NUCLEOSYNTHESIS AND CHEMICAL EVOLUTION OF GALAXIES

Second Edition

The distribution of elements in the cosmos is the result of many processes, and it provides a powerful tool to study the Big Bang, the density of baryonic matter, nucleosynthesis and the formation and evolution of stars and galaxies. This textbook, by a pioneer of the field, provides a lucid and wide-ranging introduction to the interdisciplinary subject of galactic chemical evolution for advanced undergraduates and graduate students. It is also an authoritative overview for researchers and professional scientists.

In this textbook many exciting topics in astrophysics and cosmology are covered, from abundance measurements in astronomical sources, to light element production by cosmic rays and the effects of galactic processes on the evolution of the elements. Simple derivations for key results are provided, together with problems and helpful solution hints, enabling the student to develop an understanding of results from numerical models and real observations.

This new edition includes results from recent space missions, including WMAP and FUSE, new material on abundances from stellar populations, nebular analysis and meteoric isotopic anomalies, and abundance analysis of X-ray gas, and several extra problems at the end of chapters.

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Second Edition

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Bernard E. J. Pagel

Bernard Ephraim Julius Pagel was born in Berlin on 4 January 1930, but when his father was dismissed from his post as Jewish persecution increased, the family moved to Britain in 1933. From Merchant Taylors' School he won an open scholarship in Natural Sciences at Sidney Sussex College, Cambridge, graduating with First-class honours in Physics in 1950. His early research at Cambridge (Ph.D. 1955) centred on the solar atmosphere. Inspired by Willy Fowler, a future Nobel Prize winner who was visiting from California, he started a life-long interest in the abundances of the chemical elements.

In 1956 he moved to the Royal Greenwich Observatory at Herstmonceux Castle, Sussex. A search for more accurate estimates of chemical abundances led him to develop new analytic methods of analyzing the spectra of stars. By 1967, Sussex University had established an M.Sc. programme in astronomy, where Bernard lectured. During the early 1970s he began to develop the simple but elegant theoretical models to describe the chemical evolution of galaxies that have served as a foundation for the subject.

In 1975, using the new Anglo-Australian Telescope, Bernard started a long series of collaborations on the abundance analysis of H II regions in external galaxies, starting with the Magellanic Clouds. This led to the development of a method of estimating rough values for chemical abundances when observational data were sparse and only the strongest lines could be seen. Despite the method's acknowledged limitations, it had enormous influence as modern detectors allowed spectroscopic observation of faint galaxies. Variants of the method are still extensively used today. Further collaboration through observatories in the Canary Islands resulted in his fruitful influence on a generation of Spanish research students.

Retirement at 60 from his happy years at Herstmonceux was compulsory, so he moved in 1990 to a Chair at the Nordic Institute for Theoretical Astrophysics in Copenhagen. He became respected throughout Scandinavian astronomy, aided by his extraordinary facility for languages. A major programme was completed on the

determination of the primordial helium abundance, and he started new joint work on the chemical evolution of our own Galaxy. By the time he had 'retired' again in 1998, this time from Copenhagen back to Sussex, he had written the first edition of *Nucleosynthesis and Chemical Evolution of Galaxies*, the revisions for the second edition of which he had virtually completed just before his death on 14 July 2007.

He could be a formidable, but always fair, critic, and gave freely of his time to those who asked for help and advice. The Pagel family household in Ringmer, Sussex, will be warmly remembered by many visiting astronomers. Bernard loved classical music – often playing the piano with great enthusiasm, if not with quite the accuracy of his abundance determinations! He will be remembered with great affection, particularly for the beady-eyed look over his pipe and a quick and brilliant intelligence which would even put one of his heroes, Sherlock Holmes, to shame.

To Annabel

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List of abbreviations

A & A	*Astronomy & Astrophysics*
ABB	after the Big Bang
AGB	asymptotic giant branch
AGN	active galactic nucleus
AMR	age–metallicity relation
amu	atomic mass unit
Ap. J.	*Astrophysical Journal*
AQ	Astrophysical Quantities, by C. W. Allen
Astr. J.	*Astronomical Journal*
B^2FH	E. M. and G. R. Burbidge, Fowler and Hoyle
BABI	basaltic achondrite
BBNS	Big Bang nucleosynthesis
BCG	blue compact galaxy
BDM	baryonic dark matter
B.E.	binding energy
BSG	blue supergiant
CAI	calcium-aluminium-rich inclusion
CC1	carbonaceous chondrite type 1
CDM	cold dark matter
CERN	European Council for Nuclear Research (Geneva)
CM	centre of mass
CNO	carbon, nitrogen and oxygen
CO	CO molecule, or carbon and oxygen
CP	chemically peculiar
DDO	David Dunlap Observatory, Toronto, intermediate-band system
2DF	two-degree field
3DHO	three-dimensional harmonic oscillator
E-AGB	early AGB

