Lecture 5:
Studying galaxy evolution via the fossil record

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1 Introduction

Until now, we've largely considered investigating galaxy evolution by exploiting the light travel-time to study galaxies in the early Universe. We will continue to cover this "high-redshift" approach later in the course. In this lecture, we will consider the alternative (but complementary) approach: the fossil record. Here, we study nearby galaxies in a lot of detail to try to understand how they have been "built".

2 Early type – or, Elliptical – galaxies

Elliptical galaxies are the big, boring ones without spiral arms. When Hubble came up with his galaxy "tuning fork" diagram in the early 20^{th} century, it was thought that elliptical galaxies evolved into spiral galaxies (i.e., left-to-right on the diagram), which is why they are also known as "early-type" galaxies. We now know that elliptical galaxies *do not* evolve into spirals but, unfortunately, the name has stuck and so it's still used extensively today.

2.1 Stellar populations of elliptical galaxies

As well as their shape, elliptical galaxies in the local Universe share similar properties. They tend to be quite massive (stellar masses of $\sim 10^{11}$ $M_{\odot}$ or above) and and are red in colour, which suggests an old stellar population (i.e., the massive, hot, blue stars have had time to evolve and die, leaving just the less massive, cool red ones). When we analyse their spectra using spectral synthesis (see Lecture 4), we indeed find that the spectra of the majority ($> 70\%$) of local ellipticals are best modelled by a population of old stars with ages > 8 billion years. This suggests that today's massive ellipticals have remained mostly as they are today for over half the age of the Universe.

2.2 The colour-magnitude relation for elliptical galaxies

When we study elliptical galaxies in more detail, we find there are other consistencies within the class. While elliptical galaxies are, in general, redder than their spiral counterparts, it's not the case that they are all exactly the same colour. Indeed, some are "redder" than others.[1] It turns

[1] In astronomy, we define a colour by the relative amounts of light in two bands, which means we can actually quantify how "red" or "blue" a galaxy is.

out that the redness of an elliptical galaxy is not random. Instead, it is tightly correlated with its total luminosity such that more luminous elliptical galaxies are redder.

Since the luminosity of a galaxy is related to how massive it is (i.e., in general, the more stars a galaxy contains, the brighter it is likely to be), this also means that more massive elliptical galaxies are redder. Astronomers have confirmed this by plotting the colour (i.e., "redness") of elliptical galaxies against their *velocity dispersion*, or σ, and find that redder galaxies have higher velocity dispersions. Elliptical galaxies are supported against gravity by the velocity of their stars (more on this later), so their velocity dispersion gives a direct proxy measure of their mass; the higher their velocity dispersion, the greater their mass.

The tightness of the relation between colour and mass/luminosity for elliptical galaxies in a given cluster suggests that they were all formed at roughly the same time (in that particular cluster). The argument goes that if elliptical galaxies in a given cluster were formed at different times, then they would show much more diversity in their colours (i.e., there'd be some that formed their stars recently, so would be blue, and some that formed their stars a long time ago, so would be red). However, if they're all virtually the same age, then why haven't they all got *the same* colour; why is there a colour dependence on mass/luminosity? That can be explained in terms of metallicity. More massive galaxies hold onto their reprocessed gas more easily than low mass galaxies because their gravity is stronger (they have greater "binding energies"). Due to their stronger gravities, it is more difficult for stellar winds and supernovae to push this enriched gas out of more massive galaxies. Reprocessed gas is metal rich, so when it re-collapses to form more stars, it forms metal-rich stars, which are redder than metal-poor stars of the same mass.

In summary, the slope of the colour-magnitude/luminosity/mass relation for elliptical galaxies is due to metallicity effects. The tightness of the correlation is because all ellipticals in a cluster formed at roughly the same time.

2.3 Light profiles of Elliptical galaxies

As well as measuring the total flux and luminosity of galaxies, we can also measure their light *profiles*, i.e., how their surface brightness changes as a function of distance from their centre.

2.3.1 Extended light profiles

When we model the light profiles of elliptical galaxies, we find that the light profiles *outside their central regions* fall off as roughly $R^{-\frac{1}{4}}$:

$$I(R) = I_e \exp\left(-7.67\left(\left(\frac{R}{R_e}\right)^{\frac{1}{4}} - 1\right)\right) \tag{1}$$

where I_e is the surface brightness at the effective radius of the galaxy, R_e, defined as the radius which contains half of the total light from a galaxy.

On closer inspection of the light profiles of elliptical galaxies, astronomers found that a more general form of Eqn. 2 gave a better fit to the light profile:

$$I(R) = I_e \exp\left(-b\left(\left(\frac{R}{R_e}\right)^{\frac{1}{n}} - 1\right)\right) \tag{2}$$

which is known as a *Sersic* profile. Typically, $n = 4$ to 6.

