

1

Introduction

1.1

Galaxies

Galaxies are gravitationally bound systems composed of a large number of stars, gas, dust, and other forms of matter. They span a large range in dimension, luminosity, and mass. Dwarf galaxies are composed of $\sim 10^7$ stars, while massive galaxies can have up to $\sim 10^{12}$. Massive galaxies have been classified according to their morphology into two main classes, ellipticals (E) and spirals (S) [1–8]. The first family is characterized by a smooth elliptical morphology, is dominated by an old stellar population, and generally contains little gas and dust (Figure 1.1). The motion of stars within ellipticals is mainly random. These objects are often called early-type galaxies. The second family is characterized by a flat disk with a spiral morphology, with the possible presence of a bar, a bulge, and a nucleus (S). These systems are undergoing episodes of star formation and thus include young stellar populations. They are rich in gas and can contain a significant amount of dust. Their kinematic is characterized by a more or less significant rotation. They are generally referred to as late-type systems. In addition to these two families, there exists an intermediate class of objects. The lenticular galaxies (S0) are characterized by a flat disk without any spiral structure, dominated by old stellar populations, and generally devoid of gas and dust. Besides these main families, astronomers defined the class of irregular galaxies (Irr or Pec) to include all those objects with a peculiar morphology that do not fit into the previously mentioned categories. This class includes, for instance, interacting and merging systems such as the Antennae (NGC 4038/4039) or the Mice (NGC 4676) shown in Figure 1.2. These are characterized by perturbed morphologies with clumpy regions of high surface brightness, and extended tidal tails with low surface brightness. Dwarfs are generally divided into gas-rich, star-forming Magellanic irregulars (Im) or blue compact dwarfs (BCD), and gas-poor, quiescent dwarf ellipticals (dE) and spheroidals (dS0) (Figure 1.3). Magellanic irregulars and blue compact dwarfs have irregular morphologies and are generally sustained by rotation. The former are extended and have moderate to very low stellar surface brightnesses, while the latter are very compact objects with high surface brightness and have aspects similar to that of bright HII regions. Dwarf ellipticals and spheroidals are objects with low surface brightness and are

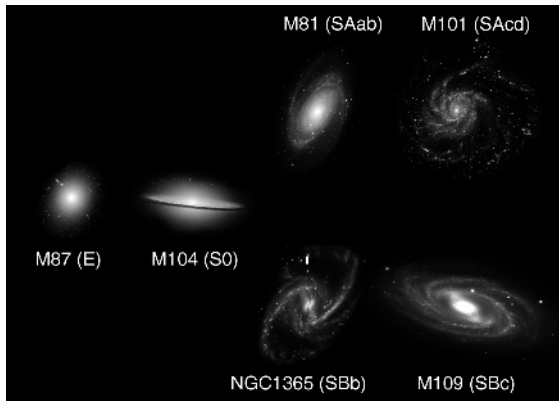


Figure 1.1 The Hubble diagram separates elliptical galaxies (E, left) from lenticulars (S0, middle left) and spirals (S, right). The spiral sequence is decomposed into normal (SA, upper) and barred (SB, lower) spirals.

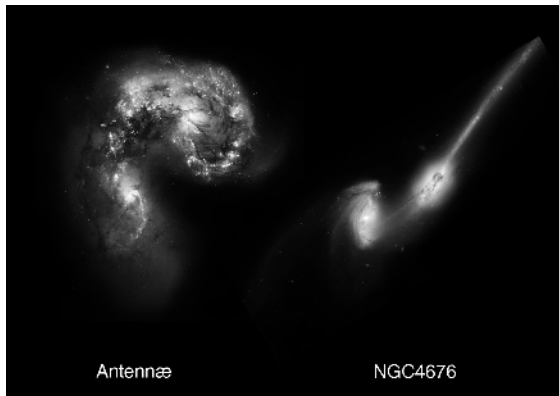


Figure 1.2 The interacting systems NGC 4038/4039 (the Antennae) and NGC 4676 (the Mice).

characterized by very smooth and regular morphologies. Galaxies can host an active galactic nucleus (AGN), where the energy necessary to sustain the powerful electromagnetic radiation is supplied by the accretion of mass onto the central supermassive black hole. Active galaxies can be divided into quasars or QSO (quasi stellar objects), which are compact sources with a stellar morphology, Seyfert galaxies, where the AGN dominates only the central region, and radio galaxies.

