Lecture 9:
The evolution of early-type galaxies

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1 Introduction

Now that we have covered the many ways astronomers study galaxy evolution – through simulation, deep multiwavelength surveys, and the fossil record – we'll explore how we currently believe the main types of galaxies in today's Universe have evolved to their current state. In this lecture, we'll cover early type (i.e., elliptical) galaxies, while in the following lecture we'll consider the evolution of spiral galaxies.

2 Ellipticals in the context of all galaxies

Recall from Lecture 5 that elliptical galaxies in the local Universe tend to be fairly massive, with masses typically between 10^{10} and 10^{12} $M_{\odot}$. Indeed, the most massive galaxies in today's Universe are elliptical galaxies that reside in the centres of dense galaxy clusters. By contrast, spiral galaxies (which we'll consider in the next lecture) dominate the numbers of galaxies with masses below about 10^{10} $M_{\odot}$ galaxies.[1]

Roughly 50% of the stellar mass in today's Universe is contained within elliptical galaxies, which also means that they contain about half of all stars by number. If we also include the *bulges* of disk galaxies in that number (which are sort of like mini-ellipticals) then that proportion goes up to as high at 70%. By that measure, so-called *spheroids* (which groups together ellipticals and spiral bulges) are the most important group of objects in today's Universe.

3 A recap of ellipticals from the fossil record

Another thing we covered in Lecture 5 was that elliptical galaxies tend to be quite red in colour, but also that their colour is tightly correlated with their mass: more massive ellipticals tend to be redder than less massive ellipticals.[2] We also saw how there are different types of elliptical galaxies that separate roughly according to mass:

- Boxy ellipticals tend to be the more the massive of the two, and have "cores". They are almost entirely supported by the random motions of their stars.

[1] In that respect, the Milky Way and Andromeda galaxies are relatively rare, being both massive and spiral galaxies.

[2] You should be able to explain why this is the case.

- Disky ellipticals tend to be the less massive of the two, and tend not to have "cores" - their stellar density continues to rise toward their centres. They are supported by a combination of rotation and random motions.

It is widely regarded that these differences arise due to different formation and evolutionary histories, with disky ellipticals forming via the merger of gas-rich galaxies and boxy ellipticals forming via the merger of gas-poor galaxies. Judging by the fossil record of disky ellipticals, it seems that many of their stars have been formed relatively recently (since $z \sim 1$), during an episode of intense star-formation triggered by the gas rich merger. By contrast, there is very little evidence of any recent star-formation in massive, boxy ellipticals.

4 The disky elliptical formation link to ULIRGs

If disky ellipticals are formed via the major-merger of gas-rich galaxies, then does this mean that the ULIRGs we observe in the local Universe are ellipticals in the making? We saw in the last lecture that ULIRGs are produced when two gas rich galaxies collide, their high star formation rates a result of the merger process compressing the gas and causing it to collapse to form stars. But, even though we see these collisions taking place, it doesn't necessarily mean that they will form elliptical galaxies. After all, a major galaxy merger will typically last for tens of millions of years, so we can't "wait and see" what will happen.

One fairly strong piece evidence that major mergers in the local Universe will ultimately lead to elliptical galaxies are the motions of stars (i.e., stellar kinematics) within ULIRGs. These are comparable in magnitude to those of elliptical galaxies and have a significant random component. Crucially, the level of rotational support vs. support from random stellar orbits is closer to that of disky ellipticals, rather than boxy ellipticals. This makes sense in terms of our understanding of how disky ellipticals are formed. The rotation is left-over from the dissipational collapse of the gas within the merging galaxies into a rotating, star-forming disk. The random orbits are those of stars that existed in the two merging galaxies *prior* to the merger. Since stars are not dissipational, any rotational velocity they had prior to the merger is converted into random motions post-merger. Finally, even the morphologies of ULIRGs in the final stages of major mergers are similar to those of disky ellipticals.

A significant amount of evidence therefore suggests that local ULIRGs represent the transformation of gas-rich spirals into disky ellipticals via major mergers. As such, galaxy evolution is not confined to the high redshift, early Universe. However, more massive disky elliptical galaxies tend to have older stellar populations compared to low or moderate mass disky ellipticals. This means more massive disky ellipticals must have formed via gas-rich mergers in the early Universe, whereas less massive disky galaxies formed from more recent mergers. This is in agreement with the "downsizing" description of the Universe in which the most massive galaxies formed first. Finally, the star-forming histories of local disky ellipticals are consistent with a large fraction of their stars being formed within a very intense, very short period of star-formation – exactly what results from a gas-rich major merger.

