

Cambridge University Press

978-1-107-01816-7 - Observational Molecular Astronomy: Exploring the Universe  
Using Molecular Line Emissions

David A. Williams and Serena Viti

Frontmatter

[More information](#)

## **Observational Molecular Astronomy**

Exploring the Universe Using Molecular Line Emissions

Molecular line emissions offer researchers exciting opportunities to learn about the evolutionary state of the Milky Way and distant galaxies. This text provides a detailed introduction to molecular astrophysics and an array of useful techniques for observing astronomical phenomena at millimetre and submillimetre wavelengths. After discussing the theoretical underpinnings of molecular observation, the authors catalogue suitable molecular tracers for many types of astronomical regions in local and distant parts of the Universe, including cold gas reservoirs primed for the formation of new stars, regions of active star formation, giant photon-dominated regions, and near active galactic nuclei. Further chapters demonstrate how to obtain useful astronomical information from raw telescope data while providing recommendations for appropriate observing strategies. Replete with maps, charts, and references for further reading, this handbook will suit research astronomers and graduate students interested in broadening their skills to take advantage of the new facilities now coming online.

DAVID A. WILLIAMS is the Emeritus Perren Professor of Astronomy at University College London. A former president of the Royal Astronomical Society (2000–2002) and recipient of the RAS's Gold Medal (2009), he has led research groups in Manchester and London and has co-authored a number of texts on astrophysics and astrochemistry. His research interests centre on astrochemistry and using molecular line emissions to describe and understand the evolution of astronomical regions.

SERENA VITI is a professor of astrophysics at University College London. She began her career working on the spectroscopy of very cool stars but soon became interested in star formation and astrochemistry. She is the secretary of the European Astronomical Society and routinely serves on national and international scientific panels and committees.

Cambridge University Press  
978-1-107-01816-7 - Observational Molecular Astronomy: Exploring the Universe  
Using Molecular Line Emissions  
David A. Williams and Serena Viti  
Frontmatter  
[More information](#)

---

Cambridge University Press

978-1-107-01816-7 - Observational Molecular Astronomy: Exploring the Universe  
Using Molecular Line Emissions

David A. Williams and Serena Viti

Frontmatter

[More information](#)

### Cambridge Observing Handbooks for Research Astronomers

Today's professional astronomers must be able to adapt to use telescopes and interpret data at all wavelengths. This series is designed to provide them with a collection of concise, self-contained handbooks, which cover the basic principles peculiar to observing in a particular spectral region, or to using a special technique or type of instrument. The books can be used as an introduction to the subject and as a handy reference for use at the telescope or in the office.

#### *Series Editors*

Professor Richard Ellis, *Department of Astronomy, California Institute of Technology*

Professor Steve Kahn, *Department of Physics, Stanford University*

Professor George Rieke, *Steward Observatory, University of Arizona, Tucson*

Dr. Peter B. Stetson, *Herzberg Institute of Astrophysics, Dominion Astrophysical Observatory, Victoria, British Columbia*

Books currently available in this series:

1. *Handbook of Infrared Astronomy*  
I. S. Glass
4. *Handbook of Pulsar Astronomy*  
D. R. Lorimer and M. Kramer
5. *Handbook of CCD Astronomy*, Second Edition  
Steve B. Howell
6. *Introduction to Astronomical Photometry*, Second Edition  
Edwin Budding and Osman Demircan
7. *Handbook of X-ray Astronomy*  
Edited by Keith Arnaud, Randall Smith, and Aneta Siemiginowska
8. *Practical Statistics for Astronomers*, Second Edition  
J. V. Wall and C. R. Jenkins
9. *Introduction to Astronomical Spectroscopy*  
Immo Appenzeller
10. *Observational Molecular Astronomy*  
David A. Williams and Serena Viti

Cambridge University Press

978-1-107-01816-7 - Observational Molecular Astronomy: Exploring the Universe  
Using Molecular Line Emissions

