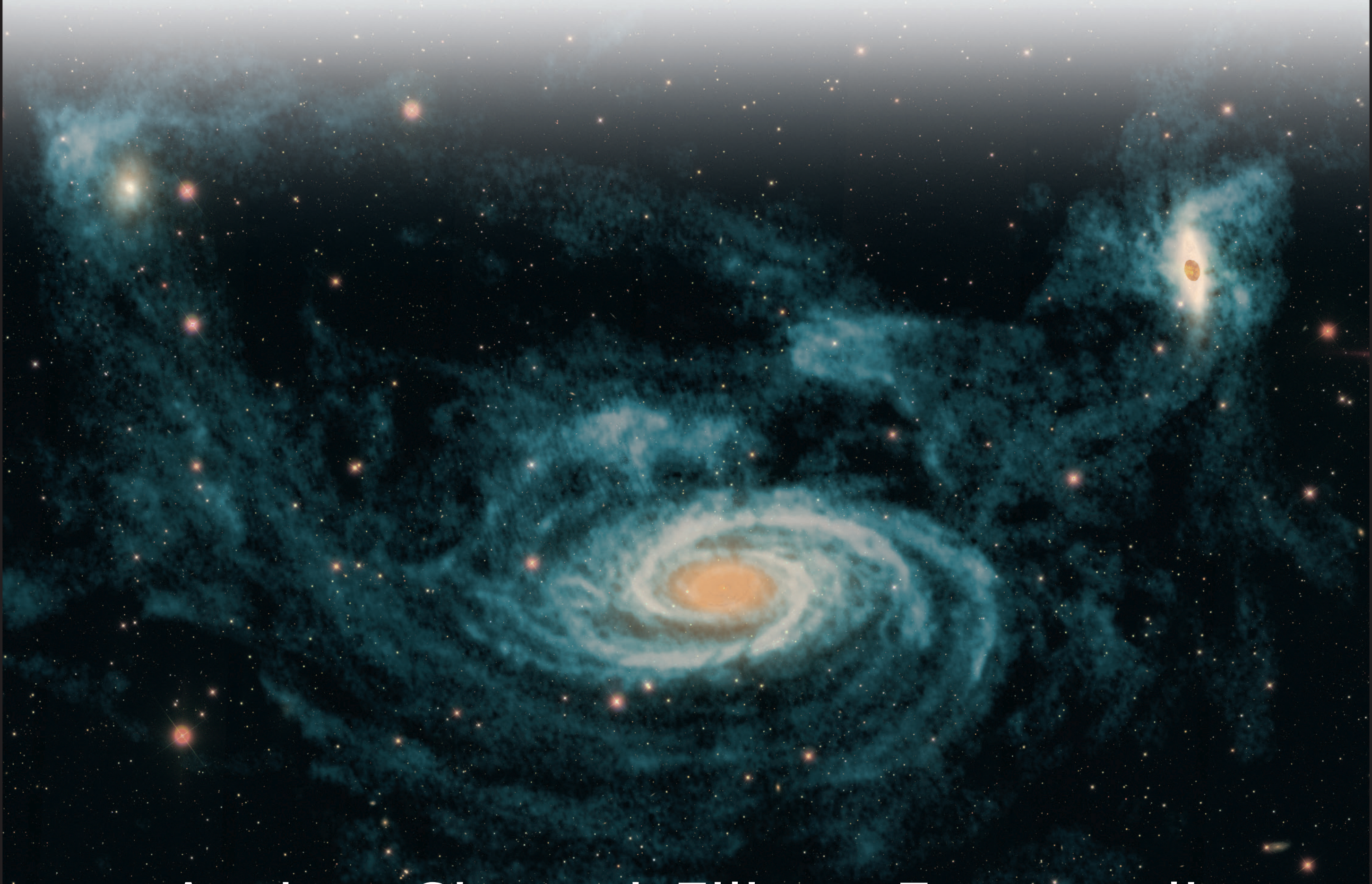
Introduction to

GALAXY FORMATION AND EVOLUTION

From Primordial Gas to Present-Day Galaxies



Andrea Cimatti, Filippo Fraternali
and Carlo Nipoti

Introduction to Galaxy Formation and Evolution

Present-day elliptical, spiral and irregular galaxies are large systems made of stars, gas and dark matter. Their properties result from a variety of physical processes that have occurred during the nearly 14 billion years since the Big Bang.

This comprehensive textbook, which bridges the gap between introductory and specialised texts, explains the key physical processes of galaxy formation, from the cosmological recombination of primordial gas to the evolution of the different galaxies that we observe in the Universe today.

In a logical sequence, it introduces cosmology, illustrates the properties of galaxies in the present-day Universe, then explains the physical processes behind galaxy formation in the cosmological context, taking into account the most recent developments in this field. This text ends on how to find distant galaxies with multi-wavelength observations, and how to extract the physical and evolutionary properties of galaxies based on imaging and spectroscopic data.

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Preface

Why This Book?

The study of galaxy formation and evolution is one of the most active and fertile fields of modern astrophysics. It also covers a wide range of topics intimately connected with cosmology and with the evolution of the Universe as a whole. The key to decipher galaxy formation and evolution is to understand the complex physical processes driving the evolution of ordinary matter during its gravitational interplay with dark matter halos across cosmic time. The central theme is therefore how galaxies formed and developed their current properties starting from a diffuse distribution of gas in the primordial Universe. This research field requires major efforts in the observation of galaxies over a wide range of distances, and in the theoretical modelling of their formation and evolution. The synergy between observations and theory is therefore essential to shed light on how galaxies formed and evolved. In the last decades, both observational and theoretical studies have undergone rapid developments. The availability of new telescopes operating from the ground and from space across the entire electromagnetic spectrum opened a new window on distant galaxies. At the same time, major observational campaigns, such as the Sloan Digital Sky Survey, provided huge samples of galaxies in the present-day Universe with unprecedented statistics and allowed one to define the 'zero-point' for evolutionary studies. In parallel, the theoretical models experienced a major advance thanks to the improved performance of numerical simulations of galaxy formation within the cosmological framework.

The idea for this book originated from the difficulties we faced when teaching our courses. We lacked a single and complete Master-level student textbook on how galaxies formed and evolved. This textbook aims to fill a gap between highly specialised and very introductory books on these topics, and enables students to easily find the required information in a single place, without having to consult many sources.

The aim of the book is twofold. The first is to provide an introductory, but complete, description of the key physical processes that are important in galaxy formation and evolution, from the primordial to the present-day Universe. The second is to illustrate what physical and evolutionary information can be derived using multi-wavelength observations. As the research field of galaxy formation and evolution is relatively young and rapidly evolving, we do not attempt to give a complete review of all topics, but rather we try to focus on only the most solid results.

Readership and Organisation

This textbook assumes a background in general physics at the Bachelor level, as well as in introductory astronomy, fundamentals of radiative processes in astrophysics, stellar evolution and the fundamentals of hydrodynamics. Although this book is primarily intended for students at Master degree level, it can be used as a complement to Bachelor-level courses in extragalactic astrophysics, and we think it can also be a valuable guide to PhD students and researchers.

The content of the chapters is organised as follows. After a general introduction to the field of galaxy formation and evolution (Chapter 1), the book starts with a brief overview on the cosmological framework in which galaxies are placed (Chapter 2). The aim of this chapter is to provide the reader with the key information useful for the rest of the textbook: the Big Bang model, the expansion of the Universe, redshift, the look-back time, the cosmological parameters and the matter–energy cosmic budget. Then, the book continues with a set of four chapters dedicated to the properties of present-day galaxies seen as the endpoint of the evolution that has occurred during the time frame spanned by the age of the Universe ($\approx$13.8 billion years). In particular, Chapter 3 illustrates the statistical properties of galaxies (e.g. morphologies, sizes, luminosities, masses, colours, spectra) and includes a description of active galactic nuclei. The structure, components and physical processes of star-forming and early-type galaxies are presented in Chapter 4 and Chapter 5, respectively. Chapter 4 includes also a description of our own Galaxy seen as a reference benchmark when studying the physics of star-forming galaxies from the 'inside' and with a level of detail not reachable in external galaxies. Chapter 6 deals with the influence of the environment on galaxy properties, and with the spatial distribution of galaxies on large scales. Then, Chapter 7 focuses on the general properties of dark matter halos, and their hierarchical assembly across cosmic time: these halos are crucial because they constitute the skeleton where galaxy formation takes place. Chapter 8 deals with the main 'ingredients' of galaxy formation theory through the description of the key physical processes determining the evolution of baryons within dark matter halos (e.g. gas cooling and heating, star formation, chemical evolution, feedback processes). The subsequent Chapter 9 is dedicated to the evolution of primordial baryonic matter in the early Universe, from the cosmological recombination to the formation of the first luminous objects a few hundred million years after the Big Bang, and the consequent epoch of reionisation. Chapter 10 provides a general description of the theoretical models of the formation and evolution of different types of galaxies, including an introduction to the main methods of numerical modelling of galaxy formation. Finally, Chapter 11 presents a general overview of galaxy evolution based on the direct observation of distant galaxies and their comparison with present-day galaxy types.

