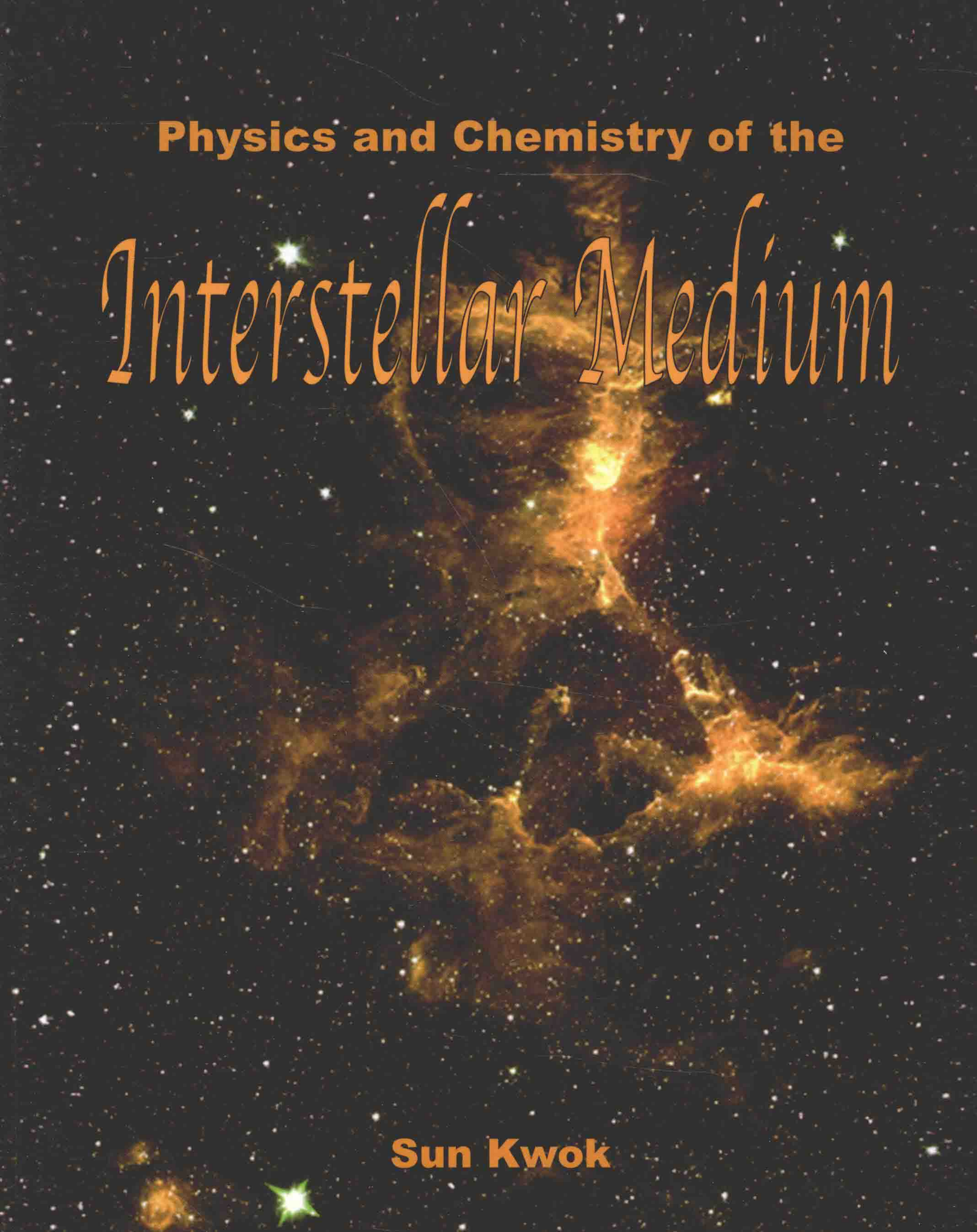

Physics and Chemistry of the Interstellar Medium

Sun Kwok

Physics and Chemistry of the Interstellar Medium

Sun Kwok
The University of Hong Kong

UNIVERSITY SCIENCE BOOKS
Sausalito, California

University Science Books
www.uscibooks.com

Production Manager: Mark Ong
Manuscript Editor: John Murdzek
Designer: Mark Ong
Compositor: Windfall Software, using ZzTEX
Illustrator: Lineworks
Printer & Binder: Maple Vail Book Manufacturing Group

This book is printed on acid-free paper.

