Morphology of galaxies

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Abstract.

The study of the morphology of galaxies is important in order to understand the formation and evolution of galaxies and their sub-components as a function of luminosity, environment, and star-formation and galaxy assembly over cosmic time. Disentangling the many variables that affect galaxy evolution and morphology, requires large galaxy samples and automated ways to measure morphology. The advent of large digital sky surveys, with unprecedented depth and resolution, coupled with sophisticated quantitative methods for morphology measurement are providing new insights in this fast evolving field of astronomical research.

The field of galaxy morphology has a long history in astronomy. It is also a very wide and active field of research at the present time. A recent review by Buta ([7]) is 174 pages long and cites about 350 papers. In this short review, due to paucity of space, only a small part of this active field can be covered. I must admit that the topics I cover are somewhat biased by my own research interests in this area. For a more comprehensive and unbiased survey of the field, the reader is referred to the excellent review by Buta [7]. For a more pedagogical introduction, the classic text by Binney and Merrifield ([6]) is highly recommended.

1. Galaxy morphology: a brief history

It was realised nearly a century ago that galaxies were indeed "island universes"; independent systems composed of a gravitationally bound assemblage of stars, gas and dust. The study of galaxy properties, began in earnest after this discovery. In the early decades of the 20th century, it became clear that most bright galaxies fell into two distinct categories - those with a smoothly declining brightness distribution with no inflections, and no evidence for a disc called "ellipticals" and the disc-dominated systems with spiral arms punctuated with star-forming complexes, called "spirals". By 1936, when Hubble's book *Realm of the Nebulae* ([12]) appeared, the study of galaxy morphology had become a well established sub-field of optical astronomy. In this book, based on lectures he had delivered at Yale University a year earlier, Hubble published the Hubble sequence for galaxy classification (popularly known as the "tuning fork diagram", due to its resemblance to the shape of a tuning fork). In Hubble's classification scheme (Figure 1), regular galaxies are divided into 3 broad classes - ellipticals, lenticulars (S0) and spirals - based on their visual appearance on photographic plates. A fourth class (added later, not seen in Figure 1) contains galaxies with
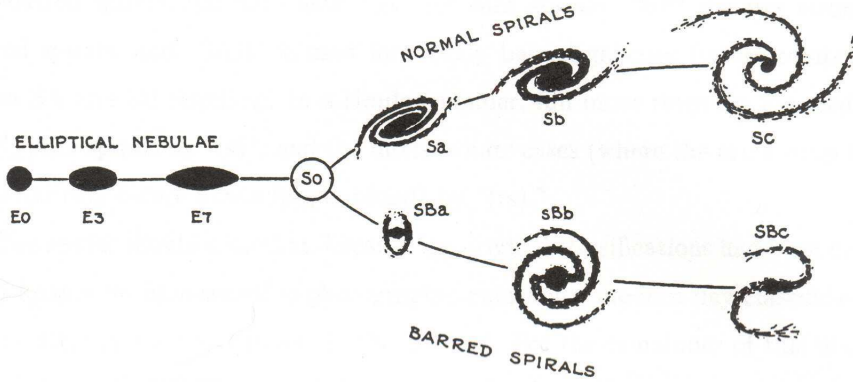
Figure 1. Hubble's scheme for galaxy classification as it appeared in [12]. Although more sophisticated versions of this scheme have been proposed by others, the basic ideas have survived for three quarters of a century.

an irregular appearance; these were invariably forming stars at a rapid rate. Although a few other other schemes of galaxy classification have been proposed in the literature (e.g. [15, 20]), it is the Hubble classification (as revised and expanded by Sandage ([18]) and de Vaucouleurs ([11])) that is most widely used. According to Sandage ([19]), one reason Hubble's view prevailed is that he did not try and account for every superficial detail, but kept his classes broad enough that the vast majority of galaxies could be sorted into one of his proposed bins.

In recent years, the field of galaxy morphology has undergone a renaissance for several reasons. These include:

 (i) Morphology is a fundamental property of galaxies. Any theory of galaxy formation and evolution has to explain the observed distribution of galaxies as a function of cosmic epoch and environment.

(ii) Galaxy morphology is strongly correlated with galactic star formation history. Galaxies where star formation ceased many gigayears ago usually have a different morphology from those where star formation continues at the present time (Figure 2). Galaxy morphology, therefore, is a zeroeth order tracer of star formation history.