Galaxies are ordinary objects inhomogeneously distributed within the universe. If ρ_0 is the mean galaxy density of the local universe, whose value is ~ 0.006 objects Mpc^{-3} down to the absolute magnitude $M_i < -19.5$ [9], the density of galaxies spans from $\sim 0.2\rho_0$ in voids to $\sim 5\rho_0$ in superclusters and filaments, $\sim 100\rho_0$ in the core of rich clusters, and $\sim 1000\rho_0$ in compact groups [10, 11]. In the nearby universe, star-forming systems dominate the population by counting for roughly 70% of the extragalactic population, while ellipticals count for $\sim 10\%$

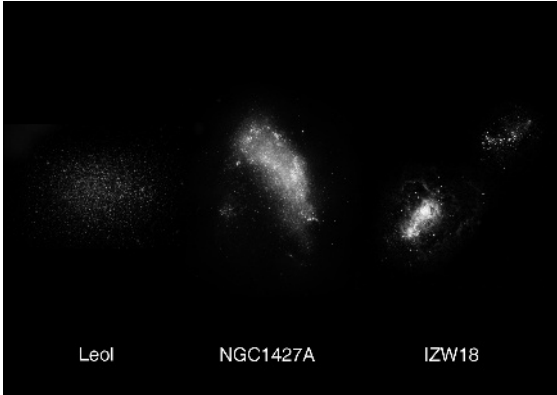
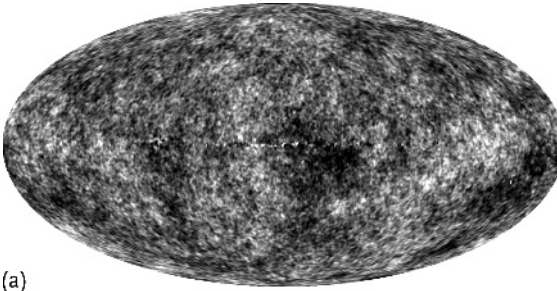
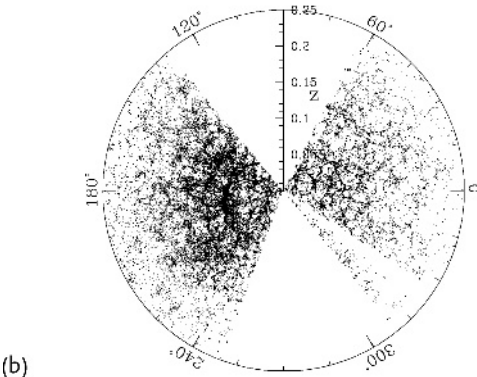


Figure 1.3 Dwarf galaxies can be divided into dwarf spheroidals (dS0, left, Leol), Magellanic irregulars (Im, middle, NGC 1427A), and blue compact dwarfs (BCD, right, IZW18).



(a)



(b)

Figure 1.4 The WMAP background sky image (a) at 1.9 mm shows the temperature fluctuations of the universe when it was $\sim 380\,000$ yr old (from [19]) (Reproduced by permission of the AAS; Credit: NASA/WMAP Science Team.). These temperature fluctuations, shown as color differences, correspond to the seeds

that grew to form galaxies. The distribution of these temperature fluctuations resembles the distribution of galaxies observed by the Sloan Digital Sky Survey (SDSS) in the local universe (b) (from [20]) (Reproduced by permission of the AAS.).

and lenticulars for $\sim 20\%$ [12]. The fraction of late-type galaxies, however, strongly decreases in high-density environments such as in rich clusters [13, 14]. Dwarfs exceed in number massive objects. However, despite their relatively low number, ellipticals, lenticulars, and spiral bulges contain $\sim 75\%$ of the mass of stars within the universe [15, 16].

Owing to the new generation of ground-based and space facilities, galaxies are now observable at redshifts larger than 5, allowing us to picture the universe ~ 1 Gyr after its formation. For this reason, galaxies can be used to probe the mass distribution at earlier and earlier epochs ($z \gtrsim 6$), providing a link between the primordial universe, now well represented by the cosmic microwave background (CMB; $z \sim 1100$), as traced by the Wilkinson Microwave Anisotropy Probe (WMAP) [17] and the Planck space mission [18], and the present epoch, as depicted in Figure 1.4. Indeed, galaxies are expected to develop within dark matter halos formed from primordial density fluctuations, whose distribution is well traced by the anisotropies observed in the microwave background image of the universe. The study of galaxy formation and evolution is thus tightly related to the evolution of the universe itself and is thus of paramount importance in cosmology.