References

As of writing this book, there are tens of thousands of refereed papers in the literature on galaxy formation and galaxy evolution; not to mention several books on galaxies and cosmology available on the market. This implies that choosing the most significant references for a book like this is really challenging. The difficulty is exacerbated by the very fast evolution of this research field. For these reasons, our choice has been pragmatic and minimalistic. We excluded references before 1900, and we decided to reduce as much as possible the citations to research articles (including our own papers), unless they present a major discovery or a turning point for a given topic, or they are particularly useful for students. Instead, we much preferred to cite recent review articles because they provide an introductory and as much as possible unbiased source of information that is more suitable for students. However, also in this case, it was not feasible to cite all the reviews available in the literature. In the same spirit, the figures selected from the literature were chosen based on their clarity and usefulness to students. Finally, we also suggested a few books where readers can find more details on several topics treated in this textbook. The obvious consequence is that the reference list is unavoidably incomplete. We apologise to any author whose publications may have been overlooked with the selection approach that we adopted.

Acknowledgements
This book has benefited from the input of colleagues and students who have helped us in a variety of different and crucial ways. Many of the figures in this book have been produced *ad hoc* for us. We are grateful to the authors of these figures, to whom we give credit in the captions. Here we also wish to explicitly thank our colleagues who have taken the time to read parts of the text, and/or gave us comments and advice that were fundamental to improve the quality of the book. These are: Lucia Armillotta, Ivan Baldry, Matthias Bartelmann, James Binney, Fabrizio Bonoli, Fabio Bresolin, Volker Bromm, Marcella Brusa, Luca Ciotti, Peter Coles, Romeel Davé, Gabriella De Lucia, Mark Dickinson, Enrico Di Teodoro, Elena D'Onghia, Stefano Ettori, Benoit Famaey, Annette Ferguson, Daniele Galli, Roberto Gilli, Amina Helmi, Giuliano Iorio, Peter Johansson, Inga Kamp, Amanda Karakas, Rob Kennicutt, Dusan Kereš, Leon Koopmans, Mark Krumholz, Federico Lelli, Andrea Macciò, Mordecai Mac Low, Pavel Mancera Piña, Antonino Marasco, Claudia Maraston, Federico Marinacci, Davide Massari, Juan Carlos Muñoz-Mateos, Kyle Oman, Tom Oosterloo, Max Pettini, Gabriele Pezzulli, Anastasia Ponomareva, Lorenzo Posti, Mary Putman, Sofia Randich, Alvio Renzini, Donatella Romano, Alessandro Romeo, Renzo Sancisi, Joop Schaye, Ralph Schönrich, Mattia Sormani, Eline Tolstoy, Scott Tremaine, Tommaso Treu, Mark Voit, Marta Volonteri, Jabran Zahid, Gianni Zamorani and Manuela Zoccali.

Introduction 1

1.1 Galaxies: a Very Brief History

Galaxies are gravitationally bound systems made of stars, interstellar matter (gas and dust), stellar remnants (white dwarfs, neutron stars and black holes) and a large amount of dark matter. They are varied systems with a wide range of morphologies and properties. For instance, the characteristic sizes of their luminous components are from ~ 0.1 kpc to tens of kiloparsecs, whereas the optical luminosities and stellar masses are in the range 10^3–10^{12} in solar units. Roughly spherical halos of dark matter dominate the mass budget of galaxies. As a reference, the size of the stellar disc of our Galaxy[1] is about 20 kpc, whereas the dark matter halo is thought to be extended out to $\approx$300 kpc. The total mass of the Galaxy, including dark matter, is $\sim 10^{12}\ \mathcal{M}_\odot$, whereas the stellar and gas masses amount to only $\approx 5 \times 10^{10}\ \mathcal{M}_\odot$ and $\approx 6 \times 10^{9}\ \mathcal{M}_\odot$, respectively.

The discovery of galaxies (without knowing their nature) dates back to when the first telescope observations showed the presence of objects, originally called nebulae, whose light appeared diffuse and fuzzy. The first pioneering observations of these nebulae were done with telescopes by C. Huygens in the mid-seventeenth century, and by E. Halley and N.-L. de Lacaille in the first half of the eighteenth century. Interestingly, in 1750, T. Wright published a book in which he interpreted the Milky Way as a flat layer of stars and suggested that nebulae could be similar systems at large distances. The philosopher I. Kant was likely inspired by these ideas to the extent that, in 1755, he explained that these objects (e.g. the Andromeda galaxy) appear nebulous because of their large distances which make it impossible to discern their individual stars. In this context, the Milky Way was interpreted as one of these many stellar systems (island universes).

In 1771, C. Messier started to catalogue the objects which appeared fuzzy based on his telescope observations. These objects were identified by the letter M (for Messier) followed by a number. Now we know that some of these objects are located within our Galaxy (star clusters and emission nebulae; e.g. M 42 is the Orion nebula), but some are nearby galaxies bright enough to be visible with small telescopes (e.g. M 31 is the Andromeda galaxy). However, Messier did not express any opinion about the nature and the distance of these systems. Since late 1700, W. Herschel, C. Herschel and J. Herschel increased the sample of diffuse objects thanks to their larger telescopes, and classified them depending on their

[1] The terms Galaxy (with the capital G) or Milky Way are used to indicate the galaxy where the Sun, the authors and the readers of this book are located.

observed features. In 1850, W. Parsons (Lord Rosse) noticed that some of these nebulae exhibited a clear spiral structure (e.g. M 51).

Since late 1800, the advent of astronomical photography allowed more detailed observations to be performed, and these studies triggered a lively discussion about the nature of the spiral nebulae and their distance. This led to the so-called Great Debate, or the Shapley–Curtis debate referring to the names of the two astronomers who, in 1920, proposed two widely different explanations about spiral nebulae. On the one hand, H. Shapley argued that these objects were interstellar gas clouds located within one large stellar system. On the other hand, according to H. Curtis, spiral nebulae were external systems, and our Galaxy was one of them. Clearly, this debate involved not only the very nature of these objects, but also the size and the extent of the Universe itself. The issue was resolved soon after with deeper observations. In 1925, using the 100-inch telescope at Mount Wilson Observatory, E. Hubble identified individual stars in M 31 and M 33 and discovered variable stars such as Cepheids and novae. In particular, Cepheids are pulsating giant stars that can be exploited as distance indicators. These stars are what astronomers call 'standard candles', i.e. objects whose intrinsic luminosity is known *a priori*, and that therefore can be used to estimate their distance. In 1912, it was found by H. Leavitt that the intrinsic luminosity of Cepheids is proportional to the observed period of their flux variation. Thus, once the period is measured, the intrinsic luminosity is derived and, therefore, the distance can be estimated. Based on these results, Hubble demonstrated that spiral nebulae were at very large distances, well beyond the size of our Galaxy, and that therefore they were indeed external galaxies.