(iii) Recent discoveries of new types of galaxies (Figure 3, [8]), and higher resolution views of nearby galaxies have expanded the field as modern digital surveys and the Hubble Space Telescope have superseded the old photographic plates, that were in use for decades.

(iv) The explosion of data is accompanied by the development of quantitative techniques for automated measurement of galaxy morphology.

 (v) Visual classification of millions of galaxies has also been revolutionised by citizen science projects such as Galaxy Zoo[1]. Galaxy Zoo has

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[1] http://www.galaxyzoo.org

transformed the field from the exclusive practice of a few experts to that of hundreds of thousands of enthusiastic Internet connected amateurs (without compromising on quality!).

(vi) The Hubble Space Telescope has enabled imaging studies of nearby galaxies at unprecedented resolutions (e.g. Figure 2) and deep surveys with the same telescope have extended morphological studies to $z = 1$ and beyond (Figure 7).

The present effort in the area is directed at obtaining an understanding of how galaxy morphology is influenced by environmental density, merger/interaction history, internal perturbations driven by instabilities, gas accretion from other galaxies, nuclear activity, internal secular evolution and star formation history (see [13] for a discussion of the interplay of all these factors). Disentangling the effect of all these interconnected influences on galaxy morphology is a complex exercise and is the central problem of galaxy evolution. Independent, yet synergistic developments in 1. the development of theories of galaxy evolution with predictions of observables such as galaxy morphology and 2. multiwavelength observations of large galaxy samples at a variety of redshifts and in different environmental conditions (clusters, groups, field) to test the predictions of the theories are enabling a better understanding of galaxy evolution. It must be noted that, increasingly, theories of galaxy evolution are developed as advanced computer simulations that take into account all the relevant physics of the gas, dust, stars and dark matter (e.g. [5]). As computing power has grown dramatically in the last two decades, the simulations have become increasingly realistic.

2. Quantitative morphology

In the traditional method of classification, images of galaxies on photographic plates (Kodak 103a-O and IIa-O were widely used) were carefully examined by an expert, who then assigned a class to each object. In blue sensitive plates, massive star clusters dominated by early type stars stand out. At the same time dust absorption is severe and provides a dramatic contrast to the star clusters. Galaxies with spiral arms (where star formation and dust are both seen) are therefore easy to classify while other types are not. There are several other issues in working with photographic plates or their digitised versions. These include:

- The visual classification process does not scale to large galaxy samples because of the limited availability of human experts. Large samples – containing millions of galaxies – are the norm today with the availability of large area digital sky surveys such as the Sloan Digital Sky Survey [1].

- Even experts tend to show a small subjective bias in their classification, which is difficult to quantify.

- Faint, distant galaxies are very difficult to classify visually, since important guides to classification such as the presence of a disc or spiral arms may be hard to see visually, or may even be physically weak or absent in the earliest galaxies.
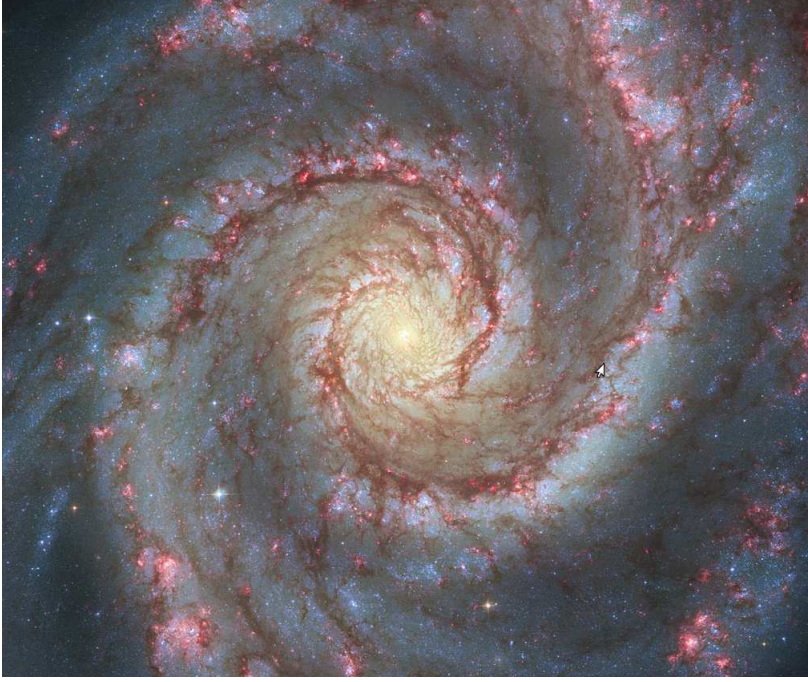
Figure 2. Hubble Space Telescope image of the central regions of M51. High resolution imaging and the clear correlation between morphological features (spiral arms) and star formation complexes (red regions within the arms) make morphology a simple tracer of star formation. Image credit: S. Beckwith (STScI), Hubble Heritage Team, (STScI/AURA), ESA, NASA
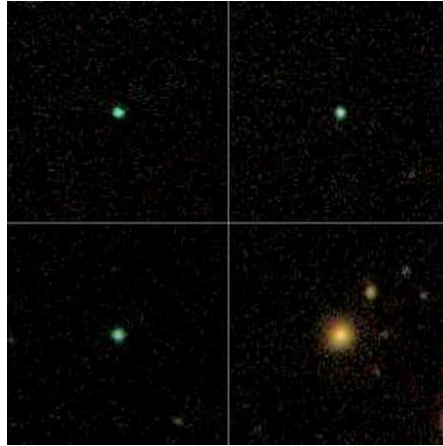

