Measuring gold molecular gas across cosmic time
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English Summary

If we look up on a clear night, we will see a white band of stars crossing the sky. That is the Milky Way, our home galaxy. It contains approximately a hundred billion stars, along with other components such as gas, dust and dark matter. Our Universe contains billions of galaxies similar to the Milky Way. The understanding of galaxies beyond our Milky Way is relatively recent, dating back just over a century to Edwin Hubble's groundbreaking revelation. He demonstrated that faint 'nebulae' observed in the sky were actually distant galaxies, millions of light-years away. Galaxies contain two types of matter: dark and light matter. The former actually constitutes most ($\sim$85%) of the matter in a galaxy. However, there is still great debate as to what exactly it is, as it does not interact with photons and therefore we cannot directly observe it through our telescopes. Conversely, luminous matter, though less prevalent, constitutes the billions of stars, planets, gas, and dust within galaxies. The gas and dust dispersed between stars form the interstellar medium (ISM).

Galaxies fall into two broad categories: star–forming galaxies, which are forming stars very quickly and have large amounts of gas; and quiescent galaxies, which have a low star formation rate and typically have almost no gas left. The gas found in galaxies is composed mainly of hydrogen, helium, and traces of heavier elements. At the coldest temperatures (around -220 degrees Celsius), two hydrogen atoms combine to form molecular hydrogen (H_2), which collapses under gravity to form new stars. This cold molecular gas thus serves as the primary fuel for star formation in galaxies, playing a pivotal role in our comprehension of galactic formation and evolution.

However, galaxy evolution is a complex process spanning billions of years, on spatial scales ranging from a few to hundreds of thousands of light years. As such, it is not possible to study changes in a particular galaxy over the course of one human lifetime. Instead, we leverage the finite speed of light to observe galaxies as they appeared in the past. Light emitted from distant galaxies requires time to travel to our telescopes, allowing us to perceive these galaxies as they existed when the light began its journey. As the universe expands continuously, light traveling from distant galaxies experiences a phenomenon known as redshift, causing its wavelength to elongate and shift towards the 'redder' end of the spectrum. This redshift (z) can be accurately measured to determine a galaxy's distance, thereby revealing the time elapsed since the light's emission. By observing large samples of galaxies at different redshifts (i.e. at different cosmic epochs), we can explore distinct evolutionary phases, unveiling the pathways that shaped the galaxies ob-

served in our local Universe today.

One of the main processes driving changes in galaxies is star formation. A multitude of surveys conducted with telescopes like the Hubble Space Telescope, *Herschel* Space Telescope, and GALEX have provided valuable insights into the evolution of the Universe's star formation rate, particularly until $z \sim 4$, when the Universe was roughly 1.6 billion years old. A parallel effort has been made in recent years to establish how the gas content in galaxies changes with time. These studies support a tight connection between the available molecular gas in galaxies and how many stars are being formed at a particular cosmic epoch. Measuring cold gas is a challenging task, however, especially in distant galaxies. H_2 molecules need specific conditions, like high temperatures or nearby energetic sources, to emit light, which are not always present where most of the cold molecular gas is located in a galaxy. To overcome this, we can infer how much H_2 there is in a galaxy in the local Universe by observing the emission coming from the first excited state of the carbon monoxide molecular, CO(1–0). However, at higher redshifts, this emission becomes too faint, which has often resulted in the use of alternative methods. These alternatives, though, often introduce biases into data interpretation, potentially impacting our understanding of galaxy evolution models.

