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Part I

Background

1
Introduction

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1.1 Star Formation in the Context of Galaxy Evolution

The formation of stars is of paramount importance in the context of galaxy evolution. Stars emit light. This light may change the physical condition of the gas in the universe (e.g. ionization of the neutral gas), or it may reach our telescopes, allowing us to study the history of galaxies, to understand the large-scale structure of the universe, or to probe the invisible dark matter filling the universe. Stellar light is also our main source of information concerning galaxies. The most massive stars evolve in the blink of a cosmic eye and distribute in their surroundings a variety of chemical elements (some synthesized in their core during their evolution) and a huge amount of energy that has the potential to remove material from galaxies, and prevent the formation of new stars or, on the contrary, promote it by inducing shocks or compression waves. Other elements are made in intermediate-mass stars that release them at a later time after their birth. Stars of small mass also play a very important role by trapping material for timescales larger than the age of the universe! Given that stars play such a fundamental role in the evolution of galaxies, some of the key questions in the field of galaxy evolution and cosmology are related to the history of their formation in galaxies. Some questions concern individual galaxies: How does star formation and its history depend on the environment or on the mass of galaxies? Others are related to cosmic scales: When do stars form globally in the history of the universe? When and how does starlight contribute to the reionization phase in the early universe?

A major goal of this book is to provide the reader with clear explanations and up-to-date definitions and references concerning the star-formation rate (SFR) in galaxies, its physical implications, together with an overall presentation of the theoretical and observational background.

Despite its importance, the details of the physics of star formation are still eluding, because of the interplay of several fundamental processes (such as gravity, turbulence, cooling, radiation, magnetic fields). The actual formation of individual stars is the subject of many studies (see e.g. the reviews by McKee and Ostriker, 2007; Hennebelle and Commerçon, 2014). Part of this complexity comes from the fact that these processes occur at completely different scales (from nuclear reactions starting in the very core of a newly formed star to the swing of majestic giant spiral arms extending on several tens of kpc that can locally enhance the gas density and help the collapse of a molecular cloud; and even on the largest scales with the accretion of gas along cosmic filaments, filling the gas reservoir for future star formation). This book is not focusing on the small-scale physics of star formation. Instead, it is written for students or researchers working in the field of galaxy evolution, for whom what matters is the collective behavior of star formation rather than the formation of individual stars. For those astronomers looking at galactic scales, star formation is a global process, playing the fundamental role of transforming interstellar gas into stars and metals. Star formation on galactic scales is the subject of many studies both in the Milky Way and in other galaxies (see e.g. the review by Kennicutt and Evans, 2012). It is crucial to be able to determine the SFR with good reliability, regardless of the details of the small-scale physics. Thus the SFR – being one of the most important properties of a galaxy (as a whole), a region of a galaxy, or the universe on the cosmic scale – is of paramount importance to understand how it can be determined, and the degree of realibility or uncertainty of these measurements. After basic definitions (see Section 1.2), we will briefly introduce the various ways to measure the SFR (see Section 1.3). Other chapters in this book will be devoted to the complementarity of different SFR indicators, as well as how they can introduce selection biases leading to wrong or incomplete evolutionary interpretations. Finally, we will mention some important current results concerning the SFR laws (see Section 1.4) and the SFR history (see Section 1.5). Both fields are very active and will remain so in the years to come. They both rely on proper SFR measurements.

1.2 Definitions

The SFR is by definition the mass that is turned into stars per unit time. The unit of choice is usually solar masses per year ($M_\odot\ yr^{-1}$). This is a convenient unit being the order of magnitude of the SFR in the galaxy most important to mankind: the Milky Way.