Figure 3. A new class of round, green coloured galaxies labeled as *green peas* were discovered by volunteers in the Galaxy Zoo project. Peas are rare, no bigger than 5 kpc in radius, lie in lower density environments than normal galaxies, but may still have morphological characteristics driven by mergers. They are relatively low in mass and metallicity, and have a high specific star formation rate, yielding doubling times for their stellar mass of only hundreds of Myr ([8]).

In such a situation, automated fitting and measurements of galaxy morphology using digital images has rapidly become popular. The most common approach involves extracting the structural parameters of a galaxy by the separation of the observed light distribution into bulge and disc components. The morphology can then be quantitatively measured by computing the bulge to total luminosity ratio B/T. The ratio is close to 1 for disc-less ellipticals and systematically decreases as one proceeds along the Hubble sequence, approaching a value of close of zero for late-type spirals (Sd). There is considerable variation in the details of the decomposition techniques proposed by various researchers. In recent years, methods that employ 2D fits to broad-band galaxy images have become popular (e.g. [23, 17]). Most of these decomposition techniques assume specific surface brightness distributions such as a generalised de Vaucouleurs profile ([10]) for the bulge and an exponential distribution for the disc.

The bulge-disc decomposition essentially involves a numerical solution to a signal-to-noise ratio (S/N) weighted minimisation problem. The technique involves iteratively building 2D image models that best fit the observed galaxy images, with the quality of the fit quantified by the χ^2 value. Weights for the χ^2 function are usually computed using the S/N ratio at each pixel of the galaxy image. The model image needs to be convolved with the measured point spread function (PSF) from the galaxy frame before the χ^2 is computed (Figure 4). The accuracy and reliability of the decomposition procedure can be assessed using simulated galaxy images. In addition to permitting a fit to a bulge and disc light profile, most modern codes allow one to fit for other structures such as a point source (usually caused by the presence of an AGN at the galaxy centre) and a bar. The most recent version of the widely used code *galfit* also allows for fitting irregular, curved, logarithmic and power-law spirals, ring, and truncated shapes ([17]). Wrapper programs, that enable fits to all galaxies in a specified image are useful to obtain morphological properties for hundreds of galaxies, in one go ([22]).

Once global parameters that describe the bulge and disc are available, predicted correlations from theory can be tested against the observations. I provide a couple of examples of how quantitative morphology is improving our understanding of galaxy formation and evolution.