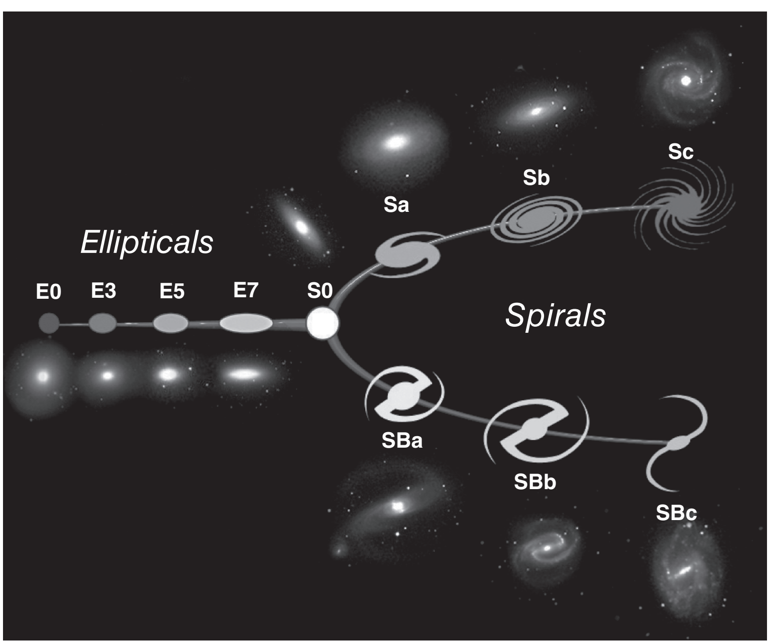
The term 'galaxy' originates from the Greek $\gamma\acute{\alpha}\lambda\alpha$, which means milk, and it refers to the fuzzy and 'milky' appearance of our own Milky Way when observed with the naked eye. Also external galaxies look 'milky' when observed with small telescopes. Discovering that galaxies were external systems also implied that the Universe was much larger than our Galaxy, and this was crucial to open a new window on cosmology in general. In modern astrophysics, the term 'nebula' is still used, but it refers only to objects within the interstellar medium of galaxies. Notable examples are the emission nebulae where the gas is photoionised by hot massive stars, dark nebulae which host cold and dense molecular gas mixed with interstellar dust, and planetary nebulae produced by the gas expelled by stars with low to intermediate mass during their late evolutionary phases. Since the discovery of Hubble, spiral nebulae have therefore been called spiral galaxies. In 1927–1929, based on galaxy samples for which radial velocities and distances were available, G. Lemaître and Hubble found that galaxies are systematically receding from us. In particular, their radial velocity is proportional to their distance: the farther away the galaxies, the higher the redshift of their spectral lines, and therefore the velocity at which they move away from us. This crucial discovery led to the Hubble–Lemaître law[2] which is the experimental proof that the Universe is expanding.

[2] In October 2018, the members of the International Astronomical Union (IAU) voted and recommended to rename the Hubble law as the Hubble–Lemaître law.

1.2 Galaxies as Astrophysical Laboratories

Present-day galaxies display a variety of properties and span a very broad range of luminosities, sizes and masses. At first sight, this already suggests that galaxy formation and evolution is not a simple process. However, the existence of tight scaling relations involving galaxy masses, sizes and characteristic velocities (e.g. the Tully–Fisher relation and the fundamental plane) indicates some regularities in the formation and assembly of these systems.

The first distinctive feature of a galaxy is its morphology. The shape of a galaxy as observed on the sky plane is a combination of the intrinsic three-dimensional (3D) structure and its orientation relative to the line of sight. Present-day galaxies show a broad range of shapes. Understanding the physical formation and evolution of the morphological types remains one of the most important, and still open, questions in extragalactic astrophysics. The first systematic study in the optical waveband dates back to 1926, when Hubble started a classification of galaxy morphologies following an approximate progression from simple to complex forms. In particular, Hubble proposed a tuning fork diagram on which the main galaxy types can be placed. Based on this classification, galaxies were divided into three main classes: ellipticals, lenticulars and spirals, plus a small fraction of irregulars. As shown in Fig. 1.1, the Hubble sequence starts from the left with the class of ellipticals (E). This class is further divided into subclasses as a function of their observed flattening.



The Hubble classification of galaxy morphology. © NASA and ESA, reproduced with permission.

Fig. 1.1

Perfectly round ellipticals are called E0, whereas the most flattened are the E7. If the observed shape of these galaxies is approximated by ellipses, their flattening is related to the ellipticity $\epsilon = (a - b)/a$, where a and b are the observed semi-major and semi-minor axes, respectively. The number written after the letter E is the integer closest to 10ϵ. Proceeding beyond the E7 class, galaxies start to display morphologies with a central dominant spheroidal structure (the so-called bulge) surrounded by a fainter disc without spiral arms. These systems are classified as lenticulars (S0) and represent a morphological transition from ellipticals to spirals. Proceeding further to the right, the tuning fork is bifurcated in two prongs populated by the two main classes of spiral (S) galaxies. In both prongs, spirals have the common characteristic of having a disc-like appearance with well defined spiral arms originating from the centre and extending throughout the outer regions. The top prong includes the so-called normal spirals characterised by a central bulge surrounded by a disc. These spirals are classified Sa, Sb and Sc as a function of decreasing prominence of the bulge (with respect to the disc) and increasing importance of the spiral arms. The bottom prong includes the barred spirals (SB) which show a central bar-like structure which connects the bulge with the regions where the spiral arms begin. Moving further to the right, i.e. beyond Sc types, all galaxies not falling into the previous classes are classified as irregulars (Irr).

Subsequent studies showed that ellipticals and lenticulars are red systems, made of old stars, with weak or absent star formation, high stellar masses, with a wide range of kinematic properties (from fast to absent rotation), and preferentially located in regions of the Universe where the density of galaxies is higher. On the other side of the tuning fork, spirals are bluer, have ongoing star formation, larger fractions of cold gas, stellar populations with a wide range of ages, kinematics dominated by rotation, and are found preferentially in regions with lower density of galaxies. Given the wide range of properties displayed by present-day galaxies, it is crucial to investigate the physical processes which led to their formation and evolution. The study of galaxies involves a wide range of galactic and sub-galactic scales ranging from hundreds of kiloparsecs down to sub-parsec level depending on the processes that are considered. In this respect, galaxies can be seen as 'laboratories' where a plethora of astrophysical processes can be investigated.

1.3 Galaxies in the Cosmological Context

Besides their role as astrophysical laboratories, galaxies can be placed in a broader context and exploited as point-like luminous 'particles' which trace the distribution of matter on scales much larger than the size of individual galaxies. This distribution, called large-scale structure, is the 3D spatial distribution of matter in the Universe on scales from tens of megaparsecs to gigaparsecs. Due to its characteristic shape, the large-scale structure is also called the cosmic web. The study of galaxies on these large scales has deep connections with cosmology, the branch of physics and astrophysics that studies the general properties, the matter–energy content and the evolution of the Universe as a whole. Modern cosmology rests on two major observational pillars. The first is the expansion of the Universe (Hubble–Lemaître law). The second is the nearly uniform radiation background observed in the microwaves, the cosmic microwave background (CMB), discovered in 1965 by A. Penzias and R. Wilson. The spectrum of the CMB is an almost perfect black body with a temperature $T \simeq 2.726$ K. The CMB radiation is interpreted as the thermal relic of the Big Bang that occurred about 13.8 Gyr ago when the Universe originated as a hot plasma with virtually infinite temperature and density. Although the detailed properties of the Big Bang itself are unknown, an expanding Universe can be described using the Einstein equations of general relativity together with the Friedmann–Lemaître–Robertson–Walker metric. The current view of the Universe relies on the Big Bang model and on the so-called ΛCDM cosmological framework. In this scenario, also known as standard cosmology, the Universe is homogeneous and isotropic on large scales, and it is made of ordinary matter (i.e. baryonic matter), neutrinos, photons and a mysterious component of cold dark matter (CDM). CDM is dominant with respect to ordinary matter as it amounts to about 84% of the whole matter present in the Universe. CDM is thought to be composed of non-relativistic massive particles that interact with each other and with ordinary matter only through the gravitational force. However, the nature and individual mass of these particles are currently unknown. For this reason, this is one of the main open questions of modern physics. In addition, a further component, called dark energy, is required to explain the current acceleration of the Universe expansion that S. Perlmutter, B. Schmidt and A. Riess discovered in 1998 exploiting distant supernovae as standard candles. In standard cosmology, the space-time geometry is flat (Euclidean), and dark energy is assumed to be a form of energy density (known as vacuum energy) which is constant in space and time. This form of dark energy is indicated by Λ and called the cosmological constant. However, other possibilities (e.g. a scalar field) are not excluded, and the nature of dark energy is currently unknown. This represents another big mystery of modern physics.

The ΛCDM model can be fully described by a small number of quantities called cosmological parameters which measure the relative fractions of the matter–energy components and constrain the geometry of the Universe. The ΛCDM model is now supported by a variety of cosmological probes such as the CMB, the Hubble expansion rate estimated from Type Ia supernovae, the properties of the large-scale structure and the mass of galaxy clusters. If the ΛCDM model is assumed, the observational results constrain the cosmological parameters with extremely high accuracy. In particular, in the present-day Universe, dark energy contributes $\approx$70% of the matter–energy budget of the Universe, whereas the contributions of dark matter and baryons amount to $\approx$25% and $\approx$5%, respectively, plus a negligible fraction of photons and neutrinos. The relative uncertainties on these fractions are very small (sub-per cent level). For this reason, modern cosmology is also called precision cosmology. However, it remains paradoxical that the nature of dark matter and dark energy, which together make 95% of the Universe, is still completely unknown despite the accuracy with which we know their relative importance.