ISBN-10: 1-891389-46-7
ISBN-13: 978-1-891389-46-7

Library of Congress Cataloging-in-Publication Data

Kwok, S. (Sun)
Physics and chemistry of the interstellar medium / Sun Kwok.
p. cm.
Includes bibliographical references and index.
ISBN 1-891389-46-7 (alk. paper)
1. Interstellar matter—Textbooks. 2. Astrophysics—Textbooks.
3. Cosmochemistry—Textbooks. I. Title.
QB790.K96 2006
523.1′135—dc22
2006046137

Printed in the United States of America
10 9 8 7 6 5 4 3 2 1

Physics and Chemistry of the Interstellar Medium

Preface

The history of astrophysics has been a series of successful applications of modern physics to cosmic phenomena. In the 20th century, we saw the success of the application of nuclear physics to the understanding of the energy generation of the Sun and the stars, the synthesis of elements, and the change in nuclear processes as the driving force for stellar evolution. The application of atomic physics was instrumental in our understanding of the spectra of stars and gaseous nebulae. The measurements of the strengths of electronic transitions of elements allow us to determine the abundance of elements and to test the models of nucleosynthesis.

The discipline of astrochemistry began with the development of millimeter-wave astronomy in the early 1970s, leading to the detection of rotational transitions of over 120 molecules. The advent of infrared spectroscopy, in particular from space missions, has made possible the detection of complex organic molecules through their stretching and bending vibrational modes. Astrochemistry is not only interesting as part of the study of the interstellar medium, but also relevant to the question of the origin of life. Astrobiology is a rapidly growing field, and its importance is reflected in this book by the inclusion of organic chemistry relevant to astronomy.

The developments in space observations, in particular in the X-ray (*ROSAT, Chandra*), ultraviolet (*IUE, FUSE*), optical (*HST*), infrared (*IRAS, ISO, Spitzer*), and submillimeter (*SWAS, Odin*) regions, have revolutionarized our understanding of the interstellar medium. These new techniques have greatly expanded the range of physical processes that can be studied in the interstellar medium. Interstellar ions, atoms, molecules, and solid materials can now be studied in the UV, optical, infrared, and millimeter parts of the electromagnetic spectrum. These capabilities will be further developed with the launch of *Herschel* and *SOFIA*. Students will find the fundamental materials in this book useful in the interpretation of data from these missions.

Although this book is called the "Physics and Chemistry of the Interstellar Medium" and is primarily written for researchers and students involved in ISM research, many of the basic materials are applicable to problems in extragalactic astronomy. In the past, extragalactic astronomers derived most of their information from photometry and spectroscopy of a few emission lines, and it was thought that just some basic understanding of stellar colors and recombination line theory would be sufficient. After all, the spectra of normal galaxies are just the superposition of starlight and active galaxies and quasars are too far away to exhibit many emission lines. However, as the power of telescopes increases, physical processes that previously were observable only in our own galaxy will be observable in external galaxies. For example, with infrared and submm observations, dust continuum emissions are now commonly observed in galaxies. The lessons that we have learned in how to interpret spectra of dust clouds in the ISM are therefore extremely valuable. With modern large optical telescopes, many atomic lines in the ultraviolet can now be detected in distant galaxies as they are being redshifted into the visible region. The conditions under which intercombination lines and collisionally excited lines arise are now relevant. The construction of powerful mm arrays such as *ALMA* will make possible the detection of many molecular species in external galaxies. The greatly improved sensitivity of *Spitzer* over *ISO* means that many of the infrared lines previously seen only in the ISM are detectable in galaxies.

Goals and Philosophy

This book is based on class notes that I have developed over a period of 20 years teaching a two-semester course in advanced astrophysics for senior undergraduate and beginning graduate students at the University of Calgary. The intended readership is a physics student who is familiar with basic physics topics such as electromagnetism, atomic structures, and quantum mechanics, as well as a chemistry background at the first-year university level. The increasing availability of computer codes to treat various problems (e.g., *CLOUDY* for photoioinization, *Raymond-Smith* for X-ray spectra, *DUSTCD* for dust continuum transfer, etc.) has resulted in many students treating these tools as black boxes without understanding the underlying principles. The goal of the book is to prepare the readers with a fundamental background in physical and chemical processes and to allow them to properly interpret modern observations. In order to help achieve this goal, I have included many sample spectra and images from actual observations to illustrate the theoretical concepts.

By sticking with fundamental principles and avoiding phenomenological descriptions, I hope that the material in this book will stay relevant for a long time, and not be made obsolete by changing models and fashions.