2.1. Evidence for luminosity dependent formation of lenticular bulges

Lenticular (S0) galaxies straddle the space between ellipticals and spirals in the Hubble tuning fork diagram (Figure 1). It has been clear for some time that bulges in ellipticals and late type spirals are fundamentally different. Those in ellipticals seem to have formed their stars rapidly at early epochs; while those in late-type spirals have grown their bulges over time through internal evolution processes such as secular evolution. Bulges of the elliptical kind follow correlations such as the Kormendy relation and the Fundamental Plane. Bulges in many spirals (called *pseudo bulges*), often show correlated bulge and disk sizes indicating their formation through the secular evolution mechanism ([13]). In this context, it is interesting to understand the formation process in the intermediate lenticular type. It has been recently demonstrated that there seem to be two populations of lenticular bulges differentiated by total luminosity of the galaxies. Faint lenticulars show a positive correlation between bulge and disc
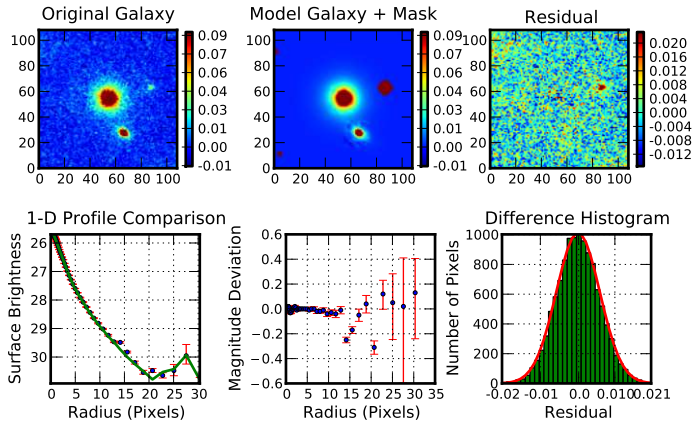
Figure 4. Sophisticated graphical front-ends are now available to visualise the outputs of bulge-disc decomposition programs ([22]). Typically, a best fit signal-to-noise weighted analytic model of the 2D light profile of the galaxy is obtained. The model usually includes different galaxy components such as the bulge, disc, nuclear source, bars, spiral arms etc. One indicator of a good fit is when the residual (galaxy − model) has a Gaussian (noise-like) distribution.

sizes, in line with predictions of secular formation processes for the pseudo bulges of late-type disk galaxies. But brighter lenticulars show an anti correlation, indicating that they formed through a different mechanism ([3]), most likely involving major mergers. Galaxy environment also has an effect. Faint cluster lenticulars show systematic differences with respect to faint field lenticulars. These differences support the idea that the bulge and disc components fade after the galaxy falls into a cluster, while simultaneously undergoing a transformation from spiral to lenticular morphologies ([4]).

2.2. Evolution of galaxy morphology in cores of clusters

It has been known for some time that the fraction of early type galaxies in the central regions of clusters has increased, as the Universe evolved. With quantitative morphology measurements on HST images of 379 galaxies in nine clusters spanning the redshift range 0.31 to 0.837, Vikram et al. ([21]) have recently measured the fraction of bulge dominated galaxies, as a function of redshift (Figure 6). They find a near monotonic decrease with lookback time in the bulge-dominated fraction of galaxies; $40.0 \, ^{+2}_{-2}$ % of galaxies at redshift $z = 0.837$ are bulge-like. This increases to $55 \, ^{+3}_{-3}$ % within ~ 3.5 Gyr.

It must be noted that the trend above is weak and statistical in nature; one needs to average over a large number of galaxies in a large number of clusters over a wide range of redshift, to see a trend. The detailed physics operating in each cluster, doubtless modifies the morphological evolution of galaxies in that cluster. Nevertheless, with a large, yet carefully selected galaxy sample, it is possible to quantitatively measure changes which would be impossible to do with a small sample.

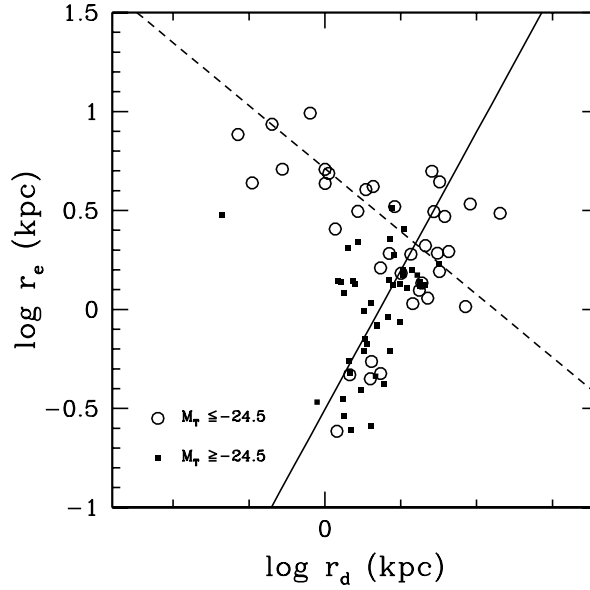Work in both the above examples was enabled by the use of 2D bulge-disc