David A. Williams and Serena Viti

Frontmatter

[More information](#)

---

Cambridge University Press

978-1-107-01816-7 - Observational Molecular Astronomy: Exploring the Universe  
Using Molecular Line Emissions

David A. Williams and Serena Viti

Frontmatter

[More information](#)

# Observational Molecular Astronomy

## Exploring the Universe Using Molecular Line Emissions

DAVID A. WILLIAMS  
*University College London*

SERENA VITI  
*University College London*



**CAMBRIDGE**  
UNIVERSITY PRESS

Cambridge University Press  
 978-1-107-01816-7 - Observational Molecular Astronomy: Exploring the Universe  
 Using Molecular Line Emissions  
 David A. Williams and Serena Viti  
 Frontmatter  
[More information](#)

**CAMBRIDGE**  
 UNIVERSITY PRESS

32 Avenue of the Americas, New York, NY 10013-2473, USA

Cambridge University Press is part of the University of Cambridge.

It furthers the University's mission by disseminating knowledge in 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/9781107018167](http://www.cambridge.org/9781107018167)

© David A. Williams and Serena Viti 2013

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.

First published 2013

Printed in the United States of America

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

*Library of Congress Cataloguing in Publication data*

Williams, D. A. (David Arnold), 1937– author.

Observational molecular astronomy : exploring the universe using molecular line  
 emissions / David A. Williams, University College London, Serena Viti,  
 University College London.

pages cm. – (Cambridge observing handbooks for research astronomers ; 10)

Includes bibliographical references and indexes.

ISBN 978-1-107-01816-7 (hard cover : alk. paper)

I. Molecular astrophysics. I. Viti, Serena, author. II. Title. III. Series: Cambridge  
 observing handbooks for research astronomers ; 10.

QB462.6.W55 2013

523'.02–dc23 2013013585

ISBN 978-1-107-01816-7 Hardback

Cambridge University Press 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.

## Contents

---

<i>List of Illustrations</i>	<i>page</i> xi
<i>List of Tables</i>	xiii
<i>Preface</i>	xv
<b>1 Introduction</b>	<b>1</b>
1.1 Why Are Molecules Important in Astronomy?	1
1.2 A Very Brief History of the Discovery of Molecules in Space	3
1.3 Gas and Dust	9
1.4 What's in This Book	14
1.5 Further Reading	15
<b>2 Spectra and Excitation of Interstellar Molecules</b>	<b>16</b>
2.1 Molecular Spectroscopy	16
2.2 Radiative Transport in the Interstellar Medium	20
2.3 Determining the Level Populations	21
2.4 Further Reading	23
<b>3 Astrochemical Processes</b>	<b>24</b>
3.1 What Drives Cosmic Chemistry?	24
3.2 Chemistry Initiated by Electromagnetic Radiation	25
3.3 Chemistry Initiated by Cosmic Rays	30
3.4 Chemistry and Dust	37
3.5 Chemistry Initiated by Gas Dynamics	42
3.6 Isotopes in Interstellar Chemistry	46
3.7 Conclusions	48
3.8 Further Reading	48

Cambridge University Press

978-1-107-01816-7 - Observational Molecular Astronomy: Exploring the Universe  
Using Molecular Line Emissions

David A. Williams and Serena Viti

Frontmatter

[More information](#)

