Highlights on Spanish Astrophysics X, Proceedings of the XIII Scientific Meeting of the Spanish Astronomical Society held on July 16 – 20, 2018, in Salamanca, Spain. B. Montesinos, A. Asensio Ramos, F. Buitrago, R. Schödel, E. Villaver, S. Pérez-Hoyos, I. Ordóñez-Etxeberria (eds.), 2019

Making galaxies passive: Insights from resolved studies of nearby galaxies.

Miguel Querejeta[1,2]

[1] European Southern Observatory, Karl-Schwarzschild-Str. 2, D-85748 Garching, Germany
[2] Observatorio Astronómico Nacional (IGN), C/Alfonso XII 3, E-28014 Madrid, Spain

Abstract

The rapid suppression of star formation is thought to be an important process in the evolution of the most massive galaxies, but the mechanisms involved are still subject to debate. In this PhD thesis, we consider two agents that can control star formation: AGN feedback and galaxy mergers. First, we focus on the interplay between stellar structures, nuclear activity, and molecular gas. We start presenting our public catalogue of stellar mass maps for more than 1500 nearby galaxies. Based on the baryonic mass distribution of the spiral galaxy M51, we show that there is sufficient molecular gas inflow to feed the AGN, as well as feedback effects which include a molecular outflow and a radio plasma jet interacting with the surrounding ISM. In a second part, we address the role of galaxy mergers in the buildup of a passive population of lenticular galaxies (or S0s), the most common early-type galaxies in the local Universe. Using numerical simulations, we show that major mergers of spiral galaxies can result in lenticulars, with a bulge-disc coupling and specific angular momentum in agreement with observations. Globally, our results show that both internal processes (transport of gas and AGN feedback) and external mechanisms (mergers) have the ability to regulate and eventually suppress star formation in galaxies.

1 Foreword

This is a summary of the PhD thesis that I conducted at the Max Planck Institute for Astronomy in Heidelberg, Germany, under the supervision of Eva Schinnerer. The thesis was developed in the framework of the European project DAGAL (Marie Curie ITN, PI: Johan Knapen), including extended stays at the Instituto de Astrofísica de Canarias, Universidad Complutense de Madrid, and the University of Groningen.

2 Introduction

It is remarkable how much our understanding of galaxies and the structure of the Universe has evolved in the last century; after all, it was less than 100 years ago that galaxies were proven to be external to our own Milky Way. At fixed stellar mass, galaxies are known to show a bimodality in terms of colour [1, 2]; in a colour-magnitude diagram, the relative scarcity of galaxies between the so-called *blue cloud* and *red sequence* has been recognised as evidence of the short timescales over which star formation is suppressed [5]. At the same time, a strong correlation exists between colour and morphology, suggesting an evolutionary link: ellipticals and lenticulars tend to be passive and red, implying low degrees of star formation, as opposed to actively star-forming blue spirals and irregulars.

One of the most fundamental challenges of modern astrophysics is indeed understanding the process by which gas transforms into stars, and how this process is orchestrated in the context of galaxies and as a function of environment. Star formation regulates the interchange of energy between stars, gas, and dust, explains the chemical enrichment of the interstellar medium (ISM), and, overall, it can determine the structure and ultimate fate of a given galaxy. In this thesis, we consider two specific mechanisms that have the ability to control and suppress star formation in galaxies: feedback from an active galactic nucleus (AGN) and galaxy mergers. However, rather than trying to learn about them by studying large samples of distant sources, our goal is to exploit the power of the high spatial resolution available for the nearest galaxies, establishing synergies between observations and simulations.

3 An important observational tool: Stellar mass maps

While light is the most direct observable in astrophysics, the evolution of galaxies is largely constrained by their *mass* distribution. However, measuring stellar mass distributions in practice is challenging: at optical wavelengths, light is biased by luminous young stars and can suffer from intense dust extinction; additionally, the large uncertainties associated with late evolutionary phases in stellar population synthesis models make it difficult to unambiguously connect light and mass. Near-infrared observations constitute a promising alternative to circumvent these problems: the stellar mass-to-light ratio is much more uniform than at optical wavelengths and extinction problems are minimised.

