Distant star formation in the faint radio sky

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Summary

When observed from a dark place on Earth, the night sky appears as a vast white band of stars, stretched out as far as the eye can see. This collection of stars, in addition to several constituents that are not so readily visible with the human eye (gas, dust, and the mysterious dark matter), is known as the *Milky Way*. It wasn't until the mid 1920s that astronomers realized the Milky Way is but one in a sea of many millions of other "Milky Ways", referred to as *galaxies*.

The earliest galaxies formed already within the first few hundred million years after the beginning of the Universe – the *Big Bang*, which in turn occurred some 13.8 billion years ago. Nowadays, we observe galaxies to take on a wide variety of shapes and sizes (as illustrated in Figure 1.2 in Chapter 1). If, for example, we could look at the Milky Way as an outside observer, we would see it to resemble a flat blue spiral disk. Other galaxies, however, may appear red and elliptical in nature, while even others are so enshrouded in cosmic dust that they are (nearly) invisible to the human eye. One of the major questions in astronomy, therefore, is to understand how galaxies evolve from the small, young systems that form in the early Universe to the varied population we observe today.

Studying the evolution of galaxies, however, is complicated by the fact that individual galaxies evolve very, very slowly. The Sun, for example, takes over 200 million years to orbit around the Milky Way just once. Indeed, the timescales involved are far too large for astronomers to watch galaxies evolve in real time. Instead, it is necessary to observe many different galaxies, at different stages in their lives, and compare the way they look. Nature, as luck would have it, provides a very useful way of looking at the youngest galaxy populations: since the speed of light is finite and – in the grand scheme of things – relatively slow, it takes the light emitted by distant galaxies a long time to reach our telescopes on Earth. In turn, observing the earliest formed galaxies is equivalent to observing the most distant ones. By then observing galaxies at various distances, across various cosmic epochs, we can attempt to infer and stitch together their evolutionary pathways.

Figure 1: The Orion nebula, the nearest – and quite possibly also most famous – star-forming region to Earth, as observed by the *Hubble Space Telescope* at various visible and infrared wavelengths. Nebulae such as Orion form the birthplace of stars in galaxies. Credit: NASA, ESA, M. Robberto (STSCI/ESA) and the Hubble Space Telescope Orion Treasury Project Team.

One of the crucial parameters describing the evolution of galaxies is their *star formation rate*, which is a measure of the average yearly mass formed in stars. These stars themselves are born out of the molecular gas in galaxies, in large stellar nurseries such as the famous Orion Nebula (Figure 1). However, star formation itself is also a lengthy process, spanning a timescale of millions of years. In addition, in distant galaxies it is generally impossible to observe individual stellar birth clouds, let alone individual stars. As such, measuring the buildup of stars in galaxies requires more sophisticated techniques, which not only encompass the light visible to the human eye, but also light at a variety of other wavelengths, such as the energetic ultraviolet light, and the low-energy infrared, millimeter and radio wavelengths.

Young, massive stars, for example, emit copious amounts of ultraviolet radiation, and in turn observing a galaxy that is bright at these wavelengths is a surefire sign it is actively forming stars. Some of the most strongly star-forming galaxies, however, are actually surprisingly faint in the ultraviolet, as they are heavily obscured by cosmic dust. Dust gets heated when it absorbs light emitted at short wavelengths, and subsequently radiates its energy at infrared wavelengths. Indeed, over half of all star formation in galaxies is in fact *dust-obscured*. Infrared-bright galaxies, in turn, can be some of the most strongly star-forming galaxies in the Universe, possibly attaining star formation rates in excess of 1000 times that of the Milky Way. Combined, ultraviolet and infrared observations have mapped the *cosmic star formation rate density* – the average star formation rate of galaxies in the Universe – all the way back to the first billion years after the Big Bang (Figure 1.7).

However, both ultraviolet and infrared-based measurements of star formation are plagued by some issues that limit their ability to accurately probe star formation in the early Universe. Sensitive ultraviolet telescopes can probe star formation even in faint, distant galaxies, but are heavily susceptible to attenuation by dust. Infrared telescopes, on the other hand tend to not be sensitive enough to detect galaxies in the very early Universe, and have poorer resolution, meaning they cannot see galaxies as sharply. Observations at radio wavelengths provide a means to circumvent these issues, and form the main topic of this thesis.

Galaxies at Radio Wavelengths

The most powerful radio telescopes are so-called *radio interferometers*. Such telescopes consist of multiple individual radio dishes, which all work in unison in order to create the sharpest view of the radio sky. In addition, having multiple dishes increases the collecting area, in turn allowing for observations of fainter objects. The radio telescope most instrumental to this thesis, the 27 dish-strong Very Large Array (VLA) in New Mexico, USA, is shown in Figure 2.

