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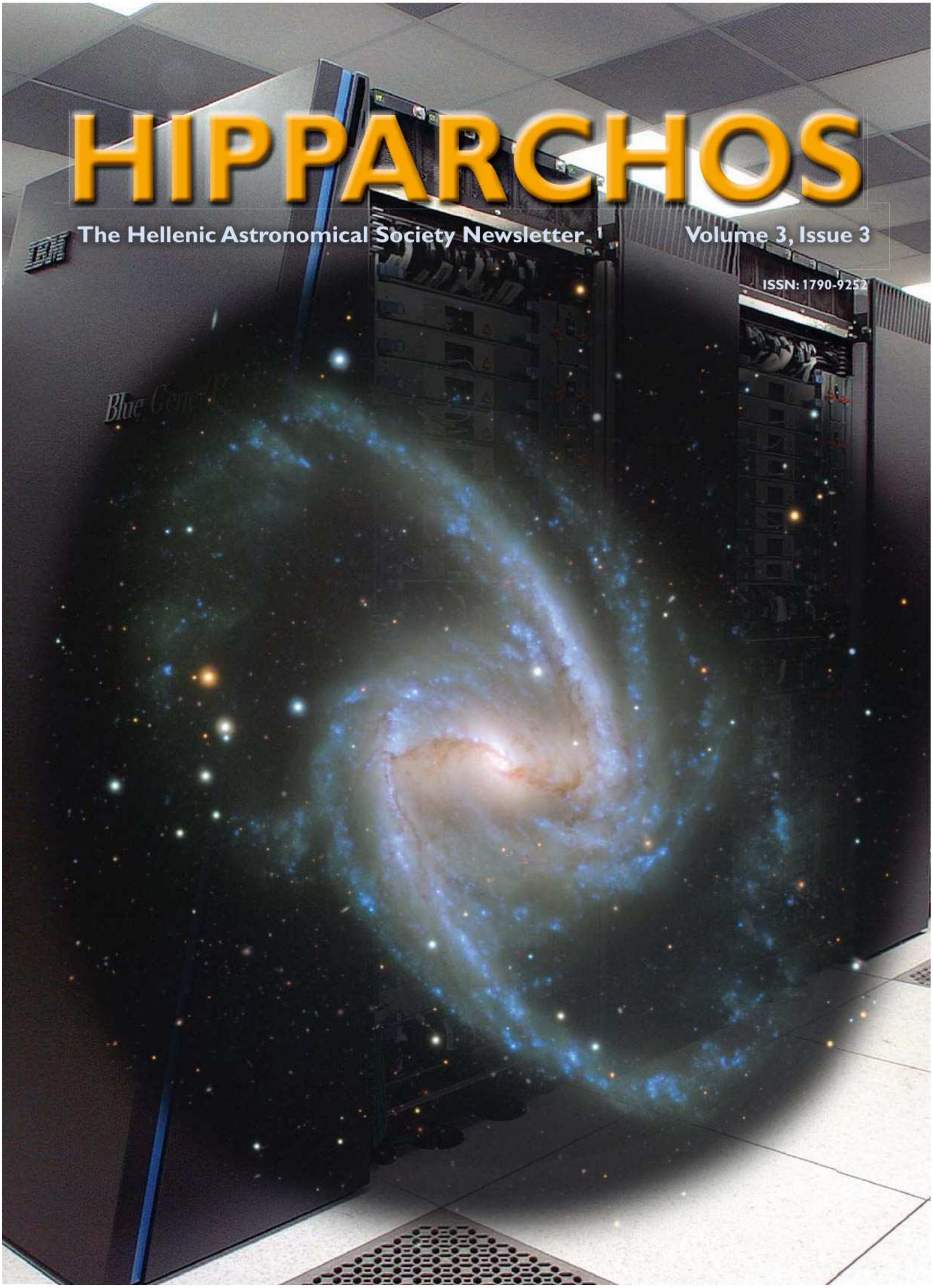

Studying galaxies with a computer: a brief overview

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1. Introduction

At present, a very large number of opportunities are open to astronomers wishing to understand how galaxies form and evolve. Supercomputers allow them to make realistic, high resolution numerical simulations, including not only stars and dark matter, but also gas and its physics (star formation, different types of feedback, cooling, etc.), and chemical evolution, thus reaching full chemo-dynamics. On the observational side, a number of large surveys, of high resolution and sensitivity, provide data of unprecedented quality and quantity. The aim of this article is to 'wet the appetite' of young astronomers and incite them to work on the formation and evolution of galaxies, by providing as an example my own personal research experience in this field, and by describing how much fun such work can be. If I focus here on simulations and on observations, it is not because I look down upon analytic work. I simply consider such work as a *sine qua non*, an absolute necessity for any astronomer or astrophysicist, independent of the specific subject they work on. This was true in the past and continues to be true. I will here concentrate on the additional impact that the very strong recent advances in computational astrophysics can provide.

2. Orbits and gas flows in barred galaxies

Spiral arms in a galaxy are like icing on a cake, and can be treated as perturbations of the axisymmetric disc that hosts them. In my thesis work – done under the supervision and guidance of Professor George Contopoulos – I studied, mainly analytically, the spiral structure in the central parts of disc galaxies, introducing an extension of the density wave theory of Lin and Shu (1971), which at the time was a hot topic. I obtained a job in France in the second half of the 1970s, and started using computational tools, enabling me to tackle a wider set of problems, beyond the linear regime mainly accessible to analytical studies. My first goal with these tools, which were new to me then, was to understand galactic bars. Indeed, these are much stronger features than spirals, and their dynamics is much more complex and more challenging. I started by studying the motion of stars and gas in and around bars. For stars, considerable understanding was already available from periodic orbit studies (e.g. Contopoulos & Papayannopoulos 1980, Contopoulos & Grosbol 1989). I extended this work to potentials where the bar was described by a Ferrers model. For the gas flow, however, I needed an adequate, high quality hydrodynamic code (Van Albada & Roberts 1981, Van Albada, van Leer & Roberts 1982), with sufficient linear resolution to describe adequately the shocks in the gas. With such a code and resolution, I could connect the shock loci in my simulations with the dust lanes on the leading sides of observed bars, and to show that their shape depends on many parameters, of which the most important ones are four, namely the mass, axial ratio and pattern speed of the bar, as well as the mass concentration in the central region.

