Elementary: the chemical fingerprints of massive galaxy formation over cosmic time

Cheng, C.M.T.

English Summary

In order to understand the formation and evolution of structure in our Universe, we first need to ask how galaxies and their host dark matter haloes, the Universe's building blocks, have grown and changed over time. Massive, quiescent galaxies hold the answers as some of the most extreme systems in existence. These ancient cosmic fossils, which have ceased forming stars, currently account for most of the Universe's stellar mass. Their properties challenge theories of cosmic structure formation, making them unique laboratories for probing the fundamental physics on which our Universe operates.

The massive galaxy formation case file

The Universe began about 13.8 billion years ago, in an extremely hot and dense state, with the Big Bang (see Figure 1). In an instant, space itself began to expand and cool, collapsing into larger and larger structures over time, from particles, to atoms, to stars and galaxies. In this way, structure in the Universe forms hierarchically. This model of the formation of the Universe is called ΛCDM cosmology.

Galaxies are huge collections of stars, gas, dust, and dark matter held together by gravity. They grow via infalling gas, by forming new stars from cold gas, and by merging with other, nearby galaxies. Eventually, many galaxies stop forming stars, a process known as quenching. In our current galaxy formation picture, galaxies may have formed in a hierarchical manner similar to the larger cosmic

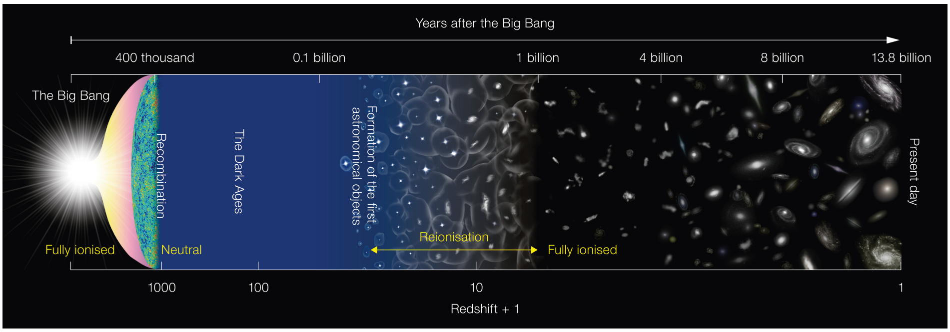

Figure 1: A diagram depicting the history of the Universe, beginning with the Big Bang. Image reproduced from ESO/NAOJ.

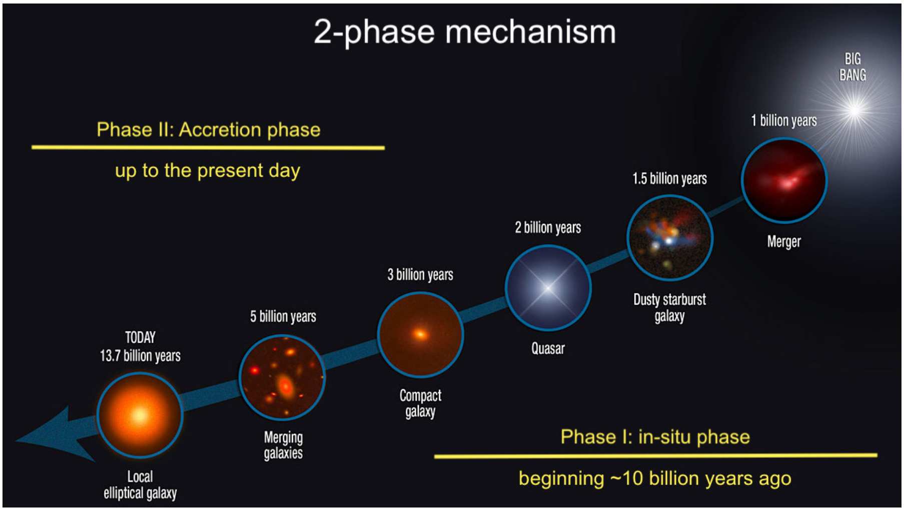

Figure 2: A diagram illustrating the two-phase model of massive galaxy formation. Figure adapted from NASA/ESA/Sune Toft.

structure of the Universe. Specifically, they may have formed in two phases (see Figure 2): their dense, compact centres likely formed early, about 10 billion years ago, during a period of rapid star formation. After star formation ended, they may have continued to grow, building up their outer regions by merging with tiny, neighbouring galaxies. This picture is supported by observations that distant, quiescent galaxies are more compact compared to nearby galaxies.