Very often, we wish to determine the SFR locally in galaxies: the SFR in a given region, or at a given radius. It is thus useful to define the SFR density, either in volume or surface density, respectively ρ_{SFR} (in $M_\odot\ pc^{-3}\ Gyr^{-1}$ and $M_\odot\ kpc^{-3}\ yr^{-1}$, which are numerically identical) and Σ_{SFR} (usually in $M_\odot\ kpc^{-2}\ yr^{-1}$ or in $M_\odot\ pc^{-2}\ Gyr^{-1}$). The volume–density definition is useful as the interstellar medium has a 3D distribution and star formation occurs in localized regions within this structure. On the other hand, surface densities have the advantage of being easy to relate to the surface photometry that we can readily measure in external galaxies. Also, several physical processes depend on the local surface density within a galaxy disk. For instance, the hydrostatic equilibrium involves the dispersion of the gas on one hand and the local gravity on the other, the latter being set by the surface density of baryons in the disk (in stellar or gas form).

Finally, cosmologists who want to determine the cosmic history of star formation also use a density ρ_{SFR} that represents a “cosmic” density, i.e. the average density over very large scales. The SFR density unit in this case is usually $M_\odot yr^{-1}$ Gpc^{-3} (e.g. Madau and Dickinson, 2014) adapted to the very large scales over which such an average may make sense.

A last introductory point concerns the distribution of the masses of stars themselves when they are formed. This Initial Mass Function (IMF) is, of course, extremely important. Indeed, the type of chemical elements that will be produced by a generation of stars or its stellar-light output as a function of time heavily depends on the IMF, since mass is the main parameter setting the properties of stars. Naturally, its influence will be discussed in many of the chapters of this book. The IMF is defined as a function of mass $\xi(m)$ describing the number of stars per mass interval dm, i.e. $dN = \xi(m)dm$. The reader should be aware of the fact that the IMF is sometimes defined per logarithmic mass interval. It is trivial to switch from one definition to the other. Finally, the IMF is often normalized in the following way:

$$\int_{M_l}^{M_u} m\xi(m)dm = 1, \quad (1.1)$$

where M_l and M_u are the lower and upper mass limits (around 0.1 and 100 $M_\odot$). With this normalization, the SFR describes the amount of material going into stars, and the IMF the statistical distribution in stellar masses of this material. The IMF is discussed in detail in Chapter 2.

1.3 Measuring Star-Formation Rates

Under the above definition, the SFR is instantaneous. It describes the formation of stars at a given time. This is usually what is computed in models. However, the rest of the book will demonstrate how difficult it is (and probably impossible in most cases) to determine an instantaneous SFR from the observational point of view. Indeed, most SFR tracers are, in fact, associated to a timescale on which they are sensitive. In the following text, we briefly review the observations that can be used as SFR indicators.

All methods aim at probing the emission from recently formed stars, avoiding, as much as possible, contamination from older stellar populations or other sources of emission. The only direct method available to quantify the SFR is by counting young stars or events tracing recent star formation (such as supernova remnants), but this method is currently applicable only to our Milky Way and very few nearby galaxies as it requires resolving objects on very small scales. For the vast majority of galaxies, the SFR can be derived from the integrated light, by applying calibrations that have been defined by assuming a certain IMF and a given star-formation history (SFH). Several indicators have been applied in the literature, spanning a wide range of photometric and spectral observations from ultraviolet (UV) to radio. Each one of these indicators suffers from its own drawbacks and is sensitive to emission from stars with slightly different stellar masses. The consequence is that each indicator samples a slightly different star-formation timescale.

The classical approach is to look for emission lines related to the production of young stars. Massive young stars produce a large amount of energetic photons ($\lambda = 912$Å) that ionize the surrounding gas and produce hydrogen recombination lines by cascade (Osterbrock and Ferland, 2006). The brightest of these lines, the Hα emission, is widely used as an SFR indicator, mainly because it falls in the optical regime for local galaxies, but in principle all the hydrogen recombination lines can be used as an SFR tracers (see e.g. Kennicutt, 1998a). Since only extremely massive stars ($M_{star} \simeq 20\,M_{\odot}$) produce an amount of high-energy radiation sufficient to ionize the hydrogen in the interstellar medium (ISM), the Hα emission is sensitive to the recent SFH, probing timescales $\tau_{SF} \sim 20$ Myr, and thus providing an almost instantaneous measurement of the SFR.

