

MOLECULAR ASTROPHYSICS

Focusing on the organic inventory of regions of star and planet formation in the interstellar medium of galaxies, this comprehensive overview of the molecular Universe is an invaluable reference source for advanced undergraduates through to entry-level researchers. It includes an extensive discussion of microscopic physical and chemical processes in the Universe; these play a role in the excitation, spectral characteristics, formation, and evolution of molecules in the gas phase and on grain surfaces. In addition, the latest developments in this area of molecular astrophysics provide a firm foundation for an in-depth understanding of the molecular phases of the interstellar medium. The physical and chemical properties of gaseous molecules, mixed molecular ices, and large polycyclic aromatic hydrocarbon molecules and fullerenes and their role in the interstellar medium are highlighted. For those with an interest in the molecular Universe, this advanced textbook bridges the gap between molecular physics, astronomy, and physical chemistry.

A. G. G. M. TIELENS is a professor of Astronomy at both Leiden University and the University of Maryland. He has held appointments at the University of California in Berkeley, NASA Ames Research Center, the University of Groningen, and the Dutch Space Agency; was the project scientist of the HIFI instrument on board the Herschel Space Observatory; and was the NASA project scientist of the Stratospheric Observatory for Infrared Astronomy (SOFIA). He is a member of the Royal Netherlands Academy of Arts and Sciences and was awarded the Spinoza Prize in 2012.

Cambridge University Press
978-1-107-16928-9 — Molecular Astrophysics
A. G. G. M. Tielens
Frontmatter
[More Information](#)

MOLECULAR ASTROPHYSICS

A.G.G.M. TIELENS

Leiden University



CAMBRIDGE
UNIVERSITY PRESS

CAMBRIDGE
UNIVERSITY PRESS

University Printing House, Cambridge CB2 8BS, 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
79 Anson Road, #06–04/06, Singapore 079906

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

Information on this title: www.cambridge.org/9781107169289

DOI: 10.1017/9781316718490

© A. G. G. M. Tielens 2021

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 2021

Printed in the United Kingdom by TJ Books Limited, Padstow Cornwall

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

Library of Congress Cataloging-in-Publication Data

Names: Tielens, A. G. G. M., author.

Title: Molecular astrophysics / A.G.G.M. Tielens, Universiteit Leiden.

Description: Cambridge, UK ; New York, NY : Cambridge University Press, 2021. |

Includes bibliographical references and index.

Identifiers: LCCN 2020023795 (print) | LCCN 2020023796 (ebook) |

ISBN 9781107169289 (hardback) | ISBN 9781316718490 (epub)

Subjects: LCSH: Molecular astrophysics.

Classification: LCC QB462.6 .T54 2021 (print) |

LCC QB462.6 (ebook) | DDC 523.01/96–dc23

LC record available at <https://lcn.loc.gov/2020023795>

LC ebook record available at <https://lcn.loc.gov/2020023796>

ISBN 978-1-107-16928-9 Hardback

Additional resources for this publication at www.cambridge.org/tielens

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>Preface</i>	<i>page</i>	ix
Book Description		x
Author		x
Cover Illustration		xi
1 Introduction		1
1.1 The Molecular Universe		1
1.2 Astrobiology		2
1.3 The Prebiotic Origin of Life		4
1.4 Molecules and the Universe		11
1.5 Astrochemistry		16
1.6 Further Reading and Resources		18
2 Introduction to Chemistry		21
2.1 Chemistry Primer		21
2.2 Reactions		29
2.3 Classes of Compounds		30
2.4 Laboratory Techniques		37
2.5 Quantum Theory		48
2.6 Further Reading and Resources		54
2.7 Exercises		55
3 Molecular Spectroscopy		58
3.1 Introduction		58
3.2 Rotational Spectroscopy		59
3.3 Vibrational Spectroscopy		75
3.4 Electronic Spectroscopy		86
3.5 Specific Examples		88
3.6 Further Reading and Resources		95
3.7 Exercises		96

