

## ASTROPHYSICAL JETS AND BEAMS

Astrophysical jets are spectacular displays of gas or dust ejected from a range of cosmic bodies; they are seemingly ubiquitous on scales from comets to black holes. This volume reviews our understanding of jet processes and provides a modern guide to their observations and the role they play in many long-standing problems in astrophysics. It covers the major discoveries in gamma-ray bursts, solar and stellar jets and cometary jets. Specific physical processes for all classes of jet are illustrated and discussed in depth, as a backdrop to explaining spectacular jet images. Current jet models raise as many issues as they solve, so the final chapter looks at the new questions to be answered.

Written at an entry level for postgraduate students, this volume incorporates introductions to all the governing physics, providing a comprehensive and insightful guide to the study of jets for researchers across all branches of astrophysics.

MICHAEL D. SMITH was awarded his Ph.D. in astrophysics by the University of Oxford in 1979. He is now the Director of the Centre for Astrophysics and Planetary Science, Director of the Kent Space School, Director of Research for SEPnet (South-East Physics Network), and holds the posts of Director of Graduate Studies and Sub-Dean in the Faculty of Sciences at the University of Kent. He is a member of the International Astronomical Union and a Fellow of the Royal Astronomical Society.

## Cambridge Astrophysics Series

### Series editors:

Andrew King, Douglas Lin, Stephen Maran, Jim Pringle and Martin Ward

### Title available in the series

5. The Solar Granulation 2nd Edition  
*by R. J. Bray, R. E. Loughhead and C. J. Durrant*
8. The Symbiotic Stars  
*by S. J. Kenyon*
10. Quasar Astronomy  
*by Daniel W. Weedman*
11. X-ray Emissions from Clusters of Galaxies  
*by Craig L. Sarazin*
14. The Physics of Solar Flares  
*by Einar Tandberg-Hanssen and A. Gordon Emslie*
15. X-ray Detectors in Astronomy  
*by G. W. Fraser*
18. Plasma Loops in the Solar Corona  
*by R. J. Bray, L. E. Cram, C. J. Durrant and R. E. Loughhead*
19. Beams and Jets in Astrophysics  
*edited by P. A. Hughes*
22. Gamma-ray Astronomy 2nd Edition  
*by Poolla V. Ramana Murthy and Arnold W. Wolfendale*
24. Solar and Stellar Activity Cycles  
*by Peter R. Wilson*
25. 3K: The Cosmic Microwave Background Radiation  
*by R. B. Partridge*
26. X-ray Binaries  
*edited by Walter H. G. Lewin, Jan van Paradijs and Edward P. J. van den Heuvel*
27. RR Lyrae Stars  
*by Horace A. Smith*
28. Cataclysmic Variable Stars  
*by Brian Warner*
30. Globular Cluster Systems  
*by Keith M. Ashman and Stephen E. Zepf*
33. The Origin and Evolution of Planetary Nebulae  
*by Sun Kwok*
34. Solar and Stellar Magnetic Activity  
*by Carolus J. Schrijver and Cornelis Zwaan*
35. The Galaxies of the Local Group  
*by Stanley van den Bergh*
36. Stellar Rotation  
*by Jean-Louis Tassoul*
37. Extreme Ultraviolet Astronomy  
*by Martin A. Barstow and Jay B. Holberg*
38. Pulsar Astronomy 3rd Edition  
*by Andrew Lyne and Francis Graham-Smith*
39. Compact Stellar X-ray Sources  
*edited by Walter H. G. Lewin and Michiel van der Klis*
40. Evolutionary Processes in Binary and Multiple Stars  
*by Peter Eggleton*
41. The Physics of the Cosmic Microwave Background  
*by Pavel D. Naselsky, Dmitry I. Novikov and Igor D. Novikov*
42. Molecular Collisions in the Interstellar Medium 2nd Edition  
*by David Flower*
43. Classical Novae 2nd Edition  
*edited by M. F. Bode and A. Evans*
44. Ultraviolet and X-ray Spectroscopy of the Solar Atmosphere  
*by Kenneth J. H. Phillips, Uri Feldman and Enrico Landi*
45. From Luminous Hot Stars to Starburst Galaxies  
*by Peter S. Conti, Paul A. Crowther and Claus Leitherer*
46. Sunspots and Starspots  
*by John H. Thomas and Nigel O. Weiss*
47. Accretion Processes in Star Formation 2nd Edition  
*by Lee Hartmann*
48. Pulsar Astronomy 4th Edition  
*by Andrew Lyne and Francis Graham-Smith*
49. Astrophysical Jets and Beams  
*by Michael D. Smith*