1.2

A Multifrequency Approach

The understanding of galaxy evolution requires an accurate study of the different processes that gave birth and transformed them. Of fundamental importance is the study of the matter cycle, that is, understanding how the primordial gas component from the Big Bang has collapsed into giant molecular clouds to form stars of different mass. These stars later modified the physical and chemical properties of the interstellar medium, intervening in the process of star formation (feedback). Indeed, the dust formed by the aggregation of metals produced and injected into the interstellar medium by massive stars during the latest phases of their life plays a crucial role in galaxy evolution since it is a catalyst in the formation of molecular hydrogen and is a major coolant of the interstellar medium.

There is evidence showing that the matter cycle might be modulated by the environment to which galaxies belong. In high-density environments, for instance, the atomic gas, which is generally located in the outer disk of spiral galaxies, is easily removed in both gravitational interactions with nearby companions or in dynamical interactions with the hot and dense intracluster gas permeating rich clusters of galaxies, while the stellar component, tightly linked to the potential well of the galaxy, is perturbed only by gravitational interactions [10].

All the physical processes regulating the matter cycle and the perturbations induced by the environment must be considered and understood simultaneously. The typical properties of galaxies spanning a large range in luminosity and mass are generally traced using scaling relations, where structural, kinematical, chemical, and spectrophotometrical properties are combined and analyzed. These scaling relations are of paramount importance in the study of the physical processes at

work in any kind of extragalactic source, and are thus widely used as constraints in models of galaxy formation and evolution. Because of their tightness, they are also powerful distance tracers generally used to study the large scale galaxy distribution within the universe.

Clearly, a coherent and complete understanding of galaxy evolution through cosmic time requires a simultaneous analysis of all the different galaxy components. This can be achieved only through a multifrequency analysis. Stars emit as black body in the ultraviolet (UV) to near-infrared (NIR) spectral domain, with a different contribution depending on their mean age. Massive young stars dominate the short wavelength range while evolved systems mainly emit in the near-infrared. The gaseous component, either atomic or molecular, can be observed using some specific emission lines; the former via the emission of the HI line at 21 cm while the latter via carbon monoxide lines emitted in the millimeter domain. The dust component is heated by the interstellar radiation field and emits in the mid- and far-infrared and submillimeter domain following different emission processes depending on whether or not it is in thermal equilibrium with the radiation. The millimeter radio and centimeter emission is due to the free-free emission of unbound electrons formed in HII regions by the ionizing radiation of the most young and massive stars, and by the synchrotron emission due to relativistic electrons accelerated in supernovae remnants spinning in weak magnetic fields. Both emission processes are tightly related to recent star formation events and have a relative weight that changes with λ , where the free-free emissions is being important at short wavelengths while synchrotron dominating at long wavelengths. The accretion phenomenon on a compact source in binary systems, or the emission of the hot gas component permeating massive elliptical galaxies or forming the diffuse interstellar medium of gas-rich systems, can be observed in the X-rays.

In the last 25 years the advent of new technologies allowed astronomers to extend to large angular scales the observations of the universe with a continuous coverage, from X-rays to centimeter radio wavelengths, previously accessible only to the optical and centimeter radio bands. The nearby universe has been completely or partially mapped by all sky or shallow extended surveys such as ROSAT (Röntgensatellite; [21]) in X-rays, GALEX (Galaxy Evolution Explorer; [22]) in the ultraviolet (UV) band, SDSS (Sloan Digital Sky Survey, [23]) in the optical, 2MASS (Two Micron All Sky Survey, [24]) in the near-infrared, IRAS (Infrared Astronomical Satellite, [25]) and AKARI [26] in the infrared, and FIRST (Faint Images of the Radio Sky at Twenty cm, [27]) and NVSS (NRAO VLA Radio Survey, [28]) in the radio continuum. The nearby universe has also been observed in spectroscopic mode in its most important emission line, the HI hydrogen at 21 cm, by HIPASS (HI Parkes All Sky Survey, [29]), HIJASS [30], and ALFALFA (Arecibo Legacy Fast ALFA Survey, [31]), while the optical lines by the SDSS [23] and the 2dF Galaxy Redshift Survey (2-degree-Field Galaxy redshift Survey, [32]). Furthermore, imaging and spectroscopic multifrequency observations of galaxies at significant distances have been obtained using very deep exposures of relatively small sky regions accurately selected to be uncontaminated by the Galactic emission. Typical examples

Table 1.1 Emitting sources and emission processes at different wavelengths.

