years in typical fields of  $0.1$ – $1$  mG. Since we have optical polarization from many jets and, at least in the case of knot HST-1 in the M 87 jet where we have strong variability at all wavelengths, we are confident that the high-frequency radiation from some jets comes from synchrotron emission. This translates into the fact that every emission region must also be an acceleration region.

#### 1.2.1

##### HST Optical/UV Jets

During the latter part of the 1900s, there were several ground-based studies of the brightest optical jets. These efforts were plagued by limited angular resolution (poor seeing) and often resulted in ambiguous results with respect to spectral properties and degree of polarization.

The quasar jet 3C 273 was almost as bright as the M 87 jet, and did not have to contend with the optical light of the encompassing galaxy, and thus was an obvious target. Therefore, once the Hubble Space Telescope (HST) was repaired, detailed morphology, robust polarization data and spectral properties could be obtained. Figure 1.2 shows a comparison of the relative brightness distributions for three different bands.



**Figure 1.2** The famous jet of the quasar 3C 273. (a) The radio panel is from the MERLIN archives at a frequency of 1.6 GHz; (b) the optical is from the Hubble Space Telescope at 6000 Å; and (c) the X-ray image is from a set of observations made by Chandra. It is filtered for the energy band 0.3–6 keV and has been slightly smoothed. The distance from the quasar (upper left) to the tip of the jet is 22.3'' which corresponds to 60 kpc (in projec-

tion) at the distance (750 Mpc) of this quasar. The large apparent diameter of the quasar in the optical and X-ray images is an instrumental effect caused by the low-level wings of the point spread functions. Note how the jet is almost invisible for quite some distance before abruptly appearing with a very bright X-ray knot which is weak in the radio. Although there are some “wiggles”, this jet is basically straight, unlike that of 3C 120 (Figure 1.1).

### 1.2.2

#### X-Ray Jets

The Einstein Observatory, launched in 1978, was the first device that had sufficient angular resolution ( $\approx 5''$ ) and sensitivity to detect X-ray knots and hot spots associated with jets. *ROSAT* (launched in 1990) had similar capabilities; both satellites had microchannel plate detectors in addition to the proportional counters. So, with some concerted effort, a handful of jets had been detected before the launch of Chandra: the hot spots of Cygnus A and the jets of Cen A, M 87, and 3C 273.

With the advent of Chandra with its much improved angular resolution ( $\leq 1''$ ), many more jets were detected. The early “surveys” targeted the brighter radio jets thought to be close to our line-of-sight, and of course the first detection was achieved by chance: the quasar PKS 0637 was thought to be a bright unresolved source and was chosen as a target for focusing the mirrors (i.e., determining the best position for the detectors; see Section 7.2.1).

X-ray data on knots and hot spots have provided key insights into several facets of jet physics. If the X-rays from a particular feature are dominated by synchrotron emission, Lorentz factors of the radiating electrons,  $\gamma$  of order  $10^7$ – $10^8$  are required in the nominal fields on the order of hundreds of microgauss ( $\mu\text{G}$ ). These extremely high-energy electrons have short half-lives and so are more restrictive than the optical data as to how large a source can be in the sense of how far these electrons can travel from their acceleration site. Additionally, the ability to estimate physical parameters for these very high-energy electrons provides insights into loss mechanisms and high-energy cutoffs in the electron distributions.

Another aspect of these X-ray detections came from the hot spots of FR II radio galaxies. It was shown that synchrotron self-Compton (SSC) emission provided a good model for the X-ray intensities observed from the high-brightness radio hot spots of the radio galaxy Cygnus A. Since the photon energy density could reliably be measured from the observed radio spectrum and the (resolved) source size, it was possible to estimate the average magnetic field strength without first assuming equipartition. While this represented an important advance, many more sources with hot spot detections have become available, and of these, only a relative few match the SSC predictions as well as the example of Cygnus A.

The case of X-ray emission from the knots in the jets of FR II radio galaxies and quasars is still a topic of debate. Since there appears to be a high-frequency cutoff in the optical for many knots, it was difficult to fit a simple synchrotron spectrum to the radio-optical-X-ray data. A relatively simple model was advanced [30, 31] to overcome this difficulty: the X-rays were identified as the result of inverse-Compton scattering between the relativistic electrons and the photons of the microwave background. To get enough intensity from this process it is necessary to assume that the bulk Lorentz factor of kiloparsec-scale quasar jets are on the order of 10 or greater in many cases. Further, it turns out that very low-energy electrons (i.e.,  $\gamma$  on the order of 100) are those that produce the observed X-rays and therefore, one must rely on a blind extrapolation of the electron spectra from the typical energies of several thousand (estimated from centimeter radio data) down to a few hundred or less. This is usually performed by assuming the observed radio spectrum can be extrapolated down to a MHz or so without any cutoffs or breaks (see Section 7.5.5).