The integrated spectrum of a galaxy in the wavelength range 1200Å $< \lambda <$ 2800Å is dominated by the emission of young stars ($M_{star} \simeq 10\,M_{\odot}$) so that the UV emission is proportional to the SFR. Calibrations to compute the SFR from the galaxy UV emission have been derived using spectro-photometric models that assume continuous SFH on a timescale of 10^8 yr. This technique can be applied to star-forming galaxies in a wide redshift range, as it requires only photometric data that are relatively easy to obtain. However, UV emission is extremely sensitive to the form of the IMF, dust absorption, and, to a lesser extent, the galaxy metal content (as metals efficiently absorb radiation in the UV part of the spectrum). Also, UV emission can be heavily contaminated by the emission of an active galactic nucleus (AGN).

A significant fraction of the optical/UV luminosity of a galaxy can be absorbed by the interstellar dust and reemitted in the thermal IR at wavelengths of $10\mu m < \lambda < 1000\mu m$. Since most of the UV/optical emission comes from star formation, the infrared luminosity can be used as an SFR tracer. In this case, the calibration has to assume, in addition to an IMF and an SFH, a dust geometry and a dust optical depth. The most widely used calibration of Kennicutt (1998a), for example, assumes that an optically thick, compact dust component is heated by young stars in a continuous burst of $\sim$100 Myr. The presence of an AGN or an older stellar population may contribute to dust heating. Far infrared (FIR) observations provide a very suitable tool for deriving the SFR without suffering dust biases. Therefore, FIR indicators are crucial when deriving the star-formation activity of dust-rich star-forming galaxies. When broad wavelength coverage is available, indicators may be combined to derive the total SFR, for example, by adding the bolometric FIR emission to the observed UV light (Papovich et al., 2007) or the Hα emission (Kennicutt et al., 2009).

State-of-the-art techniques to recover the SFR of galaxies from spectro-photometric observations covering the electromagnetic spectrum (ideally from the far-UV up to the sub-millimeter and radio bands) include the treatment of energy balance between the radiation absorbed in the UV-to-optical regime and that reemitted at longer wavelengths in the FIR. The codes most commonly used by the community include `CIGALE`[1]

[1] Code Investigating GALaxy Emission; https://cigale.lam.fr

(Burgarella et al., 2005; Boquien et al., 2019) and `Magphys`[2] (da Cunha et al., 2008). This approach minimizes the degeneracy related to the amount of dust extinction against age and metallicity of the stellar populations, when limited to UV/optical observations. A further level of complexity is introduced by models that include the solution of the radiative-transfer equation, thus providing a physical description of the ISM and the geometry of the star birth places (e.g. `GRASIL`; Silva et al., 1998).

1.4 Star-Formation 'Laws'

1.4.1 Context

Considering the fundamental role played by stars in the evolution of galaxies and in our ability to observe the universe, it is clear that it is of paramount importance to understand how stars form on galactic scales, and to be able to describe it in physics terms. We ideally need to find large-scale "laws" telling us what should be the SFR in a galaxy (or a part of galaxy), knowing other physical conditions such as gas and dust density, temperature, velocity field, or the galaxy's local environment. Such laws are absolutely needed when we turn to simulations, to be used as recipes. In galactic chemical-evolution models, where the evolution of basic quantities (abundances, gas fraction, stellar masses and ages, star-formation rate) is followed in a simple formal way, a necessary step is to decide what the SFR is at a given time before computing all other quantities at the next epoch. In semi-analytic models (SAMs), the accretion history is given by a dark-matter halo-merger tree, but the baryon physics similarly rely on some assumptions concerning the SFR. Even in full hydrodynamical simulations following not only the dark matter but also the gas and stars, it is impossible to fully resolve the scales at which individual stars form. Thus, so-called "sub-grid" physics have to be implemented to simulate star formation.

We thus need "star-formation laws" to understand what affects the SFR on galactic scales, and, in a pragmatic way, to implement in models. In an ideal world, we would like these laws to emerge from first principles. A lot of theoretical ideas have been proposed (see e.g. a compilation in Boissier, 2013). They will not all be reviewed here, but it is worth mentioning a few of the very general ideas that have been discussed.

