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

CAMBRIDGE
UNIVERSITY PRESS

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
Information on this title: www.cambridge.org/9780521834766

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

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

Contents

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* phenomenom 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 understood 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 rendevous 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,

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.