Galaxies are large systems of stars, some of which contain interstellar gas and dust. They also contain much invisible matter, which may be in the form of weakly interacting elementary particles. In this introductory textbook, the first chapter introduces the study of galaxies. This is followed by two chapters on observations of galaxies, including our own. There are three chapters on galactic structure: the manner in which motions of stars determine galactic shape, the determination of galactic masses, and the structure of disks in spirals. Galactic evolution, especially changes in chemical composition over time, is covered. The book concludes with a discussion of the origin of galaxies and their relation to more general questions in cosmology. The book includes mathematical presentation where this enables the discussion to be quantitative. This new edition, based on a book first published in 1978, has been brought completely up to date. Its semi-popular approach enables it to be read by any mathematically literate undergraduate, postgraduate or professional scientist.

Galaxies: structure and evolution

Galaxies: structure and evolution

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Preface

This book is in effect a second edition of the book *Galaxies: Structure and Evolution* published by Wykeham Publications in 1978. When copies of the original edition were exhausted, the publishers were unwilling to reprint it. I am grateful to Dr Simon Mitton of the Cambridge University Press for agreeing to take the book over and for encouraging me to undertake the necessary task of revising the text.

The problem of the structure and evolution of galaxies is central to astronomy. On the one hand a galaxy is composed of stars, whose individual properties are known at least in broad outline. However, the process of star formation, which is crucial to the evolution of galaxies, is not at all well understood. On the other hand galaxies and clusters are the main constituents in the Universe and their properties provide important information about the origin and evolution of the Universe. In addition both the origin and present structure of galaxies are influenced by the possibility that the major form of matter in the Universe is not luminous stars but invisible weakly interacting particles.

In this book I discuss in general terms what is known both about the present structure of galaxies and about their past life history. Most of the detailed discussion refers to our own Galaxy. Although the subject is treated precisely where that is possible it will be apparent that, while the main ideas appear to be well-established, there are very considerable detailed uncertainties. When the previous version was published, it was just being realised that not all elliptical galaxies were spheroidal and that there was hidden matter in galaxies which could make their total masses much larger than was previously believed. Since then there has been much work in trying to understand the origin of galaxies and their distribution in the Universe, with the hidden matter playing an important rôle.

In a book of this size on such a complex topic it is impossible to give credit for every advance in the subject or to mention all of those people from whom I have learnt and from who I have borrowed material. The books which I have found particularly useful are mentioned in the Suggestions for Further Reading on

page 204. My own interest in galaxies was greatly stimulated by discussions with Donald Lynden-Bell, Bernard Pagel and Martin Rees. I am grateful to Mrs Pauline Hinton for her careful typing of the manuscript.

I am happy once again to dedicate the book with respect and affection to Professor Jan H. Oort, who has made fundamental contributions to the study of galactic structure for more than sixty years. In particular 1992 sees the diamond jubilee of his first discussion of the Oort limit.

R. J. Tayler

February 1992

Note added in proof. Jan Oort died in November 1992. The book is now dedicated to his memory.

R. J. Tayler

Symbols

a, b	semi-major, -minor axis of ellipse
a, b	mass infall rate, dimensionless value
A, B	Oort's constants of galactic rotation
A	area of magnetic flux tube
B	magnitude of magnetic induction
$B_\perp$	transverse component of magnetic induction
$B_\nu(T)$	Planck function
d	distance of star from LSR, of closest approach of two stars
e	eccentricity of spheroid in galactic model
E, S0, S, SB, Irr, cD	types of galaxy
$E_{\rm cr}$	energy density of cosmic rays
$E_{\rm N}$	nuclear energy content of star
f	mass distribution function
$f(M)$	initial mass function
F	particle distribution function
$g_{\tilde{\omega}}$, g_z	components of galactic gravitational field
H_0	Hubble's constant
I, I_1–I_5	integrals of motion of star
j	electric current density
l	galactic longitude, mean free path
L	galactic luminosity, scale of magnetic field
$L_{\rm s}$	stellar luminosity
m	particle mass
M	mass, general or galactic
$M_{\rm HI}$	mass of neutral hydrogen
$M_{\rm P}$, $M_{\rm Sph}$	point mass, spheroidal mass in galactic model
$M_{\rm s}$	stellar mass
$M_{\rm V}$	visual magnitude

