Where stars are born:
Kinematics and photometry of starburst and postburst galaxies

Javier Blasco-Herrera
**Cover image:** Velocity map of NGC 5961, from Paper II.
Abstract

The understanding of the formation and evolution of galaxies will not be complete until we understand the physical processes that trigger and regulate star formation in them. This work is about star formation on several size scales. It includes the kinematic study of 157 H II regions in the spiral galaxy M 83, in order to test the relation, if any, between luminosity ($L$) and velocity dispersion ($\sigma$), indicative of virialization. We found that there is no strong correlation between the mentioned variables, but only an upper envelope with a maximum luminosity for a given velocity dispersion. We demonstrated that this envelope has a slope that is strongly dependent on an accurate correction of instrumental broadening.

Using our experience in H II regions, we moved to star formation at larger scales. Thus, the bulk of this thesis is on starburst galaxies and their evolutionary descendants, the postburst galaxies. A starburst is a galaxy that is suddenly creating large amounts of stars, at a rate that is not sustainable for long periods. We performed a kinematic study of a sample of 11 such objects, showing that they are, in general, not supported by rotation and that many of them are consistent with a recent merger which affected their morphology and kinematics. Furthermore, from Sloan Digital Sky Survey (SDSS) we extracted a robust sample of 1006 starbursts and 240 postbursts at redshift $0.010 < z < 0.083$. We performed a comparative study of their structural parameters, such as effective radius, sersic index, asymmetry and absolute magnitude. We have found that the majority of starbursts and postbursts in the nearby Universe are disky galaxies, with a tendency for starbursts to have shorter effective radii and larger asymmetries.
To Claire
(rolling the "r")
List of Papers

The following papers, referred to in the text by their Roman numerals, are included in this thesis.

PAPER I: An improved method for statistical studies of the internal kinematics of HII regions: the case of M83

PAPER II: Hα kinematics of SDSS selected starburst galaxies

PAPER III: Structural parameters of SB and PB galaxies from SDSS

PAPER IV: Detection of Infalling Hydrogen in Transfer between the Interacting Galaxies NGC 5426 and NGC 5427

Reprints were made with permission from the publishers.
5 Postburst galaxies

5.1 Definition of Postburst galaxies

5.1.1 Dusty starbursts

5.2 Quenching mechanism

5.3 Photometry

5.4 Kinematics

6 Summary of the papers

6.1 Paper I

6.2 Paper II

6.3 Paper III

6.4 Paper IV

6.5 Contributions not included in this thesis:

7 Future prospects
List of Figures

2.1 Schematic explanation of a Fabry-Perot etalon (left) and resulting pattern in the camera (right). For details see section 2.2

2.2 Interferograms 1, 12, 24, 36 and 48 for a Neon calibration lamp. The ring of monochromatic wavelength ($\lambda$ 6598 Å) changes with the distance between the plates of the Fabry-Perot.

2.3 A paraboloid describes the surface of constant wavelength for a Fabry-Perot interferometer. The beginning of a second paraboloid is present as a reminder of the periodicity of Fabry-Perot instruments, and to warn about the importance of a careful selection of the number of interferograms and the separation between them.

2.4 Example of the calibration line in two random pixels of the raw interferograms.

2.5 Example of a data cube, with two spatial and one spectral dimension. An image for a certain $z$ shows the object in a given wavelength, while if we slice it along a slit in the $x-y$ plane we get a spectrum equivalent to a long slit. Credit: James Clerk Maxwell Telescope/Joint Astronomy Centre. Reproduced with permission.

2.6 Data cube of NGC 1530 not corrected (left panel) and corrected (right panel) for rotation. The cube consists in 42 cycles with 48 channels and 5 seconds of exposure each. Total exposure time: 2.8h. Total exposure time per channel: 3.5min. The spatial resolution of both cubes is the same, although the FoV has been enlarged by the derotation procedure in order to conserve all the received flux.

3.1 The Luminosity vs. velocity dispersion diagram derived by Arsenault et al. (1990).
3.2 Measured instrumental response function for GHαFAS (stars), together with the best fit to a Gaussian (blue dashed line) and a Lorentzian (red solid line). The width for both functions is also labeled in km s\(^{-1}\).

3.3 Left panel: Velocity dispersion calculated assuming the IRF is Gaussian (upper red line) compared to taking into account the full profile of the IRF (lower blue line). Right panel: Luminosity as a function of velocity dispersion for 157 H\(\text{II}\) regions in M\(83\). The upper panel shows the scatter diagram using the full instrumental response function to determine the velocity dispersion, while the lower one assumes the instrumental function is a Gaussian.

5.1 Ratio of the velocity to the velocity dispersion for the sample of Swinbank et al. (2012) (red circles) and Pracy et al. (2009) (blue squares), plotted together with the sample of ellipticals and spheroidals from Emsellem et al. (2007) (small black dots). The average of the samples of E+A is presented in black squares.
List of Tables

4.1 Comparison between three classic spectroscopic methods in the optical-IR range. ........................................ 38
1. Introduction

The evolution of galaxies in the past has been dominated by interactions, mergers, episodes of strong star formation followed by long quiescent periods... Currently, we are in the process of changing from that epoch of fast evolution into an epoch where internal, slow processes dominate (Kormendy & Kennicutt 2004).

Some aspects of galaxy formation and evolution have received increasing attention in the last decades. That has allowed us to improve our understanding of the processes of star formation as a function of scale (molecular clouds, H II regions, galaxies or nucleus of galaxies) and environment (isolated galaxies, pairs, groups and clusters of galaxies), and how those processes affect the evolution of the star formation in the Universe.

An important question regarding galaxies is what triggers enhanced star formation (the so called starburst episodes) in some galaxies, and what quenches the episode, guiding them into a post-burst phase. A related as yet unanswered question is the transformation of gas-rich, star forming, disc-like galaxies into gas-poor, quiescent, spheroidal galaxies. What process (or processes) produce the transformation from one to another? Is that process common for all the galaxies or only a subclass do transform into another, while the rest of the galaxies follow a different path?

The morphology and kinematics of galaxies can solve some of those questions. Many starbursts, for example, show double nuclei, tidal tails and/or companions, which together with very perturbed rotation points towards mergers and interactions being the cause of the trigger. After the starburst fades, we think those objects tend towards postburst objects, also called E+A galaxies. Those are also mainly pressure supported, although with clear signs of rotation. They appear in a line parallel to, and slightly brighter than, the Faber-Jackson relation, which indicates they might be the missing link between the star-forming galaxies and the dead elliptical galaxies.

Throughout this thesis we address some of these questions, studying star formation in different scales and from different perspectives. We study the kinematics of the H II regions in M 83 in order to investigate their kinematic properties and to test the potential of GHαFAS Fabry-Perot, a new instrument in the William Herschel Telescope. We also study the kinematics of the ionized gas in a sample of 12 starburst galaxies to determine the degree of rotation...
and the most likely explanations for the starburst episode. Finally, and this time using photometry to quantitatively discuss the morphology, we make a statistical study of a large sample of starburst and postburst galaxies from the Sloan Digital Sky Survey (SDSS).

I hope you enjoy your lecture!
2. GHαFAS Fabry-Perot

"Derotate the data by software? It should be easy, just with the coordinates of the object we can calculate its movement as time passes."

(A more naïve version of myself to Dr. Kambiz Fathi)

The Galaxy H-alpha Fabry-Perot System (GHαFAS, Hernandez et al. 2008) is a scanning Fabry-Perot interferometer mounted on the Nasmyth focus on the 4.2 m William Herschel Telescope (WHT) on La Palma. Its field of view (3.4 × 3.4 arcmin²), and high spatial and spectral resolution (0.2″/pixel and \( R = 10000–22000 \)) make GHαFAS especially suitable for studying optical emission lines on extended objects. Furthermore, the use of an Image Photon-Counting System (IPCS) camera instead of a CCD provides the best performance for faint objects.

GHαFAS has been used to study the pattern speed of a sample of galaxies (Fathi et al. 2009), the \( \text{H} \text{II} \) regions in the central part of M 83 (Paper I), the kinematics of the planetary nebula M 1-75 (Santander-García et al. 2010) and the interaction between a pair of galaxies (Font et al. 2011), demonstrating the versatility of the instrument.

Despite the fact that GHαFAS is mounted on the optical table at the Nasmyth focus of the telescope, it has been designed not to make use of the optical derotator provided by the Isaac Newton Group for the WHT. This is due to the fact that the derotator has a field of view of 2.5 × 2.5 arcmin² and a throughput of 75%. By not using it we improve the general throughput of the instrument while conserving our original field of view, at the cost of being forced to correct the rotation by software afterwards.

Part of this thesis has been devoted to producing the software that performs that correction. In order to explain in detail the derotation procedure in Section 2.4.2, we will need to introduce the basic concepts of Fabry-Perot interferometry in Sections 2.1 to 2.3.
2.1 Fabry-Perot interferometry

A Fabry-Perot interferometer performs 3D spectroscopy, producing a spectrum for every pixel of the camera or, in other words, an image of the object for every wavelength scanned. These instruments typically have large fields of view, combined with high spatial and spectral resolution, which makes them very powerful tools for the study of extended sources. On the other hand, the spectral range covered is typically small (≲ 10Å at Hα), often covering a single spectral line, and the acquisition is based on scanning in wavelength steps, which means that the information at different wavelengths is not simultaneously recorded.

2.2 The etalon

The heart of a Fabry-Perot interferometer is the etalon, sketched in figure 2.1.