Once the cosmological framework has been established, present-day galaxies can be seen as the endpoints that enclose crucial information on how baryonic and dark matter evolved as a function of cosmic time. In this regard, galaxies are also useful to test the ΛCDM cosmology. For instance, the current age of the oldest stars in galaxies should not be older than the age of the Universe itself, estimated to be about 13.8 Gyr based on observational cosmology. This key requirement is met by the age estimates of the Galactic globular clusters based on the Hertzsprung–Russell diagram.

1.4 Galaxies: from First Light to Present-Day Galaxies

Galaxies were originated from the primordial gas present in the early Universe. Fig. 1.2 shows a sketch of the main cosmic epochs that are treated in this textbook. Soon after the Big Bang, the baryonic matter was fully ionised and coupled with a 'bath' of black-body photons. In this photon–baryon fluid, the Universe was opaque because photons could not propagate freely due to the incessant Thomson scattering with free electrons. As the Universe expanded, its temperature and density gradually decreased and, about three minutes after the Big Bang, the nuclei of elements heavier than hydrogen (basically only helium and lithium) formed through a process called primordial nucleosynthesis. About 400 000 years after the Big Bang, the temperature and density dropped enough to allow lithium, helium and hydrogen to gradually recombine with electrons and form neutral atoms. This phase is called cosmological recombination. This is the epoch when the Universe became transparent because photons started to propagate freely thanks to the negligible role of Thomson scattering. The CMB radiation observed in the present-day Universe was originated in this phase and therefore represents the earliest possible image of the Universe. After recombination, the Universe was filled of dark matter and diffuse neutral gas composed of hydrogen, helium and lithium only. It is from the evolution of this primordial gas that the first luminous objects and galaxies began to form.

Understanding galaxy formation and evolution is a complex task because it involves several physical processes, their mutual interactions, and their evolution as a function of cosmic time. This is one of the most multi-disciplinary areas of astrophysics as it requires

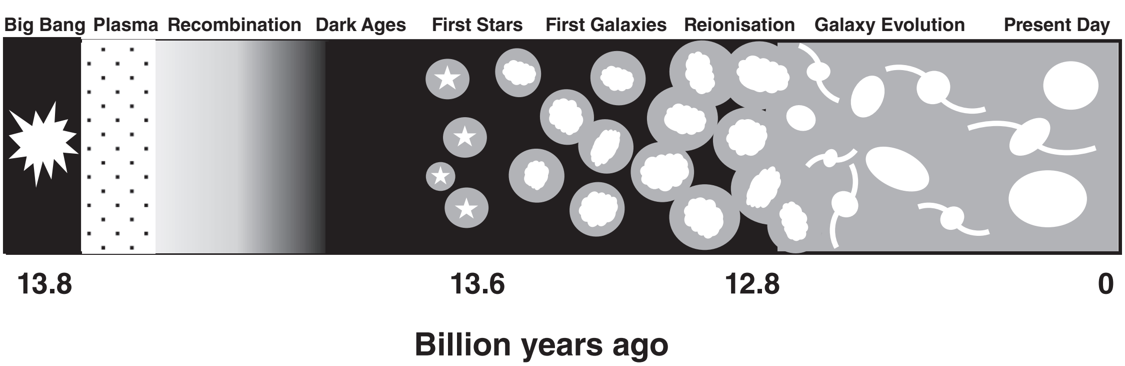


Fig. 1.2 A sketch of the main epochs which characterised the evolution of the Universe, starting from the Big Bang. After the formation of the first stars and galaxies, galaxies followed different evolutionary paths which led to the assembly of the galaxy types that we observe in the present-day Universe.

the cross-talk among a wide range of fields such as cosmology, particle physics (including dark matter) and the physics of baryonic matter. Galaxy formation and evolution is also a relatively young research field because galaxies were recognised as such only about a century ago, and their observation at cosmological distances became possibile only in the mid-1990s thanks to the advent of ground-based 8–10 m diameter telescopes in the optical and near-infrared spectral ranges, in synergy with the *Hubble Space Telescope* (*HST*).

The first step in the study of galaxy formation and evolution requires the definition of a cosmological framework (currently the ΛCDM model) within which galaxies form and evolve. The second step is to include the formation and evolution of dark matter halos which will host the first luminous objects and galaxies. In the ΛCDM model, dark matter halos are the results of the gravitational collapse of CDM in the locations where the matter density is high enough to locally prevail over the expansion of the Universe. As a matter of fact, the competition between the expansion of the Universe and gravity is one of the key processes in galaxy formation. On the one hand, if we take a large volume of the Universe at a given time, the mean matter density decreases with increasing cosmic time due to the expansion of the volume itself. On the other hand, the masses present in the same volume attract each other due to the reciprocal gravitational forces. In the early Universe, the typical masses of these halos were small, but they subsequently grew hierarchically with cosmic time through the merging with other halos and with the accretion of diffuse dark matter. Part of the gas is expected to follow the gravitational collapse of dark matter halos, and then to settle into their potential wells. The possibility to form a galaxy depends on whether this gas can have a rapid gravitational collapse. First of all, gravity must prevail over the internal pressure of the gaseous matter. However, this is not sufficient because the temperature rises as soon as the contraction proceeds. Gas heating is the enemy of galaxy formation because it increases the internal pressure and hampers gravitational collapse. This is why the second key requirement for galaxy formation is that gas cooling prevails over heating. Gas cooling can be produced by the emission of continuum radiation and spectral lines. The emitted photons abandon the gas cloud, carrying energy away, and therefore making the gas cooler and more prone to further gravitational collapse.

The cosmic epoch before the formation of the first collapsed objects (known as first stars or Population III stars) is named the dark ages because the Universe was made only of neutral gas, and luminous sources were completely absent (Fig. 1.2). We think that Population III stars began to form about 100 million years after the Big Bang from the collapse of pristine gas (H, He, Li) within dark matter halos with masses around $10^6\ \mathcal{M}_\odot$. At these early epochs, the main radiative coolants of the gas were primordial molecules such as LiH, HD and H_2 previously formed through gas-phase chemical reactions. This collapse led to the formation of protostellar objects and the subsequent ignition of the first thermonuclear reactions in the cores of Population III stars. When these systems started to shine, their strong ultraviolet radiation photoionised the surrounding gas. This was the beginning of the reionisation era. Population III stars ended their life very rapidly and vanished with the expulsion of most of their gas from their dark matter halos by violent supernova explosions. Thus, having lost most of the initial gas, these halos could not host further episodes of star formation. It is therefore thought that the formation of the first galaxies occurred later (a few hundred million years after the Big Bang) in larger dark matter halos with masses around $10^8\ \mathcal{M}_\odot$. These objects are called galaxies because they were massive enough to gravitationally retain a substantial fraction of the gas to prolong star formation without losing and/or heating it excessively due to supernova explosions.

After these early phases, galaxy formation proceeded following a wide range of evolutionary paths depending on the local conditions, the properties of the gas and the interactions with other systems (e.g. merging of their host halos). This is why the full understanding of galaxy formation and evolution is complex and requires a self-consistent treatment of the physical processes of baryonic matter (gas, stars and dust), their kinematics, their evolution within an expanding Universe, and the gravitational interactions with the dark matter component. The physics of baryonic matter is particularly complicated as it involves a variety of ingredients such as radiative processes, multi-phase gas physics and dynamics, gas cooling and heating, radiative transfer, star formation, stellar evolution, metal enrichment and feedback. Moreover, galaxy evolution involves the formation of supermassive black holes, the associated accretion of matter, and also the consequent feedback processes on the surrounding environment. A further complication is that all these processes and their evolution must be investigated on very wide ranges of spatial scales (from sub-parsec to megaparsec) and timescales, say from the lifetime of the most massive stars ($\sim 10^6$ yr) to the age of the Universe ($\sim 10^{10}$ yr). Fig. 1.3 illustrates the main ingredients that need to be included for the physical description of galaxy formation and evolution.