Radio emission from galaxies may be powered through star formation, as well as through a supermassive black hole hosted in the galaxy center known as an *active galactic nucleus* (AGN). Star-forming galaxies tend to be faint at radio wavelengths, whereas AGN are generally significantly brighter. As such, previous studies of the radio sky have predominantly been limited to either nearby or strongly star-forming galaxies and bright AGN, whereas the typical galaxy population has mostly remained undetected (see also Figure 1.8). With the 2012 upgrade of the VLA, which improved its sensitivity by an order of magnitude, the *faint radio sky* is now

Figure 2: The Karl G. Jansky Very Large Array (VLA), originally built in the 1970s in New Mexico, USA, remains the most productive radio telescope of all time, and is instrumental to this thesis. While rendering any optical telescope mostly useless, the cloud cover seen in this image cannot deter the VLA. Credit: National Radio Astronomy Observatory.

finally within reach, and constitutes the topic of this thesis.

A star-forming galaxy emits radio waves via two processes: *synchrotron emission* and *free-free emission*. Free-free emission is produced directly upon the formation of young, massive stars, while synchrotron radiation is the result of these same stars ending their lives in powerful *supernova* explosions. While free-free emission is therefore clearly a more direct, and hence more powerful, tracer of recent star formation, it is very difficult to study in the early Universe, as it is considerably fainter than the synchrotron component (Figure 1.5). Synchrotron emission, in turn, has been much more widely utilized as a tracer of star formation, despite being more complex to interpret. The structure of this thesis reflects this: in Chapters 2 & 3, we study the synchrotron emission of faint, star-forming galaxies, while we present two pioneering studies of free-free emission in Chapters 4 & 5. We summarize our findings in these chapters below.

This Thesis

In this thesis, we take advantage of the "revolution" that is currently taking place within radio astronomy: within the last decade, various new radio telescopes have been constructed, while others have been significantly upgraded, providing new, sensitive observations and revolutionizing our understanding of the radio sky. **Chapter One** introduces the current state of the field, and discusses this revolution in detail, in addition to providing the necessary background information for the subsequent chapters.

In **Chapter Two**, we analyze the faint radio population discovered in the sensitive *COSMOS-XS* survey. Carried out with the upgraded VLA, COSMOS-XS provides some of the deepest radio observations to date, at two different frequencies. We utilize the new 3 GHz data, in addition to multi-wavelength observations spanning the X-ray to sub-millimeter regime, to study the composition of the radio sky and classify the radio population as either star-forming or AGN. Among the more than 1500 galaxies detected at 3 GHz, over 90% show radio emission powered by star formation. In turn, we show that the fraction of star-forming galaxies depends strongly on the flux limit of the parent survey, with fainter galaxy populations more likely to be dominated by star formation as opposed to AGN activity. In addition, we discover an interesting subset of galaxies that remain undetected even in deep optical and near-infrared observations. Through a stacking technique, we argue that these galaxies are likely very distant in nature (with a typical redshift of $z \sim 4-5$), implying these may contribute significantly to cosmic star formation.

Chapter Three presents a detailed analysis of the *far-infrared/radio correlation* in dusty star-forming galaxies. This link between the radio and infrared luminosities of galaxies, which has been observed across a wide variety of galaxy types, as well as out to high redshift, provides the crucial recipe needed for converting radio synchrotron luminosities into star formation rates. However, its theoretical origins remain poorly understood, and likely hinges on a variety of physical processes in galaxies "conspiring". Dusty star-forming galaxies form the perfect laboratory for studies of the far-infrared/radio correlation, as they allow for an investigation of the correlation in extreme physical conditions, mostly unbiased by selection effects.

Upon combining deep observations from the *Atacama Large Millimeter Array* for nearly 700 dusty star-forming galaxies with deep radio observations from the VLA, we determine the far-infrared/radio correlation to be independent of cosmic time in these dusty starbursting systems. This is in contrast to previous studies of the correlation for more heterogeneous – and therefore likely more biased – galaxy samples. In addition, we determine the correlation for dusty star-forming galaxies in the early Universe to be offset from the correlation in local starburst galaxies, which we attribute to the different physical conditions between these systems.

In **Chapter Four** we perform a pioneering study of radio free-free emission in the early Universe. Making use of new observations taken at 34 GHz as part of the COLDz survey, in addition to radio observations spanning multiple lower frequencies, we have an unprecedented view of the *radio spectra* of the faint galaxy population. We detect 18 galaxies in the new 34 GHz observations, seven of which are star-forming galaxies. Utilizing the multi-frequency radio observations, we disentangle the radio spectra of the star-forming systems into their synchrotron and free-free emission, allowing us to use the latter as a tracer of star formation in the early Universe. We show that the star formation rates obtained from free-free emission are in agreement with those from canonically used tracers, and elaborate how next-generation radio telescopes will revolutionize studies of free-free emission in distant galaxies.

Chapter Five expands the scope of the previous chapter to significantly larger galaxy samples through the powerful technique of *stacking*. While individual galaxies are generally too faint to detect at high observing frequencies, our stacking analysis combines the emission from large numbers of distant sources and allows for a census of the average radio spectra of star-forming galaxies. This, in turn, allows us to study free-free emission in faint, representative galaxies.

We find that galaxies in the early Universe tend to be fainter at high frequencies than would be expected from a naive extrapolation of local observations. We attribute this to *spectral ageing* at high frequencies, causing a deficit of synchrotron emission in a mature starburst. We subsequently utilize the high-frequency free-free component to determine the cosmic star formation rate density, thereby providing the first such constraints with radio free-free emission.