Report on the Workshop

Deconstructing Galaxies: Structure and Morphology in the Era of Large Surveys

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Over 120 researchers — observers and theoreticians — gathered to present new results and discuss ongoing investigations on the structure of galaxies. The study of the structure and morphology of galaxies is one of the major tools that astronomers have to address how galaxies form and evolve. Recent progress in the field has enabled a boost in our understanding of the properties of the different structural components in nearby galaxies, as well as in galaxies at intermediate redshifts (z ~ 1–2).

Two main topics motivated this workshop. Firstly, there is the connection between galaxy structure and the physics of galaxy formation and evolution. After decades of fitting galaxy light profiles or images with mathematical functions to describe the various components (e.g., bulge and disc), it is imperative to advance from a stamp-collecting approach and connect the results to the physics. The link between structural properties, kinematics, stellar population content and the complex physics involved in the formation and evolution of galaxies is a much more challenging step. One of the main goals of the workshop was to address this connection, by questioning, for instance, what the structure of galaxies tells us about their formation and evolution, and how observations can help constrain models.

The second consideration was the tools that are used to measure the structural parameters in galaxies. The complexity of these tools has grown considerably in recent years. It is thus extremely important to address the strengths and limitations of the different techniques, particularly with the expectation that automated procedures designed to handle large surveys may prevail in the future.

Our first announcement ended with a bold statement: "This ESO Workshop should set the basis for the study of galaxy structure and morphology in the next decade." It was with deep satisfaction that we concluded the meeting with the realisation that this might indeed have been achieved. The conference website[1] contains the slides for all oral presentations, as well as for most posters; audio/video recordings are also available for the talks. Highlights of the meeting, necessarily biased by our own perspective and limitations of space, are subsequently presented.

Day 1: Structure, morphology and the underlying physics

The first day (Monday) began with results from GalaxyZoo, presented by Karen Masters, and the Millennium and the Galaxy And Mass Assembly (GAMA) surveys, by Simon Driver. Karen convincingly showed the power of citizen science, something that many in the community may have looked at with scepticism initially. By using statistical methods it is possible to not only separate early-types and disc galaxies, but also to assess bar fractions and sizes and even galaxy morphology at higher redshifts. Simon described the logical filter used to evaluate the quality of automated decompositions, and showed results that lead him and his collaborators to conclude that processes that form discs are more efficient than processes that form spheroids. He also questioned what a spheroid looks like when it is forming, noting that at high redshifts nothing resembles one, but possibilities include clumpy discs, thick turbulent discs and blue spheroids. Pat Côté followed, showing new results on the structure of galaxies at the core of the Virgo cluster (with the New Generation Virgo Survey [NGVS]), including the difficulties of dealing with background subtraction. He showed that nuclei are often bluer than the surrounding areas in low-mass galaxies. Lisa Fogarty showed the power of studying stellar kinematics with the Sydney Australian Astronomical Observatory Multi-object Integral Field Spectrograph (SAMI). She presented two surprising observations, namely the presence of slow rotators on the outskirts of clusters, and two brightest cluster galaxies (BCGs) that are fast rotators.

Next, the spectacular features revealed by deep imaging of galaxies, such as shell-like structures and streams, were shown by Pierre-Alain Duc and Yun-Kyeong Sheen. Duc discussed how these features provide clues to understanding galaxy formation mechanisms. For example, while gas-rich major mergers produce tidal tails lasting for about 2 Gyr — in contrast with gas-poor major mergers, which do not seem to produce lasting features — intermediate-mass mergers appear to induce shells with a lifetime of 3–4 Gyr. Chris Conselice described how more massive galaxies become Hubble types earlier than less massive galaxies and results indicating that the number of major mergers an average massive galaxy undergoes from z ~ 3 to zero is about two, roughly doubling its stellar mass. Minor mergers and gas accretion/*in situ* star formation would contribute equally to the stellar mass budget.