![Figure 2.1: Schematic explanation of a Fabry-Perot etalon (left) and resulting pattern in the camera (right). For details see section 2.2](image)

The etalon is formed by two semi-transparent plates (thick vertical lines) separated by a distance $d$, forming a cavity filled with a gas of refractive index $\mu$, usually air. Each ray that enters through the first plate will be transmitted with an angle $\theta$. Then, it will be partially transmitted and partially reflected on the second, this process being repeated several times. Each of the incoming rays has produced a series of parallel rays at the exit of the etalon, with different optical paths. Due to interference properties, only wavelengths for which the optical path of the rays differ in $2\pi$ will produce constructive interference when focused onto the focal plane of the camera. The fact that only a certain wavelength of each ray is focused is emphasized in figure 2.1 by using green
and red lines with different dashes of different length, and due to the circular symmetry of the system the image in the screen presents a green and a red circle (right panel of figure 2.1). Only two wavelengths (green and red) appear in the sketch, but the most general case would show a gradient of wavelengths from center to edge.

The equation that describes the constructive interference is:

$$m\lambda = 2\mu d\cos\theta \quad (2.1)$$

where $m$ is the interference order, $\lambda$ the wavelength for constructive interference, $\mu$ the refractive index within the plates, $d$ the distance between the plates and $\theta$ the angle of the ray transmitted through the first plate.

For a given distance between the plates and refractive index, the resulting image, usually called interferogram will present a pattern of rings of different wavelengths. Any change in $\mu$ or $d$ will cause the rings to change wavelength, effectively allowing us to perform a scan. GHαFAS uses a piezoelectric to change the distance between the plates, effectively producing a spectrum for every pixel. Figure 2.2 shows an example of the output of the scan performed on a monochromatic source, the [Ne]λ6598 emission line of the calibration lamp.

![Interferograms](image)

**Figure 2.2:** Interferograms 1, 12, 24, 36 and 48 for a Neon calibration lamp. The ring of monochromatic wavelength ($\lambda$ 6598 Å) changes with the distance between the plates of the Fabry-Perot.

Interferograms 1, 12, 24, 36 and 48 (of a total $N = 48$) show, as expected, the radius of the ring of constant wavelength changing with $d$. We can observe an important characteristic of Fabry-Perot data, the periodicity: a hypothetical interferogram 49 would be equal to the number 1. This is inferred from equation 2.1 since by increasing $d$ for a fixed $\cos(\theta)$ (i.e. for a constant ring on the focal plane), the interference order $m + 1$ will eventually appear at that
radius. Similarly, when decreasing $d$ the order $m - 1$ will also appear. Usually the maximum distance between the plates is fixed to scan one single interference order. The range between two consecutive orders is called a Free Spectral Range (FSR) which is characteristic of every etalon and wavelength, $\lambda$, as:

$$FSR = \frac{\lambda^2}{2 \mu d}$$  \hspace{1cm} (2.2)

The collection of all the interferograms in a 3D representation would show a curve of equal wavelength similar to the paraboloid represented in figure 2.3. Here the vertical axis is the scan direction and the other two represent the field of view of the instrument. The periodicity is present again as part of a second paraboloid, to illustrate the necessity of a careful selection of the number of interferograms and the separation between them. Should a case like that of figure 2.3 occur, the pixels in the central part of the image would be overexposed to the wavelength represented by the paraboloid, while underexposed to others.

**Figure 2.3:** A paraboloid describes the surface of constant wavelength for a Fabry-Perot interferometer. The beginning of a second paraboloid is present as a reminder of the periodicity of Fabry-Perot instruments, and to warn about the importance of a careful selection of the number of interferograms and the separation between them.

If, from the observations of the calibration lamp, we select two random pixels and collect the information from all the interferograms, we get the profiles in Figure 2.4 where the maximum of the line profile of the calibration lamp is displaced when comparing the two pixels. The lines are well represented by a Lorentzian function, and the width of the line, $\Lambda \lambda$, is a measurement of our spectral resolution, since with infinite accuracy we should resolve a delta function where the line is.
In order to decide the correct number of interferograms and the distance between them, we define the finesse, $\mathcal{F}$, as:

$$\mathcal{F} = \frac{FSR}{\Lambda \lambda}$$  \hspace{1cm} (2.3)

The finesse is, therefore, a measurement of the number of interferograms it would take to cover the whole FSR in steps exactly the size of the spectral resolution. Since the Nyquist criteria requires the number of interferograms to be $N \geq 2.2 \mathcal{F}$, that requirement, the spectral resolution and the FSR set the number and spacing of the interferograms.

2.3 Data acquisition

Once the finesse sets the number of channels, $N$, and the separation between them, we can scan the objects we are interested in. The targets are observed exposing each interferogram for short times ($5 - 10$ seconds), from 1 to $N$, repeating the operation for several cycles and storing each image of every cycle separately. By exposing for short times for several cycles, we achieve homogeneous atmospheric conditions and airmasses for all wavelengths while minimizing risks in case of interruption of the observations (e.g. due to bad weather or instrumental malfunction).

The process of data acquisition is particularly efficient with GH$\alpha$FAS, since it uses an image photon-counting system (IPCS) camera instead of a CCD. This allows for fast and noise-free readouts, where every photon is recorded as a single event. Furthermore, IPCS cameras are less sensitive than CCDs to cosmic rays, since a cosmic ray would be recorded as a single event,
having the same importance as a single photon in our observations. For more information about photon-counting cameras the reader is referred to Gach et al. (2002) and Hernandez et al. (2008).

For the projects in this thesis we have typically used $N = 48$, $n_{cy} \in [14, 30]$ ($n_{cy}$ being the number of cycles) and total exposure times per object of 2-4 hours.

2.4 Data reduction

2.4.1 Phase correction

The first step in the reduction of Fabry-Perot data is the phase correction. This process consists in producing a cube with $N$ monochromatic images, usually called channels from the $n_{cy} \times N$ interferograms stored during the acquisition.

In order to perform the phase correction, we calculate the position of the maximum intensity of the calibration line for every pixel. Thus we identify the wavelength each pixel has for each of the interferograms, and we easily calculate the shift we need to apply to each pixel for all of them to be coherent in the wavelength direction. This shift can be seen as a change on the phase of the signal formed by the calibration line, therefore the name of this step of the reduction process.

The shifts calculated from the calibration lamp are valid for the object observed with the same configuration of the instrument, allowing us to disentangle the wavelength information from the physical $\{x,y\}$ dimensions. We can, therefore, separate every single interferogram in a cube composed of 48 channels. For any other Fabry-Perot interferometer, we would add all of those cubes together, obtaining a data cube such as that represented in Figure 2.5. For GH\(\alpha\)FAS, on the other hand, we first need to correct for the rotation of the field of view before co-adding all the cubes.

\[1\] It is common in the literature to see the word "channel" used indistinctly for the raw interferograms and the monochromatic images.
Figure 2.5: Example of a data cube, with two spatial and one spectral dimension. An image for a certain \( z \) shows the object in a given wavelength, while if we slice it along a slit in the \( x - y \) plane we get a spectrum equivalent to a long slit. Credit: James Clerk Maxwell Telescope/Joint Astronomy Centre. Reproduced with permission.

2.4.2 Derotation of GH\( \alpha \)FAS data

Since GH\( \alpha \)FAS does not make use of a derotator, we need to compensate by software for the rotation of the field of view, the imperfections in the tracking and vibrations of the telescope. To illustrate the need of the correction Figure 2.6 shows the intensity map of a non-derotated data cube, together with the derotated version of the same cube.
The derotation of GHαFAS data is performed by identifying common and reasonably round objects (stars, circular H II regions and centers of galaxies) throughout the interferograms, calculating the rotation and translation to be applied to match all of them. This seemingly easy and straightforward method is complicated by the low number of counts present in each interferogram, due to the low exposure times (~5 – 10 sec) and the narrow wavelengths for which the interference is constructive (~0.4 Å FWHM). In some cases this produces unreasonably high uncertainties in the determination of the center of the reference objects, forcing us to stack together a certain number of interferograms until reasonably accurate values are found for at least two sources (obviously the more, the better). This means a trade-off between being able to assume that in a certain number of interferograms stacked together there is no rotation, on one hand, and accurately determining the centres of the sources used to derotate. The number of interferograms stacked together depends on the rotation speed of the FOV, the exposure time per channel and the nature of the reference objects. The latter plays a role because a bright star will show up in all the interferograms, while an H II region will usually appear only in the few channels where its Hα emission line is present.
Thus, the appropriate number of interferograms to be stacked together has to be selected on a case by case basis. Once stacked, the center of the reference objects can be estimated in all of them and the corresponding rotation and translation calculated. For this process we use the POWELL least squares technique, which estimates the set of three parameters \( \{ \Delta x, \Delta y, \theta \} \), i.e. translation in both axes and rotation around the origin of coordinates, that minimizes the maximum deviation of the reference objects. The criterion of minimizing the maximum deviation is used, instead of the mean or the median of the deviations, in order to avoid the program to accurately correct areas with several reference objects by sacrificing other areas with less references. In the general case, we prefer a homogeneous quality in the derotation over the whole FOV. The residuals produced by the minimization can be used to estimate the quality of the derotation, which depends once again on the speed of the rotation of the FOV, together with the number and nature of the reference objects.

In § 2.4.1 we have seen how we can disentangle the wavelength dimension from the physical ones. It is absolutely mandatory to do so before correcting for the rotation, since otherwise, when derotating, we would be introducing spurious shifts in wavelength. On the other hand, once the interferograms are converted into cubes with three independent dimensions, we can correct the two physical variables without affecting the spectral one.