vi	<i>Contents</i>	
4	Molecular Emission and Absorption	100
4.1	Level Populations	101
4.2	Analysis of Observations	114
4.3	Electronic Excitation	124
4.4	Further Reading and Resources	128
4.5	Exercises	129
5	Chemical Thermodynamics	134
5.1	Introduction	134
5.2	Thermodynamics	134
5.3	Examples	143
5.4	Methods	147
5.5	The Role of Thermodynamics in Space	148
5.6	Further Reading and Resources	150
5.7	Exercises	151
6	Gas Phase Chemical Processes	154
6.1	Introduction	154
6.2	Generic Reaction Processes and Their Rates	154
6.3	Photochemistry	158
6.4	Ion–Molecule Reactions	175
6.5	Neutral–Neutral Reactions	181
6.6	Radiative Association Reactions	184
6.7	Cosmic Ray Ionization	190
6.8	Dissociative Electron Recombination Reactions	194
6.9	Collisional Association and Dissociation Reactions	196
6.10	Electron Attachment	197
6.11	Associative Detachment Reactions	200
6.12	Non-LTE Effects	201
6.13	Gas Phase Chemistry Networks	202
6.14	Further Reading and Resources	204
6.15	Exercises	205
7	Chemistry on Interstellar Grain Surfaces	210
7.1	Introduction	210
7.2	Characteristics of Surface Chemistry	211
7.3	Surface Processes	213
7.4	Surface Reactions	226
7.5	Chemical Networks: Rules of Engagement	237
7.6	Desorption	239
7.7	The Stochastic Nature of Interstellar Surface Chemistry	248
7.8	Further Reading and Resources	252
7.9	Exercises	254

Contents

vii

8	Physics and Chemistry of Large Molecules	258
8.1	Introduction	258
8.2	The Physics and Chemistry of Interstellar PAHs	259
8.3	Statistical Physics	273
8.4	The Excitation of Interstellar PAHs	280
8.5	Photochemistry	288
8.6	Photo Ionization	298
8.7	Gas Phase Chemical Processes	302
8.8	Fullerenes	308
8.9	Further Reading and Resources	312
8.10	Exercises	313
9	Diffuse Clouds	318
9.1	The Characteristics of Diffuse Molecular Clouds	320
9.2	The Formation of H ₂	325
9.3	Chemistry	329
9.4	The Chemistry of Turbulent Regions	338
9.5	The Cosmic Ray Ionization Rate	342
9.6	Diffuse Interstellar Bands and the Organic Inventory of the ISM	347
9.7	Further Reading and Resources	357
9.8	Exercises	359
10	Molecular Clouds	366
10.1	Analysis of Observations of Molecular Clouds	368
10.2	Characteristics of Molecular Clouds	379
10.3	The Energy Balance	390
10.4	Molecular Abundances	396
10.5	Gas Phase Chemistry	398
10.6	Gas–Grain Interactions	418
10.7	Further Reading and Resources	439
10.8	Exercises	442
11	Star Formation	451
11.1	Introduction	452
11.2	Prestellar Cores	454
11.3	Hot Cores and Hot Corinos	461
11.4	Protoplanetary Disks	481
11.5	Astrochemistry and the Solar System	505
11.6	Photodissociation Regions	509
11.7	Stellar Jets, Disk Winds, and Outflows	532
11.8	Masers	541
11.9	Further Reading and Resources	552
11.10	Exercises	557

12	The Aromatic Universe	567
12.1	Introduction	567
12.2	The Aromatic Infrared Bands	568
12.3	Spectroscopy and the Characteristics of the Carriers	576
12.4	Buckminsterfullerene	593
12.5	PAH Emission Models	594
12.6	Anomalous Microwave Emission	599
12.7	Evolution of Interstellar PAHs	604
12.8	PAHs and the Photo-Electric Heating of Interstellar Gas	615
12.9	Further Reading and Resources	620
12.10	Exercises	623
	<i>Subject Index</i>	629
	<i>Source Index</i>	638
	<i>Index of Chemical Compounds</i>	640

Color plates can be found between pages 340 and 341

Preface

While interstellar molecules were first discovered some hundred years ago, over most of the intervening years, the molecular Universe lay dormant; the realm of a few brave pioneers that were undaunted by the prospect of the deep dive into molecular physics required to make sense of it all. Indeed, over much of this period, the Eddington quote in the Introduction sums up the attitude of the astronomical community, paraphrased to: *Molecules are not for astrophysicists*. However, over the last two decades, the opening up of the infrared and submillimeter spectral windows – driven by the rapid increase in detector technologies and ever-increasing telescope sizes – has provided us with a view of the richness of the molecular Universe. We are living in a molecular Universe where molecules are abundant and widespread and play an important role in the evolution of galaxies. We have also realized that regions of planet formation contain a rich organic inventory that may have provided the prebiotic roots of life. Finally, molecules provide an excellent tool to determine the physical conditions and probe the dynamics of many astronomically interesting objects and phenomena. Hence, molecular astrophysics has come into its own right as a key subdiscipline within astronomy. Conversely, future generations of astromomers will have to become familiar with all things molecular.

