Lecture 10:
Morphological evolution and spiral galaxies

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1 Introduction

Previously, we covered the topic of the formation and evolution of early-type galaxies. As mentioned in the last lecture, these elliptical galaxies contain roughly 50% of the stellar mass of today's Universe. In this lecture, we'll cover the formation of the other major class of galaxies in the local Universe: spiral galaxies.

2 The Milky Way's fossil record

Recall from lecture 5 that we can use the fossil record of the Milky Way to get a first-order impression of the formation of spiral galaxies. In that lecture, we learned that the Milky Way is formed of many different components, each with different star-formation histories. This points to a complex formation history consisting of both early gas collapse, current gas streaming and successive mergers.

The thin disk of the Milky Way is thought to be what's left of the gas cloud in which the fledgling Milky Way formed around 8 billion years ago. This thin disk is still being replenished by gas streaming onto the Milky Way from its immediate vicinity, providing a fuel supply for continuous star formation. By contrast, the thick disk is thought to be the result of a merger that the early Milky Way encountered when it was beginning to form (again, around 8 billion years ago), which "heated up" the orbits of the stars that had already formed by that stage. Finally, the bulge is made up of stars both from the original collapse of the early gas cloud that formed the Milky Way, and from subsequent galaxy mergers (which, again, heated the stellar orbits to create the spheroid).

However, that's just for one galaxy – our own – which could be freak event. To determine whether the Milky Way's formation history is typical of other spiral galaxies, we must study the morphological evolution of many other galaxies.

3 The morphological evolution of galaxies

We can exploit the redshift technique to study the morphological evolution of spiral galaxies. However, until recently, it was extremely difficult to do this beyond about redshift 1.5, since we need excellent spatial resolution and sensitivities to low surface brightness galaxies to resolve and measure the morphologies of distant (i.e., early) galaxies. However, redshift 1.5 corresponds to about 9.4 billion years ago, so even only going out to this "modest" redshift corresponds to studying morphological evolution across 70% of the age of the Universe.

3.1 Quantifying morphological evolution

While taking care to overcome surface brightness dimming and morphological K-corrections, astronomers can exploit the excellent seeing of the Hubble Space Telescope to study how the morphologies of galaxies have evolved over the past ~ 10 billion years. However, morphological studies are fraught with problems associated with human subjectivity. While we can easily quantify the luminosity or size of a galaxy, how do we quantify its shape in a non-subjective manner? How can you put a number on how "spirally" a galaxy is? This is a significant problem for morphological studies, with astronomers disagreeing on whether a given galaxy shows spiral structure or not (there's a few borderline cases in the lecture slides, if you want some examples). As such, it can be difficult using human classification alone to determine the degree of morphological evolution over time.

In an attempt to overcome the subjectivity problems associated with morphological classification, astronomers have attempted to identify ways to parameterise galaxy morphology, with varying levels of success. One of the most popular of these is the CAS set of parameters, which uses a simple set of measurements that can be easily made from images of galaxies. These are:

- **Asymmetry index (A)**: rotate the image of your galaxy of interest through 180 degrees, then subtract the rotated image from the original, unrotated image. Sum the absolute values of the intensities in the subtracted image, then divide by the total intensity of the original.

- **Structure index (S)**: smooth the image of your galaxy of interest then subtract the smoothed image from the un-smoothed image. Sum the intensities in the subtracted image, then divide by total intensity of the original.

- **Concentration parameter (C)**: Measure the radii that contain (i) 20% and (ii) 80% of the light of your galaxy of interest. Divide the radius containing 80% of the light by the radius containing 20%, take the $\log_{10}$ of this ratio and multiply the result by 5.

When astronomers measure these parameters and plot them against one another for various populations of galaxies, we find that they separate-out along lines of visual classification: irregular/peculiar/merger galaxies separate from spiral galaxies which further separate from elliptical galaxies.[1] As such, they provide a quantitative means of separating galaxies, reducing the subjectivity associated with visual classification alone.

3.2 The morphological evolution of galaxies

With a quantitative means to measure galaxy morphologies in-hand, astronomers can investigate how these morphologies have evolved with redshift. One of the first attempts to do this was by measuring the galaxy number counts of different galaxy types and comparing them against those expected from non-evolution models. In doing so, astronomers found that the numbers of irregular/peculiar/merger galaxies are much higher in the early Universe compared to today.

[1] Irregular/Peculiar/Mergers are often lumped together because, morphologically, it is often difficult to distinguish between mergers and irregular "clumpy" galaxies.

However, this trend is reversed for luminous spirals – there are many more luminous spirals in today's Universe compared to at $z > 0.5$.