---

# ASTROPHYSICAL JETS AND BEAMS

---

MICHAEL D. SMITH  
*University of Kent, Canterbury*



Shaftesbury Road, Cambridge CB2 8EA, United Kingdom  
One Liberty Plaza, 20th Floor, New York, NY 10006, USA  
477 Williamstown Road, Port Melbourne, VIC 3207, Australia  
314–321, 3rd Floor, Plot 3, Splendor Forum, Jasola District Centre, New Delhi – 110025, India  
103 Penang Road, #05–06/07, Visioncrest Commercial, Singapore 238467

Cambridge University Press is part of Cambridge University Press & Assessment, a department of the University of Cambridge.

We share the University's mission to contribute to society through the pursuit of education, learning and research at the highest international levels of excellence.

[www.cambridge.org](http://www.cambridge.org)

Information on this title: [www.cambridge.org/9780521834766](http://www.cambridge.org/9780521834766)

© M. D. Smith 2012

This publication is in copyright. Subject to statutory exception and to the provisions of relevant collective licensing agreements, no reproduction of any part may take place without the written permission of Cambridge University Press & Assessment.

First published 2012

*A catalogue record for this publication is available from the British Library*

*Library of Congress Cataloging-in-Publication data*

Smith, Michael D. (Michael David), 1955–

Astrophysical jets and beams / Michael D. Smith, University of Kent, Canterbury.  
p. cm. – (Cambridge astrophysics ; 49)

Includes bibliographical references and index.

ISBN 978-0-521-83476-6 (hardback)

1. Astrophysical jets. I. Title.

QB466.J46S65 2012

523–dc23 2011047479

ISBN 978-0-521-83476-6 Hardback

Cambridge University Press & Assessment has no responsibility for the persistence or accuracy of URLs for external or third-party internet websites referred to in this publication and does not guarantee that any content on such websites is, or will remain, accurate or appropriate.

Cambridge University Press & Assessment  
978-0-521-83476-6 — Astrophysical Jets and Beams  
Michael D. Smith  
Frontmatter  
[More Information](#)

---

A dedication to my wife, Daniela,  
to whom I owe the leaping delight

---

# Contents

---

<i>Preface</i>	<i>page xi</i>
<b>1 Introduction</b>	<b>1</b>
1.1 Rudimentary definitions and concepts	1
1.2 Jet presence and function	4
1.3 Early history	5
1.4 Surprising discoveries	8
1.5 Overview and points of view	10
1.6 Summary	15
<b>2 Detection and measurement</b>	<b>16</b>
2.1 Synchrotron radiation	17
2.2 Self-absorption and polarisation	20
2.3 Compton processes	22
2.4 Electrons: free-free and bremsstrahlung processes	23
2.5 Atomic processes	23
2.6 Molecular processes	25
2.7 Maser beams	26
2.8 Power and size	27
2.9 Summary	28
<b>3 The dynamical toolbox</b>	<b>29</b>
3.1 The inviscid hydrodynamic equations	29
3.2 Viscosity	31
3.3 Magnetohydrodynamics	32
3.4 Steady jets as potential flows	34
3.5 Streamlines: rotating MHD flow	35
3.6 Special relativistic flow	37
3.7 Shock waves	40
3.7.1 Relativistic shock waves	41
3.7.2 Non-relativistic shock waves	43
3.7.3 Radiative shock waves	45
3.8 Non-ideal MHD and non-MHD	47
3.9 Summary	49
	vii