viii

*Contents*

<b>4</b>	<b>Physical Processes in Different Astronomical Environments</b>	<b>50</b>
4.1	Varying the Intensity of Electromagnetic Radiation	51
4.2	Varying the Cosmic Ray Ionisation Rate	53
4.3	Varying the Dust: Gas Ratio and the Metallicity	54
4.4	Varying Shock Speeds in Interstellar Gas	56
4.5	Timescales	57
4.6	Conclusions	58
4.7	Further Reading	61
<b>5</b>	<b>Molecular Tracers in the Milky Way Galaxy</b>	<b>62</b>
5.1	Molecular Clouds	62
5.2	Star-Forming Regions and Their Outflows	69
5.3	Formation of Low-Mass Stars	80
5.4	Formation of High-Mass Stars	85
5.5	Circumstellar Material	88
5.6	The Galactic Centre	95
5.7	Further Reading	98
<b>6</b>	<b>Molecular Tracers in External Galaxies</b>	<b>99</b>
6.1	Multicomponent Galaxies	101
6.2	Characterisation of Galaxies via Molecules	111
6.3	Recent Molecular Line Studies of Galaxies	115
6.4	Star Formation and the Initial Mass Function	123
6.5	Molecules in the Perseus Cluster of Galaxies	125
6.6	Conclusions	126
6.7	Further Reading	127
<b>7</b>	<b>The Early Universe and the First Galaxies</b>	<b>128</b>
7.1	The Pregalactic Era	128
7.2	Formation of the First Stars	132
7.3	Formation of the First Galaxies	134
7.4	Further Reading	140
<b>8</b>	<b>Recipes for Molecular Submillimetre Astronomy</b>	<b>141</b>
8.1	The Antenna Temperature	142
8.2	Local Thermodynamic Equilibrium	143
8.3	Non-LTE	149
8.4	Further Reading	151



Cambridge University Press  
978-1-107-01816-7 - Observational Molecular Astronomy: Exploring the Universe  
Using Molecular Line Emissions  
David A. Williams and Serena Viti  
Frontmatter  
[More information](#)

---

*Contents*

ix

<b>9</b>	<b>Chemical and Radiative Transfer Models</b>	<b>152</b>
9.1	Chemical Modelling	152
9.2	Radiative Transfer Modelling	158
9.3	Further Reading	164
<b>10</b>	<b>Observations: Which Molecule, Which Transition?</b>	<b>165</b>
10.1	Further Reading	167
	<i>Appendix: Acronyms</i>	169
	<i>Index</i>	171

Cambridge University Press  
978-1-107-01816-7 - Observational Molecular Astronomy: Exploring the Universe  
Using Molecular Line Emissions  
David A. Williams and Serena Viti  
Frontmatter  
[More information](#)

---

Cambridge University Press

978-1-107-01816-7 - Observational Molecular Astronomy: Exploring the Universe  
Using Molecular Line Emissions

David A. Williams and Serena Viti

Frontmatter

[More information](#)


---

## List of Illustrations

---

1.1	Optical and CO image of M83.	<i>page 2</i>
1.2	UV spectrum of H <sub>2</sub> .	4
1.3	Complex molecules in star-forming regions.	5
1.4	Interstellar extinction curves.	12
1.5	The Horsehead Nebula in the visible and infrared.	13
3.1	The dark cloud Barnard 68 and the stellar jet of Herbig–Haro 49/50.	26
3.2	A schematic diagram of a PDR.	29
3.3	Comparison of PDR and XDR chemistries.	31
3.4	Comparison of UV- and cosmic ray–driven chemistries.	35
3.5	CO depletion observed in a molecular cloud.	41
3.6	J- and C-type shocks.	44
4.1	PDR transition zones.	52
4.2	Chemistry dependence on the cosmic ray ionisation rate.	55
4.3	Timescales in molecular clouds.	59
5.1	The sensitivity of the X-factor to changes in the gas physical conditions.	66
5.2	Contour maps of structure in the molecular cloud L673.	68
5.3	Herbig–Haro 111 in Orion.	71
5.4	Molecular emission near Herbig–Haro 2.	73
5.5	Outflow cones from B5 IRS1 in CO.	74
5.6	Molecular emissions from the L1157 outflow.	76
5.7	Molecular emission from the compact sources in Orion.	78
5.8	Molecular line profiles in Cep A East.	79
5.9	Computed circumstellar disk properties.	83
5.10	Emission contour from the hot core G29.96-0.02.	87
5.11	Schematic diagram of the environment near a carbon-rich AGB star.	90