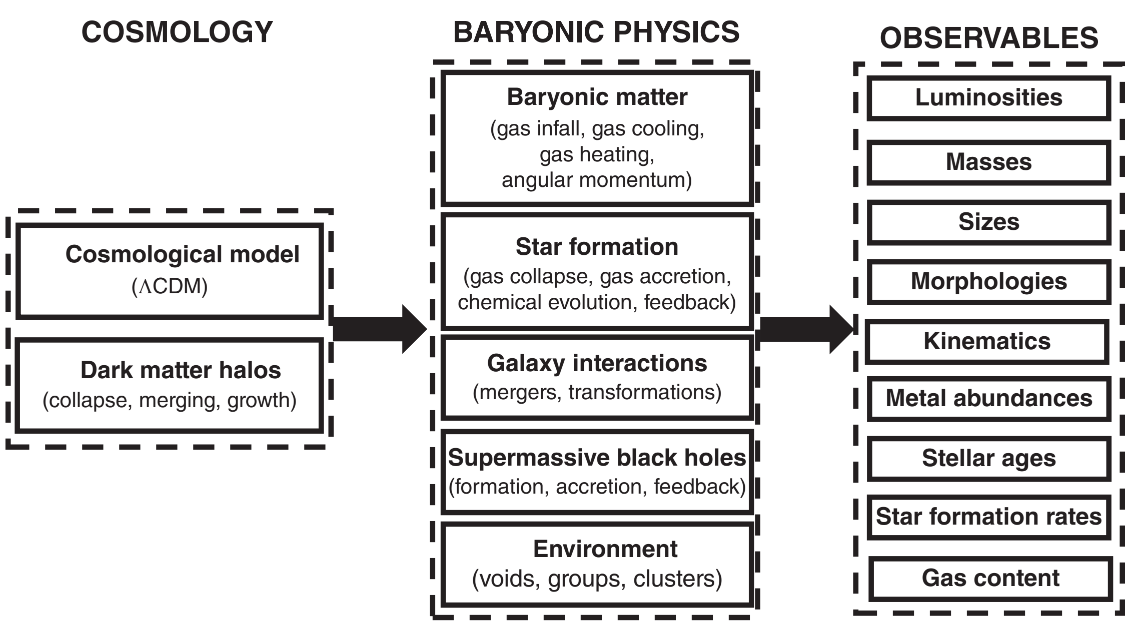


Fig. 1.3 The main ingredients of models of galaxy formation and evolution. *Left*. The cosmological model and the properties of dark matter halos define the 'skeleton' within which galaxies form and evolve. *Centre*. The main processes that drive the evolution of baryonic matter and galaxy formation. *Right*. The predicted properties of galaxies that are compared with the observations to verify the reliability of theoretical models.

1.5 Galaxies: Near and Far, Now and Then

Given the above complexity, how can we study galaxy formation and evolution? One approach is through theoretical models which describe coherently the physical processes involved in the formation of galaxies and their subsequent evolution from the smallest to the largest scales. In these models, the ΛCDM cosmology framework provides the initial conditions (e.g. the dark and baryonic matter fractions, the expansion rate of the Universe as a function of time, the properties of CDM halos and the hierarchical evolution of their masses). Once the cosmological framework is defined, galaxies can be modelled with two main methodologies. The first is based on cosmological hydrodynamic simulations, which follow as much as possible self-consistently the evolution of gas, star formation and feedback processes within dark matter halos. These simulations are very time consuming. This implies that sub-galactic scales can be simulated at the price of not covering large volumes of the Universe due to the limited computational resources. The second approach, called semi-analytic, consists in treating the physics of baryonic matter with a set of analytic prescriptions that, combined with the theoretically predicted evolution of dark matter halos, are tuned to reproduce the observed properties of present-day galaxies. The semi-analytic approach is cheaper from the computational point of view and therefore allows one to simulate large volumes of the Universe up to gigaparsec scales. However, the price to pay is that only the global properties of galaxies can be studied, and limited spatially resolved information is available. For these reasons, the two methods are complementary to each other. A further possibility is to perform analytic/numerical modelling of specific processes which take place within galaxies. An example is given by the chemical evolution models applied to the Milky Way.

The other approach to study galaxy formation and evolution is complementary to the theoretical modelling, and consists in the direct observation of galaxies in order to obtain data (images and spectra) from which the physical and structural properties can be extracted. A first possibility is the so-called archaeological approach where present-day galaxies are exploited as 'fossils'[3] from which it is possible to reconstruct their past history based on what is observed today. For instance, the ages and metal abundances of the stellar populations present in a galaxy allow us to infer how star formation and the enrichment of heavy elements evolved as a function of cosmic time. With this approach, the most reliable results are obtained when the stars within a galaxy can be observed individually and therefore can be placed on the Hertzsprung–Russell diagram. Unfortunately, with the current telescopes, this can be done only within the Milky Way and for galaxies in the Local Group, a $\approx$1 Mpc size region where the Galaxy is located together with its neighbours. The study of our Galaxy is so important as a benchmark of galaxy evolution studies that the *Gaia* space mission has been designed to obtain distances and proper motions of more than a billion stars, with radial velocity measurements for a fraction of them. *Gaia* allowed us to derive a kinematic map of our Galaxy that is essential to investigate its formation and

[3] As present-day galaxies are considered 'fossils', the archaeological approach should be more appropriately called 'palaeontological'.

evolution. Beyond the Local Group, galaxies become rapidly too faint and their angular sizes are too small to observe their stars individually. In these cases, one has to rely on the 'average' information that can be extracted from the so-called integrated light, i.e. the sum of the radiation emitted by the entire galaxy (or by a region of it).

Besides the archaeological studies in the present-day Universe, galaxy formation and evolution can also be investigated with the so-called look-back approach. This consists in the observation of galaxies at cosmological distances. Since light travels at a finite speed, the photons emitted from more distant galaxies reach us after a longer time interval. This means that distant galaxies appear today to us as they were in the past. Thus, it is possible to observe directly the evolution of galaxy properties if we observe galaxies at increasing distances. The fundamental assumption that makes the look-back time approach possible is that the Universe is homogeneous on large scales, so the global properties of the galaxy population on sufficiently large volumes are independent of the position in the Universe. This implies that galaxies in the local volume, in which our Galaxy is located, are representative of the general population of present-day galaxies. Similarly the galaxies observed in a distant volume are assumed to be representative of the past population of galaxies. For instance, if we want to investigate the evolution of spiral galaxies, we need to observe samples of this type of galaxies at increasing distances (i.e. larger look-back times) and to study how their properties (e.g. size, rotation velocity, mass, star formation) change with cosmic time. With this approach, it is truly possible to trace the detailed evolution of galaxies billions of years ago.

The archaeological and look-back approaches are complementary to each other, and their results are essential to build theoretical models and verify their predictions. However, in both cases multi-wavelength data are needed to provide a complete view of galaxy properties and their evolution. The reason is that galaxies are multi-component systems which emit radiation in different regions of the electromagnetic spectrum through diverse processes. For instance, due to the typical temperatures of the stellar photospheres, the starlight is concentrated from the ultraviolet to the near-infrared. Instead, the study of the interstellar molecular gas and dust requires observations from the far-infrared to the millimetre, the atomic hydrogen must be investigated in the radio, and the hot gas and the supermassive black hole activity in the ultraviolet and X-rays. The multi-wavelength approach is limited by the terrestrial atmosphere which is opaque and/or too bright in several spectral ranges. Ground-based telescopes can observe only in the optical, near-infrared and in a few transparent windows of the submillimetre, millimetre and radio. The other spectral ranges are accessible with space-based telescopes. The major advance in multi-wavelength studies of galaxy evolution at cosmological distances became possible thanks to the concurrence of ground- and space-based telescopes which, for the first time, allowed the identification of galaxies at cosmological distances. In the realm of space telescopes, the main contributions to galaxy evolution studies have come from the *Chandra X-ray Observatory*, *XMM-Newton* (X-rays), *Galaxy Evolution Explorer* (*GALEX*; ultraviolet), *HST* (optical/near-infrared), *Spitzer* (mid-infrared) and *Herschel* (far-infrared). In ground-based observations, the look-back approach became a reality with the advent of the 8–10 m diameter Keck telescopes and the Very Large Telescope (VLT) operating since the mid-1990s in the optical and near-infrared, followed by other facilities of comparable size (Gemini, Subaru, Gran Telescopio Canarias and the South African Large Telescope). The James Clerk Maxwell Telescope (JCMT), the telescopes of the Institut de Radioastronomie Millimétrique (IRAM) (such as the NOrthern Extended Millimeter Array; NOEMA), the Atacama Large Millimetre Array (ALMA) and the Karl G. Jansky Very Large Array (VLA) were essential in opening new windows on galaxy evolution at submillimetre, millimetre and radio wavelengths.