Radio Interferometers

The atoms and molecules that constitute the gas in galaxies emit radiation at sub–millimeter wavelengths. In order to observe them, it is necessary to use radio–interferometers. These are arrays of antennas spread over a wide area, functioning collectively as a single telescope when their signals are combined. Radio interferometers are typically situated at high altitudes to mitigate atmospheric disturbances. In this thesis, we utilized the *Karl J. Jansky* Very Large Array (JVLA) in New Mexico, the Atacama Large Millimeter/submillimeter Array (ALMA) in the Atacama Desert, Chile, and the NOrthern Extended Millimeter Array (NOEMA) in the French Alps. These instruments are capable of detecting faint signals from cold gas in distant galaxies, operating at wavelengths slightly below one millimeter

The most obvious targets to detect the faint CO(1–0) emission are the very dusty, highly star–forming galaxies known as sub–millimeter galaxies (SMGs, due to the wavelength at which they were first discovered). In order to observe cold gas in a galaxy, however, it is necessary to know their distance, or redshift. There are two ways of estimating the redshift: photometric and spectroscopic. Photometric redshifts are derived by averaging a galaxy's brightness across a fixed wavelength range and fitting an emission template to determine its redshift. This means that photometric redshifts are cheaper to obtain for large samples of galaxies, although they are very uncertain. Spectroscopic redshifts, conversely, demand more time but offer greater reliability compared to photometric methods. They require observing the emission coming from a galaxy over a continuous range in frequency, until one or more emission lines are detected and identified. As a consequence, only a limited number of SMGs have confirmed spectroscopic redshifts. Recent surveys with ALMA and NOEMA have targeted a few hundreds of SMGs in ex-

tensively studied sky regions, expanding the sample of SMGs where we can now observe CO(1–0) emission.

This Thesis

In this thesis, we use the great sensitivity of the most advanced radio interferometers to detect and measure molecular gas using the most widely–used gas tracer: the ground state transition of carbon monoxide. **Chapter One** introduces the current state of the field, in addition to providing the necessary background information for the subsequent chapters.

Chapter Two presents some of the most sensitive observations of CO(1–0) in a dusty, star–forming galaxy at $z = 3.4$, when the Universe was just 1.8 Gyrs old. The distribution of the gas is quite disturbed, and it is concentrated in two regions separated by $\sim$11 kpc, suggesting the presence of two galaxies that are in the process of merging together. The galaxy is forming stars very rapidly, and will soon exhaust its gas reservoir and become quiescent. We propose that we are observing the last stages of the merging process, which is driving rapid changes in the physical properties of the galaxy.

In **Chapter Three** we investigate the presence of cold molecular gas in unobscured quasars, a type of galaxy with an active black hole at its center. Although it has been proposed that the energy input from the black hole would expel the gas from the galaxy, we find that 70% of the observed galaxies still retain massive molecular gas reservoirs. However, they are also forming stars very rapidly, which means that they will quickly use up all the gas and become passive, 'dead' galaxies. We show that cosmological simulations of galaxy evolution are still not capable of reproducing such high star formation rates.

Chapter Four presents initial results of a large survey targeting the cold molecular gas in 30 dusty, star–forming galaxies with the JVLA during a period known as 'Cosmic Noon' (2–4 Gyrs after the Big Bang). We find that the gas shows a wide range of excitation conditions, although these do not seem to depend on any physical properties of the galaxies that we study, such as redshift or star formation rate. We show that computer simulations of galaxies have made great progress in modelling and predicting the amount of gas present in these massive, dusty galaxies.

Chapter Five presents observations of atomic carbon ([CI]) and dust emission on a subset of the 30 galaxies from the JVLA survey. Combining them with the CO(1–0) observations, which is the standard tracer of cold molecular gas, we can better establish the conversion factors needed to also use [CI] and dust as gas tracers. We derive gas masses that agree well with each other using all three tracers, supporting the use of [CI] to measure gas masses in the distant Universe. Nevertheless, we highlight the importance of making consistent assumptions to derive final masses for all three tracers. Finally, we investigate how the warmer radiation of the Cosmic Microwave Background at the epoch at which the galaxies are observed impacts our capability to measure the total flux emitted by the galaxy. While this effect is more pronounced for colder gas temperatures, its detection remains challenging with the data currently available.