Domain λ	X-ray	UV	Visible	NIR	MIR	FIR-submm	Radio
	0.1–10 keV (1–100 Å)	912–3500 Å	3500–7500 Å	0.75–5 μ m	5–20 μ m	20 μ m–1 mm	1 mm–1 m
Continuum							
Process	Black body	Black body	Black body	Black body	Thermal emission	Modified black body	Synchrotron
Emitting source	Thermal bremsstrahlung						Free-free
	Accretion disk in binary systems	Young stars	Intermediate age stars	Old stars	PAH, hot dust grains	Cold dust grains	Relativistic electrons in weak magnetic fields
	Hot gas						HII regions
Main emission lines							
Emission lines		Atomic hydrogen, metals	Atomic hydrogen, metals	Atomic and molecular hydrogen, molecules	PAH	[CII], CO, molecules	HI(21 cm)
Origin		HII regions	HII regions	HII regions	PDR	Giant molecular clouds	Diffuse ISM
Absorption lines		Hydrogen, metals	Hydrogen, metals	Hydrogen			HI(21 cm)
Origin		Stellar atmosphere, ISM, IGM	Stellar atmosphere	Stellar atmosphere			Diffuse ISM

Notes: PAH: Polycyclic Aromatic Hydrocarbons; PDR: photodissociation region; ISM: interstellar medium; IGM: intergalactic medium.

are the GOODS (Great Observatories Origins Deep Survey, [33]) and COSMOS (Cosmic Evolution Survey, [34]) surveys.

The contribution of these multifrequency surveys to the study of galaxy evolution is invaluable, since it simultaneously provides us with information on the different components of any extragalactic object (see Table 1.1 for a summary). The modern instrumentation now in our hands enables us to measure the content and trace the distribution of the gaseous, stellar, and dust components in large samples of galaxies. A typical example is illustrated in Figure 1.5 which shows the image of the interacting system M51 observed at different wavelengths, from the X-ray (Figure 1.5a) to the 21 cm HI radio line (Figure 1.5l). The distribution of the old stellar population, as traced by the near-infrared image at $3.6\ \mu\text{m}$ obtained by the Spitzer space mission, is relatively smooth. Old stars are the dominant stellar population in the companion NGC 5195, an early-type galaxy interacting with NGC 5194. The distribution of the young stellar component, as traced by the H_α narrow band (ground-based observation) and UV GALEX images, is very clumpy because of the presence of massive stars in compact HII regions primarily located along the spiral arms. The molecular gas component traced by the CO emission (IRAM) and, to a minor extent the atomic hydrogen (HI line at 21 cm; VLA) follows the distribution of the young stars. This is expected since the star formation process requires large amounts of gas to take place. A similar clumpy distribution is also evident in the $8\ \mu\text{m}$ image which traces the distribution of the Polycyclic Aromatic Hydrocarbons (PAHs), in the hot dust component ($24\ \mu\text{m}$) observed in the mid-IR by Spitzer, where the hot dust is primarily heated by the ultraviolet radiation emitted by the youngest stellar populations. To a lesser extent a similar morphology is present in the submillimeter domain ($250\ \mu\text{m}$, Herschel space mission), where dust heating from the general interstellar field becomes more important. This clumpy structure can be also seen in the radio continuum (VLA) given that the relativistic electrons responsible for the synchrotron emission are accelerated in supernovae remnants produced after the explosion of the most massive stars, and in the X-ray where the emission is dominated by binary systems and supernovae remnants.

High quality morphological studies of the high-redshift universe are routinely undertaken with subarcsecond angular resolutions at either short wavelengths (UV, visible) or in the radio regime, thanks to millimeter and centimeter interferometers. In the infrared spectral domain, where the data are collected using space facilities of moderate size, the angular resolution is diffraction limited and thus sufficient for a detailed two-dimensional analysis only in the nearby universe, while high-redshift studies are soon limited by source confusion. The sensitivity and the spectral resolution of optical spectrometers is also sufficient to measure the kinematical properties of the brightest galaxies up to redshift $z \sim 1$.