In undergraduate studies, students try to solve problems whose solutions they know exist. In graduate studies, students are given a problem which has not been solved before and try to solve it. As research scientists, we identify a problem, formulate it in mathematical terms, and then solve them. When confronted with a physical problem, we have to isolate the critical variables, the physical processes involved, and the relevant equations to use. The key for a successful scientist is to think physically, and not to be bogged down by mathematical details. In this book, I try to emphasize these principles.

Instead of writing down the most general equations and seeking the most general solutions—the common approach taken by many physics textbooks—I deliberately limit all equations to the one-dimensional case to minimize mathematical complexity, and to obtain particular solutions for the simplest case. By this approach, I try to highlight the physical meanings of each term, which may otherwise be obscured by the mathematics. I hope this will prevent students from mechanically grinding through equations without realizing their meaning.

Some readers may notice that many topics are related to research that I have done over the years. Since I am obviously limited and biased by my own background, I apologize to readers who think some topics are neglected or not covered as extensively as they could be. For example, I have left out magnetic fields, turbulence, and high-energy phenomena such as relativity and cosmic rays.

Acknowledgments

I started drafting this book from my own teaching notes about ten years ago. Since administration, teaching and research activities take up most of my normal working hours, the writing of this book, unfortunately, has to be relegated to hobby status. Much of the material was written on airplanes, in airport lounges, hotel rooms, and at home during evenings and weekends. Many sections were written during early morning hours in foreign lands when I was up early suffering from the effects of jetlag. The task of writing this book was made easier by modern computer software. The manuscript was written in LaTeX, the calculations performed using MATHCAD, and many of the figures prepared using Adobe Illustrator and AXUM.

Over the course of writing this book, I have benefited from discussions and inputs from many friends and colleagues. Various versions of the draft have been in circulation in the astronomical community in the last five years and I would like to thank everyone who has commented on what they read. In particular, I thank Kevin Volk for many years of collaboration and for his ideas and contributions to various sections of the book. The expert knowledge of Peter Bernath in atomic and molecular physics has added greatly to the respective chapters. The pioneering work done by Renaud Papoular, Walt Duley and Alan Tokunaga on organic compounds in space has influenced my own thinking on this subject. I also benefited from the discussions with Lou Allamandolla, Huan-Cheng Chang, Dale Cruikshank, Olivier Guillois, Thomas Henning, Chun Ming Leung, Yvonne Pendleton, Scott Sandford, Farid Salama, Diane Wooden, Li-Hong Xu, and many others on different aspects of the ISM. Tatsuhiko Hasegawa contributed to the chapter on chemical reactions in the ISM. Comments, criticisms from several anonymous reviewers also helped improve the book. I want to thank the many authors who kindly allow their figures or other published materials to be used in the book. I also thank Orla Aaquist and Alexander Menshchikov for their careful readings of earlier drafts, and Emily Wei for her help in preparing some of the figures. The manuscript was proofread and checked by a number of students, including Joanna Wong, Nico Koning, Rong Ying Wu, and Jo Hsin Chen. The production of this book was professionally done by University Science Books, in particular Jane Ellis and Mark Ong who handled the manuscript and the graphics respectively. I thank Bruce Armbruster for his patience and continuous support. Especially, I want to thank my wife Emily who tolerated my long working hours and frequent trips away from home. Without her understanding and support, this work would not have been possible. Finally, I would like to pay tribute to Gerhard Herzberg, whose contribution to interstellar chemistry has been a great inspiration to me and many others who work in Canada.

Sun Kwok
Hong Kong, March 2006

Contents

3 *Measurements of Radiation* 53

4 *Photoionization and Recombination* 77

5 *Line Radiation from Atoms and Ions* 103

16 *Interaction between Stars and the Interstellar Medium* 461

1

The Interstellar Medium

The existence of interstellar matter was first inferred by the absence of stars in certain dark patches of the Milky Way. The 1927 photographic atlas of the Milky Way by E. E. Barnard included many dark clouds silhouetted against the background starlight. Such dark patches are not due to a lack of stars in these regions but are the result of starlight being blocked from view by intervening interstellar dust absorption. Interstellar reddening, in which the colors of stars are modified as a result of selective extinction of starlight by dust in the interstellar medium (ISM), provides further proof for the presence of interstellar matter.

Interstellar matter can also be directly observed. The catalogue of nebulous objects compiled by Messier in 1784 contained two kinds of nebulae: those that are made up of stars (e.g., the Andromeda nebula), which we now call galaxies or star clusters; and gaseous objects (such as the Orion nebula), which are objects in the ISM. Gaseous nebulae can be just regions of higher matter concentration in the ISM (e.g., H II regions), or represent material recently ejected from stars (e.g., planetary nebulae and supernova remnants).