The multi-wavelength data provided by these facilities allow us to study galaxy evolution. Imaging observations are crucial to study the morphology and structure of galaxies and their relations with their physical properties. Spectroscopy provides information on the stellar populations, interstellar matter and the presence of supermassive black holes through the analysis of continuum spectra and spectral lines. Furthermore, the Doppler effect allows us to derive the galaxy kinematic properties, to measure dynamical masses and to study scaling relations. Last but not least, the collection of large galaxy samples over wide sky areas allows us to use galaxies as luminous markers to trace the spatial distribution of the underlying dark matter and to exploit them as cosmological probes.

1.6 Galaxies: the Emerging Picture and the Road Ahead

What is the picture emerging from the synergy of observations and theory? Most studies seem to converge on a scenario in which the evolution of galaxies is driven across cosmic times by the so-called baryon cycle. Galaxies are thought to accrete gas from the surrounding environment and gradually convert it into stars. The cooling and condensation of neutral hydrogen, and its conversion into molecular hydrogen to fuel star formation, are therefore key processes driving galaxy evolution. In this picture, galaxies grow mainly through gas accretion from the intergalactic medium, while there is a complex equilibrium between gas inflow, the conversion of the available gas reservoir into stars, and gas ejection and heating by feedback processes. In parallel, supermassive black holes form at the centres of galaxies, and trigger the temporary phase of an active galactic nucleus (AGN) whenever the accretion of cold material is efficient enough. Part of the stellar mass is lost by stars during their evolution through winds, planetary nebulae, novae and supernovae. This ejected mass seeds the interstellar medium with metals, molecules and dust grains, while starburst winds and jets from AGNs provide feedback and launch gas outflows. Metal-enriched and pristine halo gas eventually cools and accretes onto the disc to form new stars and feed the central black hole, starting the cycle again. A complex interplay is therefore expected among these processes as a function of galaxy properties, environment and cosmic time. Hence, understanding the evolution of the baryon cycle has become a key question that must be addressed to shed light on the critical steps of galaxy formation and evolution.

Despite the major progress in this research field, the overall picture is still largely incomplete, and several key questions are still open. However, new facilities operating in space such as the *James Webb Space Telescope* (*JWST*), *Euclid*, the *Wide Field Infrared*

Survey Telescope (*WFIRST*) in the optical/infrared, and the *Athena X-ray Observatory* in the X-rays have been designed to open new windows through the identification and multi-wavelength studies of galaxies across the entire range of cosmic times since the end of the dark ages. In this landscape, a key role is played by the synergistic studies done with the new generation of gigantic telescopes on the ground such as the Extremely Large Telescope (ELT), the Giant Magellan Telescope (GMT) and the Thirty Meter Telescope (TMT) in the optical/near-infrared, and the Square Kilometre Array (SKA) in the radio. In addition, the development of new numerical models and improved supercomputing facilities allow us to perform new simulations that are essential to investigate how the complex physics of baryonic matter and its interplay with the dark matter halos drove the evolution of different galaxy types as a function of cosmic time.

2 The Cosmological Framework

In this chapter we introduce a few fundamental concepts of cosmology that represent the framework for the study of galaxy formation and evolution. For a general introduction to cosmology we refer the reader to specialised textbooks such as Ryden (2017).

2.1 The Expanding Universe

The fundamental assumption of the cosmological model is the **cosmological principle**: on sufficiently large scales the Universe is **homogeneous** and **isotropic**. Homogeneity means that the Universe looks the same at any position. Isotropy means that there are not preferred directions: at any position the Universe looks the same in all directions. The cosmological principle is observationally supported by the high degree of isotropy of the cosmic microwave background (§2.4) and by the finding that the observed distribution of galaxies appears homogeneous and isotropic on scales larger than about 100 Mpc. On smaller scales the distribution of matter is neither homogeneous nor isotropic, but in practice we can consider the dynamics of a model Universe that is perfectly homogeneous and isotropic as a framework in which it is possible to study the formation and evolution of structures.

2.1.1 Comoving Observers and Scale Factor

In order to study the Universe on large scales it is useful to introduce the concept of **comoving observer** (or **fundamental observer**), that is, a point in the Universe whose motion is negligibly influenced by the local distribution of matter. Comoving observers trace the large-scale dynamics of the isotropic and homogeneous Universe. Thanks to the symmetry implied by the assumption of homogeneity and isotropy, it is possible to label the cosmological events with a single time coordinate t. It follows from the cosmological principle that if, at the present time t_0, any two comoving observers are separated by a distance $r(t_0)$, at a time t in the past they were separated by $r(t_0)a(t)$, where $a(t)$ is a dimensionless function of time known as the **scale factor**. The usual normalisation of the scale factor, which we adopt in this textbook, is such that $a(t_0) = 1$. Here, with r we have indicated the proper distance (§2.1.4), which is the separation in physical units, computed using the **physical coordinates** $\boldsymbol{r}$. It is also useful to define the **comoving coordinates** $\boldsymbol{x} = \boldsymbol{r}(t)/a(t)$. The comoving distance x (§2.1.4) between two fundamental observers is constant, while the proper distance r between two fundamental observers varies with time,

3 Present-Day Galaxies as a Benchmark for Evolutionary Studies

Our understanding of galaxy evolution relies on the possibility to observe galaxies at different look-back times, from the present-day Universe to the highest redshifts accessible with the largest telescopes. The present day refers to when the light travel time from galaxies is small compared to the age of the Universe. In this context, the redshift range $z < 0.1$ is typically considered 'present day' because the light travel time is less than one-tenth of the age of the Universe. The present-day Universe is populated by a variety of galaxy types. These systems display a wide range of luminosities, sizes, structural and kinematic properties, stellar populations and interstellar medium content. Galaxies at $z \approx 0$ are the endpoint of a long process that has lasted $\approx$13.8 billion years, from the gravitational collapse of the first luminous objects to the formation and differentiation of the galaxy types that we observe today. Present-day galaxies can be observed in the most detail because they can be studied at the highest spatial resolution and their intrinsically faintest features can be detected. The aim of this chapter is to provide an overview of the general properties of present-day galaxies in order to exploit them as a benchmark for understanding their formation and evolutionary processes.

3.1 Morphology

Morphology is a key piece of information to understand the structure and properties of galaxies and their evolution across cosmic time. As illustrated in §1.2, Hubble (1926) defined the first classification of morphologies based on four main classes: **ellipticals**, **lenticulars**, **spirals** and **irregulars** (Fig. 1.1). Galaxies on the left and right of the Hubble tuning fork are respectively called early and late types. In particular, the class of **early-type galaxies** (ETGs) includes ellipticals and lenticulars, whereas the ensemble of spirals and irregulars comprises the broad class of **late-type galaxies** (LTGs). Typically, almost all LTGs have ongoing star formation. For this reason, the classification of **star-forming galaxies** (SFGs) is often used rather than basing the classification on morphology (Chapter 4). From now on, the SFG nomenclature will be preferred throughout the book. Instead, ETGs are sometimes called **quiescent** or **passive** galaxies to indicate that they have weak or absent star formation, respectively.

The Hubble classification was revised and expanded by de Vaucouleurs (1959) who proposed additional classes of lenticulars intermediate between S0 and Sa (S0a), spirals (Sd and Sm) and Im irregulars (where the 'm' refers to Magellanic prototypes such as

4 Present-Day Star-Forming Galaxies

The term 'star-forming galaxies' (SFGs) is used to indicate galaxies that are actively forming their stellar component at the time of the observation. In the local Universe, large SFGs are called **disc galaxies**, spiral galaxies or late-type galaxies (see the morphological classification in §3.1). SFGs of lower masses (typically below a stellar mass $\mathcal{M}_\star \sim 10^9\ \mathcal{M}_\odot$) are considered dwarf galaxies: we refer to a galaxy in this category as **dwarf irregular** (dIrr). Note that dIrrs include both Sm and Im types described in §3.1. When the star formation activity is particularly vigorous, a galaxy is called a **starburst galaxy** (§3.3). Elliptical and lenticular (S0) galaxies (Chapter 5) can also exhibit low levels of star formation, but typically, for a given $\mathcal{M}_\star$, at least one order of magnitude lower than the cases discussed in this chapter.

Within the class of SFGs there are a number of subclasses that have been already discussed in §3.1. Mostly for historical reasons, this nomenclature reflects the optical morphology of these systems and thus specifically relates to their stellar content. In addition to this, the most fundamental feature of SFGs is that they have *cold* gas, at typical temperatures from tens to hundreds kelvin. This gas, detected via various emission and absorption processes across the electromagnetic spectrum, is closely related to the presence of star formation. In this chapter, we discuss the main properties of present-day SFGs and their scaling relations. At the end (§4.6), we describe the stellar and gaseous contents of our own Milky Way. Tab. 4.1 summarises the physical properties of SFGs as they can be inferred from observations in the nearby Universe.