However, alternative galaxy formation scenarios are also possible. For example, it may be that individual galaxies are not growing at all. Instead, galaxies that quench earlier may be smaller, while galaxies that quench closer to the present day may be larger. Additionally, it is unclear how and why galaxies stop forming stars and become quiescent. There are a variety of processes that can allow galaxies to achieve this quenched state, by removing, using up, or heating the reservoir of cold gas needed to form stars. In reality, a combination of processes are likely occurring. Nonetheless, isolating the mechanisms by which the majority of galaxies form, quench, and subsequently evolve is crucial to our broader understanding of structure formation in the Universe.

To achieve this understanding, we can leverage cutting-edge observatories, such as the James Webb Space Telescope (*JWST*). Commencing operations in 2021 after one of the most challenging launches ever achieved, *JWST* is an unparalleled international collaboration between the US, Europe, and Canada. With a cost of $10 billion USD and ongoing operations of $10 000/hour, this investment has transformed science. Specifically, *JWST* has facilitated the discovery of massive, quiescent galaxies at much earlier times than expected, when the Universe was about 2 billion years old. These findings suggest that galaxies began and ended star formation faster and earlier than predicted by ΛCDM cosmology, putting pressure on galaxy assembly theories and our cosmological framework.

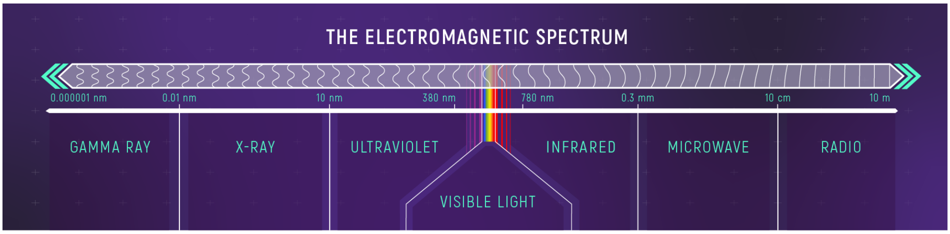

Figure 3: An illustration of the electromagnetic spectrum of light. We can disperse this light into broad colours spanning a range of wavelengths (photometry), or into individual wavelengths (spectroscopy). Image reproduced from NASA/ESA/Leah Hustak (STScI).

However, this interpretation relies on limited data and models. In particular, we rely on fitting stellar population models to a handful of photometric data points. These models may predict biased properties due to broad assumptions about galaxies' underlying chemistry and physics. Moreover, our data are limited in that they depict only 2% of the stars (the brightest and most massive) that we can see in these very distant galaxies. Finally, they represent tiny galaxy samples. As a result, these major claims about galaxy formation may be incorrect. In the era of *JWST*, traditional methods are insufficient.

Our sleuthing kit for investigating galaxy histories

The components of a galaxy, including its stellar population properties, provide clues to its evolution. This information is encoded in the chemical makeup of its stars. While we can never directly observe a galaxy's full history, we can study its past history indirectly via its stellar light. Measuring the total brightness of a galaxy in a small number of broad, photometric colours provides an initial view of its stellar content. By further dispersing galaxy light into individual wavelengths, we can unpack galaxy assembly signatures imprinted in this spectrum (see Figures 3 and 4).

We can use these data to unlock insights into galaxy formation, by inferring the properties of galaxies' constituent stellar populations. Interpreting the light from these groups of stars requires a deep understanding of the ingredients on which they are built. In particular, each star is born with a certain mass. We need to know the distribution of these birth stellar masses (called the initial mass function) to describe stellar populations. The initial mass function may vary with environment, but this is still a major open area of investigation. Additionally, we need to be able to describe how stars of different masses and chemical compositions evolve over time. Finally, we need to understand what kinds of spectra stars produce, as each type of star can change both the overall shape of a galaxy's spectrum, as well as the presence of certain dips in a spectrum (spectral lines). By studying atoms in the lab, scientists have calculated how each element absorbs light at specific wavelengths, with each element having its own spectral fingerprint. For example, hydrogen atoms absorb light at well-known wavelengths (see Figure 5), so when