In this thesis, we use near-infrared imaging, together with an algorithm to correct those images for dust emission (3.3 μm PAH feature and dust continuum) to calculate stellar masses with high accuracy. Specifically, we rely on uniform imaging at 3.6 and 4.5 μm for more than 2000 galaxies from the *Spitzer* Survey of Stellar Structure in Galaxies (S^4G), and exploit the fact that the spectral energy distribution of old stars and dust at these wavelengths have an intrinsically different shape. We have implemented a pipeline based on Independent Component Analysis (ICA) to separate both components, allowing to identify the true stellar mass distribution. This has resulted in an increase by an order of magnitude in the amount of resolved stellar mass maps available so far, which we have made publicly available. In conjunction with dynamical masses, these stellar mass maps can help constraining the distribution of baryonic to nonbaryonic matter in galaxies; the stellar mass distribution is also

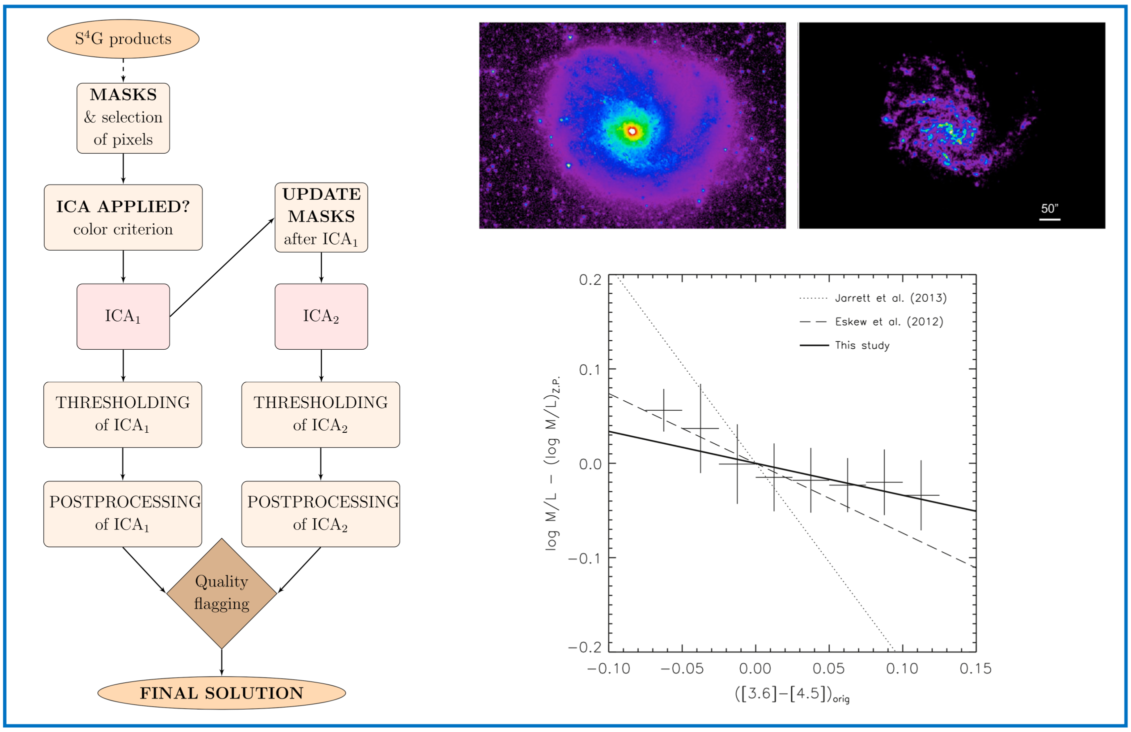

Figure 1: *Left:* Flow chart summarising the steps of the Pipeline. *Right top:* ICA separation of the 3.6 μm image of NGC 4254 into stars (left) and dust (right). *Right bottom:* New calibration for effective M/L as a function of [3.6]-[4.5] colour, based on more than 1500 galaxies, and comparison to previous calibrations.

instrumental to any calculations of specific star formation rates (SFR/$M_\odot$), and it is critical when it comes to calculating gravitational torques, which can trigger flows of gas towards an active nucleus. We will examine this last possibility in the next section.