An in-depth study of this kind necessitated a quite extended exploration of this four dimensional parameter space. Given the CPU speed of computers available at the time, this presented a serious difficulty, since high quality hydrodynamic simulations are very CPU time consuming. I was then working in the observatory of Marseille, which had then a median sized computer, shared by many astronomers. As codes were well optimised, they slowed down all data analysis more than could be accepted, so I was allowed to run my simulations only at night. Since two nights were needed for each run, it took well over a year to obtain sufficient results for a thorough analysis. However, the preliminary analysis I would obtain every morning from the previous night's results was sufficiently interesting to keep me going. Furthermore, since I used the same potentials for the orbital structure and the gas flow calculations, I could, at all stages of this endeavour, make many useful comparisons so as to understand the link between the main periodic orbits and the gas flow patterns, and to predict when shocks would form and what their shape and loci would be.

Two of my results excited me most. The first was that I could witness in my simulations how and when the gas is pushed inwards by the bar in order to form a nuclear ring, or move yet further inwards to form a central mass con-

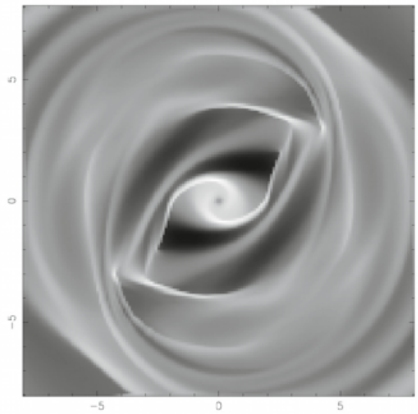

***Figure 1:** Gray scale plot of the gaseous response to a bar. Darker (lighter) shades correspond to lower (higher) densities. The bar rotates clockwise and its major axis is located along the NorthEast to SouthWest diagonal. Note that gas is concentrated in the central region and also in the shock loci along the leading side of the bar, while two extended regions on either side of the centre and near, or on, the bar have very low gas density. (This figure is reproduced from Fig. 10 in 'Unravelling the mystery of the M31 bar', by E. Athanassoula and R. Beaton 2006,* Monthly Notices of the Royal Astronomical Society, *vol. 370, Issue 3, p. 1499)*

centration and perhaps feed a central black hole. The second result was that my simulations set limits to the values of the bar pattern speed, a quantity difficult to obtain observationally. Within these limits, the shape of the shock loci reproduced well the shape of the observed dust lanes, while outside them this shape was unrealistic. Using the 225 simulations I had run, I could clearly say that the corotation radius, R_{cr}, had to be within the limit $(1.2 \pm 0.2)a$, where a is the length of the bar semi-major axis. The lower limit of this region was a confirmation of the result found by Contopoulos (1980), relying on the structure of the periodic orbits, and of my own results on bar driven spirals. However, the crucial improvement that my gas flow calculations introduced was to set an upper limit to the corotation radius, i.e. a lower limit to the bar pattern speed, thus bracketing the allowable region. Even now, nearly 30 years later, this range is still considered as *the* comparison range for all observational and theoretical studies of bar pattern speeds (e.g. Cuomo et al. 2020, Guo et al. 2019, and references therein).

3. GRAPEs

My next aim was to study the formation and evolution of the bar component itself using a fully self-consistent simulation, i.e. one in which I could follow not only the evolution of the stellar disc, but also that of the dark matter halo. This was clearly beyond the limit that our 1980s observatory computer could handle, so I applied for time on the French supercomputers and started working on this subject. However, it became soon clear to me that, although I could make some useful progress on the subject, I was depressingly far from reaching my initial goal.

The next step was actually due to pure luck. Albert Bosma and I received a letter from Piet Hut from Princeton, telling us that a young and very promising Japanese student was touring the world, visiting a number of institutes, in an attempt to get a global view of international astronomy. Hut was asking us whether we could host this student for a few days. We were most happy to do so and a few weeks later Jun Makino was in Marseille. One of the things he talked about during his stay was a novel attempt his group in Tokyo University was making to solve the N-body problem, namely building a computer board which they called GRAPE (short for GRAvity PipE; Sugimoto et al. 1990).

Let me first give some necessary background, before describing what this board meant for us. In numerical simulations such as those I wanted to do, each component is described by a number of massive particles, e.g. the disc particles, the halo particles etc., which interact between them by gravitational forces. Calculating these forces takes up the vast majority of the simulation computer time. The idea behind the GRAPE is that these forces can be calculated by hardware, rather than software. Our Japanese colleagues built such a piece of hardware, which was linked to a front end computer sending it the particle positions. The board uses these positions to calculate the forces, and sends them back to the front end computer. I.e. the GRAPE board calculates only one thing, the forces between particles, but does this extremely fast because it has been specifically wired for it. This allowed one to have, specifically for N-body simulations, a computing power equivalent to a Cray supercomputer, all to oneself and for little cost. I of course wanted to have one on my desk!

The first GRAPE board we acquired was wired by hand, with a soldering iron, and thus had relatively limited capacities. Even so, plugged into our SUN workstation, it allowed us to familiarize ourselves with GRAPEs and with the associated computer language – as the software needed to operate such boards was not trivial – particularly for software such as the tree code. We then continued with more advanced GRAPE models with custom-made chips (GRAPE-3AF and GRAPE-4). We could do good science with these, while creating a small group around this project. The most interesting work we did with these first boards was a study of Hickson compact groups, i.e. relatively isolated groups of typically four or five galaxies, in close proximity to one another. Simple calculations, but also N-body simulations (e.g. Barnes 1989), had shown that the galaxies forming such groups should have already merged. The question we tackled is why in this case do we observe so many of them at low redshift. Why had the predicted mergers not occurred? The contribution of our team here was first to find how different halo radial density profiles influence the merging rates and then to find a profile for which the merging time is of the order of the Hubble time, thus providing a plausible solution to this problem. Except for this project, with our first GRAPEs we also modelled collisional rings such as in the Cartwheel galaxy, the formation of brightest cluster members and cD galaxies, the fate of bars during interactions and mergers, and the structure of cusps induced at the centre of elliptical galaxies by a super-massive black hole.