Whereas multifrequency studies on galactic scales might still be prohibitive at high redshifts, the available data allows us to reconstruct the spectral energy distributions in the X-ray to centimeter radio regimes, such as those shown in Figure 1.6 for M51, for hundreds of thousands of galaxies up to high redshifts. Figure 1.6 clearly shows that the morphological differences between the late-type spiral NGC 5194 (Figure 1.6b) and the peculiar early-type NGC 5195 (Figure 1.6a), evident in

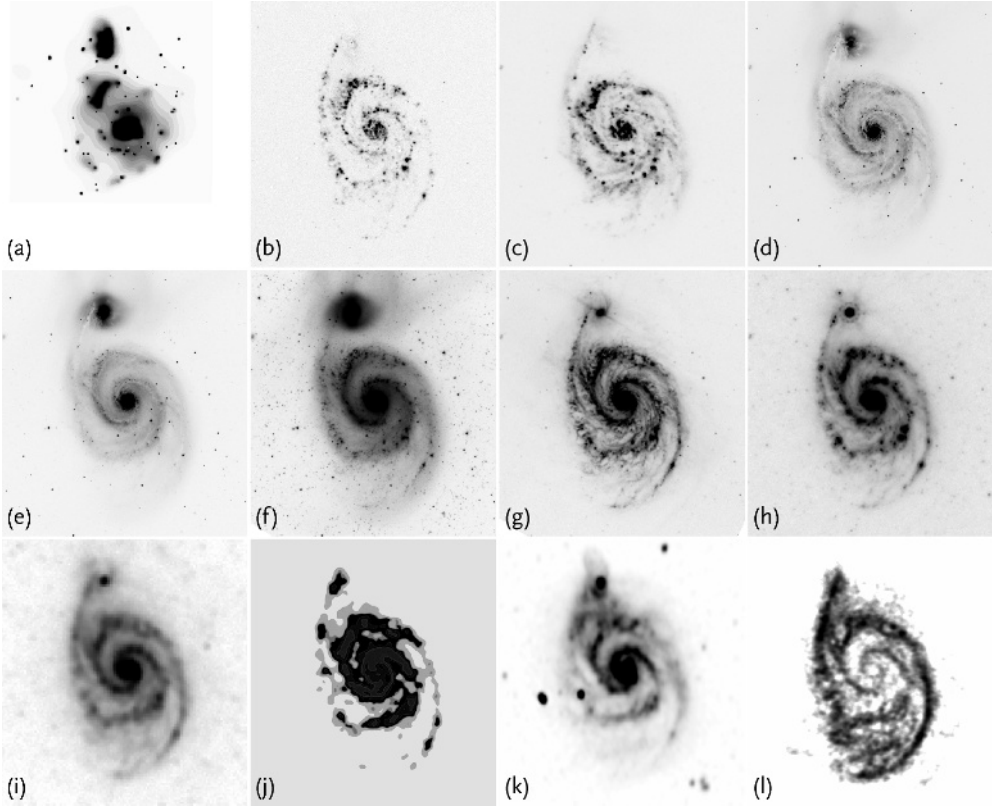


Figure 1.5 Multifrequency images of the interacting system M51 formed by the spiral galaxy NGC 5194 and the peculiar early-type NGC 5195: (a) X-ray image from Chandra ($\lambda \sim 10 \text{ \AA}$), tracing the distribution of binary systems and supernova remnants [35]; (b) $H_\alpha + [\text{NII}]$ narrow band OHP image, ionizing radiation ($\lambda \leq 912 \text{ \AA}$) produced by the youngest stellar populations [36]; (c) near-ultraviolet NUV ($\lambda = 2316 \text{ \AA}$) GALEX image, distribution of the young stellar populations [37]; (d) optical g band ($\lambda = 4825 \text{ \AA}$) SDSS image, young-intermediate age stellar populations; (e) optical i band ($\lambda = 7672 \text{ \AA}$)

SDSS image, intermediate–old age stellar populations; (f) near-infrared 3.6 \mu m Spitzer image, old stellar populations [38]; (g) mid-infrared 8.0 \mu m Spitzer image, Polycyclic Aromatic Hydrocarbons (PAHs; [38]); (h) infrared 24 \mu m Spitzer image, hot dust [38]; (i) far-infrared 250 \mu m Herschel image, cold dust; (j) $2.6 \text{ mm } ^{12}\text{CO}(1-0)$ image, distribution of the molecular gas component (IRAM, [39]); (k) radio continuum 20 cm Westerbork image, relativistic electrons in weak magnetic fields [40]; (l) 21 cm HI VLA image, distribution of the atomic hydrogen [41].

