Molecules in the Early Universe acted as natural temperature regulators, keeping the primordial gas cool and, in turn, allowing galaxies and stars to be born. Even now, a simple chemistry continues to control a wide variety of the exotic objects that populate our cosmos. What are the tools of the trade for the cosmic chemist? And what can they teach us about the Universe in which we live? These are the questions answered in this engaging and informative guide to *The Chemically Controlled Cosmos.*

In clear, non-technical terms, and without formal mathematics, we learn of the behaviours of molecules in a host of astronomical situations. We study the secretive formation of stars deep within interstellar clouds, the origin of our own Solar System, the cataclysmic deaths of many massive stars that explode as supernovae, and the hearts of active galactic nuclei, the most powerful objects in the Universe. We are given an accessible introduction to a wealth of astrophysics and a comprehension of how cosmic chemistry allows the investigation of many of the most exciting questions concerning astronomy today.

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The chemically controlled cosmos

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Astronomical molecules from the Big Bang to exploding stars

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Preface

> Still, the mind of man is reluctant to consider itself as the product of chance, or the passing result of destinies over which no god presides, least of all himself. A part of every life, even a life meriting little regard, is spent in searching out the reasons for its existence, its starting point, and its source. My own failure to discover those things has sometimes inclined me towards magical explanations, and has led me to seek in the frenzies of the occult for what common sense has not taught me. When all the involved calculations prove false, and the philosophers themselves have nothing more to tell us it is excusable to turn to the random twitter of birds, or toward the distant mechanism of the stars.
>
> M Yourcenar in *Memoirs of Hadrian*

All visible matter in the Universe has cooled to temperatures well below those at the Earth's surface at least once since the Big Bang. Just as the terrestrial atmosphere, at a temperature of about 300 degrees above absolute zero,[†] is almost entirely molecular, many of the astrophysical objects that have temperatures less than several thousands of kelvins contain large abundances of molecules. In fact, as we show in this volume, molecules have influenced the births and distributions of all stars and galaxies, often by serving as coolants but in other ways as well. Some of these 'normal' astronomical objects were the progenitors of or provided environments for the formation of more 'exotic' objects, including black holes. Molecules have, therefore, affected the birth rates and distributions of many kinds of entities, and on the large scale the cosmos is chemically controlled.

Chemistry also plays a significant role in the evolution of individual astrophysical sources. For instance, temperatures in the envelopes of many old stars drop to several thousand kelvins inducing molecule formation which triggers the production of dust grains; these grains transmit the

[†] Throughout this book temperatures will be measured on a scale on which the temperature is zero when all matter is in its lowest possible energy state. A change of 1 degree on this scale corresponds to 1 degree Celsius, but the zero point of this scale corresponds to about −273 degrees Celsius (sometimes called absolute zero of temperature). Degrees on this scale are here called 'kelvins'.

pressure of the stellar light which they absorb to the gaseous envelopes, powering strong winds which remove stellar mass, so that a vital active star is converted into a feeble dwarf. Many of the astrophysical sources which together comprise much of the contents of the cosmos are also chemically controlled.

The existence of molecules in these astronomical objects provides astrophysicists with considerable information about them. Each molecule absorbs and emits radiation at wavelengths that are characteristic of its species, but differences in physical conditions, including the temperature and the strength of the local background radiation field, alter the relative prominence of the different spectral features formed by such species. Thus, the response of the molecules to the physical conditions affects the observed radiations from many astronomical sources in ways that permit the diagnosis of conditions in those objects. Because the relative abundances of different chemical species are also sensitive to the local physical conditions (which as we have stated above are often controlled by the chemistry) observational determinations of the relative abundances together with theoretical understanding of the most important chemical reaction networks also probe the physical natures of the objects.

Hence, the chemistry controls the evolution of astronomical objects, *and* is a diagnostic of conditions in them. Furthermore, it is often interesting in its own right. Astrochemistry produces species that sometimes have never been manufactured in detectable quantities in terrestrial laboratories, and such species are recognized as components of astronomical gases because the detected spectra are compared to the results of theoretical studies of molecular structure and radiative processes. Many scientists are interested in the mechanisms by which these unfamiliar compounds come into existence simply because those mechanisms are fundamental and challenging to understand. The field of molecular astrophysics informs and is informed by the theoretical and laboratory work of a large number of molecular physicists and chemists. Many of the earliest investigations in molecular astrophysics were carried out by scientists whose first goal was to understand how astronomical molecules come to be so abundant. Only later were their control of their physical environments and their diagnostic utility more fully realized.

Our primary aim in writing this volume has been to provide those who are not professional astronomers with a concise introduction to how chemistry controls the properties and evolution of the astronomical environments in which it takes place. This book concerns the roles of microscopic processes in determining the remarkable variety of large scale structures and activity in the cosmos. Another goal has been to show how molecular emissions are used to study the objects in which they originate.