The properties of fast and slow rotators were reviewed by Michele Cappellari who discussed the mass–size relation and its evolution with redshift. A strong size increase with redshift is found only for galaxies more massive than 10^{11} $M_{\odot}$, perhaps indicating that growth via mergers is unimportant for galaxies below this mass threshold. Andi Burkert gave an inspired talk emphasising the strong role of the environment on galaxy formation via gas accretion and minor mergers. He also pointed out that we still do not know how to form the Milky Way, or how its progenitors appear at higher redshift. In addition, he showed simulations (by R. Teyssier) in which discs — contrary to common belief — are not destroyed in major mergers.

Day 2: Structure and morphology of early-type and spheroidal galaxies

Laura Ferrarese started the second day by reviewing the morphology and structure of massive early-type galaxies. She showed that early, *in situ* star formation builds high phase-space density cores, while minor mergers mostly contribute to the formation of extended envelopes — with the balance between both processes depending on mass and environment. Bililign Dullo subsequently showed

that the stellar mass deficits in core Sérsic lenticular galaxies favour a two-step inside-out scenario for their assembly: an early violent “dry” merger, followed by late accretion of gas and stars. Rhea-Silvia Remus presented evidence that the total mass density profile of elliptical galaxies is related to their merging history: at high redshift the density slopes are steep ($\gamma = -3$), and at each subsequent gas-poor merger event the slope evolves towards $\gamma = -2$. Pablo Pérez-González introduced the Survey for High-z Absorption Red and Dead Sources (SHARDS), a Gran Telescopio Canarias (GTC) narrow-band imaging survey. Through 25-point spectral energy distribution (SED) fitting, he showed that $z \sim 1$ red and dead galaxies have stellar population ages ~ 3 Gyr and formation timescales ~ 300 Myr.

Guillermo Barro followed, showing that the build-up of the red sequence occurs rapidly as star-forming galaxies at redshifts 2–3 first compactify, and then quench. Using Keck spectroscopy, Sirio Belli presented evidence for a significant evolution of quiescent galaxies in both mass and size since $z \sim 2$. However, their study suggests there is no evolution in their dynamical-to-stellar mass ratios. These results were challenged by Paolo Saracco, who argued that ellipticals have completed their mass growth by $z \sim 1.3$, with little to no subsequent structure evolution. Veronica Strazzulo presented a study of the structure of massive early-type galaxies in a cluster at $z \sim 2$. These galaxies seem to be larger than field early-types of similar masses, but larger cluster samples at high redshifts are needed to confirm these first results. Marc Huertas-Company showed that the mass–size relation of $z < 1$ early-type galaxies appears to be almost universal for all environments, and indicated that semi-analytic models of galaxy formation fail to reproduce this effect. Phil Hopkins summarised recent progress on the physics of feedback and how it regulates star formation. He pointed out that possibly the most pressing question in astrophysics today is why star formation is so inefficient.

The afternoon was devoted to the structure of dwarf galaxies. Thorsten Lisker showed that early-type dwarfs are continuously shaped by processes acting in groups and clusters. Joachim Janz showed that quiescent dwarfs are structurally complex, but the level of complexity decreases towards the faint end. It is however not yet clear what the physical nature of the “extra” structural components in these galaxies is. Rubén Sánchez-Janssen presented the first study on the intrinsic shape of dwarf spheroidal (dSph) galaxies using data from the NGVS survey. dSphs are oblate spheroids, and there appears to be no evidence for very elongated shapes in this population. On the other hand, Ricardo Muñoz showed that the ultra-faint Milky Way satellites tend to be elongated, possibly due to tidal effects. These extreme systems bridge the mass–size relation region between globular clusters and the classic satellite galaxies. Numerical simulations of the destructive effects of ram-pressure stripping on tidal dwarfs were presented by Rory Smith, who showed that 50–100 % of all stars become unbound as a result of the drag force created by the gas stripping.

Day 3: Structure and morphology of disc galaxies

Victor Debattista started the morning session by describing simulations of secular evolution in disc galaxies. He showed models in which the growth of a surrounding disc compresses a pre-existing (classical) bulge, raising its velocity dis-

Figure 1. Participants at the workshop in the Vitacura garden.

persion. This effect qualitatively accounts for the observed offset between elliptical galaxies and classical bulges in some scaling relations. Elena D'Onghia showed simulations where the formation of bars is suppressed and long-lived spiral arms form as a result of density perturbations in the disc. Then, impressive HI data were shown by Marc Verheijen, where tidal streams display no gas content and ram-pressure stripping can be seen in action. He also showed HI-derived rotation curves indicating that discs are submaximal.