2.3.2 Core light profiles

When we look at the very centres of elliptical galaxies, astronomers find that some depart from the Sersic profiles. They do this in such a way that their light profiles *flatten* within their centres (within about 1 arcsec for nearby examples, corresponding to the central few 100 pc). These are known – rather ambiguously – as *cores*. Thus, ellipical galaxies fall into two groups, those with *cores* and those without (i.e., their light profiles keep rising toward the centre). In general, galaxies with cores have higher luminosities than those without.

Today, it is thought that the reason for the deficit of light in the centres of ellipticals with cores is a consequence of how they formed. It is thought that massive ellipticals are formed by major, gas-poor – or, dissipationless – mergers (i.e., they don't contain much gas, so the kinetic energy of the merger is kept within the galaxy in the form of stellar kinematics, rather than being dissipated away). During such mergers, the central supermassive black holes at the centres of the two merging galaxies fall toward the central regions of the final galaxy. As they do so, they "throw-out" stars via gravitational sling-shot. This is known as "scouring" and is an effective way of removing stars from the central regions of a galaxy post-merger.

2.4 Disky vs. Boxy ellipticals

As well as core ellipticals, early type galaxies also separate into two separate classes according to their morphologies. Some ellipticals have a slightly "rugby-ball" shape and are known as "disky", whereas others are "squarer" in appearance and are known as "boxy". Quantitatively, we distinguis between the two by performing an angular Fourier series fit to the light profile of elliptical galaxies and measuring the fourth term:

$$\Delta r(\theta) \approx \sum_{k \gtrsim 3} a_k \cos k\theta + b_k \sin k\theta \tag{3}$$

If $a_k > 0$, then it is a disky elliptical, otherwise it is a boxy elliptical.

When we consider the two types of galaxies separately, it turns out they differ in more ways than their morphologies. While all elliptical galaxies rotate more slowly than spiral galaxies, disky ellipticals tend to rotate more quickly than their boxy counterparts. Indeed, boxy ellipticals are almost entirely supported by random motions, rather than bulk rotation. Also, disky ellipticals tend to be less luminous (and thus less massive) than their boxy counterparts. Boxy ellipticals also tend to have "cores".

All this suggests that the two types of elliptical galaxies formed via different paths. It is now thought that disky ellipticals formed at high redshifts ($z \gtrsim 1$) as a result of the merger of two gas-rich galaxies. Since gas is dissipational, it would have lost energy, and collapsed to form a rotating disk, producing lots of stars in the process. Once the gas had finished producing stars, what is left is a rotating elliptical - rotating because of the imprint of the gas, and elliptical because the orbits of the original stars would have undergone a degree of randomisation during the merger.

Boxy ellipticals are also thought to have been produced by merging galaxies, but in this case are thought to have been produced by gas poor ("dry"), dissipationless mergers. The stars were already in-place prior to the mergers (and thus are very old; estimated to have formed at $z > 3$). In this situation, there is very little gas to collapse into a rotating disk, so pretty much all the energy of the merger goes into randomising the orbits of the stars. This creates a galaxy that is entirely supported by the random motions of their stars, and is boxy due to the lack of rotation. As explained above, the cores are due to "scouring" due to black holes falling toward the cores of the merger remnant. Unlike in disky ellipticals in which new stars are formed by the gas-richer merger, in boxy ellipticals the "scoured" stars are not replaced by star formation.

3 Spiral galaxies

The other main type of galaxy on the Hubble diagram are spiral galaxies. Since the Milky Way galaxy is a spiral, we can learn a lot about spiral galaxies by studying our own Galaxy.

3.1 The strucure of the Milky Way

While the stars in the Milky Way are close compared to other galaxies, establishing its structure is hampered by the fact that we sit inside it. By measuring the distances to various stars within the Milky Way we can, however, map-out its structure, in the same way that if you're sat *inside* a wharehouse, you'd have a pretty good idea of the *outer* dimensions of the wharehouse simply by looking around you. In the case of the Milky Way, however, this is hampered by dust along our line-of-sight, which blocks out the light from some regions. This problem can be mitigated by observing at longer wavelengths which more easily penetrate the dust clouds.

When we look at our Galaxy from within using penetrating infrared wavelengths, we see that the Milky Way is a disk galaxy with a bulge. Judging by the prominence of the bulge (and comparing to other external galaxies) it is likely that the Milky Way is a "late type" spiral galaxy (i.e., it is to the right of the Hubble tuning fork), probably an Sc or SBc galaxy. The latter classification (i.e., SBc) is based on the shape of the Milky Way's asymmetric bulge, which sugests it has a weak bar.