In order to perform the correction, and to minimize the effect of the finite pixel size, a bilinear interpolation is used to calculate the derotated data cube. Thus, one by one, every individual interferogram is derotated and the resulting data cubes added together.

For example, the observations of NGC 1530 presented above are formed by 40 cycles of 48 interferograms, with 10 seconds exposure each. The optimum number of channels to be stacked together in this case was found to be 12. This compromise allows us to accurately measure the center of the stars that appear in the stacked images, while assuming rotation to be negligible within the groups of interferograms.

All the process of derotation is summarized in the following flow diagram:
2.5 Program updates

The derotation has been updated, producing a slightly different version. These changes, although made too late to be applied in Paper I or Paper II, are included here for completeness.

The update includes three main changes:

- A graphical user interface (GUI) has been added. Apart from the aesthetic improvement and ease of use, the inclusion of the GUI allows the user to select more sources, since it is easy to change the contrast of the images, including sources that with fixed contrast levels where not easy to detect.

- Inclusion of routines to derotate galaxies with no stars, using H II regions only. The problem with the H II regions is that, due to their emission line being narrow compared with the FSR we scan, they are useful sources just in some channels of the cycle, completely disappearing from the rest of it. When two or more stars are present in the field of view, they act as solid anchors and the H II regions are a mere reinforcement for the
calculations, but when there is only one star or none at all, this modification becomes mandatory. For that reason we have included a routine that starts derotating a piece of the cycle using the available H II regions and stars if present, and keeps adding new reference points as they appear, deactivating the ones that disappear as well. This leads to a bigger group of reference sources that are used for the derotation of the interferograms for which they are expected to be present.

- Removal of the “no movement” assumption within parts of the cycle. In the original code, the cycle was divided in parts (anything from 2 to 6 parts, depending on the rotation of the field of view and in the Hα flux of the source) and it was assumed that there was no rotation within those parts, applying the same correction to all the channels in each of them. Now, instead, the rotation is calculated for each channel, stacking when necessary the same number of channels before and after the one to be derotated. This improves the accuracy of the derotation and allows for a better tracking of the sources, since from one interferogram to the next (i.e. 5-10 seconds) the source moves at most a pixel in most cases, mainly due to atmospheric fluctuations, more than to actual rotation. This method helps avoiding false identifications of sources, since the rejection criteria can be more tightly constrained.
3. H II regions: the $L - \sigma$ relation

The original $L - \sigma$ relation was found by Faber & Jackson (1976) for elliptical galaxies. They reported the existence of a relation between absolute luminosity, $L$, and velocity dispersion, $\sigma$, of the form:

$$L \propto \sigma^4,$$ (3.1)

a correlation which can be derived from the virial theorem assuming both the surface brightness and the mass-to-light ratio to be constant for the sample of galaxies. Its importance resides in that it provides us with a means of estimating distances to galaxies by measuring the apparent magnitude and velocity dispersion, two quantities that are straightforward to obtain.

The Faber-Jackson relation is, in fact, a projection of the Fundamental Plane (Djorgovski & Davis 1987), which relates effective radius ($r_e$), average surface brightness ($\langle I \rangle$) and velocity dispersion ($\sigma$). From any two parameters, the third one can be derived. Any model of galaxy formation and evolution needs to explain the existence and correlations of the Fundamental Plane.

An equivalent result to the Faber-Jackson relation was found by Whitmore et al. (1979) for the bulges of spiral galaxies and by Terlevich & Melnick (1981) for a group of giant extragalactic H II regions. The last relation was interpreted by Terlevich & Melnick as proof that the giant H II regions are virialized systems and could be used as distance estimators, but the very existence of this relation is debated for H II regions. Several authors tried to reproduce the $L \propto \sigma^4$ relation for those objects, with a large variety of results. Roy et al. (1986) and Hippelein (1986) found a relation, but with exponents of 3 and 6, respectively, while Gallagher & Hunter (1983) found no relation at all. Melnick et al. (1987) found a slope of 5, and disregarded Gallagher & Hunter (1983) because most of their H II regions were not actually supersonic, i.e., were not giant.

All of these early studies were based on small samples of regions from different galaxies, thereby adding uncertainties to the determination of the luminosity. Arsenault et al. (1990) repeated the analysis with a bigger sample

1By 'giant H II regions', most authors refer to regions with supersonic velocity dispersions
of H II regions, all coming from a single galaxy, hence limiting the importance of uncertainties in the distance estimation. Their results are reproduced in Fig.3.1 which shows no clear relation between the variables. They reported, though, that there seems to be a minimum velocity dispersion for each luminosity bin or, equivalently, a maximum luminosity for each velocity dispersion bin, forming an upper envelope with a slope of 2.6. In similar studies for two different galaxies, Rozas et al. (1998) and Relaño et al. (2005) confirmed the existence of the upper envelope, finding a gradient of 2.6 and 2.0, respectively.

**Paper I** is devoted to a high precision study of 157 H II regions in M 83, paying special attention to correctly characterizing the shape of the emission line. All the mentioned studies assume a Gaussian as a fair representation of the instrumental response function (IRF) of a Fabry-Perot interferometer. If a Gaussian function is a good representation of the intrinsic shape, the observed line profile, the thermal broadening and the instrumental broadening, the observed profiles can be corrected to get the intrinsic ones using:

\[ \sigma^2 = \sigma_{obs}^2 - \sigma_{th}^2 - \sigma_{ins}^2 \]  

(3.2)

Of those assumptions, we do know that the thermal broadening is indeed well reproduced by a Gaussian. The observed profiles are traditionally represented by a certain number of Gaussian functions, accounting for contributions as different as turbulent motions, expanding shells and bubbles or flows in the system. So, the best we can say is that sometimes they are indeed a single Gaussian, or there is a main component that can be measured, disregarding...
any asymmetries or extended wings.

But the instrumental response has been demonstrated to be best represented by a Lorentzian (Bland-Hawthorn 1995; Moiseev & Egorov 2008, and Paper I). The IRF can only be assumed a Gaussian if the wings of the Lorentzian are insignificant compared with the core, which is not usually the case for Fabry-Perot interferometers, and certainly not for GHαFAS (Figure 3.2).

We followed a two-fold approach in order to quantitatively measure the importance of taking into account the full shape of the IRF. The first method represented the IRF with a Gaussian, as all the previous studies did. The second avenue used the full instrumental response to convolve it with the models (1, 2 and 3 Gaussian components) before fitting it to the observed line profiles.

Our results showed that most of our H II regions were fitted best with a single Gaussian, since the errors associated with introducing a second and third components did not justify their inclusion. We showed that, with the Gaussian assumption the velocity dispersion is overestimated by $\sim 7 \text{ km s}^{-1}$ (left panel of Figure 3.3). Moreover we confirmed the previous claims of the existence of an upper envelope (right panel of Figure 3.3). The slope of the envelope is 2.1 for the method that assumed a Gaussian for the IRF, in good agreement with (Arsenault et al. 1990; Rozas et al. 1998; Relaño et al. 2005). On the other hand, when the most accurate representation of the IRF is used, we find a shallower gradient of 1.1.

We further noticed that the upper envelope sets in for a luminosity between 38.5 and 38.6 dex (in ergs), value found also in the work by Rozas et al. (1998).
Figure 3.3: Left panel: Velocity dispersion calculated assuming the IRF is Gaussian (upper red line) compared to taking into account the full profile of the IRF (lower blue line). Right panel: Luminosity as a function of velocity dispersion for 157 H II regions in M83. The upper panel shows the scatter diagram using the full instrumental response function to determine the velocity dispersion, while the lower one assumes the instrumental function is a Gaussian.

This luminosity coincides with that for which the power law representing the luminosity function of H II regions breaks (e.g. [Kennicutt et al. 1989; Rand 1992; Beckman et al. 2000]) and, if confirmed with other studies, might provide a distance estimator analogous to the tip of the Red Giant Branch.

In any case, as discussed by [Rozas et al. (1998) and Beckman et al. (2000)], the departure from $L \propto \sigma^4$ can not be directly interpreted as a lack of virial equilibrium. They argue that, since the regions of high luminosity are density bounded and not ionization bounded, part of the ionizing radiation just escapes the H II region. This produces an underestimate of $L_{H\alpha}$ for a given mass, which in turn will give a shallower dependency between $L_{H\alpha}$ and $\sigma$. Indeed, [Rozas et al. (1998)] estimate masses for the H II regions in two different ways. The first method assumed virial equilibrium, while the second used the measured $L_{H\alpha}$ and average electron densities for H II regions to estimate the Hydrogen gas content, correcting it for He content as well. With this exercise, they showed that those regions in the upper envelope represent the closest to virial equilibrium, with virial masses a factor of 2-3 higher than the masses estimated from the luminosity.
4. Starburst galaxies

“[...] collection of objects [...] which have little more in common than that they form massive stars at some rate which by some measure can be called enhanced with respect to something else.”

Knapen and James (2009), about the definition of starbursts

Starburst (SB) galaxies are extremely important to understand the evolution of the Universe. They produce \( \sim 20\% \) of the high mass stars in the local universe, which account for \( \sim 10\% \) of the radiant energy production (Heckman 1998; Brinchmann et al. 2004). Moreover, they trace interactions and mergers of galaxies and, as gas rich systems with high star formation, actively participate in the chemical enrichment of the Universe. And their importance only increases with redshift, since starburst properties are observed in about 15\% of the galaxies at \( z = 1 \) (O’Connell 2005), which contributes to \( \sim 45\% \) of the SFR density in the range \( 0.4 < z < 1 \) (Guzman et al. 1997).