The first chapter of the book gives a brief account of the history of the field of molecular astrophysics, of its growth in the 1960s and 1970s and of its maturation in the 1980s, as well as of instrumental developments which will occur in the 1990s and maintain the subject's vitality into the next millennium.

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Before approaching molecular astrophysics, we must become familiar with some simple basic ideas of molecular science and of astronomy. We have attempted to make this book self-contained and therefore we have included a chapter (2) covering the timescales, distances, densities, and temperatures associated with different types of astronomical objects, and also a chapter (3) dealing with basic molecular structure and chemical processes. Readers who are already familiar with these concepts may wish to skip Chapters 2 and 3. To those who must read Chapters 2 and 3 to acquire a few 'technical tools' to use while studying the more exciting material of later chapters, we offer our encouragement. We hope that they will find Chapters 2 and 3 straightforward and of rewarding utility later.

Chapters 4–11 constitute the kernel of the book. The treatment of molecules in astrophysical sources is arranged, with one exception, in roughly the sequence in which the different types of sources came into existence. Hence, we have started with the molecules present even before galaxies formed and have considered the ways in which they affected the births of galaxies and of the globular clusters. Clouds of gas form in the galaxies, stars are born in those clouds, and planetary systems arise as some of the stars form. Once a star has begun to shine it loses mass in outflows which tend to be strongest when a star is young and again when it has exhausted most of its primary nuclear fuel. Some of the material left behind after star formation and some stellar outflows contain masers, which are longer wavelength relatives of lasers, and the most violent of stellar outflows are supernovae. Chapters 4–10 tell of how chemistry has controlled the properties and dynamics of astronomical sources from the pregalactic medium to the most energetic stellar events, and how molecular radiation is important in their diagnosis.

The single break from the roughly evolutionary sequential ordering occurs near the end of the book where Chapter 11 concerns active galaxies (which include quasars, Seyferts, and starburst galaxies). Such galaxies might be treated immediately after galaxy and globular cluster formation have been considered. One ground for the break in the 'evolutionary' ordering is that it seems natural to try to understand how chemistry affects interstellar clouds in our own Galaxy before attempting the diagnosis of the active galaxies through studies of their molecular emissions. Also, in contrast to Chapters 4–9 in which many of chemistry's controlling roles are highlighted, Chapter 11 concerns exclusively the passive, though interesting, diagnostic function of chemistry. Chapter 10 is the only other chapter that is so heavily balanced towards chemistry's passive properties, and the juxtaposition of the two chapters seemed to us to be natural.

Though we have treated some problems of Solar System chemistry, we have mostly restricted ourselves to questions relevant to the formation and evolution of the Solar System when a gaseous, dusty disk still extended from near the Sun to beyond the most distant planet. We have not mentioned planetary atmospheres or surfaces except obliquely when we addressed the questions of how chemistry in the proto-Solar Nebula affected the Earth's water content and whether chemistry in protoplanets resulted in comets having the ice contents that measurements show them to possess. Further exposition on planetary atmospheres has been excluded because while attempting to present molecular astrophysics as a coherent field we wished for novelty and timeliness and because of a qualitative difference between the chemistries of most of the astrophysical environments that we have treated and those of planetary atmospheres. We have tried, as far as possible in the production of a self-contained book, to write about subjects that have never before been treated extensively at a popular level; the structures and evolutions of planetary atmospheres are subjects of chapters in many texts for nonscientists. We have tried to restrict ourselves primarily to situations in which most chemical reactions of importance arise from the collision of two bodies (each of which may be an atom, a molecule, an ion, or an electron); in contrast many interesting processes in planetary atmospheres (e.g. the reactions which remove ionized species at most terrestrial altitudes and control the Earth's atmospheric electrical properties) are three-body reactions (i.e. they involve the simultaneous collision of three rather than two particles), a consequence of the relatively high densities of the atmospheres.

In the final chapter we have summarized the reasons why molecular astrophysics is about to enter a very exciting phase. Even though we have largely focused on what is known of astronomical objects and of the chemistries occurring in them, rather than on methods of research, we hope that readers will appreciate the commonality of the basic principles on which the models of the chemistries in the different environments are based. In practice one tries to explain a few observational data for a previously unobserved source with a limited model based on the realization that the data are somehow similar to those from some more familiar source. The model becomes more complicated as the passage of time leads to the collection of more data and more analysis. Then yet another type of source is observed and the similarities between data for it and the older data induce one to use the now well-articulated model in an attempt to understand the newest data. If readers succeed in seeing the commonality they will understand a great deal about the process of modern astrophysical research.

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