The Physics and Chemistry of the Interstellar Medium

This work provides a comprehensive overview of our current theoretical and observational understanding of the interstellar medium of galaxies. With emphasis on the microscopic physical and chemical processes in space, and their influence on the macroscopic structure of the interstellar medium of galaxies, the book includes the latest developments in this area of molecular astrophysics. The various heating, cooling, and chemical processes relevant for the rarefied gas and submicron-sized dust grains that constitute the interstellar medium are discussed in detail. This provides a firm foundation for an in-depth understanding of the ionized, neutral atomic, and molecular phases of the interstellar medium. The physical and chemical properties of large polycyclic aromatic hydrocarbon molecules and their role in the interstellar medium are highlighted, and the physics and chemistry of warm and dense photodissociation regions are discussed. This is an invaluable reference source for advanced undergraduate and graduate students and research scientists.

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THE PHYSICS AND CHEMISTRY OF THE INTERSTELLAR MEDIUM

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CAMBRIDGE UNIVERSITY PRESS

CAMBRIDGE UNIVERSITY PRESS
Cambridge, New York, Melbourne, Madrid, Cape Town, Singapore, São Paulo

CAMBRIDGE UNIVERSITY PRESS
The Edinburgh Building, Cambridge CB2 2RU, UK

www.cambridge.org

Information on this title: www.cambridge.org/9780521826349

First published 2005

Printed in the United Kingdom at the University Press, Cambridge

A catalog record for this book is available from the British Library

ISBN-13 978-0-521-82634-9 hardback
ISBN-10 0-521-82634-9 hardback

Contents

Preface

When, upon my return to Holland, I started to teach an advanced course on the interstellar medium in 1998, I quickly realized that there was no suitable textbook available. There is, of course, the incomparable monograph by Spitzer, *Physics of the Interstellar Medium* (1978, New York: Wiley and Sons). But that book is quite challenging and not very suitable for a student course. Moreover, by now, it is very dated. Over the intervening years, our insights into the basic physics of the interstellar medium have much improved thanks, for example, to the opening up of the infrared and submillimeter windows. In particular, molecules, which we now know to be deeply interwoven into the fabric of the Universe, play only a little role in Spitzer's book. When Eddington made his famous remark, "Atoms are physics but molecules are chemistry," he merely expressed, on the one hand, the dream of a physicist of a simple universe, which can be caught in a single equation, and, on the other hand, the dread of a reality where solutions are never clean and simple. The latter is of course obvious to a chemist and it is now abundantly clear that Eddington's fear has turned into reality, even for astronomy. Present-day graduate students will require an intimate knowledge of molecular astrophysics in order to be active in the field of the interstellar medium of our own or other galaxies whether it is in the here and now or all the way back in the early Universe. This will become even more the case with the launch of the submillimeter space mission, Herschel, in 2007, when the Atacama Large Millimeter Array is finished in 2011, and with the launch of the James Webb Space Telescope in the next decade. Together these missions will push the frontier of the molecular Universe all the way back to the initial pollution of the Universe with the first metals by the first generation of luminous objects, which forever spoiled the physicist's Garden of Eden.

This book covers both the physics and the chemistry of the interstellar medium. Chapters on heating, cooling, and chemical processes provide the students with the necessary toolbox for the astrophysics and astrochemistry of the interstellar medium. This background is rounded off with chapters on the physics and chemistry of interstellar dust and large molecules. Once the students have mastered these subjects, they are well prepared for an in-depth discussion of classical topics of the interstellar medium: HII regions, the phases of the interstellar medium, shocks, and the dynamical interaction of HII regions, supernova remnants, and stellar winds with the ISM. The chemistry of the interstellar medium is covered in chapters on diffuse clouds, photodissociation regions, and molecular clouds. All together, this forms a comprehensive course, covering most current aspects of the interstellar medium, which will prepare students well for the future.

Over the years, this book grew from the course that I taught in Groningen. Indeed, in many ways, writing this book carried me through those dark Dutch days. Fortunately, I have many good friends who understand that, when the Sun sets in October not to appear again until May, it is a good time to leave Holland and visit other institutes. I owe a deep debt of gratitude to the Miller Institute and the Astronomy Department of the University of California in Berkeley and my hosts Imke de Pater and Chris McKee, to the Space Sciences Division of NASA Ames Research Center and my hosts David Hollenbach and Lou Allamandola, to the Institute for Geophysics and Planetary Physics of the Lawrence Livermore National Laboratory and my hosts Wil van Breugel and John Bradley, to the Centre d'Etudes Spatiale des Rayonnements in Toulouse and my host Emmanuel Caux, and to the Laboratoire d'Astrophysique de l'Observatoire de Grenoble and my host Cecilia Ceccarelli for their hospitality and for providing an environment conducive to great science. Most of the chapters of this book were conceived and written during these extended visits. Of course, much of this book reflects a lifetime spent in discovering the molecular Universe. I want to thank Harm Habing without whose human touch I would have left astronomy before even finishing the first stage of my journey. Also, I owe much to Lou Allamandola and David Hollenbach, with whom I have spent so many wonderful hours on the trail of discovery: not only for sharing their deep insights and understanding of physical and chemical processes of relevance to studies of the interstellar medium but, particularly, for their friendship. I am also deeply indebted to the many graduate students, who carried me through the many stages of this course, solved the many LaTeX problems, and always succeeded in making the right figures, as well as for their careful proofreading of the manuscript. Most of all, their enthusiasm always managed to perk me up. In this regard, I specifically want to thank Adwin Boogert, Rense Boomsma, Jan Cami, Stephanie Cazaux, Sasha Hony, Jacquie Keane, Leticia Martín-Hernández, Chris Ormel, Els Peeters, and Henrik Spoon for their help. Finally, Marion understands like no other what it is to live away from what feels like home. Her encouragement to follow my dream and her support during these difficult years have made this possible. To my girls–Anneke, Saskia, and Elske–the only thing I can say is that, now, it is really done.