But the main breakthrough came with the GRAPE-5 boards, five of which we could acquire thanks to support from our main national funding agency, as well as help from our University and a regional government agency. My main collaborators here were A. Bosma and J. C. Lambert, but part of the initial work was also done by a bright Greek student, Angelos Misiriotis.

4. Bars

In the seventies and eighties I had been impressed by two seminal papers. The first one was by Lynden-Bell and Kalnajs (1972) who studied analytically the exchange of angular momentum within a spiral galaxy, focusing on the resonances and their role. The second one, about a decade later, was a paper by Tremaine and Weinberg (1984b, see also Weinberg 1985), who, mainly analytically, focused on how a spheroidal system, e.g. a halo, could absorb angular momentum at its resonances.

These two papers, together with the knowledge I had acquired on orbital structure in bars, led me to apply our quite considerable, GRAPE based, computing capacity, to study in the nonlinear regime the role of individual resonances on bars and their evolution. This involved not only running fully self-consistent N-body simulations with very high resolution both for the disc and for its spheroids (i.e. the halo and the classical bulge), but also following the orbits during the simulation and studying their properties. My first step was to test the importance of the angular momentum exchange for the evolution of galaxies. For this, I compared the evolution of two simulated galaxies with initially identical discs (i.e. disc particles with the same positions and velocities), and spherical haloes with the same density distribution. The only difference between the two simulations was that in one of the two the halo was rigid – i.e. represented by a spherically symmetric, rigid, non-evolving potential which is not able to emit or absorb angular momentum – while in the other it was live, i.e. described by particles responding to any change in the disc and participating in the angular momentum exchange and redistribution. The difference between the two is stupendous (see Figure 2). In the first case no bar formed and the disc stayed axisymmetric (rightmost panels), while in the second a very strong bar formed (middle panels). Just a single glance makes it clear that angular momentum exchange plays a major role in bar evolution. Hence, results from all simulations with rigid haloes should be taken with a pinch of salt, or rather simply discarded.

The next steps were less straightforward, because they implied understanding how the various resonances – whether in the disc or in the halo – worked, how the bar properties were linked to the angular momentum exchanged, and how various properties of the galaxy influenced this exchange. Guided by the analytical work, I could easily see that angular momentum is emitted at the inner Lindblad resonance within the bar region, and absorbed partly by the resonances in the outer disc, but also, and indeed mainly, by the halo resonances. This implies a major redistribution of angular momentum within the galaxy and a corresponding change of the bar, disc and halo properties with time. Thus, barred galaxies can never reach equilibrium, but keep evolving in time. The more angular momentum is exchanged, the stronger and longer the bar gets, while its pattern speed keeps decreasing. Such strong changes are found not only for bar properties, but also for those of other components of a galaxy.

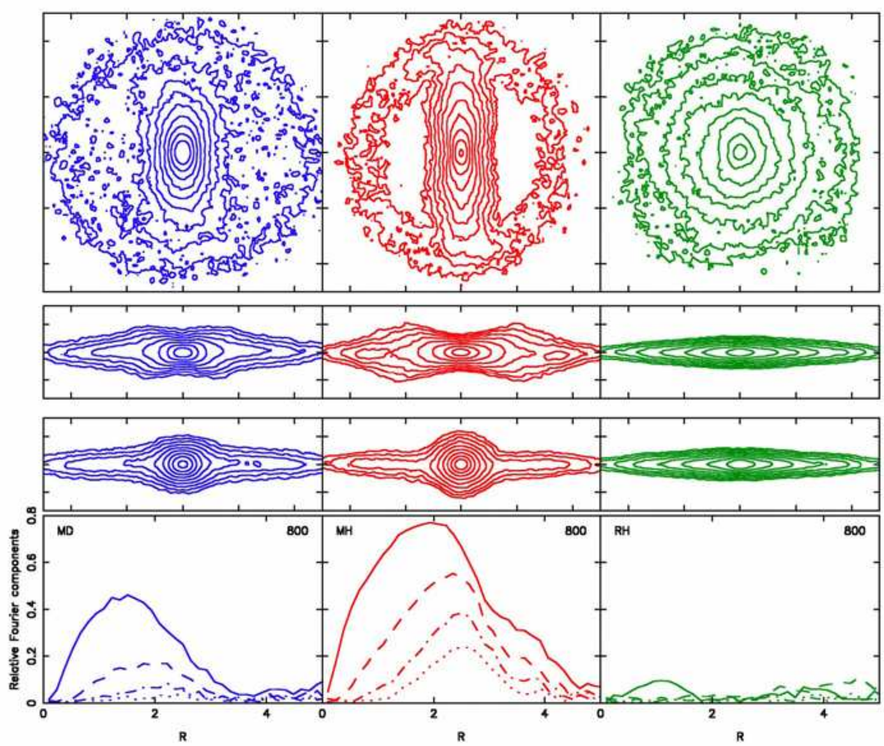

Figure 2: The effect of the halo on bar formation and evolution. From top to bottom: Isodensity curves of the face-on view of the galactic disc at the end of the simulation (first row), of the side-on view (i.e. edge-on, with the line of sight along the bar minor axis; second row), of the end-on view (i.e. edge-on, with the line of sight along the bar major axis; third row) and relative amplitude of the Fourier components m=2, 4, 6 and 8 of the density (with solid, dashed, dot-dashed and dotted lines, respectively; bottom row). Each column corresponds to a different simulation. The rightmost and the middle ones correspond to the same case, except that for the former the halo potential is rigid, i.e. does not participate in the angular momentum redistribution, while in the latter it is live, i.e. does participate. The difference is astounding. The left-most column is an intermediate case where the halo is live, but has been built so as to be able to absorb considerably less angular momentum. These three columns together argue strongly about the effect of the halo on the bar formation and evolution. (The three simulations of which we show some properties here were initially run for "Bar-Halo Interaction and Bar Growth", by E. Athanassoula, 2002, The Astrophysical Journal*, vol. 569, p. L83.)*

While emphasising the angular momentum redistribution, simulations also established a further, even more important point. Namely, that barred galaxies must evolve continuously, and can never be stationary. Indeed, when a component or a region absorbs or emits angular momentum, its properties must change, both morphologically and kinematically. Since it is the bar that drives the angular momentum exchange and redistribution, we can say that it is the bar that drives this evolution. Compared to the changes brought by interactions and mergers, this evolution is quite slow, and is thus called secular evolution. It lasts several Gyr, i.e. much longer than interactions, and can influence the properties of disc galaxies as much, or even more than the latter.