viii	<b>Contents</b>	
<b>4</b>	<b>Observations of extragalactic jets</b>	50
4.1	The morphological classes of radio galaxies	51
4.1.1	Edge-brightened and edge-darkened	51
4.1.2	Wide-angled tails	56
4.1.3	Narrow-angled tails	59
4.1.4	Classical doubles	61
4.1.5	Lobe-dominated quasars	62
4.1.6	Relaxed doubles	63
4.2	Detailed structure and multiwavelength features	65
4.2.1	X-ray cavities and relics	65
4.2.2	Hot spots	66
4.2.3	Optical and X-ray jets	67
4.3	Host galaxies and triggering jets	68
4.4	Summary	69
<b>5</b>	<b>Jets in galactic nuclei</b>	70
5.1	Individual blazar jets	71
5.1.1	3C 279	71
5.1.2	3C 273	74
5.1.3	M 87	78
5.2	Speed and Doppler boosting	82
5.3	The class of blazar jets	84
5.4	Variability and temperature	85
5.5	The Lorentz factor crisis	88
5.6	Polarisation	89
5.7	Summary	89
<b>6</b>	<b>Jets from young stars and protostars</b>	91
6.1	Optical jets	92
6.1.1	The HH 30 jets	94
6.1.2	The RW Aur jet	96
6.1.3	The DG Tau jet	98
6.1.4	Optical jets: general results	101
6.2	Embedded protostellar jets	103
6.2.1	HH 34 and HH 111	105
6.2.2	Deeply embedded jets: HH 211 and HH 212	110
6.3	Termination: Herbig–Haro and molecular hydrogen objects	114
6.4	Bipolar outflows	117
6.5	Small-scale jets: radio and masers	118
6.6	Summary	119
<b>7</b>	<b>Jets associated with evolved stars</b>	121
7.1	Planetary nebulae	121
7.2	Symbiotic systems	124
7.3	Supersoft X-ray sources	129
7.4	Cataclysmic variables	131
7.5	Microquasars: XRB jet systems	131

<b>Contents</b>	ix
7.5.1 Low-mass X-ray binaries	132
7.5.2 High-mass X-ray binaries	133
7.5.3 Microquasars	135
7.5.4 SS 433	136
7.6 Pulsar jets	138
7.7 Gamma-ray bursts	140
7.8 Summary	143
<b>8 Jets within the solar system</b>	144
8.1 Cometary jets, pre-2000	144
8.2 Cometary jets, post-2000	146
8.3 Moon jets	151
8.4 Solar jets	153
8.5 Summary	156
<b>9 Jet launching</b>	157
9.1 Hydrodynamic methods	158
9.1.1 Hydrodynamic methods: nozzles	158
9.1.2 Hydrodynamic methods: discs	162
9.1.3 Hydrodynamic methods: vents	163
9.2 Jets via magnetic reconnection	168
9.2.1 Spicules	169
9.2.2 Coronal jets	171
9.3 Magnetic field methods	172
9.3.1 Hydromagnetic driving from rotating discs	172
9.3.2 Magnetocentrifugal quantities	174
9.3.3 X-winds	176
9.3.4 Spinning black holes	179
9.3.5 Poynting jets	180
9.4 Alternative models and mechanisms	182
9.4.1 MHD simulations	182
9.4.2 Magnetic towers and funnels	182
9.4.3 ADAF jets: ion-supported flows	183
9.4.4 The disc–jet connection	183
9.4.5 Radiation-driven jets	184
9.5 Summary	184
<b>10 Jet propagation</b>	186
10.1 Components and structure	186
10.2 Jet shapes	190
10.3 Jet disruption	193
10.4 Jet flares and knots	195
10.5 Instability	197
10.6 Changing direction	200
10.6.1 Precession and wiggling	200
10.6.2 Bending	201
10.7 Summary	202



x	<i>Contents</i>	
	<b>11 The astrophysical jet</b>	203
	11.1 Composition	203
	11.2 Regulation	205
	11.3 Feedback	206
	11.4 Unification	206
	11.5 The future	207
	<i>References</i>	209
	<i>Index</i>	224