This chapter will introduce SB galaxies, including definition, characteristics, triggering mechanisms and kinematics.

4.1 Definition of starburst galaxies

A starburst is, intuitively, a galaxy with an enhanced *star formation rate (SFR)*. Then the question arises, enhanced with respect to what? Definitions in the literature often involve the comparison of the SFR with:

A typical SFR: starbursts are defined simply as unusually high SFR for the galaxy type.

B the past SFR: a starburst galaxy produces stars at a faster pace than it previously was (Scalo 1986; Kennicutt 1998).

C the gas reservoir: a starburst galaxy will typically exhaust its Hydrogen in a time much shorter than a Hubble time (Weedman 1983).

D the total stellar mass: a starburst is a galaxy for which the time it would take to build up the mass of the galaxy at the current SFR is much smaller than a Hubble time (Östlin et al. 2001).
the luminosity of the new stars: starbursts are galaxies for which the bolometric luminosity of the newborn stars is larger than the luminosity of the underlying galaxy (Terlevich 1997).

A list of objects selected using any of these definitions will partially overlap with the list defined by any of the others. In fact, such an experiment has been done by Knapen & James (2009), who found that there is no coherent definition that match all the ones mentioned above. Let us assume as an example a dwarf galaxy which is creating stars at a much faster pace than it used to (definition $B$). This galaxy will fulfill criteria $D$, since the time it would take for the increased SFR to form the stellar mass of the galaxy will be, by definition, much shorter than the time it actually took. Depending on how large the reservoir of gas is it might also fulfill definition $C$, although this is not necessarily (or even often) the case (again Knapen & James 2009). On the other hand, the fact that the galaxy is creating stars much faster than it used does not mean it is creating them fast enough to fulfill definitions $A$ or $E$. A second example would be a galaxy which is creating stars at a very fast rate. Typically it will fulfill definition $E$ and, again depending on the gas reservoir, definition $C$ might be true, but that galaxy might have been creating stars at a similar rate for a long time, not fulfilling criteria $B$.

During this thesis, when referring to a starburst, we mean the second definition, since it is the literal definition of a “burst”, a sudden increase in the SFR. Within this definition, Scalo (1986) defined the birthrate parameter as:

$$b = \frac{SFR}{<SFR>_{past}} \quad (4.1)$$

How large a $b$ is needed to define a starburst is a matter of taste. In a recent proceeding, Bergvall (2011) calls galaxies with $b > 3$ mild starbursts, while a strong starburst will have $b > 10$. Equation 4.1 was modified by McQuinn et al. (2009) to restrict the average in the denominator to the last 6 Gyr in order to not consider initial bursts over the time of the assembly of galaxies. They also use 2 as a threshold.

The application of the birthrate parameter is hindered by the difficulty in the reliable determination of past SFRs for most galaxies. Whenever resolved stellar populations are available, the fit of isochrones to the color-magnitude diagram allows the derivation of SFRs, typically in the last $\sim 1–2$ Gyr (Cannon et al. 2003; Annibali et al. 2008; Angeretti et al. 2005; McQuinn et al. 2010). But the number of objects accessible through this technique is very limited, and for most of the galaxies indirect tracers of star formation need to be used. Among them, one of the most common is the H$\alpha$ equivalent width, $EW(H\alpha)$. Since the nebular emission traces massive (hence young) OB stars while the
continuum depends on both new and old stars and in the nebular continuum, it follows that the higher the \( EW(H\alpha) \), the larger the contribution of new stars as compared to the old. Again, the question is: how large must \( EW(H\alpha) \) be? Lee et al. (2009), using population synthesis codes from Bruzual & Charlot (2003), argues that \( EW(H\alpha) = 100 \) Å is roughly equivalent to a \( b \approx 2.5 \) and therefore suffices to define a galaxy as starburst. This particular threshold is questioned by the models of Zackrisson et al. (2001), which can reproduce \( EW(H\alpha) = 100 \) Å with a continuous star formation during a Hubble time superposed to a modest recent burst. Therefore, probably a more restrictive limit should be used, with \( EW(H\alpha) = 120 \) Å.

4.2 The diversity of Starbursts

The definition of SB galaxies given above includes objects with different physical properties and phenomenology, as different from each other as Blue Compact Galaxies (BCGs, Searle & Sargent 1972, Kunth & Östlin 2000) and (Ultra-)Luminous Infrared Galaxies ((U)LIRGs, Sanders & Mirabel 1996). A brief introduction of this two types follows, since we will mention them often from now on.

4.2.1 Blue Compact Galaxies

First reported by Zwicky (1965), the name of this class of objects gives away some clues about their phenomenology. Blue Compact Galaxies (BCGs) were thought to be blue stars when first observed, until their spectra revealed them as extragalactic sources. Their high SFR, in many cases several tens of solar masses per year, is responsible for the existence of a large population of OB stars, which confers on these galaxies their blue colour (\( B - V \approx 0.0 - 0.3 \); Kunth 1995) and their high surface brightness. The highly energetic UV photons emitted by those massive stars ionize the interstellar medium (ISM), producing another of the characteristics of BCGs, i.e., their strong emission lines (e.g. Campbell et al. 1986, Terlevich 1997). Those emission lines usually proved BCGs to be low metallicity objects, with a metal content \( Z \) between 1/50 and 1/3 of the solar metallicity (e.g. Searle & Sargent 1972, Masegosa et al. 1994, Kunth & Östlin 2000), which induced Searle & Sargent (1972) to suggest that BCGs might be genuinely young galaxies producing their first generation of stars. This hypothesis lost grounds with the improvement of the detectors, when many studies in optical and NIR showed an underlying and extended old population of stars, in which the starburst is embedded (Thuan 1983, Loose & Thuan 1986, Kunth et al. 1988, Papaderos et al. 1996, Kunth & Östlin 2000, and many others). Nowadays, the favoured theory is that these
objects are old galaxies which have recently increased their SFR (for details on the triggering mechanism see Section 4.3).

Once again, several subgroups can be defined within this general phenomenology, leading to a wealth of different names and definitions which, in one way or another, modify the one given here. To that group belong the luminous compact blue galaxies (LBCGs), blue compact dwarfs (BCDs), HII galaxies, ultraviolet luminous galaxies (UVLGs) etc. As interesting as it might be to discuss the peculiarities of every group, throughout this thesis I will refer to them all as BCGs because it is more than they have in common than what differentiates them.

4.2.2 (U)LIRGs

Luminous Infrared Galaxies (LIRGs) and their more extreme cases, the Ultra Luminous Infrared Galaxies (ULIRGs) are star-forming galaxies that, due to their large dust content, emit most of their energy in the infrared, with \( L_{\text{IR}} = L_{\text{8-1000\mu mmm}} > 10^{11}L_\odot \) for the LIRGs and \( L_{\text{IR}} > 10^{12}L_\odot \) for ULIRGs. They were discovered (Houck et al. 1984; Soifer et al. 1984) in the Infrared Astronomy Satellite (IRAS) survey (Neugebauer et al. 1984). A merger or strong interaction of gas rich galaxies is present in almost every ULIRG, while LIRG systems are probably the result of minor mergers (Sanders & Mirabel 1996; Sanders et al. 2009). Under certain circumstances, these processes lead to starburst episodes, which is the main power source of, at least, the lower luminosity objects. The contribution from active accretion of mass onto a Black Hole, the so called Active Galactic Nucleus (AGN), becomes increasingly important as the LIRGs evolve (Veilleux et al. 1995; Goldader et al. 1995; Yuan et al. 2010). In the case of the ULIRGs, the relative contributions of the starburst and AGN is more complex to analyze (Farrah et al. 2003; Imanishi et al. 2007; Farrah et al. 2007), but agreement seems to be reached in the fact that they have very enhanced SFR, that can be of the order of \( 10^2M_\odot \text{ yr}^{-1} \) at low redshift, while exceeding \( 10^3M_\odot \text{ yr}^{-1} \) for \( z > 2 \) (Lonsdale et al. 2006).

4.3 What triggers the starburst?

Once it is clear that starburst galaxies undergo transient periods of highly efficient star formation, the question ’What triggers them?’ is next in line. Several theories have been proposed, and the diversity of objects that form the category ’starbursts’ could mean that there is not a unique valid answer.

In one of the first attempts to explain the trigger of BCGs, Searle et al. (1973) proposed that statistical fluctuations in the SFR during less than 1/10 of the lifetime of the galaxy (i.e. 5-10 episodes of \( \sim 10^8 \text{ yr} \)) is enough to explain
the colors of BCGs. Furthermore, in an stochastic model for the star formation, variations are expected to be largest for small systems, which indeed is observed, with SB galaxies being much more common in dwarf galaxies. This idea was further developed by Gerola et al. (1980), who carried out simulations of stochastic self-propagating star formation (SSPSF) models. In those models, the feedback of the massive star formation (increase in gas temperature and outflows) in one cell of the galaxy model would halt the star formation in it and propagate to each surrounding cell with a certain probability. The fact that smaller galaxies have less number of such cells provide a fast exhaustion of the star formation burst, leaving the galaxy in a quiescent state, while bigger systems always display star formation in some part of the galaxy. A later addition to SSPSF models was the inclusion of galactic-scale winds (Matteucci & Chiosi 1983; Carigi et al. 1995).