But that's just the overall appearance. Studying the fossil record of the Milky Way involves much more detailed analyses of the stellar content of the Galaxy, such as:

- **Kinematics**: This is the motion of stars within the Milky Way relative to the Sun or, more generally, the Galactic Centre.
- **Metal Abundances**: Since stars generate metals as they evolve and, eventually, die in supernovae, the metal content of stars provide information on the ages and star-forming histories of stellar populations.
- **Ages**: Calculating the ages of indvidual stars is hard, but for populations, we can use the relative numbers of a population across the HR diagram (akin to the technique using in spectral synthesis) to calculate accurate ages of populations.
- **Precise positions**: Mapping out the above properties as a function of position relative to the Galactic centre provides clues as to how the Milky Way (or, for that matter, other galaxies) was built-up.

By considering all the above, we now know that the Milky Way is made up of different populations of stars which make up four different components of the Galaxy: the *Thin Disk*, the *Thick Disk*, the *Bulge*, and the *Halo* populations.

3.1.1 The Thin Disk

The thin disk is made up of relatively young, metal rich stars (known, confusingly, as Population I stars. At the location of the Solar System, this disk rotates *in bulk* around the centre of the Milky

Way at a speed (relative to the centre) of about 220 km s^{-1}. This disk is about 50 kpc in diameter (outer edge to outer edge), but has a scale height of just 325 pc (i.e., $\rho(z) \propto e^{-z/325 \text{ pc}}$, where ρ is the density of stars and z is distance perpendicular to the disk). The ratio of thickness to diameter of the thin disk is roughly the same as a vinyl LP or a CD; it is *very* thin!

The Milky Way is still continuously forming stars at a rate of about 1 $M_\odot$ yr^{-1}, most of which takes place within the thin disk. The thin disk contains a lot of gas and dust from which these stars are being made. Today this disk is thought to be what's left of the dissipational collapse of a large gas cloud that formed the fledging Milky Way about 8 billion years ago.

3.1.2 The Thick Disk

In addition to the Thin Disk, there is a Thick disk which, as you may expect, has a larger scale height (≈1000 pc), but which has roughly the same diameter. The thick disk is made up of older, more metal-poor stars (Population II) than the thin disk. Thick disk stars orbit slightly more slowly around the Milky Way's centre – at around 180 km s^{-1} – compared to thin disk stars. As they rotate, however, they also oscillate up and down throughout the thick disk, so at any given time, some of the thick disk stars are *within* the thin disk. However, the distance between two stars in the thin disk is so large that the likelihood of collision between thin and thick disk stars is tiny.

It is thought that the thick disk is what is left over from when the very young Milky Way collided with a smaller galaxy around 8 billion years ago (i.e., just as the natal gas cloud was collapsing to form the thin disk). The stars in the then collapsing thin disk were "thown out" by this collision, which formed the "puffed up" thick disk. Because kinetic energy was tranferred from the galaxy collision to partially *randomize* the stellar motions, this process is known as "heating" (elliptical galaxy have very "hot" stellar kinematics because they are almost entirely help-up by random motions). Because there is little gas within the thick disk (other than at the point it is cospatial with the thin disk), it does not form stars, so the thick disk stellar population provides a snapshot of what the thin disk was like very early-on in the Milky Way's history.

3.1.3 The Bulge

The bulge of the Milky Way is roughly spherical in shape, with a radius of about 3 kpc. It is formed from metal-rich, Population I stars, the rotation velocity of which is proportional to their metallicity. The stellar density of the bulge is significantly higher than the rest of the galaxy with, on average, 5×10^4 stars per cubic parsec.[2] That's just the average, the stellar density profile of the bulge falls off as $\approx r^{-2.2}$, so it is even more dense in the centre.[3]

The bulge is thought to have a very complex formation history. Some of the stars in the bulge are likely to have formed early on in the history of the Milky Way from the natal cloud of gas. Then, later, the successive accretion of satellite galaxies likely heated the bulge up (helping to make it the shape it is) and introduced more metal-rich stars.

[2]This means that the average distance between two stars in the bulge is about 0.03 pc, compared to the 1.3 pc between the Sun and our nearest star, Proxima Centauri. Yet, 0.03 pc is still about 120 times larger than the radius of Pluto's orbit. Yep, space is *big*.

[3]You should be able to take this density profile and use the above numbers to calculate the average density of the central 10 pc.

3.1.4 The Halo

Finally, we have the low-density spherical halo of stars that surrounds the entire Milky Way. This consists of very old, metal poor stars, that orbit the milky way very slowly (at about a charectristic velocity of about 40 km s^{-1}. The density of the halo drops off as r^{-3}.