### 1.2.3

#### Jets in $\gamma$ -Rays

While jets in AGN can often be resolved on parsec and larger scales, most radio-loud AGN possess bright cores on subparsec scales, which are spatially unresolved. It is commonly believed that  $\gamma$ -ray emission, present in a special class of radio-loud AGN called blazars, is produced in this unresolved core region. One of the major surprises of the EGRET experiment on board the satellite-borne Compton Gamma-Ray Observatory (1991–2000) was the discovery that high-energy (100 MeV up to a few GeV)  $\gamma$ -ray emission is a common property of blazars, and that power emitted in the  $\gamma$ -ray band typically surpasses the power emitted at longer wavelengths. At even higher energies, ground-based experiments can detect  $\gamma$ -rays in the TeV energy range. Pioneering observations with the Whipple Cherenkov Telescope between 1992 and 1996 showed that some blazars (e.g., Mrk 421) are not only sources of extremely energetic TeV  $\gamma$ -rays, but that the TeV emission shows time variability on extremely short ( $\sim$  min) time scales. The fast flux variability constrains (via causality arguments) the size of the emission region. The fact that TeV  $\gamma$ -rays are observed and are not absorbed in  $\gamma\gamma \rightarrow e^+e^-$  pair production processes of TeV  $\gamma$ -rays interacting with IR and optical photons leads to the conclusion that the jets have to be highly relativistic with bulk velocities exceeding 99%

of the speed of light (see the discussion in Section 3.2.1.2). Modeling the broadband radio to  $\gamma$ -ray energy spectra of TeV-bright blazars indicates even higher jet velocities: 99.98% of the speed of light. Intensive observational campaigns involving a large number of ground-based and spaceborne observatories have resulted in rich data sets with detailed information about the time dependence of the broadband energy distributions. The blazar phenomenon will be discussed in detail in Chapter 8.

#### 1.2.4

#### **Gamma-Ray Bursts**

Gamma-ray bursts (GRBs) have been known for almost 40 years as short flashes of  $\gamma$ -rays which dominate the entire  $\gamma$ -ray sky for durations of  $\lesssim 1$  s to a few minutes. With the successful operation of the Italian-Dutch BeppoSAX satellite in the late 1990s, it became possible to associate GRBs with afterglows at longer (X-rays, optical) wavelengths. This also allowed for the determination of redshifts of their counterparts, establishing that these sources must be extragalactic. Once the distance to a GRB is known, one can convert the observed  $\gamma$ -ray flux into a luminosity, assuming that the  $\gamma$ -rays are emitted isotropically. This calculation yielded total released energies up to  $\sim 10^{54}$  erg, that is, surpassing the typical radiative energy release of a supernova by a factor of  $\sim 1000$ . The fast flux variability on time scales  $\Delta t \sim \ll 1$  min, suggests a very small emission region of size  $R \ll c\Delta t \sim 1.8 \times 10^{12}$  cm. As for blazars, the fast flux variability and enormous brightness of GRBs implies a lower limit on the velocity of the emitting plasma (the only way to avoid high optical depth to pair production). In the case of GRBs, the lower limits typically lie between 99.995 and 99.99995% of the speed of light (i.e., bulk Lorentz factors  $\Gamma$  of 100–1000). This velocity implies that clocks in the co-moving frame go between 100 and 1000 times slower than in the observers frame. Relativistic aberration leads to an extremely narrow emission cone with a  $\lesssim 1^\circ$  opening angle. This makes GRBs the most extreme examples of relativistic jets known. Common traits of AGN and GRB jets and breakthroughs in the theoretical understanding of the jets from these two types of objects will be discussed in Chapter 10.

### 1.3

#### **The Role of Simulations**

As the physics of jets are governed by classical physics (the special and general theories of relativity and classical electrodynamics) and by well-understood components of quantum mechanics, one might think that it is straightforward to simulate the formation and propagation of jets and their electromagnetic emission. Quite the opposite is the case, and it is only quite recently that numerical simulations are becoming an increasingly useful tool to complement analytical modeling of jet processes. As an example, the interested reader may consult a seminal – and still

very instructive – review article on the theory of AGN jets [32], which hardly mentions any simulation results, and in the few cases in which it does, it does so for demonstrative purposes.