Real galaxies are observed at one single time, and can, therefore, be compared only with specific snapshots in a numerical simulation sequence. Observations can thus produce only indirect evidence for secular evolution by testing for the evolution results, and I was happy to participate in a number of such works (see also Sect. 9). Secular evolution has also a strong influence on theoretical work, since many major problems cannot be tackled by time-independent dynamics, but need to take evolution properly into account.

Note that all this is in no way really new, as it simply confirms what was already discussed more than two thousand years ago by Heraclitus, as witnessed in his famous sentence "Ta panta rei" (in greek *Τα παντα ρει*).

The next step was to find which galaxy properties, preferably observable, may determine the amount of angular momentum exchanged. Even though I was to some extent expecting it, I was and still am flabbergasted by the complexity of this problem. Until then, the analytical or numerical calculations had shown that increasing the halo mass damped the bar strength in a model galaxy. It was thus thought that a halo is the worst enemy of a bar. Several papers discussed the amount of halo necessary to stop the bar from forming, or at least to slow it down sufficiently for no bar to form in less than a Hubble time, (see e.g. the classical pa-

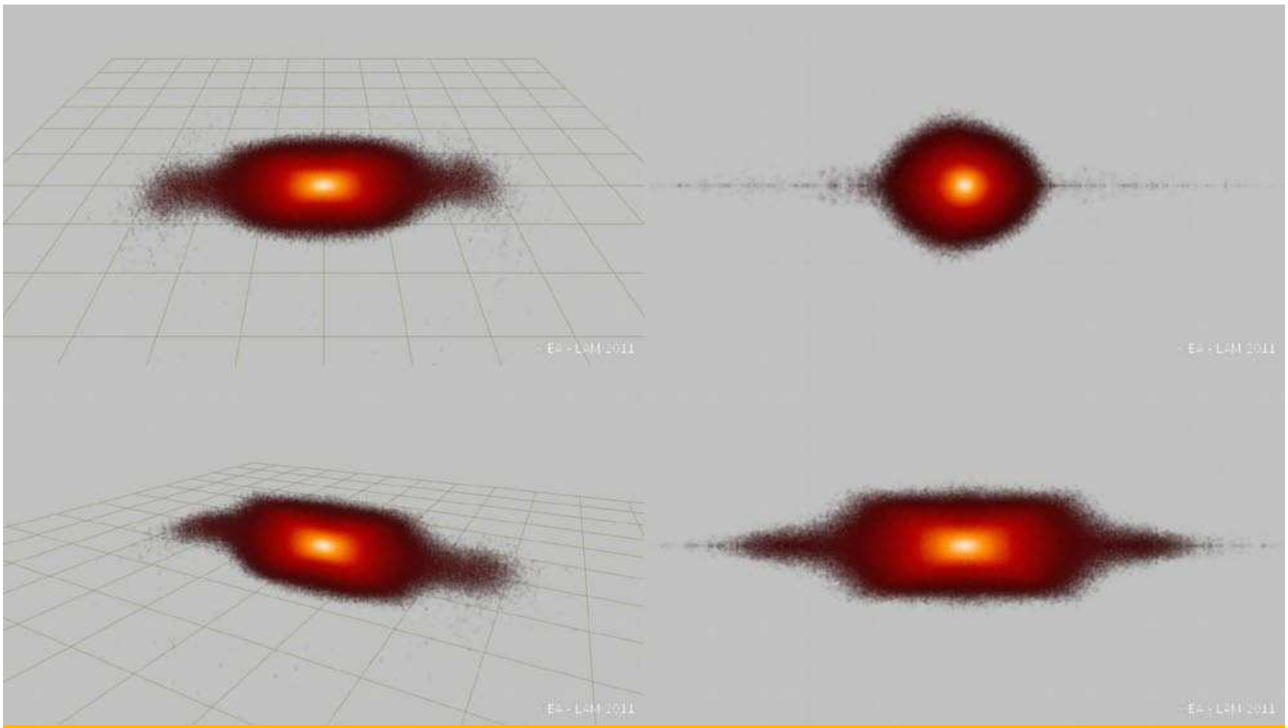

Figure 3: *Viewing the stellar bar from various angles. The right column gives a near end-on (upper row) and a near side-on (lower row) view. The left column gives two viewings from intermediate angles, which can be estimated from the cartesian grid on the bar equatorial plane. All viewings show that the inner part of the bar is considerably thicker than the outer part, i.e. that not the whole of the bar is vertically thick, only its inner part, which is also known as the boxy/peanut bulge. (The lower right panel is taken from the upper panel of Fig. 1 in "Modelling the inner disc of the Milky Way with manifolds – I. a first step ", by M. Romero-Gomez, E. Athanassoula, T. Antoja and F. Figueras 2011,* Monthly Notices of the Royal Astronomical Society, *vol. 418, Issue 2, p. 1176.)*

per by Ostriker & Peebles 1973).

I could, however, clearly see in my simulations that this was true only in the initial, linear stages of the simulation, while later on, after the bar has sufficiently grown and the problem has become strongly nonlinear, the halo will help the bar grow, as it absorbs the angular momentum emitted by the bar. The more massive the halo, the more angular momentum it can absorb and the more the bar will grow. But the mass of the halo is not the only relevant quantity. Its central concentration, its mean rotation and its velocity dispersion also influence the amount of angular momentum the halo can absorb. To this, one must add quantities that affect the mass and the velocity distribution in the disc resonant regions, the existence and properties of the classical bulge, those of the thick disc, etc. etc. I will not bore the reader with discussions of these numerous properties or quantities influencing bar formation and evolution, which have been the subject of many papers, while more are still to come. I will only mention that, as with all problems where the relevant parameter space has many dimensions, it is exceedingly difficult, if at all possible, to use the strength or the pattern speed of the bar to set limits on the values of relevant parameters, such as the halo mass, or shape.