Constants

Physical constants

Symbol	Description	SI		cgs	
		Value	Unit	Value	Unit
c	Speed of light	2.9979 (8)	m s^{-1}	2.9979 (10)	cm^{-1} s^{-1}
h	Planck's constant	6.6261(−34)	J s	6.6261(−27)	erg s
k	Boltzmann's constant	1.3807(−23)	J/K	1.3807(−16)	erg/K
σ_{SB}	Stefan–Boltzmann constant	5.6704 (−8)	W m^{-2} K^{-4}	5.6704 (−5)	erg s^{-1} cm^{-2} K^{-4}
G	Gravitational constant	6.674 (−11)	N m^{-2} kg^{-2}	6.674 (−8)	dyn cm^{-2} g^{-2}
N_A	Avogadro's constant	6.0221 (23)	mol^{-1}	6.0221 (23)	mol^{-1}
m_e	Electron rest mass	9.1094(−31)	kg	9.1094(−28)	g
m_p	Proton rest mass	1.6726(−27)	kg	1.6726(−24)	g
m_u	Atomic mass unit	1.6605(−27)	kg	1.6605(−24)	g
e	Electron charge	1.602 (−19)	C	4.803 (−10)	esu
α	Fine-structure constant	7.2974 (−3)		7.2974 (−3)	

Values $a \times 10^b$ are given as a (b).

Astronomical constants

Symbol	Description	SI		cgs	
		Value	Unit	Value	Unit
AU	Astronomical unit	1.496 (11)	m	1.496 (13)	cm
ly	Light year	9.463 (15)	m	9.463 (17)	cm
pc	Parsec	3.086 (16)	m	3.086 (18)	cm
pc^2	Square parsec	9.5234 (32)	m^2	9.5234 (36)	cm^2
kpc^2	Square kiloparsec	9.5234 (38)	m^2	9.5234 (42)	cm^2
$L_\odot$	Solar luminosity	3.85 (26)	J s^{-1}	3.85 (33)	erg s^{-1}
$M_\odot$	Solar mass	1.989 (30)	kg	1.989 (33)	g
$R_\odot$	Solar radius	6.96 (8)	m	6.96 (10)	cm
$T_\odot$	Solar effective temperature	5.78 (3)	K	5.78 (3)	K
Jy	Jansky	1.00 (−26)	W m^{-2} H z^{-1}	1.00 (−23)	erg s^{-1} cm^{-2} Hz^{-1}

Values $a \times 10^b$ are given as a (b).

Conversion factors

Angles and lengths

Unit/symbol	Description	SI		cgs	
		Value	Unit	Value	Unit
deg	degree	1.745 3 (−2)	rad	1.745 3 (−2)	rad
arcmin	arcminute	2.908 88 (−4)	rad	2.908 88 (−4)	rad
arcsec	arcsecond	4.848 1 (−6)	rad	4.848 1 (−6)	rad
sq deg	$degree^2$	3.046 (−4)	sr	3.046 (−4)	sr
Å	angstrom	1.0 (−10)	m	1.0 (−8)	cm
μm	micrometer	1.0 (−6)	m	1.0 (−4)	cm

Values $a \times 10^b$ are given as a (b).

SI and cgs units

Description	SI		cgs	
	Value	Unit	Value	Unit
Time	1	s	1	s
	1	year	3.16 (7)	s
Length	1	m	1 (2)	cm
Velocity	1	m s^{-1}	1 (2)	cm s^{-1}
Force	1	N	1 (5)	dyne
Pressure	1	Pa	1 (−1)	dyne cm^{-2}
Energy	1	J	1 (7)	erg
Charge	1	C	2.9979 (9)	esu
Magnetic flux density	1	T	1 (4)	gauss

Values $a \times 10^b$ are given as a (b).

Energy conversion factors

	erg	eV	K	cm^{-1}	Hz
erg	1.00	6.242 (11)	7.243 (15)	5.034 (15)	1.509 (26)
eV	1.602 (−12)	1.00	1.1604 (4)	8064.4	2.418 (14)
K	1.3806 (−16)	8.617 (−5)	1.00	0.695	2.084 (10)
cm^{-1}	1.9865 (−16)	1.240 (−4)	1.4389	1.00	2.9970 (10)
Hz	6.626 (−27)	4.136 (−15)	4.798 (−11)	3.336 (−11)	1.00

Values $a \times 10^b$ are given as a (b). To convert from unit in column 1 to units above the rows, multiply by value; e.g., $1\,\mathrm{eV} = 1.602 \times 10^{-12}$ erg.

A useful compendium of constants can be found in C. W. Allen, *Astrophysical Quantities*, (London: The Athlone Press). The website http://physics.nist.gov/cuu/, maintained by the National Institute of Standards and Technology, provides a wealth of information on constants.