A more frequent explanation invokes tidal interactions and mergers as the triggering mechanism of starbursts. As we have seen, (U)LIRGs were from the first moment associated with them (Sanders et al. 1988; Sanders & Mirabel 1996) and the evidence came even earlier for BCGs. In a very influential article, Larson & Tinsley (1978) were the first to put forward this theory, showing that a sample of galaxies with signs of tidal interactions produced extra scatter in colour-colour diagrams of galaxies. They explained the phenomenon in terms of recent short (∼20 Myr) bursts of star formation involving ∼5% of the total mass of the galaxy. Using IR data (Lonsdale et al. 1984) found equivalent results for a sample of interacting/merging galaxies, and measured an increase in SFR of a factor of ∼3. However, both studies used galaxies from Arp’s "Atlas of peculiar galaxies" (Arp 1966), a point criticized by Kennicutt et al. (1987) due to the selection bias toward high surface brightness galaxies, i.e. active systems. Using a complete sample of pairs of galaxies observed in Hα they also found an increase of SFR for interacting galaxies, but only present in 10 − 15% of their sample and explained by a short (10 Myr) burst that would involve 1 − 2% of the mass of the galaxy. Many other pieces of evidence supported this idea, including star formation using radio wavelengths (Condon et al. 1982; Taylor et al. 1995; Taylor 1997), multiwavelength (Bushouse 1987), spectroscopy (Keel et al. 1985) and simulations (Mihos & Hernquist 1994a,b). Hence, by the end of the nineties it was clear that interactions and mergers can indeed produce high star formation enhancement.

And then, dissonant studies started to emerge. Bergvall et al. (2003) studied two magnitude limited samples of isolated pairs and isolated individual galaxies. The difference between this work and previous ones (an exception is Kennicutt et al. 1987) is that the two samples of galaxies studied by Bergvall et al. (2003) are selected to have the same distribution of morphological types. The colours found do not support a significant increase in the SFR for the inter-
acting galaxies. They concluded that interactions (and specially mergers) are probably a necessary but not sufficient condition to trigger SB galaxies, which do exist in their sample, but are uncommon and shortlived, probably constituting $\sim 0.01\%$ of the sample. In the last years many other authors support this view, (e.g. Knapen & James [2009], Jogee et al. [2009], Robaina et al. [2009]) finding an average increase of SFR in interacting galaxies of a factor $2 - 5$. The starburst episodes contribute to $\lesssim 10\%$ of the star formation since $z \sim 0.6$, with the rest being produced in regular star formation modes (Robaina et al. [2009]). Of course, strong starbursts are found in their samples, pointing once again to the idea that interactions and mergers are not the only ingredient for a successful starburst. Simulations show that some of these missing ingredients include the relative distances and masses of the objects, the gas mass fractions or the orbital geometry of the interaction (e.g. Mihos & Hernquist [1996], Cox et al. [2006], Di Matteo et al. [2007]). The models describe an increase of the SFR on every close passing of the galaxies, with tidal interactions as an effect of resonances if the galaxy encounters are prograde (Toomre & Toomre [1972]) and a final burst if fuel is still available by the time of coalescence.

4.4 Photometry of starbursts

Although Zwicky [1965] described BCGs as compact objects with blue colours and high surface brightness, we know now that he was describing just the starburst episode taking place inside a fainter underlying galaxy, as proven by many deep photometric studies in the optical (e.g. Loose & Thuan [1986], Papaderos et al. [1996], Bergvall & Östlin [2002]) and in the near infrared (e.g. James [1994], Bergvall & Östlin [2002], Bergvall et al. [2003]). The host galaxy, formed by an older population, usually dominates in mass and extends out to several kiloparsecs, while the star forming region provides a centrally concentrated, transient increase in luminosity, usually with small contribution to the mass budget. The resulting luminosity profile is described by a shallow gradient at large radii, where the old population dominates, with a much steeper rise at the centre, representing the contribution of the starburst (Papaderos et al. [1996]). When quantitatively studying the photometric properties of starburst galaxies, the two components must be taken into account. It is rather common to fit an exponential luminosity profile to the host galaxy:

$$I(r) = I_0 \cdot e^{-r/r_d}$$

where $I_0$ is the central surface brightness and $r_d$ is the scale length of the galaxy. Papaderos et al. [1996] and Cairós et al. [2003], for example, fitted an exponential luminosity profile to describe the host galaxy and a superposed Gaussian
profile for the area of the starburst. Bergvall & Östlin (2002) and Caon et al. (2005), on the other hand, fit the outer parts of the galaxies to a Sersic profile (Sersic 1968):

\[ I(r) = I_e \cdot e^{-b_n \left[ \left( \frac{r}{r_e} \right)^{1/n} - 1 \right]} \]  

(4.3)

where \( r_e \) is the effective radius (also called half-light radius) which marks the radius that contains within half of the total luminosity of the galaxy, \( n \) is the Sersic index (\( n = 1 \) for an exponential profile, \( n = 4 \) for a de Vacouleurs profile) and \( b_n \) depends on the Sersic index as \( b_n \approx 2n - 0.324 \) for \( 1 \leq n \leq 15 \) (Trujillo et al. 2001).

Bergvall & Östlin (2002) found that the hosts in their sample of BCGs could be well fit by \( n \gg 4 \), suggesting elliptical underlying objects. Ulterior works find more modest Sersic indexes of \( 0.5 < n < 2 \) (Caon et al. 2005; Amorín et al. 2009), compatible with disc galaxies of \( \langle r_e, B \rangle \sim 0.5 - 2 \) kpc. It is, in any case, very difficult to distinguish between different profiles for the host galaxy using only the outskirts, so the projection of that profile into the centre to distinguish the contributions of the host and the starburst is indeed complicated. One way out of the problem is the combination of photometry and long-slit spectroscopy covering the whole galaxy. Some individual galaxies have been studied in this way (Guseva et al. 2003a,b,c; Cairós et al. 2007), but the total time required per object is of the order of two nights, making it a very inefficient process and with uncertainties derived from the different instrumentation used. Integral Field Units (IFU), on the other hand, are able to obtain 3D spectra of the object under identical instrumental and atmospheric conditions allowing for the separation of the starburst and the old stellar components (Lagos et al. 2009; Cairós et al. 2009b,a, 2010). Those studies are recent, though, and only individual galaxies are available for the moment.

4.5 Kinematic studies

For a full understanding of the origin and evolution of starburst galaxies, the study of the kinematics of those systems is essential. It can answer how and under what conditions the starburst episode is triggered and the nature of the quenching mechanism(s), for example. Unfortunately, and as we have already discussed, starburst galaxies are not a well defined and homogeneous population, which means that several mechanisms might be (and most likely are) playing a role. This means that the sample we select conditions the result we observe, as will do the type of data we use. Typically radio wavelength observations are well suited to study the outskirts of galaxies, while optical and near infrared (NIR) observations are preferred to probe the inner regions of the objects. Among the latter, long slit spectroscopy, Fabry-Perot and Integral Field
Table 4.1: Comparison between three classic spectroscopic methods in the optical-IR range.

<table>
<thead>
<tr>
<th>Method</th>
<th>Aim</th>
<th>3D information</th>
<th>High spectral res.</th>
<th>High spatial res.</th>
<th>Large FoV</th>
<th>Large spectral range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long-slit</td>
<td>Gas+stars</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Fabry-Perot</td>
<td>Gas</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>IFU</td>
<td>Gas+stars</td>
<td>✓</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>✓</td>
</tr>
</tbody>
</table>

Units (IFUs) are preferred, each with pros and cons, as briefly summarized in Table 4.1.

4.5.1 Kinematics of BCGs

The radio observations typically describe BCGs as generally rotating objects, although with various degrees of complexity in their kinematics and concentration of H I gas in the centre (Bergvall & Jorsater 1988, Meurer et al. 1996, van Zee et al. 1998, Thuan et al. 2004). High resolution H I velocity maps are difficult and time consuming to obtain, though, and the samples studied in those works range from 1 to 5 objects. The results from optical and IR studies reinforce the idea of overall gas rotation (Thuan et al. 1987, Östlin et al. 2001), but showing in general perturbations such as secondary dynamical components, tidal tails or outflows (e.g. Östlin et al. 2001, Pérez-Gallego et al. 2011, Paper II). Some authors even find their samples to be dynamically hot, i.e., supported by velocity dispersion and not by rotation (Bershady et al. 2005, Puech et al. 2006).

The combination of rotation at large radii with more complex kinematics in the inner regions fits well with the photometric description given in § 4.4, of starbursts as enhanced star formation in the centre of host galaxies.

The secondary components and tidal tails suggest interactions, and especially mergers, as triggers of the starburst episodes, as suggested by the studies of Östlin et al. (2001) using Fabry-Perot data and Pérez-Gallego et al. (2011) with IFU observations. Another option is that it is the feedback of the enhanced star formation which, a posteriori, perturbs a normally rotating host galaxy. Strong feedback processes, such as galactic-wide outflows, have ac-
ually been observed in the case of dwarf galaxies ($M_B \geq -18$), where the gravitational potential is lower (Marlowe et al. 1995). A means to differentiate this two scenarios might be the stellar component. If the stellar and gaseous components share kinematics, including where the velocity map of the gas is chaotic, then the creation of the stars and the perturbation where most likely simultaneous simultaneous, favouring the merger/interaction hypothesis. That seems to be the case, at least for ESO 338-IG04 (Cumming et al. 2008) and He-2-10 (Kobulnicky & Gebhardt 2000). A counterexample with stellar and gaseous components being kinematically decoupled can be found in ESO 400-G43 (Ostlin et al. 2004). For this object, star formation feedback or dynamical processes in a merger process are invoked as possible explanations.