One important issue in this field is the existence (or not) of a threshold for star formation. The work of Toomre (1964) has presented the instability of a galactic disk against axi-symmetric (or large-scale shell) perturbations. He introduced the concept of a threshold radius beyond which the local density is too small to induce collapse with respect to the orbits and dispersion velocity. There are many variations of the "Toomre parameter" Q, taking into account, for instance, the contribution of gas and stars, or based on the

[2] Multi-wavelength Analysis of Galaxy Physical Properties; http://astronomy.swinburne.edu.au/∼ecunha/ecunha/MAGPHYS.html

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shear due to differential rotation. The concept has been largely discussed and compared to profiles with various SFR tracers (e.g. Martin and Kennicutt, 2001; Boissier et al., 2007; Goddard et al., 2010). Another possible reason for the existence of a threshold is the balance between a warm and cold gas phase (in which stars form), which is weakly influenced by the metallicity, the gas fraction, and the flux of ionizing photons (Schaye, 2004).

The other issue is to understand what determines the amount of star formation given the physical conditions in a galaxy (or a galaxy region). Many propositions have been discussed (e.g. Leroy et al., 2008; Boissier, 2013, and references therein). One simple way to present this question is to write (e.g. Larson, 1992; Wang and Silk, 1994):

$$\Sigma_{\rm SFR} = \epsilon \frac{\Sigma_{\rm GAS}}{\tau}, \qquad (1.2)$$

where ϵ is an efficiency and τ the timescale to form stars from gas. The most basic assumption (Madore, 1977) is that τ is set by the free-fall time $\left(\tau \propto \rho_{\rm GAS}^{-0.5}\right)$. For a constant scale height, this gives that $\Sigma_{\rm SFR}$ is proportional to $\Sigma_{\rm GAS}^{1.5}$. A wide variety of ideas can be found in the literature to decide which physical processes set up the timescale τ, or if other factors affect ϵ. These ideas include the possibility to consider hydrostatic equilibrium, gravitational collapse, self regulation, the influence of spiral arms sweeping up material at the rotation frequency, and cloud-cloud collisions. As a result, we can deduce that the $\Sigma_{\rm SFR}$ may be proportional not only to $\Sigma_{\rm GAS}^{\rm N}$, with N varying between 1 and 2 (Wyse, 1986; Larson, 1992; Bigiel et al., 2008; Leroy et al., 2008) but also to the stellar surface density to some power (Abramova and Zasov, 2008; Blitz and Rosolowsky, 2006; Corbelli, 2003), or to the angular rotation velocity Ω (Wyse, 1986; Wyse and Silk, 1989; Larson, 1992; Tan, 2000). These dependencies are quite degenerate, so that it is not clear which effects are really at play or are dominant.

In the next sections, we show a few empirical works providing the state of the art on such star-formation laws that play an important role in the community.

1.4.2 Simple Relations between Gas and Star-Formation Rate

The first study trying to relate the SFR (in fact the number of young stars) and the gas density in the Milky Way dates back to Schmidt (1959). Many empirical works have followed up to today, increasing the size of the samples, improving the resolution, using different SFR and gas tracers. We will only mention a few of the most famous studies to illustrate this part. The work of Kennicutt (1998b) is especially notable because it combine circum-nuclear starbursts, centers of galaxies, and disk averages to construct a relation between the total gas density and the SFR density over five orders of magnitude. It found an index of N = 1.4 for the $\Sigma_{\rm SFR}$– $\Sigma_{\rm GAS}$ relation, close to the expectation obtained with the free-fall time scale (1.5). As can be seen in the left part of Fig. 1.1, this relation nevertheless presents some dispersion. Especially, using only the "normal" galaxies, a