From this and subsequent studies, astronomers have now developed a consistent picture of how the morphologies of galaxies have evolved since $z \sim 1.5$:

- At redshifts below about 0.3 (i.e., up to about 3.5 billion years ago), luminous "grand design" spirals – like the Milky Way, Andromeda, the Whirlpool galaxy – exist. As such, the Hubble diagram exist in its full form.
- At around $z \sim 0.5$ (i.e., around 5 billion years ago), barred spirals become rarer and the spiral arms of all massive spirals are much less well-defined. The splitting of Hubble's tuning fork among barred and unbarred spirals is much less obvious.
- At earlier times ($z > 0.6$, or > 6 billion years ago) the proportion of merger and irregular galaxies relative to spirals increases significantly. By around $z \sim 1$ around a third of all massive galaxies cannot by placed on today's Hubble diagram (in other words, they have irregular/peculiar/merger morphologies).

4 The morphological evolution of field galaxies

We saw in the last lecture that the most massive ellipticals have lived in the densest regions of the Universe throughout all of cosmic time. By contrast, other types of galaxies have predominantly lived in the less dense regions of the Universe between the clusters. Galaxies within these more sparse regions are known as "field" galaxies, with the more massive ones dominated, in terms of number, by spiral galaxies. So, if we want to know how spiral galaxies have evolved, we therefore need to study massive field galaxies out to high redshifts. One of the most comprehensive attempts to do this has been the Canada-France Redshift Survey (CFRS).

4.1 The Canada-France Redshift Survey

To determine the environments of galaxies in 3 dimensions requires both their position on the sky (i.e., x, y position) and their redshift. The more precise the redshift measurement, the more reliably astronomers place a galaxy at a given location, and thus in a given environment. Thus, the reliable identification of large samples of field galaxies benefits greatly from spectroscopic redshifts for lots of galaxies.[2] The development of multiplexing spectrographs on large telescopes in the mid-90s greatly advanced the study of field galaxies by providing redshifts measurements for large samples of galaxies.

Using the multi-slit spectroscopic instrument on the Canada-France-Hawai'i telescope on Mauna Kea, Hawai'i, Lilly et al. (1995) took the spectra of around 600 field galaxies. This survey is "complete" to all galaxies within the survey area with redshifts < 1, with B-band absolute magnitudes brighter than -20.4, and masses between $3-30\times10^{10}$ $M_{\odot}$. In other words, it samples the population of moderate mass field galaxies out to $z \sim 1$; in other words, the galaxies that would eventually become today's massive spirals.

The CFRS survey has had a significant impact on our understanding of how field galaxies have evolved. For example, the lower redshift sections of the Madau diagram (i.e., $z < 1$) are largely

[2] This is less of a requirement for dense environments, as these can be identified as overdensities in x-y space, then confirmed with redshift measurements of just a handful of cluster galaxies.

based on star formation rates measured via the [O II]$\lambda 3726\mathring{A}$ emission line in CFRS spectra.[3] One the greatest impacts that the CFRS survey has been, however, on our understanding of the morphological evolution of field galaxies.

4.2 The morphologies of CFRS galaxies

With spectroscopic redshifts from the CFRS in hand, astronomers could reliably identify field galaxies for more detailed follow-up. With this in mind, Hammer et al. (2005) obtained high resolution Hubble observations for a sub sample of 185 CFRS galaxies in order to measure their detailed morphologies. These detailed morphological studies confirmed the results from number counts described above: that the population of massive field galaxies contained a significantly greater proportion of irregular/peculiar/merger galaxies at $z > 0.4$ compared to today, while the relative numbers of spiral galaxies at these redshifts are significantly reduced compared to locally. For example, while around 70% and 7% of $\sim 10^{11}$ $M_\odot$ galaxies in today's Universe are spirals and irregular/peculiar/mergers, respectively, roughly 43% and 34%, respectively, are at $z > 0.4$. Furthermore, the number density of LIRGs (see lecture 8) at $z > 0.4$ among $\sim 10^{11}$ $M_\odot$ galaxies is roughly 30 times higher at $z > 0.4$ than it is today, with 64% of LIRGs at these high redshifts having irregular/peculiar/merger morphologies. As such, the CFRS provides clear evidence of *significant* morphological evolution of field galaxies since $z > 0.4$.

As the changing proportions of LIRGs suggests, the CFRS also provided evidence of strong evolution in the star-forming properties of $\sim 10^{11}$ $M_\odot$ field galaxies. Most of the spectra of CFRS galaxies show clear evidence of recent star-formation, again confirming that the star formation density of the Universe was significantly higher at $z > 0.4$. Importantly for this lecture, however, is that the *bulges* of $z > 0.4$ galaxies are *bluer* than those of similar mass galaxies today. This can be interpreted as evidence of increased levels of star formation within the central regions of $z > 0.4$ galaxies relative to galaxies in the local Universe. Of course, these enhanced levels of star-formation led to the production of heavy elements, which explains why galaxies in the CFRS have roughly half the metallicity of today's field galaxies (i.e., the metals were still in the process of being made in the $z > 0.4$ field galaxies).