4.5.2 Kinematics of (U)LIRGs

We mentioned in § 4.2.2 that LIRGs seem to be produced by minor mergers, while the ULIRGs are in general the result of major mergers of gas-rich galaxies (Sanders et al. 2009). The kinematics of those objects, obviously, betrays such origin. Mihos & Bothun (1998) observed a sample of 4 ULIRGs of similar luminosity, and found signs of mergers in different stages, from just after first encounter to coalescence. Even if it is true that most ULIRGs are in advanced stages of the merger, the fact that Mihos & Bothun find a galaxy that is just past first encounter rules out an scenario in which merging galaxies would start their starburst episodes as BCGs during the first phases of interaction/merger to evolve into ULIRGs in the last stages and coalescence. Other factors have to determine whether a merger produces an ULIRG. Mihos & Hernquist (1996) find in simulations that some of those factors are the total gas content of the progenitors, the geometry of the encounter (co-planar encounters producing the faster and more luminous ULIRGs) and the internal structure of the pre-merger objects, where for example they find that galaxies with a dense bulge are more stable against inflows and therefore suffer the highest levels of activity during the last stages of the merger.

Colina et al. (2005) found for 11 ULIRGs that the velocity field of stars and warm gas tends to agree, especially in the centre of the objects, where the velocity dispersion of both components are virtually identical. The velocity maps for the warm gas show a minority of objects being rotationally supported, with most galaxies having complex and incoherent velocity maps. Moreover, they show that the cold gas seems to have different kinematics, more consistent with a rotationally supported component. The Colina et al. (2005) paper is part of a series (see also Arribas et al. 2008; Monreal-Ibero et al. 2010; Rodríguez-Zaurín et al. 2011; Bellocci et al. 2012) that characterizes the properties of LIRGs and ULIRGs using integral field spectroscopy.
Monreal-Ibero et al. (2010) studies 32 LIRGs, classifying them into three different types (isolated, interacting pairs/triplets and merger remnants). They focused on the extra-nuclear regions, and reported higher velocity dispersion for the three groups as compared to normal spirals, indicating dynamically hotter objects. They also found that shocks have a large impact in interacting and merging galaxies, while being unimportant for isolated systems. This, together with the absence of a trend with the infrared luminosity indicates that the shocks are mainly induced by interactions, and not by the stellar winds or SNe.

4.6 From low to high redshift starbursts

The study of local starburst galaxies can give us an insight into the star formation processes in the early Universe. This common statement is not as straightforward and uncontroversial as it looks. Given that the star formation rate in the Universe has declined since $z = 1$ (Lilly et al. 1996), with the Universe in transition from rapid violent development to passive evolution of galaxies (Kormendy & Kennicutt 2004), it is fair to ask ourselves how similar the star-forming galaxies at high redshift are compared to the local population.

As in local starburst galaxies, we can find different groups of high-redshift analogs, depending on the techniques used to detect them.

The Lyman Break Galaxies (LBGs), star-forming galaxies which are identified by the lack of radiation at rest-frame wavelength shorter than $\lambda < 912\text{Å}$, can be traced to high redshifts of $z \gtrsim 7$ (e.g. Ravindranath et al. 2006; Bouwens et al. 2007; Oesch et al. 2010). Ravindranath et al. (2006) studied the multi-wavelength Great Observatories Origins Deep Survey (GOODS) sample from $z \sim 1.2$ to $z > 2.5$, finding that the sample was morphologically divided into 40% of disk-like galaxies, 30% spheroidal and 30% objects with profiles shallower than a disc (sersic index $n < 0.8$), which were shown to correspond to very irregular morphologies, close pairs and mergers. When comparing as a function of redshift, they found that at $z \sim 4$ the fraction of spheroids is larger than at $z \sim 1.2$. This means that spheroids would need to rebuild their discs in between those redshifts, maybe by gas accretion. Furthermore, the distribution of ellipticities peak at $\epsilon = 0.7$ for $z \sim 4$, at $\epsilon = 0.5$ for $z \sim 3$ to end up being a flat distribution by $z \sim 1.2$. The skewed distribution have at least two interpretations: the distribution of the LBGs is not that of inclined discs, but more elongated shapes, or what we see as elongation is actually bars and similar structures inside the galaxies.

Infrared luminous galaxies at $z \sim 1.5$ seem to be intrinsically different from our local ULIRGs (Daddi et al. 2010b; Sargent et al. 2012). First of all, they seem to have ordered rotation (i.e. not merging) and $L_{CO}/L_{IR}$ is a factor of...
3 higher at high redshift than in the local Universe (Daddi et al. 2010a). This ratio is a proxy for SFR efficiency, since it compares the amount of gas reservoir and the SFR as traced by IR emission. One valid explanation for this fact is a top-heavy initial mass function (IMF) for starbursting systems, first proposed by Elbaz et al. (1995). Indeed, if the proportion of high-mass stars is larger than what we assume in our models, the SFR would be overestimated, explaining the increase in $CO/IR$ ratio. Daddi et al. (2010b) find that this ratio seems to be inversely proportional with the dynamical timescales, suggesting instead that general properties of galaxies which determine the timescales, are also playing a role, most likely through high volume densities that increase the efficiency.

Observational challenges, unfortunately, produce a bias towards the brightest, most extreme objects, and such a bias has to be taken into account when interpreting the results.
5. Postburst galaxies

After a starburst episode is suddenly quenched, the galaxy goes through several important changes. The massive $O$ and $B$ stars die, and once they do not dominate any more the $A$ and $F$ stars take the lead, producing deep changes in the spectral and photometric properties of the galaxy. In this chapter we will go through the definition, phenomenology, formation mechanisms and implications of this type of galaxies.

5.1 Definition of Postburst galaxies

Postburst (PB) galaxies (Dressler & Gunn 1983) are characterized by their strong Balmer absorption lines and lack of emission lines, as a result of a large population of $A$ stars dominating the spectra of the galaxy after an abrupt end of a burst of star formation. Actually, the clear signatures of $A$ stars on top of an otherwise elliptical galaxy spectra led to Dressler & Gunn (1983) referring to them as E+A galaxies. Dressler & Gunn described the three objects, found in a cluster at $z \sim 0.46$, as consistent with a burst of star formation 1 Gyr earlier. Many other studies have confirmed the existence of this type of objects, not only in clusters (Couch & Sharples 1987; Fabricant et al. 1991; De Lucia et al. 2009) but in any other environment (Zabludoff et al. 1996; Norton et al. 2001; Tran et al. 2004; Yan et al. 2006).

The definition of a PB, like that of their progenitors, is not strictly established. A large equivalent width for Balmer lines in absorption is generally the criterion to select them, usually accompanied by weak or absent nebular emission lines, such as $[O\text{ II}]\lambda 3727$ or $H\alpha$. But, of course, the exact lines and limits are not rigid, leading to different sample selection criteria in the literature, such as:

- $EW(H\delta) < -4\,\text{Å}$ and $EW([\text{O II}]) < 5\,\text{Å}$, (e.g. Goto et al. 2003; Balogh et al. 2005)

- $EW(H\delta) < -4\,\text{Å}$, $EW([\text{O II}]) < 5\,\text{Å}$ and $EW(H\alpha) < 5\,\text{Å}$ (e.g. Yan et al. 2006; Swinbank et al. 2012)
\begin{itemize}
  \item $\langle EW (H_\delta) \rangle < -5$Å (e.g. Zabludoff et al. 1996; Norton et al. 2001; Pracy et al. 2009).
  \item $EW (H_\delta) < -5$Å, $EW (H_\gamma) < -4$Å, $EW (H_\beta) < -4$Å and $EW (H_\alpha) < 2.5$Å, (Pracy et al. 2012).
  \item $EW (H_\delta) < -6$Å, (Goto 2004, and Paper III).
\end{itemize}

The first definition is the most classic one, from times where the star formation would be traced better in [O II] $\lambda$3727 and not using H$\alpha$. The second one adds the H$\alpha$ criterion in order to better exclude AGNs and dusty starbursts (see § 5.1.1). The same aim is behind the third set of criteria, which demands a mean equivalent width for the three Balmer lines indicated. In the fourth, again, three Balmer lines in absorption and a low H$\alpha$ emission are demanded. Finally, requiring the galaxies to have extremely large H$\delta$ absorption will produce a sample of young postbursts.

5.1.1 Dusty starbursts

Since the star formation occurs surrounded by dust, the obscuration is larger for the newborn stars. This produces the well-known effect of emission lines suffering approximately twice as much attenuation as the continuum (e.g. Calzetti et al. 2000). The inclusion of H$\gamma$ and H$\beta$, with longer wavelengths and, therefore, more prone to be filled by the emission lines of residual or dusty star formation, helps in selecting a clean postburst sample. Using radio observations, Miller & Owen (2001) proved that the sample selected by Zabludoff et al. (1996) contained very little star forming galaxies, while Goto (2004) found no dusty starbursts in a sample selected using the last criteria in the list above.

Some authors have claimed that dusty starbursts such as ULIRG systems might be excellent precursors of the postbursts (Poggianti et al. 1999). Bekki et al. (2001) modelled a major galaxy merger to produce very dusty starbursts, which will show strong H$\delta$ absorption and modest [O II] emission (called e(a) galaxies). They showed that the dynamical and spectral evolution of such systems is consistent with an evolution from e(a) to E+A and then to passive red galaxies.

5.2 Quenching mechanism

If it is difficult to establish the trigger of a starburst galaxy, the quenching mechanism that suddenly stops the star formation, turning it into a postburst, is also very much debated. Moreover, since postbursts are found in very different
environments, such as field galaxies and clusters, a variety of mechanisms are most likely involved.