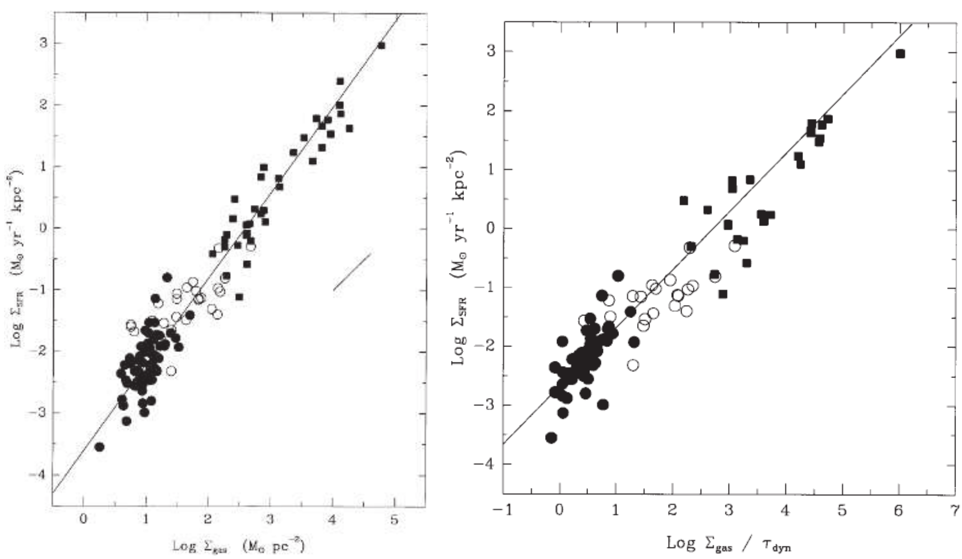

Figure 1.1 *Left*: The classical Schmidt law (slope 1.4) obtained by combining entire galaxies (circles), centers of galaxies (open circles), and circum-nuclear starbursts (squares).
Right: The dynamical Schmidt law for the same data. Figures from the seminal paper of Kennicutt (1998b), ©AAS. Reproduced with permission.

steeper index would have been found (as it was the case in other works). While this relation is not the "ultimate law" (as sometimes used by modelers), it is nonetheless a very influential one.

In more recent years, it has became possible to obtain resolved images of galaxies in multiple wavelengths, sensitive to young star emission (e.g. ultraviolet with GALEX[3]), to dust emission (with *Spitzer Space Telescope (Spitzer)*[4] or *Herschel Space Observatory (Herschel)*[5]), to ionized-gas, and to the neutral-gas content (molecular-gas maps, usually traced by CO lines, and neutral HI gas). In the coming years, we can expect even more well-resolved data concerning the gas and the star formation in galaxies, with many integral field units being now available, and with the new large radio/millimetric observatories (NOEMA,[6] ALMA,[7] SKA[8]). A noted study in the domain of resolved star-formation law

[3] GAlaxy Evolution Explorer; www.galex.caltech.edu/index.html
[4] *Spitzer Space Telescope*; www.spitzer.caltech.edu
[5] *Herschel Space Observatory*; www.cosmos.esa.int/web/herschel/overview
[6] NOrthern Extended Millimeter Array; http://iram-institute.org/EN/noema-project.php
[7] Attacama Large Millimiter/submillimeter Array; www.almaobservatory.org/en/home/
[8] Square Kilometer Array; www.skatelescope.org

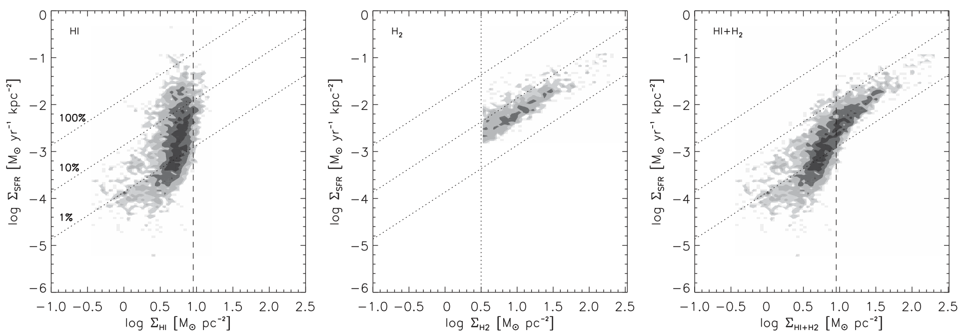

Figure 1.2 Local star-formation laws observed in few 100-parcsec pixel scales for the HI, H_2, and total gas. From Bigiel et al. (2008) ©AAS. Reproduced with permission. Color version available online.