Figure 5. Dependence of the bulge effective radius r_e on the disc scale length r_d for a sample of luminous and faint lenticulars. Dashed line is the best fit to the luminous lenticulars (circles) excluding five outliers, which shows an anti correlation. Solid line is the best fit to the less luminous lenticulars (squares) which show a positive correlation, indicating secular formation processes are active ([3]).
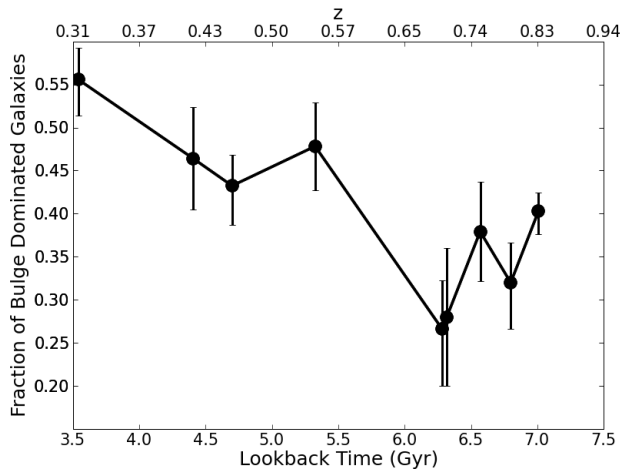

Figure 6. Evolution of the fraction of bulge dominated galaxies in the cores of nine clusters with redshift in the range 0.31 to 0.837. The fraction of bulge dominated galaxies was lower when the Universe was younger ([21]).
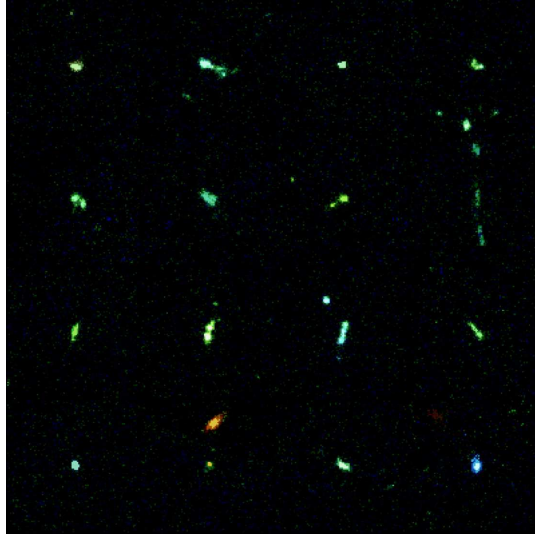
Figure 7. At the centre of each of the 16 panels in the figure, is a star forming galaxy at $z \sim 3$ ([24]) imaged with the GOODS survey on HST. At such early cosmic epochs, the well defined morphologies of galaxies in the nearby Universe are not seen, and an analytic decomposition of the light profile is unlikely to work well.

decomposition of galaxy images to measure quantitative parameters describing the bulge and disc. The two examples quoted above are merely representative of the work being done in this area. One has only to glance through the large number of citations of [16, 17] to get a feel for the enormous amount of research happening with quantitative morphological measurements.

3. Galaxy morphology at high redshifts

Beyond $z \sim 1$, even with HST data, the parametric 2D bulge disk decomposition technique does not work well. Besides the galaxies appearing faint and small, the dropout selection technique frequently used to find these distant galaxies, is biased towards highly star forming ones, which are more likely to show disturbed morphologies (Figure 7).

To make classification possible at very high redshifts, several non-parametric methods have been proposed and are widely used ([2, 9, 14]. Non-parametric methods are not computationally intensive compared to the parametric methods. However, with non-parametric methods, it is not easy to convert measured quantities to physically meaningful parameters such as bulge or disc luminosity.

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