So far I have given only a 2D view of bar formation and evolution. But the formation of bars due to a disc instability is only a beginning. A further instability occurs after a bar forms, because some of the bar orbits become vertically unstable. As a result, some simple, planar, elliptical-like bar orbits jump out of the galactic plane and take the shape of a smile, or a frown. Hence part of the bar thickens vertically and protrudes out of the galactic plane, taking the form of a box, or of a peanut, and becomes the so-called boxy/peanut bulge. The knowledge of orbital structure now becomes indispensable, since it allows us to understand the complex shape of bars, based on the vertical stability or instability of families of periodic orbits.

All the above results rely on a very large numbers of high resolution simulations, i.e. required a lot of CPU time, which can be obtained only with parallel supercomputers and/or new types of software (e.g. Dehnen 2000, 2002). Thus the GRAPEs were gradually phased out. This became definite when it was realized that in order to understand many aspects of secular evolution it was necessary to include the gaseous component and its physics in the simulations. The behaviour of gas in galaxies is not easily described by a simple code which can be hardwired onto a computer chip.

5. Bars in yet more realistic models

In collaboration with R. Machado and S. Rodionov, I undertook two further steps which were necessary in the quest for realistic bar formation and evolution scenarios in simulations. The first one concerned the shape of the dark matter halo component, which had been, in most previous studies, considered as spherical, for simplicity. It was clear, however, that gravitational interactions could alter this shape, as is also shown by cosmological simulations. In cases with triaxial haloes, the galaxy will have two non-axisymmetric components, the bar and the halo, both of which can exert torques, so that angular momentum can be redistributed within the galaxy.

We found that the triaxiality of the halo has two different effects. In the early stages, when the bar just starts forming, a non-axisymmetric halo and its torque incite the bar to form earlier. At later stages, however, and, more specifically during the secular evolution phase, the halo non-axisymmetry in general damps bar growth.

What makes these simulations even more realistic is that they include gas and its physics, i.e. star formation, feedback and cooling. They showed that, when all the remaining galactic properties are the same, a more massive gaseous component makes the stellar disc stay near-axisymmetric over longer times than a less massive gas component. Furthermore, in such gas rich galaxies, when the bar starts to grow, it does so at a much slower rate. This predicts that bars should be in place earlier in massive red disc galaxies than in blue spirals, in good agreement with what has been observed (see Sect. 9).

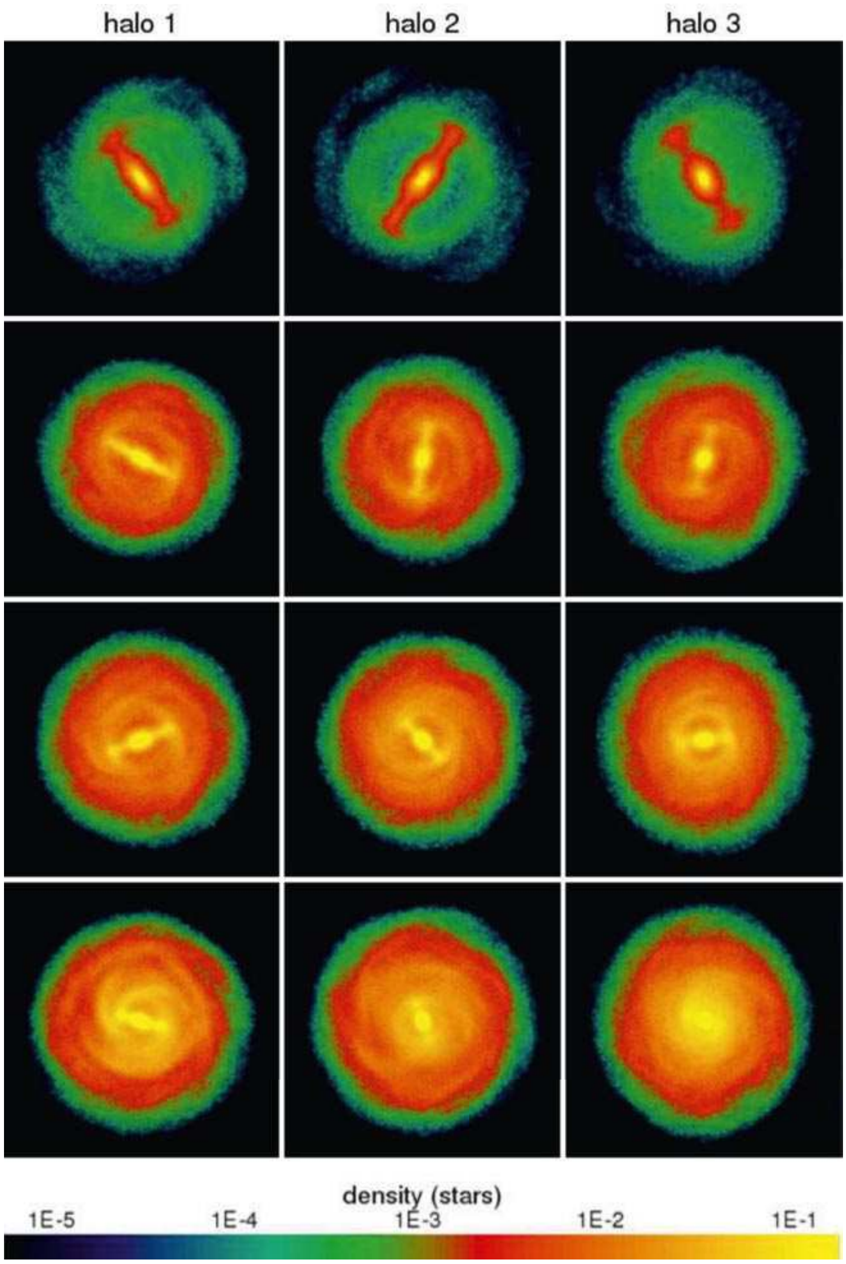

Figure 4: *Face-on view of the stellar population in twelve simulations with different initial gas fractions and dark matter halo shapes. From top to bottom, the various rows correspond to an initial gas fraction of 20%, 50%, 75% and 100%, respectively. From left to right the three columns correspond to spherical, somewhat triaxial, and strongly triaxial dark matter haloes. Rotation is counterclockwise. Colour represents projected density and the corresponding numerical values are given by the colour bars in the bottom of the figure. The size of each square box corresponds to 40 kpc. (This figure is part of Fig. 5 in 'Bar formation and evolution in disc galaxies with gas and a triaxial halo: morphology, bar strength and halo properties', by E. Athanassoula, R. E. G. Machado and S. A. Rodionov, 2013,* Monthly Notices of the Royal Astronomical Society*, vol. 429, Issue 3, p. 1949.)*