So, the formation and evolution of disky ellipticals can be summarised as:

- The most massive disky ellipticals were formed by major, gas rich mergers in the early Universe, as evidenced by their old stellar populations and rotation (due to dissipative gas collapse).

- Less massive disky ellipticals also formed via the major merger of gas rich galaxies, but at later times. This is another case of *cosmic downsizing.*

In both cases, a large fraction of the stars in disky ellipticals were formed in a short period of time due to the intense levels of star-formation induces during the merger. This is supported by the measured star-forming histories of disky ellipticals.

5 The formation and evolution of boxy ellipticals

As we have seen (from Lecture 5 and above), our current understanding of elliptical galaxies is that major galaxy mergers have played a crucial role in their formation. For disky ellipticals this means major, gas-rich mergers. But what about the other type of elliptical galaxies – the boxy ellipticals that dominate the numbers of high mass elliptical galaxies?

Boxy ellipticals show very little evidence of rotation, which indicates that their mergers were highly non-dissipational. This means they must have contained very little gas, as gas is *very* dissipational. As we know, this strongly suggests that boxy ellipticals are formed by gas-poor (also known as "dry") mergers. Since gas-poor mergers do not form stars (since gas is needed to form stars), this means that all of the stars that make up a massive boxy elliptical galaxy were already in place prior to the merger. All the merger process did was randomise, or "heat-up" the orbits of the stars that already existed pre-merger. Since no stars are produced in the merger process, the stellar populations in boxy ellipticals should have simply been evolving "passively" for the past few billion years.

Do we see evidence of this passive evolution? To investigate this, astronomers need to find populations of massive, boxy ellipticals at higher and higher redshifts. At any redshift, the most massive galaxies always live in the most dense environments: massive clusters and superclusters. So, to find large numbers of boxy ellipticals at different redshifts, astronomers search for increasingly distant clusters of galaxies. To determine the evolutionary state of these massive ellipticals, astronomers measure their rest-frame colours. If they have evolved passively since their formation, then boxy ellipticals at high redshifts should be bluer than local boxy ellipticals by a predictable amount.

When astronomers plot the colour-magnitude diagram for massive ellipticals in dense clusters at different redshifts, they do indeed find that earlier ellipticals are bluer by *precisely* the right amount to be explained by passive evolution. This has been confirmed up to at least $z \sim 1$, indicating that massive, boxy ellipticals have evolved passively (i.e., have not formed any significant numbers of stars) for *at least* the past $\sim$6 billion years (or roughly half the age of the Universe). Further, neither the slope nor the scatter around the colour magnitude diagram has changed significantly over this time. This suggests that the stellar populations in massive ellipticals were already well-evolved even before $z \sim 1$.

5.1 Identifying elliptical galaxies at $z > 1$

Finding dense clusters of galaxies at higher and higher redshifts becomes increasingly difficult for both practical (they're faint) and physical (they become less dense, and thus more difficult to detect) reasons. As such, beyond about $z > 1$, astronomers use other techniques to identify elliptical galaxies.

Since elliptical galaxies don't contain lots of hot, massive stars producing UV photons (i.e., they're not strongly star-forming), we can't use either the Lyman break technique to identify them, nor exploit the benefits of the positive K-correction in the sub-mm. Instead, astronomers use the fact that the old stellar populations of massive ellipticals will look extremely red due to their age. As such, they can use colour selection to find very red objects, often exploiting rest-frame near-infrared observations, which are particularly sensitive to populations of old, cool stars which dominate in massive ellipticals. Because of their colours, such galaxies are known as *Extremely Red Objects* (EROs). Although it is an effective means of identifying old populations, astronomers need to be careful to avoid galaxies that are, instead, red due to dust absorption. Indeed, roughly half of EROs are, in fact, reddened star-forming galaxies.

On studying the stellar populations of non-star-forming EROs at $z \sim 1.5-1.8$ via spectroscopy, astronomers find that their stellar populations are roughly 3.5 Gyr old. This is quite incredible, considering that the age of the Universe at $z \sim 1.8$ is only 3.7 Gyr! Clearly, this suggests that stars in early EROs must have formed very soon after the Big Bang. Even more incredibly, some of these galaxies at $z \sim 1.5 - 1.8$ have masses of 10^{11} to 10^{12} $M_{\odot}$, indicating that they must have formed hundreds of billions of stars in the space of just a few hundred million years! Interestingly, however, their sizes are very compact, having a half-light radius of about a 1 kpc compared to the $\sim$ 5 kpc of similar mass galaxies today.