4 AGN and their relation to quenching: Feeding and feedback in M51

Active galactic nuclei are recognised as some of the most energetic sources of the Universe, with the potential to dramatically influence the evolution of their host galaxy: their bolometric luminosities of $10^5 - 10^{13}\, L_\odot$ can sometimes outshine their host [12]. Active nuclei also play a pivotal role in reconciling cosmological simulations with observations; indeed, AGN feedback is invoked to explain the lower stellar-to-total mass ratio in the halo of the most

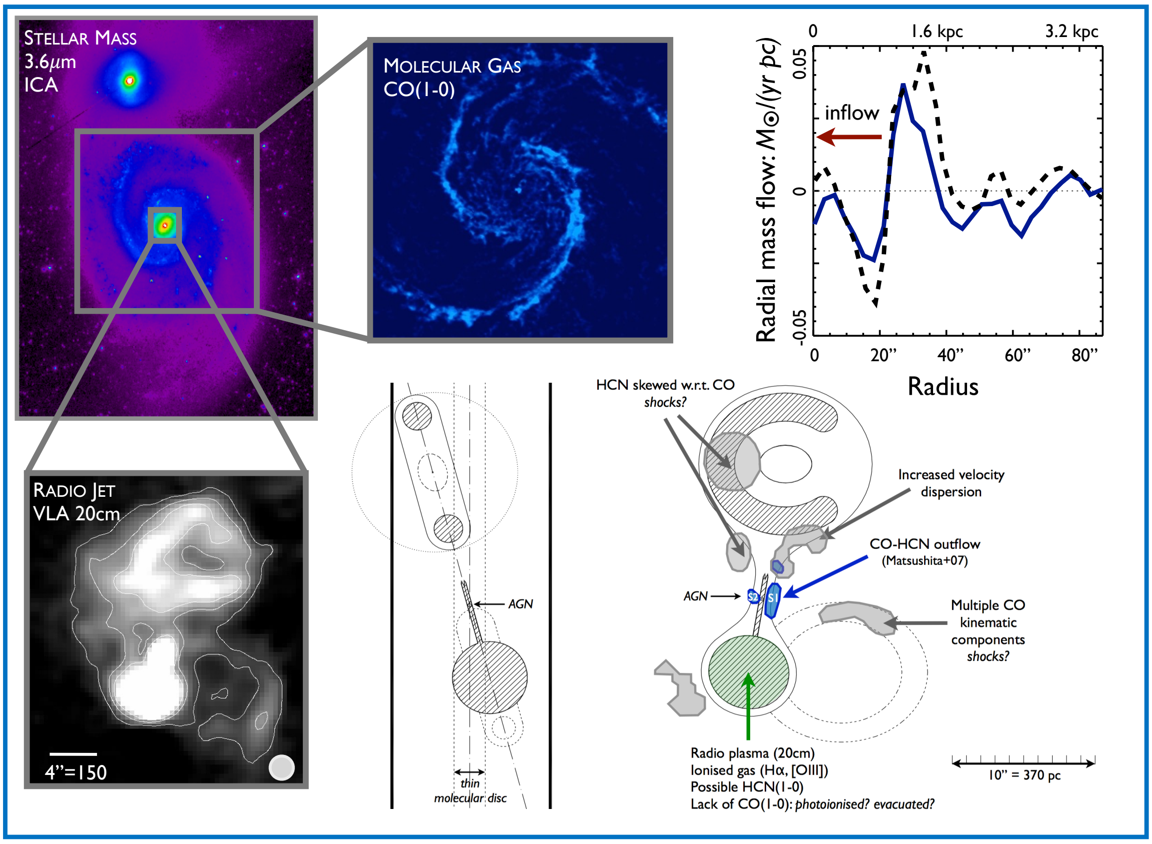

Figure 2: *Top left:* stellar mass map of M51. *Top right:* plot demonstrating that gravitational torques imply gas inflow for the central kiloparsec of the galaxy (*dashed*: uncorrected 3.6 μm). *Bottom left:* VLA 20 cm continuum map revealing the radio plasma jet through synchrotron emission. *Bottom right:* summary of AGN feedback effects found in M51, with the proposed geometry.

massive galaxies [11], but it remains to be confirmed whether the strong feedback effects introduced *ad hoc* by simulators are realistic.

Here, we quantify the transport of gas to the nucleus as the result of gravitational torques in the spiral galaxy M51. We derive the torques from the stellar mass map obtained as part of the previous project, and assess their effect on the molecular gas distribution mapped by the PAWS survey [13]. We show that there is evidence for molecular gas inflow in the central ~kpc due to the asymmetry introduced by a nuclear bar, and we carefully analyse the uncertainties and limitations involved in such calculations.