Alister Graham then showed that the locus of high-redshift ellipticals in the mass–size relation is similar to that of low-redshift bulges, suggesting that the two systems may be connected. Jairo-Méndez-Abreu came next, showing that there is no clear kinematical difference among bulges spanning a range of structural properties in a small early-type galaxy sample from the Calar Alto Legacy Integral Field Area (CALIFA) survey. Ronald Läsker subsequently demonstrated that the black hole mass – galaxy luminosity relation appears to be very tight, and then Mauricio Cisternas showed that most active galactic nuclei (AGN) activity is in discs, with only a minority in mergers.

Day 4: Structure and morphology of disc galaxies (cont'd)

Thursday saw us continuing the discussion on disc galaxies, with Stéphane Courteau reviewing scaling relations. He pointed out that scale parameters, obtained through decompositions, are rarely derived with an accuracy better than 20%, and showed further evidence for submaximal discs. Nacho Trujillo next reviewed the outer structure of disc galaxies, concluding that down-bending breaks are associated with changes in the stellar population at the position of the break — possibly through radial migration and bar resonances. Truncations, on the other hand, are associated with real drops in the density of stars. Up-bending breaks and outer light excesses are related to the stellar halo and/or interactions with companion galaxies.

The effects of ignoring the variety in disc profile shapes in galaxy image decompositions was discussed by Taehyun Kim. Using data from the Spitzer Survey of Stellar Structure in Galaxies (S^4G) , she showed that bars almost exclusively have exponential profiles in bulgeless galaxies, whereas the presence of a bulge almost always results in bars with flat luminosity profiles. She further showed that in galaxies with prominent bulges, down-bending breaks in discs are at the bar outer Lindblad resonance.

Thick discs, their existence and formation mechanisms were reviewed by Peter Yoachim, who showed that early mergers create a population of old stars that later can radially migrate and thicken. David Streich presented results on thin and thick discs from the GHOSTS survey, and noted that thick disc heating seems to happen on time scales larger than ~ 500 Myr. By using numerical simulations, Ivan Minchev showed that radial migration is able to cool discs during mergers. In addition, he suggested that thick discs form from the flaring of the different age populations. Further impressive data from the GHOSTS survey were shown by Roelef de Jong with findings that inner stellar halos (< 25 kpc) have Sérsic indices around 4–6, and are very flattened (c/a ~ 0.3). These data show that the substructure in stellar halos is diverse.

The afternoon session was devoted to bars. Alfonso Aguerri reviewed studies on the fraction of barred galaxies in the local Universe. He showed that the bar fraction is strongly dependent on galaxy mass — this is likely the main cause of the disagreement among studies in the literature. He also presented results that indicate that a dense environment can heat up thin discs and destroy bars in low-mass galaxies, whereas it induces bar formation in more massive galaxies. Kartik Sheth pushed the topic to higher redshifts, showing the decline of bar fraction to $z \sim 1$. He argued that more massive discs form bars earlier than less massive ones, as they become dynamically mature earlier. Using data from the Near Infrared S0 Survey (NIRS0S) and the S^4G survey, Eija Laurikainen introduced barlenses, a stellar structure often seen in barred galaxies. These structures are probably box/peanuts seen at a different projection, and not inner discs or classical bulges.

Evidence for bar-induced secular evolution in massive disc galaxies was presented by Dimitri Gadotti. He showed that: (i) longer bars tend to be stronger; (ii) discs in barred galaxies show fainter central surface brightness and longer scale lengths than discs in unbarred galaxies; and (iii) that bars rejuvenate the stellar population of bulges. Juan Carlos Muñoz-Mateos followed, showing with S^4G data how bars and spiral arms can produce down-bending disc breaks through resonances and radial migration. With CO data, he also showed that molecular gas profiles are broken too, with sharper breaks than stellar profiles.