Before constructing a theory for the morphological evolution of field galaxies (which, remember, are dominated by Spiral galaxies today), let us, in true "Look through the keyhole"-fashion, consider the evidence:

- The numbers of $\sim 10^{11}$ $M_\odot$ field galaxies are dominated by irregular/peculiar/merger galaxies at $z > 0.4$, whereas today they dominated by spirals.
- The proportion of $z > 0.4$ field galaxies that show evidence of rapid, recent star formation is significantly higher than for field galaxies today.
- There is clear evidence of enhanced levels of star formation in the central regions of $z > 0.4$ galaxies compared to today's spirals.
- The metal abundances of $z > 0.4$ field galaxies is roughly half that of local galaxies.

[3] Like Hα, [O II]$\lambda 3726\mathring{A}$ is only produced by high energy photons, and thus provides a measure of the numbers of massive, young stars in a galaxy. The reason [O II]$\lambda 3726\mathring{A}$ is often used in preference over Hα in the distant Universe is because Hα gets shifted out of the optical bands at $z > 0.4$, whereas [O II]$\lambda 3726\mathring{A}$ remains observable in optical spectra until $z \sim 1.5$.

5 The formation of local spirals

To explain the above observations, astronomers have developed a theory of how today's field galaxies have evolved:

5.1 An early merger phase

The irregular/peculiar/merger morphologies of early field galaxies suggests that most have undergone some form of major, gas-rich merger during the past 8 billion years or so. During this time, the disk is suppressed by the random motions of the stars while the dissipational gas falls toward the centre of mass of the system. This merger is associated with a sudden burst of star-formation, but which only lasts for a few hundred million years. This explains the LIRG nature of a lot of these early irregular/peculiar/merger galaxies. The merger phase is then followed by...

5.2 A compact galaxy phase

Many of the stars that formed during the intense episode of star-formation triggered by the gas-rich merger have now fallen toward the central regions of the galaxy. These stellar populations are still comparatively young, which explains the blue colours of the bulges of early field galaxies. The star formation rate falls significantly over the next couple of billion years from its peak during the merger. Any further gas remaining from the merger that has not already fallen into the central regions may dissipationally collapse to start to form a fledgling rotating disk around the central bulge.

5.3 Growth of disk phase

Stars form from the collapsing disk of gas left over from merger, but at a much slower rate than before. Additional gas is then accreted by the galaxy (due to its high mass) from the surrounding regions. Irrespective of the trajectory along which this accreted gas falls onto the galaxy, because of the dissipational nature of gas collapse it will ultimately become part of the rotating disk. This gas feeding is responsible for the observed low level of star formation in spiral galaxies since $z \sim 0.4$. The galaxy may then go through a series of successive *minor* mergers which, since too small to disrupt the disk, will actually build up the mass of stars and gas in the disk.

5.4 Plus downsizing

Finally, it should be noted that while the above applies to field galaxies in general, precisely *when* each phase occurred during the history of the Universe changes with galaxy mass in a way consistent that is with downsizing. For example, while moderate mass (i.e., $\sim 10^{11}$ $M_{\odot}$) field galaxies grew most of their mass at $z < 1$, it is thought that the most massive field galaxies (such as Andromeda) will have started to form at even earlier times (i.e., $z \sim 2$).

6 Massive disks forming at $z > 2$

Of course, there has been significant advancements in observing facilities since the first CFRS studies. The development of 8m class telescopes and, in particular, adaptive optics has helped us to obtain high spatial resolution integral field spectra for large numbers of galaxies at high redshifts.

Such spectra enables us to map-out the kinematics of galaxies at high redshifts, which can be used to identify rotating disks or major mergers *kinematically*.

These surveys have reported evidence of rotating disks among moderately massive ($\sim 10^{11}$ $M_\odot$ galaxies at $z > 2$. Indeed, at these redshifts roughly two thirds of the irregular/peculiar/merger galaxies appear to be "clumpy" galaxies that are in the process of forming disks of stars, with the remainder being mergers. As such, it has been suggested that these are today's massive spirals (like the Milky Way) and disky ellipticals forming at high redshifts.

7 Lecture 10 learning objectives

In this lecture, we have covered the evolution of the other main type of large galaxy in today's Universe: spiral galaxies. These dominate the numbers of field galaxies in the local Universe, so by studying the morphological evolution of field galaxies, we can build up a theory to explain the build-up of today's spirals. The learning objectives for this lecture are:

- Revise the fossil record of the Milky Way.
- Understand how astronomers quantify galaxy morphologies (i.e., CAS).
- Have an appreciation of the how Hubble number counts and the CFRS have provided evidence of the morphological evolution of field galaxies .
- Be able to describe our current understanding of how today's spirals have evolved, together with the observational evidence that backs this up.