the multifrequency images shown in Figure 1.5, are also present in their spectral energy distributions. Indeed, NGC 5194 is characterized by a relatively intense UV emission due to the presence of recently formed stars and by an important mid-infrared, far-infrared, and submillimeter emission (dust heated by the young stellar population), while NGC 5195 is dominated by emission from an older stellar population, with an important contribution from the dust. These systematic differences

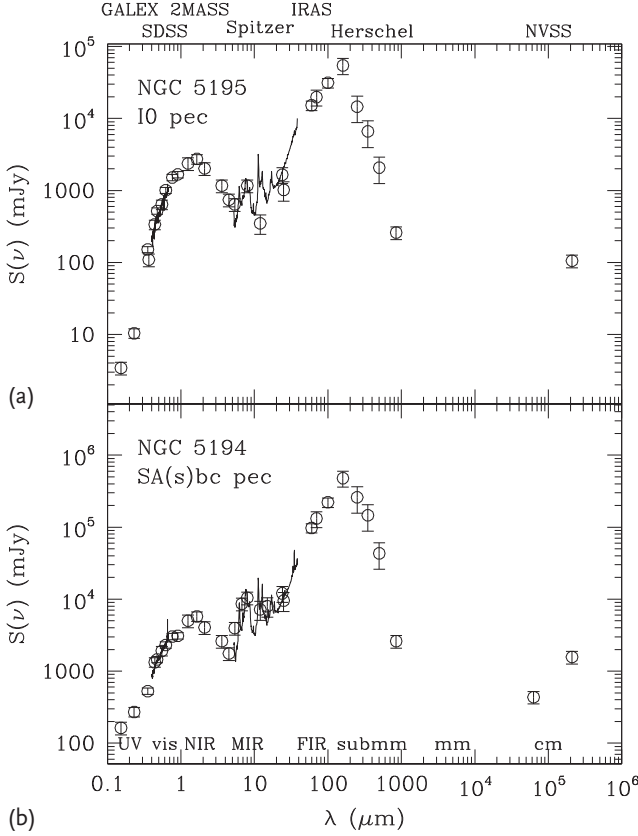


Figure 1.6 The UV to centimeter radio spectral energy distribution (SED) of the two galaxies NGC 5194 (M51) and NGC 5195. Data are taken from [42] or from NED.

are also evident both in the visible (Figure 1.7) and in the near-infrared (Figure 1.8) spectra when the two galaxies are observed at higher spectral resolution. The early-type NGC 5195 has a much redder optical spectrum than the late-type NGC 5194, indicating at the same time the presence of a dominating old stellar population and of an important dust attenuation. Its optical spectrum does not show strong emission lines, which are prominent in NGC 5194, due to the ionization of the gas in star-forming regions. The mid-infrared spectra obtained by Spitzer reveal the presence of PAHs emission in both galaxies ($5 \mu\text{m} < \lambda < 15 \mu\text{m}$), with some atomic emission lines at longer wavelengths only present in the star-forming NGC 5194.

Spectral energy distributions and optical or mid-infrared spectra are useful tools since they can be reproduced by models and compared to observations in samples of objects at different redshift, thus providing us with one of the most popular and powerful tools for constraining galaxy evolution. The spectral resolution and wavelength coverage of both models and observations have significantly improved

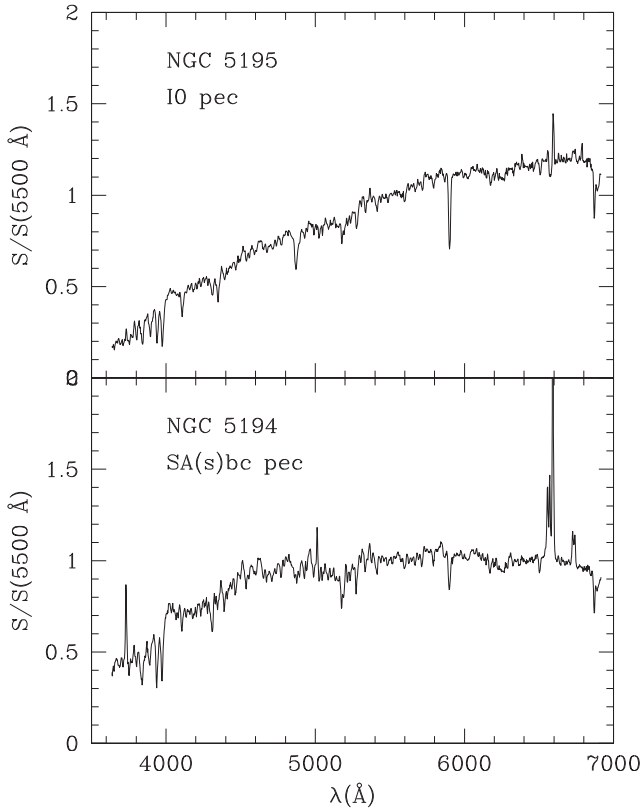


Figure 1.7 The 3600–6900 Å medium resolution ($R \sim 700$) optical spectrum of the two galaxies NGC 5194 (M51) and NGC 5195, from [43].