In cluster environments, for example, ram-pressure stripping (Gunn & Gott 1972; Farouki & Shapiro 1980) and galaxy harassment (Moore et al. 1998) can be efficient mechanisms to deprive a galaxy of its H\textsc{i} reservoir. The same effect can be produced by the gravitational potential of the whole cluster, which might strip a galaxy while it is being captured (Byrd & Valtonen 1990; Bekki et al. 2001).

Another suggested mechanism to stop the star formation in a starburst galaxy is the feedback from supernovae explosions and/or AGN activity, which will heat or expel the gas, quenching the star formation (Yan et al. 2006; Kaviraj et al. 2007; Tremonti et al. 2007). Swinbank et al. (2012) also find that low luminosity AGNs are present in 20-40% of the sample, which is a factor $\sim 8$ higher than expected, but they do not find any correlation between the active vs non-active galaxies, suggesting that either AGN are not of consequence or that their effects were too short to be observed in a small sample.

5.3 Photometry

Using a sample of 21 galaxies, Zabludoff et al. (1996) found signs of mergers and interactions for $\gtrsim 25\%$ of their sample. For the same sample, but using HST data, Yang et al. (2008b, 2009) rise the fraction of mergers to 55% as measured from tidal features, and report concentrated young populations (also expected in merger systems) for 70% of their objects. They also found large sersic index ($n \gtrsim 4$) and large bulge-to-total ratios (median $B/T = 0.59$) which, once the young population fades away, will transform postbursts in early type galaxies. Goto (2005) used SDSS Data Release 2 to quantify the fraction of postburst galaxies with tidal features, which they estimated to be 30%. This slightly lower value, as compared with Yang et al. (2008a) is not completely unexpected since, even if Goto (2005) have more robust statistics, the images provided by SDSS are much shallower and with less angular resolution than HST data.

Balogh et al. (2005) studied near-infrared images of 222 objects with $EW (H\delta) < -4\text{Å}$, including both galaxies with emission lines (e(a) galaxies), and real postbursts, where the nebular emission is weak or nonexistent. Those two groups have different photometric properties, with $B/T \sim 0.6$ for the postbursts, while the e(a) galaxies are disc dominated systems ($B/T \sim 0.1$). They found that both colours and morphologies distinguished the postbursts from the truncation of normal disc galaxies, leaving the SB progenitors as the only viable progenitors. Indeed, the colours are consistent with galaxies that have recently formed $> 5\%$ of their stellar mass.
5.4 Kinematics

Norton et al. (2001) observed the sample by Zabludoff et al. (1996) using long slit spectroscopy. They found that the young stellar population is more centrally concentrated than the old population, but it still extended over several kpc. Eighteen out of 21 objects are pressure supported, with only six showing any rotation at all within radius of 1-3 kpc.

On the other hand, since 3D spectroscopy became available, we have changed our picture of postburst galaxies. First Swinbank et al. (2005) studied a single object, finding that the velocity map and the position of gas and A stars (concentrated in an area of the galaxy the former, widespread the latter) was consistent with the accretion of a gas-rich spiral and a gas-poor passive galaxy. The second attempt in a single object was made by Goto et al. (2008), who studied a system formed by interacting galaxies. They found again that the population of A stars was spread over a large area of the galaxy, and not concentrated in the centre. The kinematics of this object was also extremely perturbed, with no signs of clear rotation. Two samples of 10 (Pracy et al. 2009) and 11 objects (Swinbank et al. 2012) further confirmed the large spread of A stars in the two samples. Figure 5.1 reproduces a plot from Swinbank et al. (2012). It shows the ratio of the rotational velocity to the line-of-sight velocity dispersion, $v_{\text{sin}}(i)/\sigma$, as a function of R-band magnitude. It includes both the sample from Swinbank et al. (red circles) and the sample from Pracy et al. (2009) (blue squares), with the average calculated and represented by black squares. They also plot the data from a recent sample of elliptical (E) and S0 galaxies from Emsellem et al. (2007). Although the sample of E+A galaxies has slightly higher values for the $v_{\text{sin}}(i)/\sigma$ ratio, a large part of them blend well with the sample of ellipticals and S0, suggesting that the postburst samples might be indeed the connection between star-forming rotating spirals and quiescent pressure-supported E and S0 galaxies. In general, and according to this simple ratio of circular velocity over velocity dispersion, postburst galaxies are not rotationally supported, even if they show rotation.
Figure 5.1: Ratio of the velocity to the velocity dispersion for the sample of Swinbank et al. (2012) (red circles) and Pracy et al. (2009) (blue squares), plotted together with the sample of ellipticals and spheroidals from Emsellem et al. (2007) (small black dots). The average of the samples of E+A is presented in black squares.

A more accurate description of the dynamical state of the galaxy is given by the formalism of Emsellem et al. (2007). They measure the luminosity-weighted stellar angular momentum per unit mas, $\lambda_R$, as:

$$
\lambda_R = \frac{\langle R|v| \rangle}{\langle R \sqrt{v^2 + \sigma^2} \rangle}
$$

(5.1)

with $R$ the distance of every pixel, $v$ the velocity and $\sigma$ the velocity dispersion. According to their definition, objects with $\lambda_R < 0.1$ are slow rotators (dominated by ellipticals), while fast rotators are those with $\lambda_R > 0.1$ (dominated by low mass spheroids).

Almost every galaxy from the samples of Pracy et al. (2009) and Swinbank et al. (2012) are declared fast rotators, with a median for the latter sample of $\lambda_R = 0.35 \pm 0.1$. This is consistent with the values of the sample of E and S0, increasing the similarities between both types of galaxies and indicating the possibility of the postbursts being the precursors of ellipticals and spheroidals.
6. Summary of the papers

6.1 Paper I

There is two main reasons to perform this study, one is technical, the other scientific.

The technical is partially explained in Section 2.4.2. GHαFAS Fabry-Perot is a relatively new instrument in the Nasmyth focus of the William Herschel Telescope (WHT). By not making use of the derotator in the WHT, we improve the throughput of the telescope with a large field of view, at the cost of needing to correct for the rotation of the Earth, vibrations of the telescope and deficiencies in the tracking by software. Part of my thesis was dedicated to create the software necessary to carry out that data reduction. It is an alive piece of code that still today keeps changing and improving.

The scientific reason was to test the relation between luminosity $(L)$ and velocity dispersion $(\sigma)$. This relation, $L \propto \sigma^a$ is found for elliptical galaxies (Faber & Jackson 1976) and bulges of spirals (Whitmore et al. 1979) and is the result of those systems being in virial equilibrium. The same relation was claimed for H II regions by Terlevich & Melnick (1981), leading to the conclusion that H II regions are also in virial equilibrium. Different attempts of confirming this relation have given different results, one of them being an upper envelope when plotting log$L$ as a function of log$\sigma$ (Arsenault et al. 1990).

We studied 157 regions in M 83, finding the upper envelope described by Arsenault et al. and not the linear relation. We further demonstrated that the slope of that upper envelope strongly depends on how we correct for the effect of the instrument in the measurement of $\sigma$. If assumed a Gaussian, which is rather common, the result will overestimate the velocity dispersions and, therefore, the slope of the envelope. When using the full description of the instrumental response function, a slope of $\sim 1$ is found.

6.2 Paper II

This work is devoted to the study of the kinematics of starburst galaxies and trace their evolution into postbursts. Three samples were created from the Sloan Digital Sky Survey (SDSS). The first sample was formed by starburst
galaxies, defined using the equivalent width in H\(\alpha\), \(EW(H\alpha) > 120\text{Å}\), the second group is formed by postbursts, selected using H\(\delta\) in absorption \((EW(H\delta) < -6\text{Å})\), while the third sample is made of intermediate objects, with \(EW(H\delta) < -4\text{Å}\) and \(EW(H\alpha) > 20\text{Å}\). A total of 25 galaxies were observed, although only 12 (11 starbursts and 1 intermediate object) are presented in this study. The rest showed no extended emission, were impossible to derotate or had little signal-to-noise ratio, making them of little use.

We extracted 2D maps for the velocity, velocity dispersion, continuum and line emission. The velocity and velocity dispersion where used to show, together with the asymmetry of the spectral H\(\alpha\) line, that most of the galaxies in the sample show signs of recent mergers or strong interactions, that have affected the kinematics and morphology of the systems. From the line emission we have calculated the star formation rate, which is consistent (within a factor of two, which is common) with many other studies in different wavelengths. Furthermore, three different estimates for the masses of the objects were calculated, two assuming general rotation of the objects and one estimated from the \(\sigma\), which represents the mass supported by pressure and the contribution from non-equilibrium. The latter one demonstrated to have a lose correlation with the luminosity, much in the style of the \(L - \sigma\) relation explained in Paper I, with a slope \(\sim 3\).

6.3 Paper III

The third paper in my thesis aims at providing a comparative study of the structural parameters of starbursts and postburst galaxies. This kind of study, with large samples of both types of objects can determine, for example, if a typical postburst galaxy is spheroidal, if the starbursts do tend to be concentrated in the inner kpc of the hosts or if there is an obvious trend in the absolute magnitudes between the two types of galaxies.

We use SDSS to select the samples of objects. The images are downloaded and a single 2D Sersic profile, convolved with the seeing, is fitted to both samples, measuring sersic index, effective radius and magnitude, among other parameters. The asymmetry of the samples is also calculated, in order to determine if the two types of objects show systematic differences.