How do we define interstellar matter? Stars are gaseous objects bound together by gravitational self-attraction (Section 15.2). So at the fundamental level, stars are not different from interstellar gaseous nebulae. However, the gravitational forces inside stars are sufficiently strong that stars take on well-defined spherical shapes. The concentration of high densities also provides sufficient opacity for stars to be seen to have an apparent surface (the photosphere) that allows them to be viewed as distinct entities. Most importantly, stars are self-luminous with energies generated by thermonuclear reactions in the interior.

Interstellar clouds, to different degrees, also self-radiate, although not necessarily at visible wavelengths. Clouds that are self-gravitating can take on well-defined shapes, but others can be diffuse in appearance and often do not have well-defined structures. Their low densities also imply that they are usually transparent (optically thin, Section 2.6) at some spectral regions, unlike stars, which are opaque at all wavelengths.

Most stars (including the Sun) have stellar winds (Chapter 15) that eventually merge with the ISM, which, to a certain extent, is an extension of the stellar atmosphere. This connection is more obvious for planetary nebulae, nova shells, Wolf–Rayet star nebulae, and supernova remnants. Therefore, we should not view interstellar matter in isolation, but instead it should be studied in the context of a system in which stars play a crucial role.

What is the origin of interstellar matter? While galaxies contained a significant amount of gaseous material when they formed, most of the primordial gas has been used up to form stars. The material in the present ISM has mostly been replenished from stellar ejecta such as stellar winds or supernovae. The ISM therefore can be considered as the result of mixing of ejecta from different generations of stars, and the shaping and processing by subsequent radiative and mechanical events.

1.1 States of Matter in the ISM

Because of high temperatures, matter inside stars is primarily in an ionized state, where atoms have lost one or more of their electrons. The ISM, on the other hand, has a wide variety of temperature conditions, and almost all states of matter (ionized, neutral atomic, molecular, and solid state, with the exception of liquid) are present. Since optical astronomy was the first observational technique to be developed, highly excited atomic and ionic lines originating from high ($\sim 10^4$ K) temperature environments were the first to be detected (Chapter 5). After the ionized component, the molecular state was the next to be discovered as the result of molecular electronic transitions observed in absorption against background stars (Section 7.6). The effect of stellar reddening (Section 10.1) and the existence of dark clouds also suggested the presence of absorbing material in a solid form in the ISM. The development of radio astronomy in the 1950s led to the detection of the $\lambda = 21$ cm hyperfine transition of the hydrogen atom (Section 5.4.1) and demonstrated the wide distribution of atomic hydrogen in the Galaxy. In the late 1960s, radio receivers of higher frequencies became available and the rotational lines of molecules were detected at millimeter wavelengths (Section 7.4). Vibrational transitions of molecules occur generally in the near infrared, and vibrational bands of simple molecules were widely observed by 1980 (Section 7.5). The advent of infrared detection technology also led to the discovery of continuous emission from solid-state substances (dust grains) in the ISM (Section 10.3). The detection of neutral heavy atoms in low temperature environments is more difficult because the low-lying energy states that are likely to be excited have small energy separations and the transitions lie in the far infrared or submillimeter (submm) parts of the electromagnetic spectrum. Demanding technologies, combined with an opaque Earth atmosphere in this spectral region, are the reasons why the neutral state of many common atomic species (e.g., carbon and oxygen) were detected only after the deployment of infrared telescopes in high-flying aircraft (Section 5.3).

The opening of all spectral observing windows by the placing of telescopes in Earth-orbiting spacecraft has allowed a comprehensive study of the ISM. Most electronic transitions of atoms and ions occur in the ultraviolet and can now be observed by ultraviolet telescopes (Section 5.1). The diffuse interstellar clouds excited to high temperature by high-velocity shocks have been detected as a result of their continuous emission in the X-ray region (Chapter 16). The greenhouse gas molecules (e.g., H_2O, CO_2, CH_4), which are responsible for the opacity of the Earth's atmosphere and therefore impossible to observe from ground-based observatories, have been detected by space-based far-infrared and submm telescopes. As the sensitivities of detecting instruments continue to improve and the spectral coverage continues to widen, large complex molecules (many of them organic) have been discovered by infrared and millimeter observations. The chemical reactions that lead to the formation of such large molecules will provide invaluable clues to the question of the origin of life.