---

## Preface

---

Jets are amongst the most mysterious phenomena to be discovered in modern astronomy. They are able to form and propagate under almost all conditions associated with a vast range of astrophysical objects. This book is concerned with all the diverse jets which have so far been found beyond our own planet. It will be seen that our universe is replete with jets because they act as essential outlets or valves for regulating the birth and early development of discrete objects and their extended environments.

The purpose here is to assimilate all we know from the different disciplines in which they are encountered. I cannot try to review radio galaxies, star formation, comets or planetary nebula, but only the parts in which jets are essential to their understanding. We thus learn about the driving mechanisms involved and their consequent impact, and so learn to appreciate the diversity. The idea is to accumulate, perhaps possible for the last time, all the material which relates to *the* phenomenon referred to as jets. Hence this is not a series of reviews but a gathering of essential knowledge. And, consequently, by establishing their common properties, this book hopes to represent a turning point in what we have come to understand as jets and what we will go on to discover.

It will be attempted to make this book self-contained with a modicum of required knowledge. It should serve as a timely introduction for astronomy students who seek to develop a broad approach to understand the ‘bigger picture’. On the other hand, the theoretician may relish the range of phenomena which depend upon supersonic flow and shock waves for their explanation. In my early career, my research focused on the extragalactic variety before veering towards the emanations from young stars and protostars. In this time, the astrophysical jet has seen only rare complete reviews. It has been twenty years since the last comprehensive jet book and the subject has moved on. Even in the last five years, since this book was started, tremendous progress has been witnessed with wide-field astronomy, serendipitous discovery and space rendezvous providing new types of jet with data that often contradict our preconceptions and challenge our conceptual skills.

What knowledge is essential to understand jets? It would be inexcusably naive to suggest that just a few physical processes lie at the heart of the matter. We will have to become familiar with a number of launching configurations, radiation mechanisms and observing techniques. Yet, there are common threads to bind the book’s material: above all, gas dynamics – especially the behaviour of gas accelerated from low speed to high speed. A second strand is the cause of the containment or collimation of this flow. Thirdly, the impact as the high-speed jet is disrupted or abruptly terminated. These flows invariably involve shock waves, the sudden transitions within a jet driven up to supersonic speeds. Hence,

xii      *Preface*

some general insight into fluid flow or magnetohydrodynamics is an advantage, while some understanding of the underlying equations must be developed as our intuitive understanding of flow patterns becomes insufficient.

I have taken pains to ensure that this book contains a useful guide to the literature by including a sensible proportion of citations to research papers. However, it is not a reference book and many authors in the field will be disappointed to find that their names and their pet jets are not directly linked. My apologies. My hope is that the papers which are cited can be consulted not as the authority, but as apt starting points for forward and backward panning through the archives. Without this strategy, the task of presenting a concept such as the astrophysical jet within one medium-sized book would be unwieldy.

The *Astronomical Journal*, *Astronomy & Astrophysics*, the *Astrophysical Journal* and *Monthly Notices* are the four time capsules supporting the cornerstones of this work. It would, in addition, take a separate volume to thank the individuals who have contributed to the knowledge within. I will therefore limit myself to thanking all my colleagues in the School of Physical Sciences and all my collaborators in the jet set. The work of several communities of jet setters is embodied here; all I have done is to take their treasures and, hopefully, reveal them. However, there remains one treasure more mysterious and alluring – still as true as in 1979, for inspiration I thank Daniela Rohr.