This book has grown out of lectures presented at a number of different summerschools on molecular astrophysics organized over the years. While preparing these lectures and discussing with students the molecular physics involved, I realized that a comprehensive introduction into molecular physics and its application to molecules in the interstellar medium of galaxies at the level of graduate students was sorely lacking. My earlier textbook on the physics and chemistry of the interstellar medium covers some of these aspects, and relevant chapters have been incorporated but updated with the latest developments and, in addition, their scope has been greatly expanded. The introduction to each chapter provides a short guide on what aspects would be particularly relevant for a course and which sections are, instead, provided for in-depth study by graduate students entering the field. Each chapter also provides a further reading and resource guide that will provide entry points for students into the rich literature of the field. Here, I have to appologize as, due to lack of space, it is impossible to do justice to all the relevant literature. The resource guide will typically provide references to some of the earliest studies and to some of the

more recent developments. Together, this should enable students to trace back all relevant ideas and concepts. Finally, each chapter also contains a set of exercises that will allow students to test their comprehension of the material.

This book was largely written over a period of three years during extensive stays at the Astronomy Department of the University of California in Berkeley, the Astronomy Department of the University of Maryland in College Park, and the Astronomy Department of the University of Colorado in Boulder. I owe a deep debt of gratitude to these institutions for their hospitality and for providing a great atmosphere for science that was conducive to creative writing. Much of this book reflects a lifelong interest in the molecular Universe. I am deeply grateful to Harm Habing who, during the early stages of my career, taught me that graduate students are to be treated humanly. I wouldn't be where I am now if Harm hadn't stepped in at the right moment. I am also much in debt to Lou Allamandola and David Hollenbach who have been my guides through the molecular Universe over much of my career. Last, but not least, I gratefully acknowledge the many great students, postdocs, and collaborators who never tired of showing me the parts of the molecular Universe that inspired them.

Book Description

This work provides a comprehensive overview of our understanding of the molecular Universe, in particular the organic inventory of regions of star and planet formation in the interstellar medium of galaxies. It contains an extensive discussion of the microscopic physical and chemical processes that play a role in the excitation, spectral characteristics, formation, and evolution of molecules in the gas phase and on grain surfaces. Based on our current experimental, theoretical, and observational understanding of the molecular physics relevant for the interstellar medium of galaxies, this book includes the latest developments in this area of molecular astrophysics and provides a firm foundation for an in-depth understanding of the molecular phases of the interstellar medium. The physical and chemical properties of gaseous molecules, mixed molecular ices, and large polycyclic aromatic hydrocarbon molecules and fullerenes and their role in the interstellar medium are highlighted. This is an invaluable reference source for advanced undergraduate and graduate students and research scientists. Related resources for this book can be found at TBD.

Author

A. G. G. M. Tielens is a professor of Astrophysics at Leiden Observatory, the Netherlands, and at the Astronomy Department of the University of Maryland, College Park. Prior to this, he worked as an assistant researcher in the Astronomy Department of the University of California, Berkeley, a senior scientist at NASA Ames Research Center, California, professor of Astrophysics at the Kapteyn Institute in the Netherlands, and a senior scientist with the Dutch space agency, SRON. He was the project scientist of the HIFI instrument

that flew on the Herschel Space Observatory, launched by the European Space Agency in 2009, and he was the NASA project scientist of the Stratospheric Observatory for Infrared Astronomy, SOFIA, from 2005 to 2007. He has published extensively on various aspects of the physics and chemistry of the interstellar medium of galaxies.

Cover Illustration

The tip of Orion's sword, where bright stars set their environment aglow in the light of large polycyclic aromatic hydrocarbon molecules. Figure courtesy of NASA/JPL-Caltech & T. Megeath (University of Toledo, Ohio).

Cambridge University Press
978-1-107-16928-9 — Molecular Astrophysics
A. G. G. M. Tielens
Frontmatter
[More Information](#)