5.2 A consistent evolutionary theory for boxy ellipticals

Collating all this observational evidence, astronomers have developed a consistent evolutionary theory to explain the appearance of massive (boxy) ellipticals at different redshifts. Their old stellar populations (even at high redshift, when the Universe was only a few Gyr old) indicates that the stars in massive ellipticals were formed at a very early time - just a few hundred million years after the Big Bang. However, these were not formed in-situ. Instead, it is thought that they were formed very early-on by the collapse of lots of comparatively small clouds of gas. Initially, these clouds of gas would have collapsed dissipationally, forming rotating stellar disks.

In the dense regions of a natal cluster, these early rotating disks of stars (which would have quickly exhausted their gas supply) would have soon merged together in dry major mergers.[3] This explains why we see ellipticals in the early Universe that contain old stars – the stars are old because they formed in these dense natal clusters from collapsing gas clouds soon after the Big Bang, and they are elliptical due to the dry merger of all these smaller, natal galaxies in rapid succession. An important consequence of successive, major dry mergers is that the galaxies will "puff-up" in size, which explains why today's massive ellipticals are larger (in physical extent) than similar mass galaxies in the early Universe.

So, to summarise, it is thought that massive ellipticals formed by:

- Clouds of gas collecting in the densest parts of the early Universe (which would become today's clusters and superclusters).
- These clouds collapsing to form stars in small "natal" galaxies just a couple of hundred million years after the Big Bang.
- The successive non-dissipative mergers of these small, now gas-poor galaxies which randomise the orbits of these stars (destroying any diskiness and rotation) and "puffs them up" in size.

[3]Remember, "major" simply refers to the *ratio* of galaxy masses, not the absolute mass. The merger of two small galaxies (e.g., each of 10^8 $M_{\odot}$) would still be referred to as a major merger, as the ratio of galaxy masses is 1:1

- Since the mergers are gas poor, little or no new stars are formed after the initial collapse of the early gas clouds.

- After a few billion years, all of the small galaxies that are going to merge have already done so, meaning that the masses of the most massive ellipticals stay largely the same from $z \sim 1$.

6 The evolving elliptical galaxy luminosity function

The different evolutionary paths of massive (boxy) and less massive (disky) ellipticals can be summarised nicely in terms of the evolving elliptical galaxy luminosity function.

When astronomers measure the luminosity functions of elliptical galaxies at various redshifts, they find that the number density of the brightest (and thus most massive) elliptical galaxies in the Universe has barely changed over the past ~ 6 billion years. As such, the numbers and masses of the most massive (and thus boxy) elliptical galaxies in the Universe has remained largely the same: these galaxies were already in place in the early Universe and have barely evolved since.

By contrast, the low-luminosity end of the elliptical galaxy luminosity function has evolved considerably. Today, there are many more low mass (and thus disky) elliptical galaxies than there were in the early Universe. This implies that gas-rich mergers have been slowly building up the numbers of disky ellipticals over the past 13 billion years to "catch up" with the numbers of massive boxy ellipticals that were formed much earlier on.

Thus, the evolution of elliptical galaxies is perfectly consistent with the idea of *downsizing*: that the most massive galaxies formed first in the early Universe, followed by more moderate, and then low-mass galaxies. It's just that the two different types of elliptical galaxies (boxy vs. disky) have formed via different routes.

7 Lecture 9 learning objectives

Some of this lecture is a recap of what we covered in Lecture 5 on the fossil record. As such, there has not been as much new material to read as usual. You may now want to take another brief look through the Lecture 5 notes to ensure that it all makes sense to you. Since massive ellipticals contain a large fraction of all the stars in the Universe, understanding how they have formed and evolved is a major component of our understanding of galaxy evolution overall. Here are the learning objectives for this lecture:

- Knowledge and understanding of the fossil record for early-type galaxies in the local Universe

- Understanding of the methods used to detect early-type galaxies in the distant Universe

- Knowledge of the main results obtained for early-type galaxies at high redshifts

- Understanding of the main evolutionary trends with redshift for both high and low mass early-type galaxies

- Understanding of the concept of cosmic downsizing

- Be able to describe the formation and evolution of both boxy and disky ellipticals.

- Understand how the elliptical galaxy luminosity function supports these our understanding of their evolution.