ELS	Eggen, Lynden-Bell and Sandage
EW	equivalent width
FIP	first ionization potential
FUN	fractionation and unknown nuclear
FUSE	Far Ultraviolet Spectroscopic Explorer
GCE	Galactic chemical evolution
GCR	Galactic cosmic ray
GT	Gamow–Teller
GUT	grand unification theory
HB	horizontal branch
HR	Hertzsprung–Russell
HST	Hubble Space Telescope
IGM	intergalactic medium
IMF	initial mass function
IMS	intermediate-mass stars
IR	infrared
IRAS	Infra-Red Astronomy Satellite
ISM	interstellar medium
ISW	infinite square well
IUE	International Ultraviolet Explorer
KBH	Kulkarni, Blitz and Heiles
K.E.	kinetic energy
LBG	Lyman-break galaxy
LEP	Large Electron–Positron Collider
LINER	low-ionization nuclear emission line region
LMC	Large Magellanic Cloud
LTE	local thermodynamic equilibrium
MEMMU	Milne, Eddington, Minnaert, Menzel and Unsöld
MNRAS	*Monthly Notices of the Royal Astronomical Society*
MS	main sequence
MWB	microwave background radiation
NDM	non-baryonic dark matter
ORS	Oliver, Rowan-Robinson and Saunders
PDMF	present-day mass function
PN	planetary nebula
PP	Partridge and Peebles
QM	quantum mechanics
QSO	quasi-stellar object
RGB	red-giant branch
RSG	red supergiant

SBBN	standard Big Bang nucleosynthesis
SDSS	Sloan Digital Sky Survey
SFR	star formation rate
SGB	subgiant branch
SMC	Small Magellanic Cloud
SN	supernova
SN Ia	Type Ia supernova
SN II	Type II supernova
SNR	supernova remnant
snu	solar neutrino unit
SSP	single stellar population
SZ	Searle and Zinn
TAMS	terminal main sequence
TP-AGB	thermal pulse AGB
UBV	Johnson UBV broad-band system
UV	ultraviolet
WMAP	Wilkinson Microwave Anisotropy Probe
WIMPS	weakly interacting massive particles
WR	Wolf–Rayet
ZAHB	zero-age horizontal branch
ZAMS	zero-age main sequence

Preface to the first edition

This book is based on a lecture course given at Copenhagen University in the past few years to a mixed audience of advanced undergraduates, graduate students and some senior colleagues with backgrounds in either physics or astronomy. It is intended to cover a wide range of interconnected topics including thermonuclear reactions, cosmic abundances, primordial synthesis of elements in the Big Bang, stellar evolution and nucleosynthesis. There is also a (mainly analytical) treatment of factors governing the distribution of element abundances in stars, gas clouds and galaxies and related observational data are presented.

Some of the content of the course is a concise summary of fairly standard material concerning abundance determinations in stars, cold gas and ionized nebulae, cosmology, stellar evolution and nucleosynthesis that is available in much more detail elsewhere, notably in the books cited in the reading list or in review articles; here I have attempted to concentrate on giving up-to-date information, often in graphical form, and to give the simplest possible derivations of well-known results (e.g. exponential distribution of exposures in the main s-process). The section on Chemical Evolution of Galaxies deals with a rapidly growing subject in a more distinctive way, based on work in which I and some colleagues have been engaged over the years. The problem in this field is that uncertainties arising from problems in stellar and galactic evolution are compounded. Observational results are accumulating at a rapid rate and numerical models making a variety of often arbitrary assumptions are proliferating, leading to a jungle of more or less justifiable inferences that are often forgotten in the next instant paper. The analytical formalism on which I have been working on and off since my paper with the late B. E. Patchett in 1975, and to which very significant contributions have also been made by D. D. Clayton, M. G. Edmunds, F. G. A. Hartwick, R. B. Larson, D. Lynden-Bell, W. L. W. Sargent, L. Searle, B. M. Tinsley and others, is designed not only to keep the computations simple but also to introduce some order into the subject and provide the reader with an insight into what actually are the important factors

in chemical evolution models, whether analytical or numerical, and which are the major uncertainties.

The book should be considered basically as a textbook suitable for beginning graduate students with a background in either physics or astronomy, but it is hoped that parts of it will also be useful to professional scientists. For this purpose, I have tried to keep the text as expository as possible with a minimum of references, but added notes at the ends of some chapters to provide a guide to the literature.

I should like to take this opportunity to thank Donald Lynden-Bell for arousing my interest in this subject and for his continued encouragement and stimulation over the years; and likewise Michael Edmunds, whose collaboration in both observational and theoretical projects has been a source of pleasure as well as (one hopes) insight. Thanks are due to them, and also to Sven Åberg, Chris Pethick and the late Roger Tayler, for helpful comments on successive versions. Finally, I warmly thank Elisabeth Grothe for her willing and expert work on the diagrams.

Bernard Pagel

Preface to the second edition

Much has happened since the book first came out in 1997. Cosmology has been transformed by balloon and satellite studies of the microwave background and by studies of distant supernovae. Host galaxies of γ-ray burst sources have been identified and some of their properties revealed. Cosmological simulations have been very successful in accounting for the large-scale structure of the Universe, although they are still challenged by observed element:element ratios suggesting that the largest galaxies were formed rapidly a long time ago, limiting the time available for their formation by mergers. The coming of 10-metre class telescopes, supplementing the Hubble Space Telescope, has led to enormous advances in abundance determinations in stars of all kinds and in galaxies, notably at high redshifts. Some stellar atmospheres can now be modelled by *ab initio* hydrodynamical simulations which account for granulation and eliminate the need for ad hoc parameters describing 'macro-turbulence' and 'micro-turbulence', leading to increasingly sophisticated abundance determinations. Nevertheless, simple analytical treatments retain their usefulness because of the insight they provide into the essential ingredients of more elaborate numerical models, whether of stellar atmospheres or of galactic chemical evolution.

I thank Monica Grady, Chris Tout and Max Pettini for critically reading through the revised Chapters 3, 5 and 12 respectively, and Mike Edmunds for continued cooperation and enlightening discussions. I owe particular thanks to my wife Annabel Tuby Pagel for her loving care during difficult times.

Bernard Pagel