was conducted by the THINGS[9] team which obtained exquisite HI maps of a few nearby representative galaxies. Figure 1.2 shows the star-formation law published by Bigiel et al. (2008), as observed at scales of a few hundred parsecs. A new paradigm emerged from this study with a very good correlation (with slope of unity) between the molecular gas and the SFR. In contrast, the HI saturates at a density of around 10 $M_\odot$ pc^{-2}, indicating that the gas becomes mostly molecular at high total gas density. In their results, the molecular fraction correlates with various quantities (distance from the center, stellar density, pressure, orbital timescale). Several works have also suggested that star formation is closely related to the dense gas that may be better traced by molecules such as HCN rather than CO (Gao and Solomon, 2004).

The trends in Fig. 1.2 are actually well reproduced by the simple local model of Krumholz et al. (2009), which predicts the correct amount of molecular gas and star formation once the total gas density is set. However, the spatial distribution of the total gas is not set in this model, and should result from many other physical effects (spiral arms, accretion) that could affect other star-formation laws (i.e. global or radial ones instead of the local ones).

1.4.3 Influence of Other Parameters

Kennicutt (1998b) noted that a dynamical law (right panel of Fig. 1.1) also provides a good fit to his data in nearby galaxies. In this case, the gas density is divided by the dynamical timescale of the system. Star-formation laws including a dynamical factor (e.g. rotation timescales for disks) are thus credible alternatives. Several works have also proposed

9 The HI Nearby Galaxy Survey; www.mpia.de/THINGS/Overview.html

(and tested) the possible influence of the stellar density on star formation (e.g. Dopita and Ryder, 1994; Shi et al., 2011) that can find some theoretical support as seen above. The influence of the stellar density on the gas scale-height may result in better laws involving the volume densities rather than the surface densities. A few works have attempted to study the volume star-formation law (Abramova and Zasov, 2008; Bacchini et al., 2017). Another possibility is that several timescales must be combined to properly describe star formation itself and the inhibition to form stars that results from it afterwards (Madore, 2010; Semenov et al., 2017).

The main difficulty concerning additional parameters is to distinguish between variations with galactocentric radius, stellar density, and dynamical timescale, as all these quantities vary in a correlated way.

1.4.4 The Star-Formation Law at High Redshift

Most early works on the star-formation law were performed in the nearby universe. Its evolution with redshift is a very important issue, especially for scientists who wish to model the evolution of galaxies over cosmic times. In recent years, it became possible to obtain constraints on the gas (mostly molecular) in distant galaxies (with NOEMA or ALMA, for instance), allowing astronomers to attempt to empirically determine star-formation laws at various redshifts. In the future, we shall also have access to the HI content of distant galaxies (SKA) and pursue these studies. The first studies suggested a higher efficiency in starburst galaxies at redshifts up to $z \simeq 2.5$, by a factor of 4 or so. However, a lot of unresolved issues make this picture unclear. In particular, the possible variation of the conversion factor for the molecular gas tracer (i.e. the conversion factor between an easily traced species, typically CO, and the total molecular mass which is dominated by H_2; see e.g. Carilli and Walter, 2013). The higher efficiency could also be related to the inclusion of starbursting galaxies at high redshift, in which the mode of star formation may be more efficient, e.g. because of the compressive mode of turbulence (Renaud et al., 2014). It was also noticed that the dynamical law seems to hold at high redshift (Daddi et al., 2010; Genzel et al., 2010). Other attempts to determine the high-redshift star-formation law made use of the dust emission of ALMA (Scoville et al., 2016) or of stacked HI absorbers (Rafelski et al., 2016), and various statements on the variation of efficiency with redshift have been issued. These observations, however, involve different types of gas tracers or SFR tracers and different range of masses or density, which makes the comparison between results difficult.

Figure 1.3 shows a compilation of star-formation laws in the nearby and more distant universe, illustrating quite some diversity. More work will be needed in the future to get a complete and clear picture of the star-formation laws, on different scales, and their evolution with redshift. For this purpose, it will be important to use accurate determinations of the SFR, and be well aware of the limitations of each method.