6. Forming discs in mergers

In scientific research a question often leads to a result, which, in turn, leads to another question. So, after having spent several years on trying to understand the formation and evolution of bars with the help of N-body simulations, I found myself wondering whether the standard approach followed by dynamicists was the right one. The initial conditions in these numerical simulations are a disc in quasi-equilibrium in its host halo, so that, dynamically, the problem is well set. But is this how bars form in real galaxies? Does a disc form first in its halo, and then evolve to an axisymmetric equilibrium which is bar unstable, so that bar formation starts? Was the disc always bar-stable as it grew to an axisymmetric equilibrium? Moreover, could it be that by starting in such a quiescent way, we bias our results? To try and answer such questions I had to take a step back and start thinking about how discs may have formed.

Obtaining an even simplified and schematic view about this is far from trivial. We know that there are a number of mergers even in the local Universe, and that their number increases strongly as we go further back in time. So I thought of trying to use these mergers to create disc galaxies.

In the seventies, Alar Toomre had presented mergers as a possible way of creating elliptical galaxies, thereby introducing the notion that a merger does not necessarily lead to a messy heap of stars, but to another galaxy, presumably of a different kind (Toomre & Toomre 72, Toomre 77). Although this picture was initially heavily criticised[1], it gradually got adopted after both obser-

1. Gerard de Vaucouleurs once remarked that "after a collision a car is a wreck, not a new type of car!"

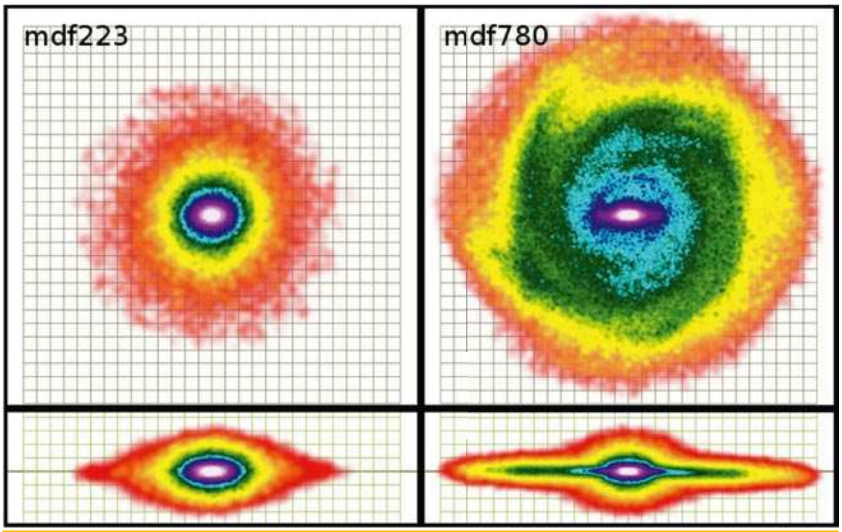

***Figure 5:** The effect of a hot gaseous halo in disc galaxy formation. Comparison of two simulations, one with (right panels) and the other without (left panels) a hot gaseous halo, both at time t=10 Gyr. The upper and lower panels show the face-on and edge-on views, respectively. The Cartesian grid included in the background has cells of 1×1 kpc size. (This figure is part of Fig. 8 in "Forming Disk Galaxies in Wet Major Mergers. I. Three Fiducial Examples", by E. Athanassoula, S. A. Rodionov, N. Peschken and J. C. Lambert, 2016,* The Astrophysical Journal*, vol. 821, article id 90.)*

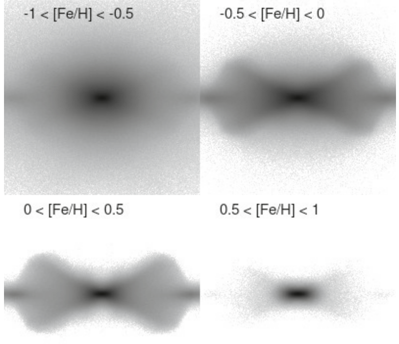

***Figure 6:** Bar/bulge region viewed side-on to the bar, separately for stellar groups of different metallicity. This increases from left to right and from top to bottom, and one can see it roughly as an age sequence. Note that the distribution of the oldest stars (top left panel) is roughly a triaxial ellipsoid, not reminiscent of the side-on shape of the bar. The second group (top right) shows clearly a peanut/X shape, but looking carefully one can see the ellipsoid of the older stars, as well as part of the disc. The latter has disappeared from next group (bottom left), while the youngest group (bottom right) must presumably be mainly the discy pseudo-bulge. (This figure is reproduced from Fig. 3 in "Metallicity-dependent kinematics and morphology of the Milky Way bulge", by E. Athanassoula, S. Rodionov and N. Prantzos 2017,* Monthly Notices of the Royal Astronomical Society, *vol. 467, Issue 1, p. L46.)*

vations and simulations came up with results that argued in its favour. Many of the simulations following this seminal work included gas, and a number of them showed some disc formation. The resulting disc, however, is too small and insufficiently massive, much less so than the large and very massive classical bulge at the galaxy centre. Thus, such simulations never formed any proper disc galaxy. There were strong hints that by increasing the gas fraction in the two colliding galaxies one got a better disc component, but even unbelievably high gas fractions proved insufficient.