Cambridge University Press

978-1-107-01816-7 - Observational Molecular Astronomy: Exploring the Universe  
Using Molecular Line Emissions

David A. Williams and Serena Viti

Frontmatter

[More information](#)

xii

*List of Illustrations*

5.12	Image of the protoplanetary nebula CRL 618.	92
5.13	Infrared emission from the supernova SN 1987A.	95
5.14	Molecular emission from the Central Molecular Zone.	96
6.1	Optical image of M82 and CO contour maps.	102
6.2	Cloud temperature as a function of cosmic ray ionisation rates.	107
6.3	Image and CO contour map of the colliding galaxies Arp220.	121
6.4	Predicted antenna temperatures for several galaxy models.	124
6.5	Image of the Perseus Cluster.	125
6.6	Image of the galaxy NGC 1275.	126
7.1	Chemical species in the recombination era.	132
7.2	Sketch of the formation of the first galaxies.	135
7.3	Integrated infrared luminosity versus CO luminosity.	137
8.1	Rotational diagram for CO emission in L1157-B1.	144
9.1	Flow diagram of the molecular line radiative transfer problem.	162
9.2	Variation of the CS integrated line fluxes for the ultracompact core (right-hand side) and the envelope (left-hand side).	163

Cambridge University Press

978-1-107-01816-7 - Observational Molecular Astronomy: Exploring the Universe  
Using Molecular Line Emissions

David A. Williams and Serena Viti

Frontmatter

[More information](#)


---

## List of Tables

---

1.1	List of detected molecular species	<i>page</i> 6
1.2	ISM components	9
1.3	Initial abundances	10
3.1	Observed ice composition	42
3.2	Examples of radical-radical reactions on grains	42
3.3	Fractionation in IRAS 16293-2422	46
3.4	Tracers of ISM drivers	48
4.1	Metallicity effects on the chemistry	56
4.2	Relevant timescales for interstellar processes	60
4.3	Sensitivity of chemical abundances	60
5.1	Classification of low-mass stars	70
5.2	Observational data for IRAS 16293–2422	81
5.3	Molecules in disks	85
5.4	Molecules in CRL618	93
6.1	Galaxy classification	101
6.2	Detected molecules in NGC253	103
6.3	HCN/HCO <sup>+</sup> and HCN/CO for three galaxies	104
6.4	<i>X</i> -factor for several galaxy types	110
6.5	Detectable molecules in galaxies	113
6.6	Detectable molecules in dense gas in external galaxies	115
6.7	Molecular comparison of the Milky Way with NGC253 and M82	118
7.1	Physical characteristics of the key stages in the history of the Universe	130
7.2	Values of <i>X</i> -factors for several CO rotational transitions	138
10.1	Critical densities	166

Cambridge University Press

978-1-107-01816-7 - Observational Molecular Astronomy: Exploring the Universe  
Using Molecular Line Emissions

David A. Williams and Serena Viti

Frontmatter

[More information](#)

---

Cambridge University Press  
978-1-107-01816-7 - Observational Molecular Astronomy: Exploring the Universe  
Using Molecular Line Emissions  
David A. Williams and Serena Viti  
Frontmatter  
[More information](#)

---

## Preface

---

This is a handbook for those astronomers who wish to use molecular line emissions as probes of astronomical sources. These sources may include molecular clouds and star-forming regions, circumstellar envelopes, and ejecta from evolved stars. Molecular lines are particularly useful in deconvolving complex emissions from distant unresolved galaxies.

This is not a textbook; it does not present detailed explanations and derivations. Textbook information can be found in the Further Reading sections at the end of each chapter. This handbook aims to provide a background of understanding so that the observer can begin to address the following questions:

- Why are different astronomical regions best traced in lines from different molecules?
- Which are the most suitable molecular tracers for studying the observer's selected sources?
- How does the observer convert raw telescope data into astrophysically useful information?
- How can the most complete physical description be extracted from the data?