n	number density
OBAFGKMRNS	spectral types of stars
p	yield of heavy elements
P, $P_{\tilde{\omega}}$	period, general, epicyclic
$P_{\rm gas}$, $P_{\rm cr}$, $P_{\rm mag}$	gas, cosmic ray, magnetic pressure
$P_{\rm rad}$	radiated power radio source
q_0	deceleration parameter
r	spherical polar radius
r, R	radius, general
$r_{\rm s}$	stellar radius
R, R_0	scale factor in Universe, present value
R_0	distance to galactic centre
$R_{\rm Sch}$	Schwarzschild radius
S	mass of stars formed
t	time
$t_{\rm H}$	Hubble time
$t_{\rm ms}$	main sequence lifetime of star
T	temperature, total kinetic energy
$T_{\rm e}$, $T_{\rm s}$	effective, surface temperature of star
u, v, w	velocity components of star relative to Sun
$\overline{u}$, $\overline{v}$, $\overline{w}$	mean velocity components of stars
$u_\odot$,$v_\odot$,$w_\odot$	solar motion
v	velocity, general
$v_{\rm circ}$	velocity of galactic rotation
$v_{\rm esc}$	escape velocity
$v_{\rm gas}$	velocity of gas
$v_{\rm R}$, $v_{\rm T}$	radial and tangential velocities of star
$v_{\tilde{\omega}}$, v_ϕ, v_z	velocity in cylindrical polar coordinates
$v_{\phi 0}$	velocity of Local Standard of Rest
x, y, z	cartesian coordinates
x, y	dimensionless value of star formation rate and of mass in stars
z	redshift
Z, Z_1	fractional mass of heavy elements, present value
α	semi-major axis of spheroid in galactic model, mass fraction locked up in dead stars
η	electrical resistivity
$\varkappa$	epicyclic frequency
λ	fractional mass converted into heavy elements and ejected from stars, wavelength
Λ	half thickness galactic disk
μ	proper motion of star
μ, μ_1	gas fraction in galaxy, present value
υ	frequency
ξ, η	displacement of star from circular orbit

$\tilde{\omega}, \phi, z$	cylindrical polar coordinates
ρ	density
ρ_0	critical density to close Universe
$\rho_{\rm gal}$	smoothed out density of galactic matter
$\rho_{\rm gas}, \rho_{\rm cr}, \rho_{\rm stars}$	gas, cosmic ray, star densities
σ	mass of gas in unit area of galactic disk
Σ	mass of stars formed
$\tau_{\rm c}$	collision time
$\tau_{\rm D}$	decay time of magnetic field
Φ	gravitational potential
ω	angular velocity
ω, ω_0	angular velocity of galactic rotation, at Sun
$\omega_{\rm s}$	spiral frequency
Ω	total gravitational potential energy
Ω_0	ratio of density of Universe to critical density
$\mathscr{E}, \mathscr{E}_{\rm tot}$	energy of cosmic ray electron, total energy of system of electrons

Because of the large number of symbols required and of the desirability of conforming to standard usage, some symbols are used with more than one meaning. Which meaning is intended will be clear from the context.

Numerical values

Fundamental physical constants

a	radiation density constant	7.55×10^{-16} J m^3 K^{-4}
c	velocity of light	3.00×10^{8} m s^{-1}
e	charge on electron	1.60×10^{-19} C
G	gravitational constant	6.67×10^{-11} N m^2 kg^{-2}
h	Planck's constant	6.62×10^{-34} J s
k	Boltzmann's constant	1.38×10^{-23} J K^{-1}
m_e	mass of electron	9.11×10^{-31} kg
m_H	mass of hydrogen atom	1.67×10^{-27} kg
μ_0	permeability of free space	$4\pi \times 10^{-7}$ H m^{-1}

Astronomical quantities

$L_\odot$	luminosity of Sun	3.86×10^{26} W
$M_\odot$	mass of Sun	1.99×10^{30} kg

Approximate astronomical quantities

A	Oort's first constant	14 km s^{-1} kpc^{-1}
B	Oort's second constant	-12 km s^{-1} kpc^{-1}
H_0	Hubble's constant	50 km s^{-1} Mpc^{-1}
R_0	Distance to galactic centre	8.5 kpc
t_H	Hubble time	2.0×10^{10} yr
$v_{\phi 0}$	Circular velocity near Sun	220 km s^{-1}

Non SI Units

light year (unit of distance)	9.5×10^{15} m
parsec (unit of distance)	3.09×10^{16} m
year	3.16×10^{7} s