I was about to give up this line of thought, when I saw some light at the end of the tunnel. I realised that the main problem was that, during the merging, the gas was pushed inwards to the innermost regions, where its density reached high levels and triggered very strong bursts of star formation. Thus the gas was consumed and could not form a decent disc. This explained why all these trials with very gas-rich progenitors could not form proper disc galaxies. Hence what was necessary was some gas that would escape this fate and rain in after the main star formation burst. If I was making this chain of thoughts today, it would be obvious how this gas would come in. But at that time relatively little was known about the circumgalactic medium, so I lost quite a bit of time pondering about whether this was a reasonable path to follow.

To understand this fully, S. Rodionov and I ran two simulations, both starting with a pair of two protogalaxies. In the first simulation, the two protogalaxies had a hot gaseous halo each, while in the second one this gas was replaced by dark matter particles (to keep the dynamics of the two cases as similar as possible). The stellar component of the remnant is shown in Fig. 5, with the first simulation to the right and the second to the left. The effect of the circumgalactic gas in disc formation became now quite clear at a glance. The merger remnant of the simulation with circumgalactic gas has an extended thin disc with realistic structures, such as a bar and spiral arms, while the one without this gas had a short, low mass disc with practically no structure. Viewed edge-on the former shows a realistic classical bulge outline and an extended thin disc component, both of which are clearly absent from the latter (see Fig.5).

Of course a lot of work was still necessary to show that the merger remnant can have properties that are in agreement with the main properties of observed disc galaxies. My collaborators in this endeavour are S. Rodionov, A. Bosma, N. Peschken and J. C. Lambert. We still have not completed all this, but we have found a lot of very encouraging results and, most important, a number of very good agreements with observations. Here is a partial list: The discs from the simulations are exponential and have a break, which in most cases was type II (i.e. downbending compared to the inner exponential disc), although there are also type III profiles (i.e. upbending compared to the inner disc). The disc has two components, a thin and a thick one. A classical bulge, as well as a fair part of the thick disc, is formed from the stars born before the merging, so that at the end of the simulations, i.e. around redshift zero, the classical bulge and the thick disc contain on average older stars than the thin disc. Boxy/Peanut bulges as well as discy pseudo-bulges and classical bulges formed in many cases, sometimes all three in the same simulated galaxy. The properties of the bars and the spirals that formed in these discs are also quite encouraging.

More recently, we coupled the chemical evolution code of N. Prantzos to the code we use to follow the dynamical and hydrodynamical evolution, which opened yet further perspectives. In particular, it allows us to set tighter constraints on the models, using age, metallicity and alpha-element radial profiles. We showed that in the central region of the Galaxy, known as the bar/bulge region, cohabitate a number of components, such as the stellar halo, the various types of bulges (classical, discy, and boxy/peanut), the thin and the thick disc, and their corresponding bar components. Each of these has its own morphology, kinematics and dynamics. It is thus a very complex, but very interesting region to study, and the results can now be compared with detailed observations provided by Gaia, and related surveys of various types of stars in the Milky Way.

7. Dark matter halo

The dark matter halo can not be directly observed as it does not emit in any observable wavelength. Thus, our knowledge of its properties is severely limited. We can, nevertheless, study it indirectly from the effects it has on other components, which we can observe. Therefore, the main tool with which we can obtain information on this halo is galaxy dynamics. The basic approach is very easy to understand. The velocities of stars and/or gas can be observed as these are constituted by baryons. We can then use dynamics to calculate the part of these velocities that is due to the gravitational forces of the baryonic distribution. Whatever can not be accounted for by the baryons must come from the dark matter. In this way we can obtain constraints on the amount and distribution of the dark matter mass assuming that the forces are Newtonian. More recently, other laws of gravity have started being explored.

It is also possible to use more elaborate dynamics. For example, in an early collaboration with A. Bosma and S. Papaioannou, I used constraints introduced by the swing amplification theory of spiral structure (Toomre 1981). Assuming that this theory can indeed explain the formation of spirals in observed galaxies, we reached some useful conclusions on the dark matter haloes in nearby disc galaxies.

Given the importance of dark matter in all galactic dynamics, I also participated in a number of studies aiming to detect it. The first one considered the effect of the halo shape on the dark matter annihilation signal expected from the weakly interacting massive particle (WIMP) in the region of the Galactic centre. In a second study, we estimated the gamma ray and neutrino fluxes coming from dark matter annihilation in a Milky Way framework using a Milky-Way-like, cosmological N-body simulation. We also used a cosmological simulation which includes baryons to study the dark matter direct detection signal. Although the results of all these attempts gave useful constraints, they are only a very minor step and much more effort is necessary before we have a definite solution to the dark matter problem.

8. Orbital structure

If one wants to build a house, one must first consider what bricks and other components to use. In the same way, in order to understand how a galaxy forms and evolves, one must first study the orbits of the stars that constitute it. This is a fascinating part of dynamics, as it can reveal many interesting aspects of galaxies. Two questions attracted me most:

The first question, on which I worked mainly in collaboration with P. Patsis and Ch. Skokos, is how orbits can get together to form the thin and the thick part of bars. Simple straightforward studies of periodic orbits can provide answers to crucial questions such as: what sets the limits to the extents of bars? Why are the inner parts of the bar thick, in contrast to the outer parts that are thin? Why don't we observe bars that, in their face-on view, have a major to minor axis ratio smaller than a certain limit? What is the role of chaos in forming bars? etc. etc.

The second question, on which I worked mainly in collaboration with M. Romero-Gomez, is whether spirals in barred galaxies can be due to manifolds. At first sight this might seem incongruous, as manifolds are linked to chaos, while spirals are thin, well defined structures with clear limits. This, however, is somewhat of a rush, since the manifold driven orbits are spatially guided by their manifolds and therefore able to outline structures. The corresponding chaos is often referred to as 'confined chaos'. Manifold theory is relatively simple, relying on the dynamics of the Lagrangian points of the bar, and has had many successes. It can account both for spirals and for inner/outer rings, and the thus formed outer rings have the observed R1, R'1, R2, R'2 and R1R2 morphologies, as well as the dimples near the direction of the bar major axis. It also explains why the vast majority of spirals in barred galaxies are two armed and trailing, and naturally comes to the conclusion that stronger bars will create more elongated rings.

