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1 What are metals?

In moments shortly after the Big Bang, the infant Universe was both sufficiently hot and dense to fuse protons and neutrons together to form atomic nuclei. However, because the Universe was rapidly expanding and cooling, there was sufficient time to only form the lightest elements, and consequently the early Universe was almost entirely composed of Hydrogen and Helium gas.

Over time this gas coalesced under gravity to create very dense regions of space that would become stars. At the centres of stars the temperatures and densities were once again high enough to fuse Hydrogen and Helium into heavier elements. These “heavy” elements are termed metals by astronomers.

2 Why study them?

Because metals must have been produced in stars, if we study the amount of metals in galaxies then we are able to trace the past star-formation activity of galaxies. The more metals we observe, the more star formation there must have been in the past.

However, it turns out that if we measure the metallicity of galaxies (the ratio between metals and Hydrogen in galaxies), we typically observe a lower metallicity than we would expect given the number of stars observed. This discrepancy can be reconciled if galaxies are able to expel metal-rich gas and/or acquire fresh metal-poor gas during their lives.

Galaxies are not isolated from their environment. Understanding the flow of gas into and out of galaxies is key to explaining the evolution of galaxies. Metallicity provides a powerful tool for studying the fuelling of galaxies.

3 How to measure metallicity?

There are two types of metallicity one can measure: the fraction metals in stars themselves (stellar metallicity) and the fraction of metals contained in the gas between stars (gas-phase metallicity). While the former is a more direct quantity to measure, it is more observationally challenging and requires detailed observations of the stellar light. While on the contrary the hot, ionized gas that surrounds massive young stars emits light at very specific wavelengths (colours of light). These emission lines show up prominently in the spectra of galaxies that are actively forming stars (see Fig. 7.1).

The relative strengths of the emission lines depends on the complex balance between the ultraviolet light produced by the young stars (which heats the gas) and the rate at which the gas
Figure 7.1: A typical spectrum of a star-forming galaxy. The bright emission lines (highlighted in orange) punctuate the comparatively faint stellar light (shown in blue). We label the elements that are responsible for each of the emission lines.

can cool. And because both these factors are sensitive to the metallicity\(^1\) we are able to infer the metallicity of the gas from the ratio of emission-line strengths.

To make these observations one needs to split light into its constituent wavelengths. Traditionally this would be done by extracting a narrow portion of the sky observed by a telescope (a slit) and dispersing the light with (for example) a prism. The result of which is a two-dimensional image, with the spatial distance along the slit in one image direction, while the spectrum at each spatial position runs perpendicularly.

### 3.1 The Multi Unit Spectroscopic Explorer (MUSE)

A fundamental limitation of these traditional slit-based spectrographs is that we only observe a narrow patch of sky. Not only is this wasteful use of the precious little light that enters the telescope, but it also only provides a narrow window into the universe.

Fortunately, the past decades have seen the development of integral-field spectrographs that, through a variety of techniques, are able to obtain spectra over a two-dimensional patch of sky. At the current cutting edge of these instruments is The Multi Unit Spectroscopic Explorer (MUSE), which has been heavily optimized for the purpose of making long observations. Up until now, deep spectroscopic observations of distant galaxies were only performed on select galaxies. However, MUSE heralds the opportunity for an unbiased spectroscopic window into the distant universe, without such need for preselection.

### 4 This thesis

In this thesis we focus on not only determining the metallicity of galaxies, but also how metallicity varies with distance from the centre of galaxies. Since there is no one single value for the metallicity that can describe the whole of the galaxy, we can gain a much deeper insight if we resolve (map) these variations.

**Chapter 2** We study a sample of 50 relatively nearby galaxies (approx. 350 million light-years\(^1\))

\(^1\)Strictly speaking the former depends on stellar metallicity, while the later depends on gas-phase metallicity.
away), at a time when the universe was roughly 97% of its present age\(^2\). These galaxies were chosen because, while similar in many respects, the amount of gas they contained was significantly varied. We followed up on previous suggestions that the outskirts of the most gas-rich galaxies were anomalously metal poor. This might be the case if galaxies had recently acquired fresh gas at their outskirts, simultaneously explaining the low metallicities and their excess gas. However, our results do not support this. Indeed, while we do find galaxies with spuriously low outer metallicities, we do not find these occurrences to be associated with the total amount of gas in galaxies. Instead we find that if one accounts for the spatial distributions of gas and stars, then the outer drops in metallicity are to be expected. In fact if one could observe sufficiently far from the centre, we might expect to observe drops in all galaxies.

Chapter 3 One of the most significant limitations for observations made from ground-based telescopes is the blurring caused by the Earth’s turbulent atmosphere (an effect termed atmospheric seeing by astronomers). While there is a some impact on the galaxies we study in Chapter 2, for more distant galaxies the effect can be catastrophic if we want to spatially resolve galaxies. In the distant galaxies that we study in Chapters 4 & 5 we are unable to study the metallicity variations in detail. The best we can hope to measure is the metallicity the centre of galaxies and the average change in metallicity throughout the galaxy (i.e. the metallicity gradient).

Even then the atmosphere will partially wash out the metallicity gradient in galaxies, therefore, if we want to derive the true metallicity gradient we must correct for the atmospheric seeing. To do this we construct a model galaxy, from which we can simulate our observations. By adjusting the metallicity in our model we can find metallicity gradients that best matches our observed data, and thereby infer the true metallicity gradient.

Chapter 4 We apply the method developed in Chapter 3 to a sample of 84 galaxies observed with MUSE. These galaxies are between 1 and 7 billion light-years away, corresponding to a period when the Universe was between 92% and 48% of its present age (a range not yet explored by other metallicity gradient studies).

In general we find galaxies with a range of metallicity gradients; some galaxies have metal-rich centres and metal-poor outskirts, like galaxies in the Universe today, and others have metal-poor centres and metal-rich outskirts, consistent with galaxies observed in the distant Universe. We also find tentative evidence that the metallicity gradient depends on the galaxy size, such that the largest galaxies are typically most like the well-evolved galaxies today.

Chapter 5 In Chapter 4 we identified examples of galaxies with negative metallicity gradients (galaxies where the outskirts have a lower metallicity than at the centre) and cases of galaxies with positive metallicity gradients (galaxies where the outskirts have a higher metallicity than at the centre). An important question to ask is what drives these peculiar galaxies with positive metallicity gradients. Are the outskirts excessively metal rich, or are the centres unusually metal poor?

After accounting for the number of stars in the galaxies, we find that the galaxies with the most positive metallicity gradients have lower than expected central metallicities. Our results, however, do not preclude the possibility that outer metallicities are not simultaneously elevated. Nevertheless, the method we present could (with a larger sample of galaxies) allow one to constrain to what extent galaxies redistribute gas from the centre of galaxies to their outskirts.

\(^2\)Because light does not travel instantaneously, by studying distant galaxies are able to see the Universe at an earlier stage.