Another critical piece in the puzzle of AGN and their potential relation to the regulation of star formation is the so-called AGN feedback process. The ability of gas to flow towards the nucleus can indirectly control any feedback effects, which could in turn contribute to explaining the tight scaling relations observed between the properties of the nuclear black hole and the surrounding stellar bulge [9, 7]. We have also revisited this important topic in the context of new observations for M51, one of the few galaxies that affords the possibility to study the distribution and kinematics of the circumnuclear gas at high spatial resolution as a consequence of its proximity. We analysed both the bulk molecular gas traced by PAWS (through the CO line) and new NOEMA observations of dense gas tracers (e.g. HCN); these show an intimate connection with the kpc-scale radio plasma jet detected in radio continuum (clearly visible in archival VLA imaging). We find evidence for a massive molecular outflow (traced both by CO and HCN), as well as shocks and increased turbulence which are probably the result of the interaction of the expanding radio plasma structures and the surrounding molecular gas. We also find a large region where CO emission is significantly under-abundant, and which coincides with the position and extent of a radio plasma bubble (connected to the end of the collimated radio jet). We also find that the HCN line profiles have higher velocity dispersions and are more skewed than the CO line for positions in the vicinity of the radio plasma structures, which is suggestive of shocks. Overall, we interpret these features as the result of the radio jet propagating across the disc plane and pushing the molecular gas as it expands. Such effects could alter the phase balance of the interstellar medium and eventually affect the fraction of gas which can be converted into stars. Thus, AGN feedback can be regarded as a mechanism which is capable of indirectly regulating star formation.

5 Passive discs: Creating lenticular galaxies with mergers

Disc-dominated lenticular galaxies represent the majority of early-type galaxies in the local Universe [4]; therefore, far from being exceptional examples, they constitute one of the most important end-products of galaxy evolution. They have some transversal properties, in the sense that they share with elliptical galaxies low levels of star formation (relative to their stellar mass), while they contain large-scale galactic discs, in analogy to spiral galaxies. However, in spite of their cosmological relevance, the evolutionary tracks that lead to lenticular galaxies are still poorly characterised. Arguably, the most popular process to explain the emergence of lenticular galaxies is *ram-pressure stripping*, the expulsion of gas from a spiral galaxy by the pressure exerted by the intergalactic medium, which is expected to be especially relevant in clusters [8]; deprived of fuel to form new stars, the stellar populations will gradually age. However, this and similar mechanisms (e.g. harassment, strangulation), which operate preferentially in high-density environments, are not expected to significantly modify the stellar kinematics of the progenitor galaxy.

We explore whether mergers of spiral galaxies can explain the origin of lenticular galaxies in groups rather than clusters, where they are at least as common [14]. Comparing N-body numerical simulation from the GalMer project [3] with observations, we show how, after initially destroying the pre-existing discs, the debris from major mergers of spirals can settle down into a new stellar disc under favourable orbital conditions. The remnant would be visually classified as an S0, and the disc and bulge of the resulting galaxy obey the tight photometric scaling relations observed in real lenticulars, and even the presence of pseudo-bulges [10]. In addition, we have also analysed the kinematics of the resulting lenticular systems in these simulations, and found that they can explain the recent finding from the CALIFA