A major difficulty of numerical calculations is the wide range of scales (spatial and temporal), which are relevant for the properties of jets. Jets form in the surroundings of supermassive black holes with a characteristic size of the Schwarzschild radius

$$r_{\text{Sch}} = \frac{2G M_{\text{BH}}}{c^2} = 3 \times 10^{13} \frac{M_{\text{BH}}}{10^8 M_{\odot}} \text{ cm}, \quad (1.1)$$

which is comparable to the diameter of Earth’s orbit, and carry energy over distances of several 100 kpc ( $3.1 \times 10^{23}$  cm) – often exceeding the size of the host galaxy. Simulating a jet all the way from its base and covering its propagation over its full length is already a formidable task, given that the simulations should be in 3D, as 1D and 2D simulations cannot capture the topology of true plasma flows. Another issue that complicates simulations is that the processes of jet formation, acceleration, and confinement depend on processes on much smaller scales. The viscosity of the accretion disk and the magnetic field in the accretion disk are thought to be generated by the magnetorotational instability on spatial scales  $\ll R_{\text{S}}$ . The stability of the jet, the shocks in the jet, and the particle acceleration processes in the jet are ultimately governed by processes on the order of a gyroradius  $r_{\text{g}}$  of mildly relativistic electrons and/or protons with

$$r_{\text{g}} = \frac{c p_{\perp}}{e B} \approx 3.3 \times 10^7 \frac{c p_{\perp}}{10 \text{ GeV}} \left( \frac{B}{1 \text{ G}} \right)^{-1} \text{ cm}, \quad (1.2)$$

where  $p_{\perp}$  is the momentum of the particle perpendicular to the magnetic field, and  $B$  is the magnetic field. The magnetic field is thought to be on the order of  $B \sim 10^4$  G in the accretion disk of a  $10^8 M_{\odot}$  black hole accreting with the Eddington rate [33], and  $B \sim 1$  G at the base of the jet where gamma-rays are emitted [34].

A full simulation of jets and their emission would start with a dark matter plus magnetohydrodynamics simulation of the interstellar and/or intracluster plasma based on a cosmological simulation, which grows primordial density perturbations into the environments of AGNs. Subsequently, the accretion and jet formation process would be simulated, best with a general relativistic magnetohydrodynamic simulation. Last but not least, one would simulate the jet flow including the formation of shocks, the acceleration of high-energy particles, the various emission processes of these high-energy particles, and the interaction of the jet with the ambient material.

Although no one has carried through such a comprehensive simulation, numerical studies have achieved substantial progress over the last 30 years by focusing on well-defined problems (see Chapters 4, 10, and 11 for detailed descriptions). As examples, we would like to highlight a few results:

- Early hydrodynamical jet simulations improved our understanding of the structure of radio galaxies (e.g., [35] and references therein).

- Magnetohydrodynamical simulations of differentially rotating accretion disks have led to rediscovery of the magnetorotational instability, which produces viscosity in accretion disks (e.g., [36–38]).
- General relativistic magnetohydrodynamical simulations include all ingredients which are deemed to be important for the process of jet formation: general relativity, hydrodynamics, and magnetic fields [39]. Simulations are now able to reproduce how highly relativistic jets may form and accelerate, and are beginning to validate earlier analytic models (e.g., [40–42]).
- Codes have been developed to simulate the acceleration of high-energy particles [43, 44] and their emission [45, 46]. The codes can be used to determine the properties of jets even though they do not contain jet formation, nor the formation of shocks in the jets.
- Recent particle-in-cell simulations are starting to be able to simulate astrophysical shocks and the acceleration of particles in these shocks [47, 48].

Although in many cases, simulations reproduce observed characteristics, there may be fundamental aspects of real jets which are not included in the simulations. Conceptually, one might imagine that it would be possible to compare jets dominated by Poynting flux, protons, and pairs. We could then perform a test of each by attempting to bend the jets with an external force provided by the “wind” of a thermal plasma such as occurs for tailed radio galaxies in clusters of galaxies. As the growth of computing capabilities has followed Moore’s law for the last half century (i.e., doubled approximately every two years) and is expected to continue in this way for quite some time to come, we can expect an interesting decade in which jet simulations will make enormous progress and will enable comparisons of simulated and observed characteristics, and of simulated and analytic results.

## 1.4

### Jet Composition

By the term “jet composition” we mean “What is the means of transporting energy over vast distances?” We are fairly confident that we know the essential ingredients of the emitting volumes we call “knots” and “hot spots”: a relativistic plasma consisting of at least a magnetic field (average value  $\geq 1 \mu\text{G}$ ), a rather wide (in energy) distribution of relativistic electrons (and/or positrons), and photons of the CMB and of other sources more particular to the local environment. A relatively straightforward argument [49] convinces us that the particles responsible for the electromagnetic radiation observed cannot be the means of transporting energy: electrons with  $\gamma \geq 2000$  would lose their energy long before they reached the end of many long jets. Thus knots and hot spots should be viewed as products of the jet: sites where jet energy is transferred to the radiating plasma.