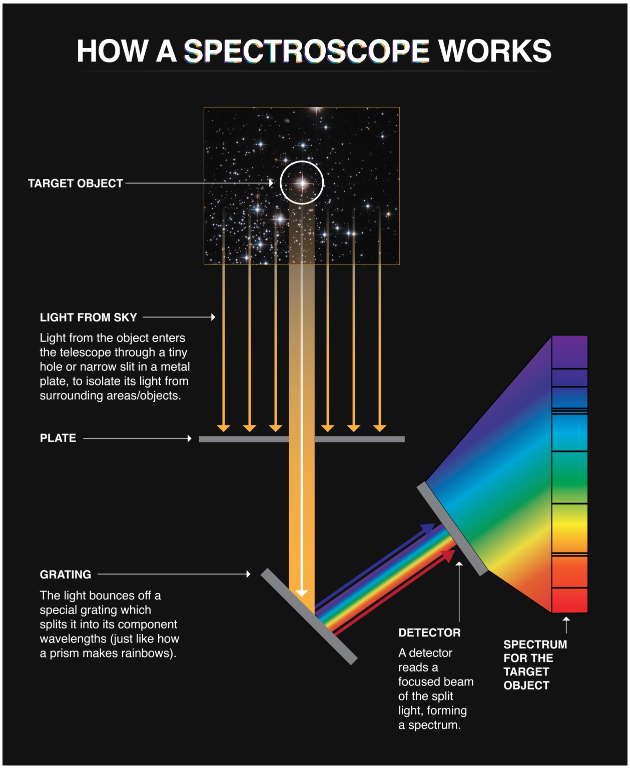

Figure 4: A diagram showing how we can obtain spectra of galaxies using a spectrograph on a telescope. Image reproduced from NASA Goddard/Shireen Dooling.

we observe these same dips or lines in a galaxy spectrum, we know that hydrogen is present. We can then quantify the amount of hydrogen based on the depths of these features.

By understanding these ingredients, we can infer the ages and detailed chemistry of stellar populations, which provide a window into the processes that drove a galaxy's evolution. In particular, a galaxy's past star formation and interactions can be inferred from its overall chemistry. Additionally, different types of stars forge different elements on varying timescales as they evolve and die. The ratios of elements can give us insight into the chemical evolution and star formation histories of a galaxy. However, interpreting observed galaxy data is complicated by the fact that different properties can have similar observed effects on the shapes of spectra and the depths of spectral lines. For example, changes in stellar age and chemistry can have nearly identical spectral impacts. This is known as the age-metallicity degeneracy. Additionally, variations in the shape of the initial mass function can have similar effects as variations in chemistry. Thus, correctly disentangling the specific age, chemical composition, and initial mass function of a galaxy in order to understand it's place in evolutionary history is extremely challenging.

We can apply these physical principles to real data, in order to interpret galax-

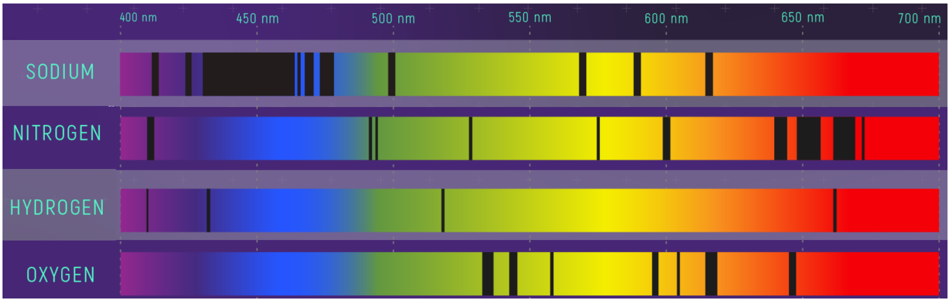

Figure 5: Absorption spectra for various elements. Image adapted from NASA/ESA/Leah Hustak (STScI).

ies' constituent stellar populations. To disentangle galaxy ages and detailed chemical compositions, and to constrain the initial mass function in diverse galaxies, we can fit models to spectra. This can be done by examining individual spectral features, which are primarily sensitive to certain properties. For example, the strengths of hydrogen lines are primarily sensitive to the age of a galaxy, while iron lines are primarily sensitive to the amount of iron in a galaxy.

In practice, however, individual elements and galaxy properties contribute to the signal of the entire spectrum. We can thus gain more information and more robustly constrain galaxy properties by modeling the entire spectrum of a galaxy simultaneously. In this way, we can also constrain a galaxy's initial mass function, which presents itself as extremely subtle variations across the whole spectrum.

Dusting for galaxy formation fingerprints

The tools described above have been applied to data of a wide variety of galaxies. In particular, by looking at light averaged over whole galaxies, we have learned that massive galaxies in the nearby Universe are also the oldest objects and are rich in elements like iron and magnesium. These findings suggest that these galaxies both formed their stars and quenched early and quickly. Moreover, we have learned that nearby, massive galaxies have an excess of low-mass stars in their centres compared to the Milky Way, indicating that their initial mass functions are different.

These measurements have guided our understanding of the global properties of galaxies, but we can unlock more detailed insights by spatially resolving a galaxy's constituent stellar populations. Stellar population gradients encode stellar mass build-up, allowing us to differentiate possible quenching and assembly mechanisms. Spatially resolved data have shown us that nearby, massive galaxies tend to have redder colours in their centres and bluer colours in their outskirts, which are driven by the fact that galaxy centres are richer in iron compared to their outskirts. These findings reinforce the idea that galaxies formed hierarchically.