The studies of the atomic, molecular, and solid-state components of the ISM also serve as useful probes to the physical conditions of the ISM, giving us measurements of the density, temperature, and kinematics of interstellar clouds. Some of the molecular and solid-state materials are preserved in primitive solar system objects such as meteorites and comets. Although most of our knowledge of the ISM is gained through remote observations, the possibility of physically examining meteorites or interplanetary dust in a laboratory provides an alternate avenue for studying the content of interstellar matter (Section 13.5).

At the beginning of the twenty-first century, we are witnessing the golden age of interstellar medium research. In this book, we will cover all the constituents of the ISM, discuss how they can be excited under interstellar conditions, and with what physical mechanisms they can radiate and be observed with ground-based or space-based telescopes.

1.2 Interactions between Stars and the ISM

Stars, with thermonuclear burning in their interiors, are the energy source of almost all the phenomena observed in the interstellar medium. The only other minor contributor is the cosmic background radiation. Stellar energy is transferred to the ISM in two ways: radiatively and mechanically. Diluted starlight intercepted by interstellar gas and dust is responsible for the excitation of interstellar matter above the minimum excitation provided by the cosmic background 2.7-K radiation. In addition to photons, stars also eject matter in the form of stellar winds (Sections 15.6 and 15.7), and occasionally by violent events such as supernova explosions (Section 16.2). Although neutrinos are also produced by stars, they are believed to pass through the ISM without much effect because of the small cross section of neutrino–baryon/lepton interaction.

Besides energy exchange, another effect of stellar influence on the ISM is chemical enrichment. All the heavy elements and much of the helium present in the Universe today were produced by stellar nucleosynthesis. These heavy elements are deposited in the ISM by stellar winds and supernovae, thereby gradually enriching the metal content of the Galaxy.

Our current understanding of single star evolution and nucleosynthesis is summarized in Table 1.1. The different stages of nuclear burning that can occur in a star are primarily a function of its initial mass. Whether a star can go through to another phase of nuclear burning is dependent on the end product from the previous phase. Mass loss on the surface can deplete the envelope, and therefore limit the mass of the end product, terminating the evolution. The products of nuclear burning in the core are

Table 1.1
The evolution of single stars and the enrichment of the ISM

Mass range	Nuclear processes	End product	ISM enrichment
$M \leq 0.08\ \mathrm{M}_\odot$	no H ignition	brown dwarfs	—
$0.08 < M/\mathrm{M}_\odot < 0.5$	H core burning no He ignition	He white dwarfs	—
$0.5 < M/\mathrm{M}_\odot < 2.2$	ignite He degenerately in the core	C–O white dwarfs	He, ^{14}N, *s*-process elements
$2.2 < M/\mathrm{M}_\odot < \sim 8$	ignite He nondegenerately	C–O white dwarfs	He, C, ^{13}C, ^{17}O, *s*-process elements
$8 < M/\mathrm{M}_\odot < \sim 10$–$12$	ignite C nondegenerately	neutron stars	He
10–$12 < M/\mathrm{M}_\odot < \sim 40$	supernovae before H depletion in the envelope	neutron stars or black holes	O, Ne, Mg, Si, S, Ar, Ca, *r*-process elements
$40 < M/\mathrm{M}_\odot < \sim 100$	supernovae after WR phase	neutron stars or black holes	O, Ne, Mg, Si, S, Ar, Ca, *r*-process elements
$M > 100\ \mathrm{M}_\odot$	O burning after He exhaustion	none	^{16}O

brought to the surface through convective processes. These elements are then returned to the ISM through stellar winds or explosive events.

Because of the initial mass function, stars in the 3rd and 4th rows of Table 1.1 represent 95% of the evolved stars in the Milky Way Galaxy and are therefore mainly responsible for the enrichment of the ISM. The nuclear-processed materials are ejected in the form of a stellar wind during the asymptotic giant branch (AGB) (Section 15.7). Theoretically, C could be ignited degenerately in the core, but AGB mass loss invariably depletes the H envelope before the core grows to the Chandrasekhar limit, so this never occurs, at least not in the Milky Way at present epoch. Carbon ignition under degenerate conditions may occur in an earlier generation of metal-poor stars when mass loss was less efficient.

For massive stars (stars in rows 5–7 of Table 1.1), a series of elements can be ignited after C, leading to the formation of an iron (Fe) core. In addition to the supernova explosion in the end, these stars also enrich the ISM through stellar winds during the main sequence (O, B supergiants) and Wolf–Rayet phases (Section 15.6). Therefore the present distribution of elemental abundance reflects the nucleosynthesis history of previous generations of stars.

The chemical evolution of galaxies is the result of the star formation rate, the initial mass function, the yield of processed material returned to the ISM, and other physical processes such as galactic inflows and outflows. It should be emphasized that