Our results show that, contrary to other reports, most of the postbursts selected from SDSS are actually disc galaxies, contrary to many other studies that found a spheroidal (sersic index, \(n \sim 4\)) luminosity radial profile. We justify the difference in the fact that we have restricted our sample to very low redshifts, in order to resolve any structure of size \(\sim 1\text{kpc}\). Thus, the fiber of SDSS in which we have based our selection is sensitive to nuclear starbursts/postbursts in disc galaxies, that show as unaltered discs in our results.
On the other hand, if extending the study to larger redshifts, the 3″ fiber will cover larger areas in the galaxy, diluting the spectral signal of the postburst area into a much larger area occupied by the disc.

Our results indicate that \( \gtrsim 50\% \) of our postburst sample is well represented as a disc of effective radius \( R_e \sim 3 \text{kpc} \). On the other hand, the starburst episode seems to be concentrated in the inner \( 1 - 2 \text{kpc} \), which agrees with previous observational works and simulations.

6.4 Paper IV

The aim of this article was the kinematic study of the pair of galaxies NGC 5426 and NGC 5427. This pair of interacting galaxies form part of the Atlas of Peculiar Galaxies (Arp 1966), and are an interacting pair of \( \sim \)equal mass objects.

After careful examination of the line profiles of NGC 5427, a curious secondary component was found. When decoupled from this galaxy, the secondary component resulted to mimic the velocity map of the companion galaxy, NGC 5426. After ruling out the possibility of this secondary component being a reflection inside the instrument (the so called ghosts), the conclusion is that what appears in the data is gas pulled by NGC 5427 from its NGC 5426, which still resembles the original pattern of the latter at the time of an earlier close passage.

Since the secondary component is stronger in the inter-arm regions, it is concluded that the gas is infalling from behind NGC 5426. The necessary source of ionization is considered to be Lyman continuum photons escaping from NGC 5427, and that allows the calculation of the total infalling gas and the distance to the cloud, which are estimated to be \( 10 \text{M}_\odot \text{yr}^{-1} \) and \( \sim 1 \text{kpc} \), respectively.

6.5 Contributions not included in this thesis:

1. **HII Regions Feeding the Interstellar Medium in M 83**

2. **Massive young star clusters in the Antennae galaxies: Luminosities and internal kinematics from 2D Halpha spectroscopy.**
3. The resonant structure of late-type disc galaxies from Fabry-Perot interferometry.
Font, J., Epinat, B., Querejeta, M., Beckman, J.E., Blasco-Herrera, J., 2012 (in preparation)
7. Future prospects

Any future prospects in galaxy formation and evolution are most likely linked to a multi-wavelength study of large samples of galaxies, in order to clearly, and with as little biases as possible, determine the properties of the objects studied: current and past star formation (i.e. star formation histories), dust content and its effects at every wavelength, the kinematics of ionized and neutral components of different species of gas, together with the stellar kinematics...

From the different aspects of this thesis, probably it is in the postburst galaxies where more work is needed. The samples are small and very dependent on selection effects, and the studies are mainly based on photometry at a reduced number of wavelengths. For a full understanding of those objects that we call E+A galaxies, we need to accurately determine, among other things, the degree of rotational support, the physical distribution of new and old populations, the current star formation and dust content, the reservoirs of gas... We need all of that resolved in angular space, combining high spectral and spatial resolution. This implies the combination of different techniques, such as Integral Field Spectroscopy (IFS), radio-interferometry and photometry in as many wavelengths as we can manage. Only then we will be able to answer questions about the evolution from star-forming, disc-like galaxies into the spheroidal quiescent objects such as elliptical and S0.

Regarding starburst galaxies, we need to determine the processes that are responsible for the trigger and subsequent quenching of the star formation. We have a clear picture about mergers or (very) strong interactions being part of the solution, but we need to work out the details about what other mechanisms and under what circumstances. Much effort is currently being put in probing the largest possible redshifts to determine the characteristics of star formation in the distant past and relate it with the nearby Universe. Diverse studies of $Ly\alpha$ emitters and submm galaxies, for example, will provide us with large samples of extreme star-forming objects, that we will need to model and compare with the nearby galaxies in order to understand. This requires the state-of-the-art space telescopes, together with the much larger ground-based ones in order to observe not only large, but also representative samples (not only the most extreme beasts in those large redshifts) and a better understanding of the closer objects, in order to be certain that we compare like with like.
Sammanfattning

Förståelsen av bildandet och utvecklingen av galaxer kommer inte att vara komplett förrän vi förstå de fysikaliska processer som utlöser och reglerar stjärnbildning i dem. Denna avhandling handlar om stjärnbildning på flera storleksskalor. Den omfattar kinematiska studier av 157 H II-regioner i spiralgalaxen M83, för att undersöka förhållandet mellan luminositet och hastighetsdispersion och om H II regioner är virialiserade. Vi fann att det inte finns någon stark korrelation mellan nämnda variablerna, endast en övre gräns med en maximal luminositet för en given hastighetadispersion. Vi visade att relationen har en lutning som är starkt beroende av en noggrann korrigerings av den instrumentella breddningen. Vi flyttade sedan vårt fokus till stjärnbildning på större skalar. Sådes är huvuddelen av denna avhandling om så kallade starburstgalaxer och de postburstgalaxer som de i som tid utvecklas till. En starburst är en galax som är tillfälligt skapar stora mängder stjärnor, i en takt som inte är hållbar under en längre tid. Vi utförde en kinematisk studie av 11 sådana galaxer, som visar att de är i allmänhet inte hålls upp av rotation och att många av dem syns påverkade av växelverkan med andra galaxer. Vi extraherade dessutom ett urval av 1006 starbursts och 240 postbursts vid rödförskjutning 0.010 < z <0.083 från Dessutom, från Sloan Digital Sky Survey (SDSS). Vi utförde en jämförande studie av deras strukturella parametrar, såsom effektiv radie, sersic-index, asymetri och absolut magnitud. Vi har funnit att majoriteten av starbursts och postbursts i det närliggande universum är skivformade galaxer, med en tendens för starbursts att ha kortare effektivradier och större asymmetrier.
Acknowledgements

You often read that the acknowledgments are a very tough section to write \[1\]. Even more true for someone with the memory-span of a fish like me, so, please, forget me if you should be in this list and you did not make it. Anyway, if you should be here you probably know how I am ;).

First, and foremost, I want to thank my two supervisors: Göran Östlin and Kambiz Fathi, Kambis Fathi and Göran Östlin. As different as their styles are, both of them have been invaluable during my PhD. I am not always an easy person to work (or live, but that part of the acknowledgements will come later) with. I usually entertain myself too long in the way if I think the path is interesting and challenging enough. This rather poetic way of putting it was actually expressed in other terms by Kambiz: "We are very good at making plans, but you are not good at sticking to them!!". Thank you both for your infinite patience in guiding me all these years. I am also in debt with Erik Z for useful discussions and proof-reading my thesis and to my mentor, Claes Fransson, who always cared and joked about me. And yes, I thank him for both!

Second, it is fair to thank the people without whom the Department would fall into pieces. In the administrative part Ulla, Sandra, Lena and Rickard make our life a little bit easier with their amiable help. And when things go wrong, when something does not compile or a program crashes and you feel like throwing your computer through the window, as if superheroes with powers we can not even start to understand, Sergio and Bengt always save the day. And impossible to forget the stories and mechanical abilities of Uno, the big ‘amigo’.

Besides Jaime’s opinion\[2\] I want to tell my friends how much support their very presence has given me. This includes Jaime himself, who with I held discussions that, from time to time, even included scientific topics!! Angela and Nuria have been more than office mates, and I thank them immensely for their friendship. Also in this category enter Genoveva and Martina, to

\[1\]e.g. Adamo (2011, PhD)

\[2\]He believes that the acknowledgements are for scientific purposes only.
whom I have the privilege to call friends.

Wow, a whole page and only half way through, I hope you are not tired after reading my whole thesis... ... ... 😊

It has been an honor to be surrounded by so many good fellow PhD students. An exhaustive list would defeat the purpose of mentioning them, I guess, so there it goes some examples **Michael, Matthias, Laia, Vasco, Anders, Gautam, Jens, Fabio, Jörn** and a long list of **et al.** Allow me also to mention **Magnus Nässlund** as an honorary PhD, to whom I am in eternal debt for introducing me to *Fawlty Towers* (Qué? Sí, sí, señor).

My PhD is linked to GH\(\alpha\)FAS Fabry-Perot, and GH\(\alpha\)FAS is possible thanks to the outstanding team around it including, among others, **John Beckman, Joan Font, Marie-Maude de Denus-Baillargeon** and **Benoit Epinat**. There is not a night in while observing that I do not think of you all, for good and for bad :).

Finally, it is time to thank the most important part of my life: my family. And for that, allow me to change to my mother tongue. Muchas gracias a mi familia por todo el amor que me han dado tantos años. Por no entender qué demonios hago aquí, pero apoyarme igualmente. A mis padres, mis hermanos, a las dos enanas (**Patricia y Adriana**) y a **Claire** por tomar el relevo aquí en Estocolmo. En definitiva, ¡les quiero familia!
References


Bergvall, N. 2011, ArXiv e-prints


Bland-Hawthorn, J. 1995, 71, 369


Heckman, T. M. 1998, 148, 127
Kunth, D. 1995, Astrophysics, 38, 329
Kunth, D. & Östlin, G. 2000, A&AR, 10, 1
O’Connell, R. W. 2005, 329, 333 31


Scalo, J. M. 1986, FCP, 11, 1 31 32


Sersic, J. L. 1968 37


Terlevich, R. 1997, 6, 1 32 33


Thuan, T. X., Williams, T. B., & Malumuth, E. 1987, 151 38

Toomre, A. & Toomre, J. 1972, Apj, 178, 623 36