over the recent years, thus making it possible to remove some of the degeneracies affecting the reconstruction of the evolutionary history of the analyzed galaxies.

1.3

The Purpose of this Book

We are now entering a new era in the study of galaxy evolution: the surveys previously described are providing the community with hundreds of thousands of galaxies with imaging and spectroscopic data at various wavelengths. Astronomers had to slightly change the attitude of their approach to galaxies when dealing with these new huge datasets. In the past, the study of galaxies was generally carried out using heterogeneous samples of objects mainly selected according to their morphological type, separating ellipticals and lenticulars from spirals, irregulars and active galaxies. Today's extragalactic research is based on enormous datasets, where objects are selected independently of their morphological nature, but rather according to

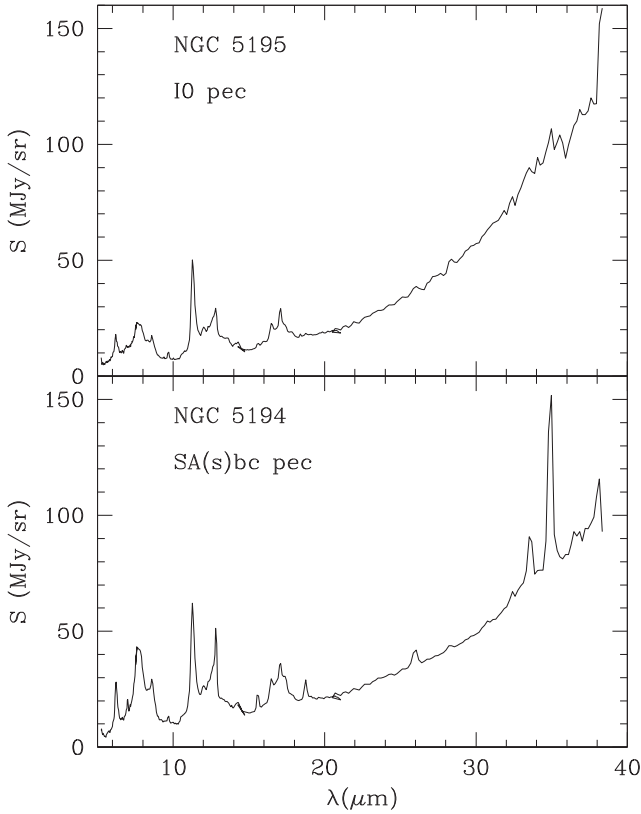


Figure 1.8 The Spitzer 5–40 μm low resolution mid-infrared spectrum of the two galaxies NGC 5194 (M51) and NGC 5195, from [44].

strict flux or luminosity criteria, in order to minimise selection biases. This new approach had several major consequences. First it contributed improving statistical tools which were developed on purpose for treating such large amounts of data. Among these, we can mention the determination of the galaxy counts, the luminosity or the mass function, and the density functions, which respectively give the number of galaxies per unit area, the number of galaxies per bin of luminosity or mass per unit volume, and the mean density of galaxies in the universe. Secondly, the spectral coverage combined with the angular and spectral resolution, the large field of view of the multifrequency surveys, and the depth of the data are allowing us to sample, at the same time, the whole parameter space necessary for a complete and coherent study of galaxy evolution. We can indeed see how the inter-relations between the different galaxy components on galactic scales change as a function of galaxy luminosity, redshift, and density. The early systematic studies of large, high-redshift samples were mainly limited to the determination of their statistical properties such as the luminosity function as well as to the reconstruction of the 3-D distribution of the detected objects. The availability of modern multifrequen-

cy datasets now allows us to undertake detailed studies of the physical processes at play in galaxies at different epochs, such as star formation and feedback, or determining the evolution of the scaling relations with time. Thus, works that were conceivable only for the nearby universe a few years ago can now be extended to high redshift. A third major change with respect to the past is that these deep, blind surveys naturally bring the discovery of unexpected objects. The most typical example are the Ultra Luminous Infra Red Galaxies (ULIRGs) discovered by IRAS [45]. These extragalactic objects are extremely luminous in the infrared and their origin is probably due to the merging of two gas-rich late-type galaxies [46].