4.1 Stars

The stellar constituents of SFGs are primarily two: the disc and the bulge. The relative prominence of discs and bulges is one of the main drivers of the Hubble/de Vaucouleurs classifications (Chapter 1 and §3.1). Spiral galaxies of earlier types (Sa) have large bulges and the prominence of the bulge component progressively decreases moving to Sb, Sc and Sd spirals. Roughly 60% of all spiral galaxies host stellar bars (§4.1.2). Moreover, disc galaxies are embedded in extended stellar components, called stellar halos (§4.1.3). Low-mass SFGs have a more irregular morphology and the irregularity often correlates with the level of star formation. Stars belonging to the different galaxy components tend to have different physical properties. In the following we give a description of the various stellar components of present-day SFGs. Other reference textbooks on this topic are Sparke and Gallagher (2006) and Binney and Merrifield (1998).

5 Present-Day Early-Type Galaxies

Based on the Hubble classification (§1.2 and §3.1), galaxies with smooth light distributions and approximately elliptical isophotes are globally classified as early-type galaxies (ETGs; §3.1). Because of their observed shape, ETGs are sometimes called **spheroids**, though strictly speaking this is a misnomer because ETGs do not necessarily have intrinsic spheroidal shape (§5.1.1). The family of ETGs comprises several types of galaxies, ranging from dwarf galaxies such as **dwarf ellipticals** (dEs) to luminous galaxies such as lenticulars (S0s), ellipticals, up to giant ellipticals, which are often the central and most luminous galaxies in clusters of galaxies (usually referred to as brightest cluster galaxies; §6.4.1). The optical luminosity of ETGs spans a wide range: for instance in the B band, $10^7 \lesssim L_B/L_{\odot,B} \lesssim 10^{12}$ ($-25 \lesssim M_B \lesssim -13$). The characteristic properties of different classes of ETGs are summarised in Tab. 5.1.

Present-day ETGs have weak or absent ongoing star formation, little cold gas and do not have prominent stellar discs and spiral arms. For these characteristics, ETGs are also called quiescent or passive galaxies, in contrast to LTGs, which are star-forming (Chapter 4). Dwarf spheroidal galaxies (dSphs[1]), though sharing a few properties with ETGs (they are quiescent and have spheroidal morphology), represent a distinct class of objects and are not included in the family of ETGs: they are described in §6.3. Observations of ETGs across the electromagnetic spectrum have revealed the existence of important emission that is not due to stars. Ellipticals have hot ($10^6\,\mathrm{K} \lesssim T \lesssim 10^7\,\mathrm{K}$) gaseous halos that, especially in the brightest systems, are detected as smooth extended sources in X-rays. Ellipticals can also host, in their centre, an AGN (§3.6), which is believed to be powered by accretion onto an SMBH and gives an important contribution to the galaxy emission, especially in the radio band.

Assessing the properties of the present-day quiescent galaxies, and in particular of massive ellipticals, is important for understanding galaxy evolution, because these galaxies are believed to be the end product of a complex formation process. Given their regular structure and their brightness, luminous ellipticals have been studied in great detail and represent in a sense the prototypes of ETGs. Therefore in this chapter we will often refer specifically to ellipticals, though many of the observational and modelling techniques described for ellipticals also apply to other ETGs and, to some extent (for instance in the analysis of the stellar component), also to SFGs.

[1] For the classification of dSphs and dEs we follow Kormendy and Bender (2012). In practice, centrally concentrated dwarfs following the sequence of luminous ellipticals in the surface brightness–magnitude diagram of Fig. 3.4 are classified as dEs.

The Environment of Present-Day Galaxies 6

In Chapters 3–5 we have described present-day galaxies, focusing on their internal properties. However, galaxies are by no means closed systems, so a fundamental ingredient to understand the formation and evolution of galaxies is their **environment**, that is, the ensemble of properties of the region of the Universe in which each galaxy is located. In this chapter we describe the environment of present-day galaxies from the smallest scale (pairs of interacting galaxies) to the very large scale (large-scale structure of the Universe).

6.1 Interacting Galaxies

A significant fraction of the observed galaxies are found to be interacting. In the simplest case a pair of **interacting galaxies** appears as two nearby galaxies, with clearly distinct bodies, which are characterised in the outskirts by tidal features (§8.9.4), are connected by stellar and gaseous **bridges**, or have, in general, very disturbed morphology. These features reveal not only that the two systems are physically close to each other, but also that their structures are mutually affected by each other's gravitational fields. These kinds of systems are often classified as **peculiar galaxies**. Spectacular and prototypical examples of peculiar galaxies are NGC 4038/4039 (known as the Antennae) and NGC 4676 (the Mice), which are believed to be SFGs caught in the early stage of a merger process (Toomre and Toomre, 1972; §8.9). When, as in these cases, the involved galaxies are gas-rich, the interaction is associated with important star formation, often a starburst (§4.5). These processes are called dissipative or 'wet' mergers (§8.9). When the interacting galaxies are gas-poor, there is no substantial associated star formation: these are dissipationless or 'dry' mergers (§8.9). Not all peculiar galaxies are ongoing mergers: when the disturbance is milder, the two galaxies might be undergoing only a temporary interaction (fly-by; §8.9).

Ring galaxies, such as the so-called Cartwheel galaxy (ESO 350-40) or the peculiar galaxy Arp 148 (leftmost top panel of Fig. 6.1), show beautiful large-scale rings of star-forming gas, which likely originate from the perturbation due to the interaction with a smaller companion galaxy. In some cases the signatures of interaction are less evident. Examples are **shell galaxies** such as NGC 474 (Fig. 5.4), NGC 1344 and NCG 3923, ETGs in which deep photometry reveals the presence of shells in the outer surface brightness distributions. These shells are believed to be the remnant of the accretion of a satellite disc galaxy. Finally, there are cases of galaxies, such as NGC 5907 (Fig. 4.4) and NGC 474 itself, that show in deep images extended star streams strikingly similar to those expected along the orbit of an accreted companion in a minor merger (§10.4; Fig. 10.9).

7 Formation, Evolution and Properties of Dark Matter Halos

Galaxies are believed to form from collapse and cooling of gas in dark matter halos. Dark matter halos form as a consequence of the gravitational instability and the growth of primordial perturbations in the matter density distribution of the Universe. In this chapter we describe the main steps that lead from the linear evolution of density perturbations to the virialisation of dark matter halos. We then describe the main structural and kinematic properties of dark halos. We note that this is only a brief overview of the complex process of structure formation in the Universe. We refer the reader to Coles and Lucchin (2002), Mo et al. (2010) and Schneider (2015) for more details.

7.1 Observational Evidence for Dark Matter Halos

The proposal that a substantial part of the matter in the Universe is in the form of dark matter dates back to much earlier than the study of structure formation in cosmological models. Back in the 1930s, Zwicky (1933) suggested that most of the mass in the Coma cluster of galaxies is in the form of dark matter. Nowadays, thanks to the combination of different methods to measure the mass of groups and clusters of galaxies, we have detailed information not only on the total mass of their dark matter halos, but also on their mass distribution (§6.2 and §6.4.4), which can be compared with the cosmological predictions that we discuss in the following sections.

Moving to the smaller scales of galaxies, Ostriker and Peebles (1973) envisaged the presence of dark matter in galaxies, based on their conclusion that massive spherical halos are necessary to stabilise galactic discs against bar instability (§10.2.1). In the 1970s it was also realised that extended halos of dark matter are necessary to explain the observed rotation curves of disc galaxies, and in particular the flat outer parts traced by H I (§4.3.3). In general these rotation curves can be reproduced assuming cosmologically motivated halos on large scales, while the theoretical interpretation of the observationally inferred central distribution of dark matter is not always straightforward (§4.3.5 and §7.5.5). While HSB galaxies are baryon-dominated in the inner regions, dark matter is dominant down to the centre in LSB galaxies, so among SFGs there is a diversity in the dark matter distribution.