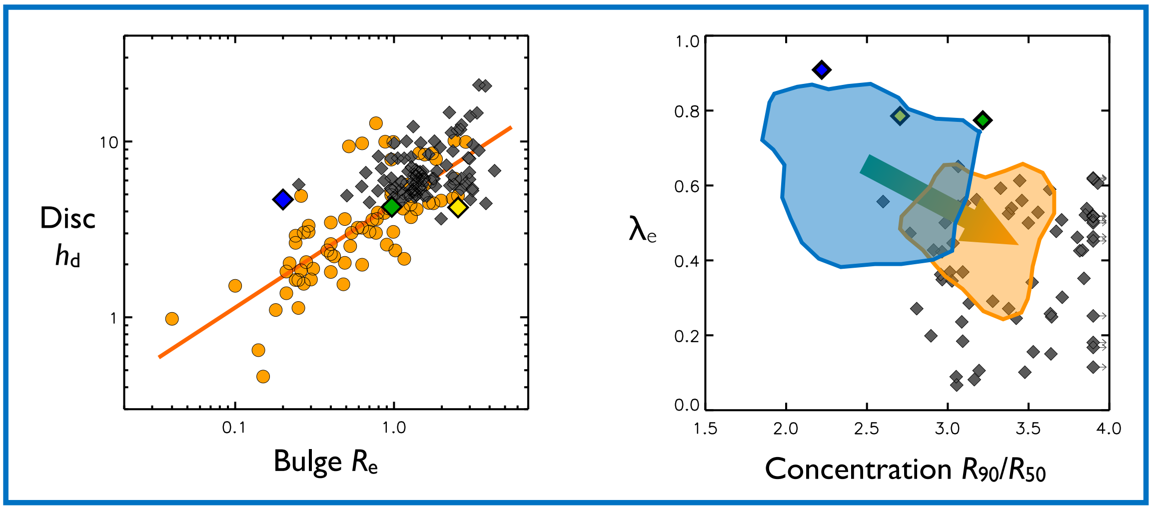

Figure 3: *Left:* the S0-like remnants (black diamonds) of major mergers of spirals simulated by GalMer (progenitors: colour diamonds). They have scaling relations compatible with observational S0s (orange circles); here, disc scale-length vs bulge effective radius. *Right*: the simultaneous change in angular momentum and concentration triggered by those major mergers explains the discrepancy in $\lambda_{\rm Re} - R_{90}/R_{50}$ between spirals (blue cloud) and S0s (orange cloud) found by CALIFA.

survey pointing to a systematic offset between spirals and S0s when the specific angular momentum ($\lambda_{\rm Re}$) and light concentration (R_{90}/R_{50}) are simultaneously taken into account [6]. Since simple fading is not expected to substantially change the angular momentum of the galaxy, this constitutes an important challenge to that paradigm, and suggests that mergers could play a relevant role in quenching spiral galaxies into lenticular systems.

6 Towards an integral picture of star formation suppression in galaxies

The main conclusion from our work is that both *internal* processes (gas transport and AGN feedback) and *external* mechanisms (mergers) have the potential to control star formation in galaxies. Many of these processes are interdependent: our results suggest an intimate connection between gas inflow and AGN feedback; nuclear activity is indirectly controlled by the transport of gas to the centre of the galaxy, and, at the same time, the feedback from the nucleus regulates the amount of gas that can reach the AGN. On the other hand, the main lesson learned from this thesis could well be that it is important to be aware of the uncertainties and limitations intrinsic to a certain method, and that it can be extremely fruitful to explore synergies between observations and numerical simulations. We live in exciting times for the study of galaxy evolution, with ALMA and NOEMA eventually reaching their full power; in that sense, this thesis has presented some results which can be easily built upon in the near future, and which could be useful in guiding the exploitation of the datasets that these new instruments are just starting to deliver.

Acknowledgments

I would like to warmly thank Eva Schinnerer and Sharon Meidt for their constant support supervising my thesis, and Carmen Eliche-Moral for introducing me to the fascinating realm of lenticular galaxies. I acknowledge financial support to the DAGAL network from the People Programme (Marie Curie Actions) of the European Union's Seventh Framework Programme FP7/2007- 2013/ under REA grant agreement number PITN-GA-2011-289313. I would also like to acknowledge the International Max Planck Research School for Astronomy and Cosmic Physics at the University of Heidelberg (IMPRS).

References

[1] Baldry, I. K., Glazebrook, K., Brinkmann, J., et al. 2004, ApJ, 600, 681

[2] Brinchmann, J., Charlot, S., White, S. D. M., et al. 2004, MNRAS, 351, 1151

[3] Chilingarian, I. V., Di Matteo, P., Combes, F., Melchior, A.-L., & Semelin, B. 2010, A&A, 518, A61

[4] de Vaucouleurs, G., de Vaucouleurs, A., Corwin, Jr., H. G., et al. 1991, Third Reference Catalogue of Bright Galaxies, Vol. Volume 1-3, XII, 2069 (Springer-Verlag Berlin Heidelberg New York), 7

[5] Faber, S. M., Willmer, C. N. A., Wolf, C., et al. 2007, ApJ, 665, 265

[6] Falcón-Barroso, J., Lyubenova, M., & van de Ven, G. 2015, in IAU Symposium, Vol. 311, IAU Symposium, ed. M. Cappellari & S. Courteau, 78–81

[7] Ferrarese, L. & Merritt, D. 2000, ApJL, 539, L9

[8] Gunn, J. E. & Gott, III, J. R. 1972, ApJ, 176, 1

[9] Häring, N. & Rix, H.-W. 2004, ApJL, 604, L89

[10] Laurikainen, E., Salo, H., Buta, R., Knapen, J. H., & Comerón, S. 2010, MNRAS, 405, 1089

[11] Moster, B. P., Somerville, R. S., Maulbetsch, C., et al. 2010, ApJ, 710, 903

[12] Robson, I. 1996, Active galactic nuclei

[13] Schinnerer, E., Meidt, S. E., Pety, J., et al. 2013, ApJ, 779, 42

[14] Wilman, D. J., Oemler, Jr., A., Mulchaey, J. S., et al. 2009, ApJ, 692, 298