9. Observations

My husband is also an astronomer, doing observations at many different wavelengths. Thus, I learnt very early-on that a theory which does not compare reasonably well with observations, even if it is very elegant and mathematically correct, is of little use.

The first large scale collaboration that he and I were invited to join together was the S^{4}G (Spitzer Survey of Stellar Structure in Galaxies, Sheth et al. 2010). This is a survey comprising images of roughly 2400 galaxies taken by the Spitzer space telescope at 3.6μm and 4.5μm, i.e. the wavelengths where mainly the older stars emit. Since these stars contribute the bulk of the baryonic mass in galaxies, they can provide information which is essential for understanding galactic dynamics and evolution.

The S^{4}G group consisted of about three dozens astronomers, covering with their expertise all the necessary fields. Of major importance is the fact that this group found from the very start optimum ways of collaborating,

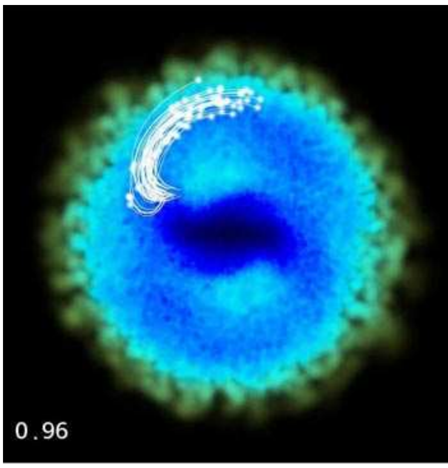

Figure 7: *Disc component in a simulation snapshot, on which are overlaid the locations (white filled circles) and trajectories (white solid lines) of a representative set of particles. Note how the latter trace the spiral arm. (This figure is the middle row, left column panel of Fig. 4 in 'Manifold-driven spirals in N-body barred galaxy simulations', by E. Athanassoula, 2012,* Monthly Notices of the Royal Astronomical Society, *vol. 426, p. L46.)*

leading to a very large number of interesting results, on a wide variety of subjects such as the galaxy stellar mass, its morphology, the thick disc, bars, spirals, rings, disc breaks, secular evolution, links with environment, studies of individual galaxies, etc.

The study of the structure of our Galaxy is now being revolutionized, thanks to the Gaia satellite, and the related ground-based spectroscopic surveys. I was involved in a number of such works, and particularly in the ARGOS survey (Ness et al. 2013, and references therein) which gave us the kinematics, metallicity and alpha enhancements of about 28000 stars in the bulge region and out into the thick disc. We first sought the origin of the split red clump in the Galactic centre and linked it to the boxy/peanut shape of the Galactic bar. This, together with our kinematics and metallicity results, demonstrated that the Galactic bulge is most likely due to internal dynamical processes, rather than mergers. Using a simulation which includes the various stellar populations in the bar/bulge region we reproduce very adequately the observed velocity dispersion profiles with longitude and their variations with galactic latitude and metallicity of the populations (see Sect. 6 for more information).

In extragalactic astronomy, the main new optical instruments are integral field spectrographs, and many surveys such as CALIFA, MaNGA and SAMI are already delivering 3D (2D spatial and 1D spectral) kinematic information from the gaseous and stellar components. The precursors of the SKA (Square Kilometre Array) radiotelescope, doing 21-cm HI line imaging and kinematics, are just entering this phase. Here also I am part of a number of collaborations, to which I contribute mainly in the modelling and interpretation of the data. In collaboration with a large team from several countries, we used MaNGA data and the Tremaine-Weinberg method (1984a) to get estimates of the bar pattern speed for a large number of barred spirals and compared them with those from simulations. Other collaborations focused on star formation in the centres of galaxies, trying to understand why this can be very strong in some cases, and very low in others, or trying to establish the role of bars and of interactions using data from CALIFA and EDGE. This list is far from complete, but gives some feeling of the many possibilities that are now available.

In order to understand the formation and evolution of bars better, I also participated in a few studies extending to higher redshifts. I was a member of a large team from various countries, headed by K. Sheth, which, using the 2 square degrees COSMOS data set (Sheth et al. 2008), found that the fraction of spiral galaxies that have a bar component is a strongly declining function of redshift. We further found that the bar fraction depends also on the galaxy stellar mass, integrated colour and bulge prominence. In very massive, luminous spirals the fraction that is barred is roughly constant out to $z \sim 0.84$, while for the low-mass, blue spirals this fraction decreases considerably with redshift beyond $z = 0.3$.

10. In way of a conclusion

It is usual to end such articles by some conclusions. I will not do that because this is a subject in which every end is just another beginning. But I can definitely bring up a few points.

The first is that it is great fun to work on galaxies, their structure, dynamics, formation and evolution. In this field of research, there are so many very interesting and yet unanswered questions, for which a lot of information is available and awaiting eager minds.

The second is that this is indeed a very good time to study galaxies. Observational data in many wavelengths and covering morphology, kinematics and photometry are publicly available and awaiting to be modelled and understood. Moreover, computer hardware, with several thousands of processors working in parallel, and coupled to the appropriate software, allows us now to explore questions which, not too long ago, would be only considered as in the realm of science fiction. So this is the moment to work on galaxies and if any young student is looking for an exciting thesis subject, my advice to them would be to consider galaxies, their formation and evolution!

Last but not least, this is a subject for which it is very useful to have a relatively broad view. The best is to repeatedly ask oneself how the specific thing one is concentrating on at the time fits in the general picture. This allows one to make links which had not been noticed before and stops one from devoting too much time to things which are secondary. Furthermore, it is a strong asset to be able to choose from a wide spectrum of 'tools' the ones that are most appropriate for tackling the problem at hand. Such 'tools' can range from theoretical techniques, to state-of-the-art numerical simulations, to data from large available observational surveys and to data reduction and visualisation tools. It is always refreshing to try a new field or a new technique.

Good luck in your quest for understanding galaxies. You will find it good fun, so be sure you enjoy every minute of it.

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