It is believed that many of the halo stars are the remnants of the tidal disruption of satellite galaxies that ultimately merged with the Milky Way. These stars were formed early-on in these satellite galaxies, then were tidally stripped as the galaxy orbited and, eventually, fell into the Milky Way. There is also the prospect that some of the halo stars were formed out of the natal gas cloud that would eventually collapse to form the Milky Way.

3.2 Streams around the Milky Way

As we have seen, the merger of satellite galaxies can explain a lot of the bulk features of the Milky way. Today, there is significant evidence that the Milky Way has cannibalised many smaller, satellite galaxies over the past few billions of years. The most striking of such evidence are the "Fields of Streams", which are streams of stars that loop around the Milky Way.

As a smaller satellite galaxy orbits and spirals into a larger satellite like the Milky Way, the differential gravitational pull on one side relative to the other causes it to get stretched-out and ripped apart. The resulting "stellar debris" forms impressive loops around the galaxy, which are known as "tidal streams" (tidal forces are those created by differential gravitational pulls; the tides on the Earth are caused by the Moon's gravitational pull being different on one side of the Earth compared to the other).

3.3 Is the Milky Way normal?

If we're going to use the Milky Way as an example of how spiral galaxies have formed, we'd better check that it is typical of the population. It turns out, in fact, that the Milky Way is somewhat atypical of Spiral galaxies since, as far as we can tell, it falls below the Tully-Fisher relationship (i.e., the correlation between orbital velocity and the luminosity of a spiral galaxy). It is thought that this may be because the Milky Way has actually undergone *fewer* merger events compared to other spirals, which has maintained its high rotation speed relative to its mass (i.e., other spirals are "hotter" and have more support from random motions). Despite this, the Milky Way isn't *drastically* different from other spirals, so it can give us a decent "first-order" view of how spiral galaxies have formed.

4 The local galaxy population

Going beyond the Milky Way, we can get a better understanding of galaxy evolution *in general* by surveying galaxies in the local Universe. When we do this, we find that the galaxy population forms a bi-modal distribution in terms of their colours. There is a population of red galaxies – known as the "red sequence" when plotted on a colour-magnitude plot – and blue galaxies –known as the "blue cloud". Red-sequence galaxies are mainly ellipticals and tend to be more massive than blue cloud galaxies (which are mainly spirals). Their colours give a clue to their star-forming activities – galaxies in the blue cloud are star-forming, whereas red sequence galaxies tend to be gas-poor and "dead".

4.1 The population fossil record

With the availability of spectra for tens of thousands of nearby galaxies, astronomers can perform spectral synthesis on the whole local population to work out their star-forming histories. In doing so, they have been able to piece-together the average star formation rates of the Universe throughout its history.

For example, say we perform spectral synthesis for a single galaxy – galaxy A – and find it formed a quarter of its stars in a burst 1 Gyr ago, another quarter of its stars were formed in a burst 5 Gyr ago, and the remaining half was formed continously over the past 10 Gyr. We could then plot the star formation rate of this galaxy A as a function of time – it would have a two sharp spikes of star-formation superimposed on a continuous low-level. Then, we could consider the next galaxy – galaxy B – and add its history of star-formation to our plot. Then move onto the next, and the next, each time adding the star-forming histories to our plot. Eventually, if we did this for all the nearby galaxies, we'd have a plot of the total star-forming history of the local Universe. If we then assume that we don't live in a special place in the Universe (i.e., the Extended Copernican Principle) then we can apply this result to the whole Universe, i.e., we can say it is a reasonable measure of the star-forming history of the Universe.

When astronomers do this, they find that the star-forming history of the Universe peaked at about redshift 2, corresponding to roughly 10 billion years ago. Since this time, it seems that the rate of stellar production in the Universe has slowed significantly – by a factor of > 10. We'll explore why this is the case later in the course.

Finally, since we have pieced together the global star forming history from individual galaxies, we can also explore the star-forming histories of galaxies split into various different subcategories (e.g., what's the global star-forming histories of spirals vs. ellipticals? or for galaxies of different mass?). A very important result that we get when we do this is that the rate of star formation for today's most massive galaxies peaked at earlier times than less massive galaxies. In other words, today's massive galaxies started to form *first*, with less massive galaxies forming later. This process is known as **Cosmic Downsizing**.

5 Learning objectives for Lecture 5

- Knowledge of what detailed observations of nearby galaxies (the fossil record) tells us about the evolution of both spiral and elliptical galaxies
- An appreciation of how less detailed (statistical) studies of large samples of galaxies in the local Universe aid our understanding of galaxy evolution
- Familiarity with the concept of cosmic downsizing