Lia Athanassoula showed the variety and complexity of the physical phenomena that influence bar formation and evolution. Dark matter halo triaxiality and mass, disc kinematics, gas fraction and the presence of a thick disc, all influence the speed with which bars form. These factors, plus the velocity distribution function in the halo, and the presence of a central mass concentration, also influence the angular momentum redistribution in the galaxy, and therefore how strongly the bar develops. Classical bulges and halos slow down bar formation, but help bars to grow stronger later. To close this important section, Francesca Iannuzzi showed her promising, ongoing work on the signatures box/peanuts imprint on 2D stellar kinematic maps. By using numerical simulations of edge-on systems, she showed that these maps can reveal hidden peanuts seen end-on, thus avoiding the likely confusion of an end-on bar with a classical bulge.

Day 5: Structure of the Milky Way, tools and analysis methods

The last day of the meeting was an atypical closing day, which led us to finish the meeting on a high point. Joss Bland-Hawthorn reviewed the properties of the Milky Way in the context of external galaxies. He also made the important remark that half of all stars in the Galaxy were in place by $z \sim 1$, and that its current star formation rate puts it in the green valley.

The session on tools and analysis methods began with Luc Simard discuss-

ing the pros and cons of automated bulge/disc decomposition applied to very large samples. Boris Häussler followed, describing MegaMorph and its multi-wavelength galaxy image fitting, showing that structural parameters are recovered with lower uncertainties if they are forced to vary smoothly with wavelength. Lee Kelvin showed how the stellar mass content is distributed among different structural components and morphological types, using data from the GAMA survey.

Imfit, a new, flexible and powerful image decomposition code was introduced by Peter Erwin, who also showed how using Cash statistics — as opposed to the familiar χ^2 statistics — leads to more accurate measures of galaxy structural parameters, particularly in low signal-to-noise regimes. Marina Vika discussed the tricky distinction between elliptical and lenticular galaxies when using two-component image decompositions. The last talk of the meeting was given by Steven Bamford, who showed how including a non-parametric component to account for difficult features, such as spiral arms, improves the determination of structural parameters through parametric fits.

The meeting closed with a lively general discussion that lasted for over an hour and consisted of three sections. The first dealt with practices that should be avoided. For observers, these include: (i) not using v/σ alone, without information on ellipticity, to separate fast and slow rotators; (ii) not fitting edge-on galaxies without taking into account the dependence of the luminosity on the vertical distance from the disc plane; and (iii) not ignoring the presence and harmful effects of bars on decompositions that contain only models for the bulge and disc. For modellers, it was pointed out that the term “morphology” has been often used to express concepts that are not equivalent from a physical perspective. A remark that applies to both modellers and observers is not to use catalogues of morphology or structural measures without paying attention to the biases and limitations of such catalogues.

The second section concerned practices that we, as a community, suggest for advancing the field. Two observed properties that were often discussed during the meeting are found to be robust, and modellers are encouraged to try and reproduce them. The first property is the offset in the mass–size relation observed at the high-mass end between elliptical galaxies and bulges at $z = 0$. The second property is the merger rate as a function of lookback time.

Finally, the third section was devoted to a wish list of facilities/concepts deemed necessary for further progress. These included obtaining data on resolved stellar populations out to the Virgo cluster (feasible with the European Extremely Large Telescope, but with some pioneering work using the MUSE narrow-field mode also possible), and making simulations/models publicly available in a style similar to the Virtual Observatory initiative. Gas distributions out to $z \sim 1$ (with the Square Kilometer Array), and an imaging survey providing a physical spatial resolution similar to that of the Sloan Digital Sky Survey at $z \sim 0.05$, but out to $z \sim 1$ (with the Euclid satellite), were also mentioned. Finally, we agreed that the future of studies like the ones presented during the workshop depends on the interest of the general public in astronomy in general and galaxies in particular. Initiatives like GalaxyZoo are widely viewed as fantastic ways to keep the general public engaged.

Links

[1] Workshop website: http://www.eso.org/sci/meetings/2013/morph2013.html

ESO/P. Grosbol

Gallery of six spiral galaxies in near-infrared images taken by HAWK-I on the VLT. They represent just a few examples for the enormous variety of spiral patterns in galaxies. From left to right the galaxies are NGC 5247, M100 (NGC 4321), NGC 1300 (upper row) and NGC 4030, NGC 2997 and NGC 1232 (lower row). See Release eso1042 for more details.