While we have learned a lot about galaxy evolution from studying nearby, massive galaxies, it is important to keep in mind that in the two-phase model, we expect these galaxies to be in a relatively late stage of evolution. In particular, their outskirts may have already been built up by merging with tiny, neighbouring galaxies. To truly understand the formation of massive, quiescent galaxies, we must look back in time, and study their more pristine stellar populations, closer to the epoch when they formed. Because light takes time to travel, observing galaxies at greater distances allows us to see them as they were earlier in the Universe's history. As a result of the expansion of the universe, this time is quantified by redshift, with higher redshift corresponding to earlier cosmic times.

Observing these distant, high-redshift galaxies is more challenging than studying nearby galaxies, as they are much dimmer due to their extreme distance from us. Additionally, their element-sensitive absorption features are very faint and redshifted into wavelength regions where our telescopes are less sensitive. Thus, we must observe individual distant galaxies for tens to hundreds of hours to measure detailed ages and chemical compositions.

With innovative technological advancements in astronomical observations over the last ~ 15 years, we have begun to survey massive, quiescent galaxies out to very early times. Surprisingly, our picture of galaxy formation is actually becoming muddier as we reach back towards the advent of the Universe. In particular, it is not clear how these high-redshift, quiescent galaxies evolve into those we see in the nearby Universe (if they are even related). For example, as discussed above, *JWST* has facilitated the discovery of massive, quiescent galaxies at much earlier times than predicted by ΛCDM simulations. The formation and evolution of massive, quiescent galaxies thus remains an open question. To make progress in isolating the dominant mechanisms of stellar mass assembly and star formation quenching, and to confirm findings of 'impossibly early' galaxies, we require large samples of distant, massive galaxies with high-quality and spatially resolved data.

This thesis: identifying the culprits

In this thesis, we provide some of the most detailed constraints to date on galaxy formation out to ~ 10 billion years ago. Through flexible modeling of the highest quality integrated and spatially resolved spectra, we present novel measurements of age and chemical gradients in distant galaxies, reveal discrepancies in model predictions, and make the first robust measurements of the initial mass function in the distant Universe.

In **Chapter 2**, we measure gradients in a large sample of distant, massive, quiescent galaxies, using data from the LEGA-C survey. These galaxies existed ~ 7 billion years ago, when the Universe was about half of it's current age. We find that the stars in the centres of these galaxies have the same age and magnesium content as in their outskirts, but have higher amounts of iron. Our findings are consistent with a scenario in which these galaxies underwent a large amount of star formation in their centres before they quenched, followed by their outskirts being built up by small, neighbouring galaxies with lower amounts of iron. However, alternative scenarios can also explain our results.

In **Chapter 3**, we combine our detailed spectroscopic measurements with independent photometric colours to challenge predictions made by stellar population models. We measure ages and chemical compositions of a large sample of massive, quiescent galaxies, again from the LEGA-C survey. We compare the measured colours of our galaxies to the predicted colours based on our measured ages and chemical compositions. We find that stellar population models are not able to reproduce the age-colour and age-chemical composition trends that we find in the data. Our results demonstrate that commonly used stellar population models are incorrect, illustrating that the underlying physical assumptions on which these models are built must urgently be re-assessed.

In **Chapter 4**, we measure age and chemical gradients in 8 massive, quiescent galaxies that existed $\sim$ 10 billion years ago, close to the epoch when these galaxies formed and quenched. Using data from the *JWST*-SUSPENSE program, we find that the stars in the centres of these galaxies are older and richer in magnesium compared to their outskirts, but have the same amount of iron. These findings suggest a picture where the centres of galaxies quenched their star formation first, followed by their outskirts. Towards the present day, these galaxies may have built up their outskirts through merging with small, neighbouring galaxies to produce the gradients that we found in Chapter 2. On the other hand, it may be that different quenching mechanisms are occurring at different times and result in different gradients.

Finally, in **Chapter 5**, we present the first robust measurements of the initial mass function, in a sample of 9 massive, quiescent galaxies beyond the nearby Universe. This study is based on data from our *JWST*-IMFERNO program. We find that the most massive, distant galaxies have excess low-mass stars compared to the Milky Way. In combination with previous findings that the centres of nearby, massive, quiescent galaxies also have excess low-mass stars, our results are consistent with the two-phase model. Our oldest and most massive galaxy is a likely descendant of the distant, massive, 'impossibly early' galaxies found with *JWST*, implying that they may have also had this excess of low-mass stars. Our constraints suggest that their stellar masses are even greater than originally reported, heightening the tension between observations of massive, early galaxies and current galaxy formation models.

The case continues...

This work has contributed substantially to our understanding of massive galaxy formation over the last $\sim$ 10 billion years, however questions still remain. To identify the dominant galaxy formation pathways, we must examine larger samples of galaxies with even higher spatial resolution, taking advantage of the next generation of modern telescopes (including the *Extremely Large Telescope*), and simultaneously developing more sophisticated modeling methods. These ways forward will allow us to paint a more complete picture of galaxy formation over cosmic time.