Disentangling the distributions of luminous and dark matter in ETGs is more difficult than in disc galaxies, but, mainly thanks to gravitational lensing measurements (§5.3.4), it is now well established that dark matter halos are required also in ETGs (§5.3.5): stars

8 Main Ingredients of Galaxy Formation Theory

Galaxy formation is the outcome of the complex interplay between dark matter, gas and stars in the cosmological framework. In Chapter 7 we have described the formation and evolution of dark matter halos. In the present chapter we focus on the physics of baryons, introducing some of the processes that are considered the main ingredients of the theory of galaxy formation (see also Fig. 1.3): gas cooling and heating (§8.1), gas infall and accretion onto dark halos (§8.2), star formation (§8.3), feedback from stars (§8.7) and AGNs (§8.8), and galaxy mergers (§8.9). Other fundamental tools presented in this chapter are models of the evolution of the ISM (§8.4), of chemical evolution (§8.5) and of galaxy spectra (§8.6). These ingredients are used in Chapters 9 and 10, where we describe the essential properties of the currently favoured theories of galaxy formation.

8.1 Thermal Properties of Astrophysical Gases

Generally speaking, an astrophysical gas can be subject to different forms of both cooling and heating. For instance, it can cool or be heated adiabatically (because of expansion or contraction), or be heated gravitationally via shocks (§8.2.2). In this section we focus on cooling and heating mechanisms that are due not to adiabatic or gravitational processes, but to emission (§8.1.1), absorption (§8.1.2) or scattering (§8.1.3) of radiation, or interaction with cosmic rays (§8.1.2). In §8.1.4 we introduce the concept of thermal instability.

8.1.1 Radiative Cooling

When a cosmic gas emits radiation it cools because it loses the energy carried by the emitted photons, which ultimately is subtracted from the kinetic energy of the gas particles. This fundamental process is called **radiative cooling**. We consider here the case, relevant in the context of galaxy formation, of an optically thin gas, that is gas in which the emitted photons are not absorbed by the gas itself and thus escape from the system. Depending on the gas density, temperature and ionisation state, there are several mechanisms responsible for radiative cooling. In this respect a discriminant temperature is $T \approx 10^4$ K, which roughly separates, for hydrogen, regimes of ionised and neutral gas.

9 From Recombination to Reionisation

This chapter describes the main topics related to the early evolution of baryonic matter during the first billion years after the Big Bang, the formation of the first luminous objects and their influence on the IGM. At these cosmic epochs (say from $z \sim 1000$ to $z \sim 10$) the Universe goes through crucial transition phases. The first is the cosmological recombination, when baryonic matter changes from a fully ionised plasma (§2.4) to an almost completely neutral gas composed of H, D, He and Li atoms and a few simple molecules. This gas is called pregalactic because neither luminous stars nor galaxies were present at that time, and therefore this era is named the **dark ages**. At these early times, primordial molecules are fundamental to allow the efficient radiative cooling of the gas despite the low gas temperatures and the lack of metals. This cooling is essential to promote the gravitational collapse and the formation of the first stars in the history of the Universe at $z \approx 20-30$ within dark matter halos with masses $\sim 10^6\ \mathcal{M}_\odot$. The formation of the first galaxies occurs later ($z \approx 10$) in halos of $\sim 10^8\ \mathcal{M}_\odot$ where atomic hydrogen cooling becomes possible. It is thought that also the seeds of SMBHs start to form at these epochs at the centres of primordial galaxies. The formation of the first sources of UV radiation marked the end of the dark ages. The energetic photons emitted by the first luminous objects gradually ionise the surrounding IGM and lead to the second major transition called cosmological reionisation. As a consequence, an essential ingredient of this chapter is also the description of the IGM, its physical properties and its evolution due to cosmological reionisation. More details on the topics of this chapter can be found in Stiavelli (2009) and in the reviews suggested in the next sections.

9.1 The Cosmological Recombination

A few thousand years after the Big Bang, the Universe consists of a fully ionised plasma composed of protons, electrons and the stable atomic nuclei formed during the primordial nucleosynthesis (i.e. ^{4}He, ^{3}He, D and ^{7}Li; §2.5). This plasma is sometimes called the **primeval fireball**. Its temperature is too hot ($k_B T \gg 13.6$ eV) to allow the stable recombination of the electrons with protons and nuclei to form neutral atoms. Photons and matter are strongly coupled due to very frequent scattering interactions, and the fireball radiates as a perfect black body. Due to the incessant scattering by free electrons, the Universe is opaque because photons are not free to propagate and the scattering rate is much higher than the expansion rate of the Universe (§2.4). Neutrinos and dark matter

10 Theory of Galaxy Formation

Understanding the formation and the evolution of galaxies is a very ambitious endeavour that has occupied astrophysicists for decades. Analytic calculations (such as those presented in Chapter 8), though very useful to describe the basic principles of the theory of galaxy formation, cannot capture the details of the involved processes and must therefore be complemented by the results of sophisticated numerical models.

The starting point of galaxy formation is the collapse of matter overdensities in the early Universe (§7.2). These overdensities are dominated by dark matter, but a fraction $f_{\rm b} \simeq 0.16$ (§2.5) of their matter is baryonic, namely primordial gas (§9.2). While the dark matter halos assemble hierarchically (§7.4.4), the gas hosted in these halos cools (§8.1.1) and forms stars (§8.3), leading eventually to the galaxies that we observe today. On the one hand, the extraordinary variety of galaxies in the present-day Universe indicates that this conversion of infalling gas into galaxies follows different paths. On the other hand, the existence of specific classes of galaxies and tight scaling relations suggests that galaxy formation must be regulated by a few dominant physical mechanisms.

Throughout this book, we have followed the general classification of present-day galaxies that divides them into SFGs and ETGs, with SFGs being essentially discs and ETGs spheroids (§3.1). However, when looked at in detail, the properties of a single object are more complex and a large fraction of galaxies comprise more than one baryonic component. For instance, several disc galaxies host bulges with properties similar to ellipticals, as well as bars or pseudobulges (§4.1.2); some ETGs (in particular S0s) have disc components and significant rotation (§5.1.2). Moreover both SFGs and ETGs can be embedded in stellar halos (§4.1.3) that may have their own formation mechanism.

In the light of the above, in this chapter we first investigate the formation mechanisms of the different *galaxy components* (§10.1–§10.4), which we summarise in Tab. 10.1. Then, after introducing some characteristic scales of galaxy formation (§10.5) and the concept of quenching of star formation (§10.6), we describe possible *assembly histories* of different classes of present-day galaxies (§10.7–§10.9). Finally, we discuss the origin of the *demographics* of galaxies (§10.10) and give an overview of the numerical models of galaxy formation (§10.11).

10.1 Formation of Galaxy Components: Discs

A distinctive property of present-day galaxy discs with respect to spheroids (which we describe in §10.3) is that they are rotation-supported in all their baryonic matter

11 Observing Galaxy Evolution

Previous chapters presented a global view of galaxy properties in the present-day Universe and a general description of the physical processes of galaxy formation. This chapter illustrates what the observations can tell us about the evolution of galaxies across cosmic time. This is a young research field characterised by a very fast development. Before the mid-1990s, the spectroscopic identification of galaxies at cosmological distances (say $z > 1$) was limited to a few cases, or to AGNs thanks to their high luminosities. Since the mid-1990s, this limitation was overcome when ground-based telescopes with 8–10 metre diameters became available (Keck and VLT) and allowed the spectroscopic identification of normal galaxies out to $z > 3$. This milestone, together with *HST* deep and high-resolution imaging, and the synergy with multi-wavelength data from the gamma-rays to the radio, opened a brand new research field allowing the direct observation of evolving galaxies at cosmological distances. However, despite this major progress, our understanding of galaxy formation and evolution based on observations is still incomplete. For this reason, this chapter is focused only on the most robust observational results. The topics are divided into three main sections. The first deals with the galaxy physical properties that can be derived from observational data. The second describes how to identify high-redshift galaxies and illustrates their main characteristics. The third discusses the key results inferred from the observation of galaxy samples as a function of redshift. Specialised reviews are cited for each topic in order to guide readers who may want to have more details.

11.1 The Main Observables of Galaxy Evolution

The aim of this section is to review some of the main galaxy properties that can be derived from the observations (the so-called **observables**). Here the focus is on distant galaxies ($z > 1$), but the same methods can be applied to galaxies at lower redshift, as they were implicitly used in Chapters 3–6. The spectral regions mentioned in this chapter (e.g. UV, optical, IR) are defined in §C.1. Unless otherwise specified, magnitudes are given in the AB photometric system (§C.3; §C.4). Tabs. 11.1 and 11.2 give a summary of the galaxy properties that can be derived from the observational data.

11.1.1 Redshifts

When a galaxy spectrum is available and spectral lines are detected, the **spectroscopic redshift** (spec-z) is derived as $z = (\lambda_{\rm obs}/\lambda_{\rm rest}) - 1$, where $\lambda_{\rm obs}$ and $\lambda_{\rm rest}$ are the observed

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