The purpose of this book is to provide the community with a text that summarizes the information required to use the modern multifrequency datasets in a complete and coherent way, in order to gain insight on the structural and physical properties of galaxies selected according to various criteria, with the final aim of reconstructing their evolution. The book is thus structured as follows: in the first section I give a summary of the main radiative processes acting in galaxies, with an overview of the principal emitting sources dominating several classes of objects. The various emission processes are described for different wavelengths, starting from the X-ray and covering the UV, optical, near-infrared, the infrared and finally the millimeter and centimeter domain, separating the continuum emission from the line emission and absorption.

In Part Two, I show how the available multifrequency data can be used to derive physical quantities suitable for a complete study of the physical and structural properties of the selected galaxies. Given the practical purposes of this book, I list the relations most commonly used for determining those entities generally necessary in any study, such as the mass and the temperature of the gas and the dust, the mass of stellar components, and the dynamical mass of galaxies. At the same time, I report the most commonly used recipes necessary for correcting the data for dust extinction as well as those used to quantify the star formation activity in galaxies. I describe how the contribution of the different components can be separated in radio data and explain how photometric and spectroscopic data can be combined to reconstruct the spectral energy distribution of any extragalactic source. I also give the general recipes for classifying galaxies using different spectral features or for measuring gas metallicities.

In Part Three, I give some representative examples on how these derived quantities can be used to study galaxy evolution. I first summarize the statistical tools most frequently used (galaxy counts, luminosity functions). I then explain how the most important scaling relations can be determined. I also describe how the multifrequency data can be used to study the matter cycle in galaxies and to reconstruct the star formation history of the universe. This third section, whose purpose is that of presenting the most recent observational results, is certainly the one most lacking completeness given the huge amount of publications that are continuously made available on the web, which cannot all be mentioned due to lack of space. The book also includes some practical appendices useful for determining photometric redshifts and K -corrections and for homogenizing data obtained in different photometric systems.

I naturally focus my attention on the nearby universe, where angular and spectral resolution, combined with sensitivity, permit an accurate study of the different physical components (gas, dust, stars...) on galactic scales for almost all kinds of extragalactic sources. This choice is also justified by the fact that both the emitting sources and the emission processes and, as a consequence, all the relations used to quantify the physical entities described in Part Two, do not change with redshift. The relationships described in Part Three are standard and can be determined without distinction in samples of nearby and far galaxies, provided that appropriate *K*-corrections are applied to the data, as indeed explained in the text. The only difference resides in the fact that generally all these relationships are better determined in the nearby than in the far universe, not only because of the quality of the data (higher sensitivity, angular and spectral resolution, wavelength coverage), but also because the dwarf galaxy population can be investigated only locally. It is therefore only in the nearby universe that the whole parameter space of galaxy properties is fully sampled.

The novelty of this book resides in the fact that it describes galaxies as seen at different wavelengths and explains how the multifrequency data can be used in studying their properties. This approach is quite different from that proposed by classical text books, where galaxies are generally first divided according to their morphological type (ellipticals and lenticulars, spirals and irregulars, dwarfs, AGNs) and then described separately according to their properties (structure, kinematic, stellar populations, interstellar medium).

Given the extent of the subject of this book, a panchromatic view of galaxies, all the different topics are treated in a relatively basic way. The idea is to provide the reader with several practical instruments useful for a direct interpretation of the data. I want to convince the reader that the multifrequency analysis is a very powerful tool for studying the properties of any extragalactic source and for constraining models of galaxy formation and evolution. At the same time, I hope to stimulate new ideas in the use of multifrequency datasets in new and original studies of any extragalactic source. There are certainly more specific and complete books or review articles focused on single topics to which the reader should refer if he/she wants to develop some specific analyses. For this reason, I give extensive references to works that I consider important for a deeper investigation. Given the vastness of the topic and my limited knowledge, I certainly missed several important works and I apologize. The book might also suffer from another weakness related to my personal lack of experience in some of the covered fields. Despite this weakness, my intention is to give an overview of the tools that astronomers apply to multifrequency analyses of galaxies, as complete as possible. I hope that this text can be used by PhD students and senior scientists working on multifrequency data to easily find the information they need to deal with unfamiliar data.

