A radio view of dust-obscured star formation
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Citation
Vlugt, D. van der. (2023, December 6). *A radio view of dust-obscured star formation*. Retrieved from https://hdl.handle.net/1887/3665936

Summary

The first stars and galaxies formed a few hundred million years after the *Big Bang*, the beginning of the Universe, which occurred some 13 billion years ago. The foundations from which those galaxies formed were established shortly after the Big Bang. To understand how galaxies and star formation evolved from that period to the present day is a challenging and complex question, considering that the processes involved work on very different size scales and time ranges. A group of stars forms on a much smaller scale than a galaxy, for example, while it takes millions of years to build up a galaxy-size population of stars, since the gas from which the stars are formed first has to cool and fall on the galaxy from large distances. Because of the large timescales, the evolution of galaxies cannot be followed in real time, but can be inferred using the finite speed of light. Light emitted by galaxies at great distances from Earth needs time to reach the observing telescopes. Galaxies are thus observed as they appeared when the light was emitted. Furthermore, the wavelength of light emitted increases because of the expansion of the Universe. In other words, the light emitted by galaxies reddens depending on the distance it has to travel to its observers, an effect known as *redshift* (z). Redshift can be measured to precisely determine the distance to a galaxy, thereby establishing the time at which the light was emitted. By observing many different galaxies at different stages in their evolution and across various cosmic epochs, we can attempt to infer and stitch together their evolutionary pathways.

Stars are the most visible constituents of galaxies and can be studied to help us understand how galaxies evolve. Stars are born from molecular clouds and the rate at which they form, the *star formation rate*, is a crucial parameter used to describe the evolution of a galaxy. Since it is not possible to observe single stars in galaxies at great distances, sophisticated techniques are needed to measure the buildup of stars in galaxies. For instance, to obtain as much detail as possible about the galaxies observed, measurements involve not only optical wavelengths of light, but also light emitted at other wavelengths, such as ultraviolet, low-energy infrared, millimeter and radio wavelengths. Ultraviolet light is emitted by young massive stars, such that this wavelength range of the spectrum traces galaxies that are actively star-forming. However, dust obscures ultraviolet light which means star formation can be partly obscured. Additionally, some of the most intense *star-forming galaxies* appear dark when observed at ultraviolet wavelengths and are thus missed in ultraviolet based measurements. The obscuring dust is heated by the young massive stars and re-emits the light absorbed at (longer) infrared wavelengths. Hence, dust-obscured star formation can be observed by means of infrared observations. However, infrared-based measurements also have limitations on their capacity to measure star formation accurately. Infrared telescopes lack the sensitivity to detect galaxies in the very early Universe and have poorer resolution, meaning galaxies are not delimited as sharply and some galaxies may blend together in observations. Ground-based sub-millimeter/millimeter continuum observations can help to overcome some of the problems in infrared observations. They offer high resolution and hence do not suffer from source blending.

However, the field of view of sub-millimeter/millimeter telescopes are typically small which means many expensive observations are needed to overcome cosmic variance. Observations at radio wavelengths provide both high resolution and do not suffer from dust attenuation. In addition, they generally have a large field of view. Radio observations offer therefore an alternative way of studying star formation in galaxies and form the main topic of this thesis.

Measuring star formation with radio observations

Radio observations, carried out with the *Very Large Array* (VLA) in New Mexico, USA, are used in this thesis to trace star formation in galaxies. The VLA constitutes an *interferometer*, which uses 27 antennas to reach the angular resolution and depth needed to study star formation in galaxies at high redshift. Radio emission in star-forming galaxies has two components related to star formation: *free-free emission* and *synchrotron radiation*. Free-free emission is produced directly by young massive stars, while synchrotron radiation arises from *supernova* remnants associated with the death of those young massive stars. Isolating the free-free component and measuring its flux density is difficult since free-free emission is much fainter than synchrotron radiation. Synchrotron emission can therefore be used more easily as a star formation tracer. However, when studying star formation in galaxies using radio observations, it is important to verify that the observed radio emissions are indeed produced by stars. Notably, accreting *supermassive black holes* located in the centers of galaxies, known as *active galactic nuclei*, can also produce synchrotron emission.

Redshifts of a sample of observed radio sources are needed to perform more advanced analysis on the sample, such as measuring the evolution of the star formation rate as function of time. Since the radio spectrum mimics by a featureless power law, radio observations alone cannot constrain the redshift. Multi-wavelength data, either from *photometric* or *spectroscopic* surveys, are thus needed to determine redshifts for radio sources. Photometric surveys give the average brightness of a galaxy over a fixed wavelength band, with a single data point per band, whereas spectroscopic surveys deliver a high-resolution spectrum of a galaxy. Obtaining photometric redshift is cheaper and can be done over larger survey areas, but the redshifts obtained are more uncertain. Spectroscopic redshifts are measured to high precisions by means of time-consuming spectroscopic surveys. Spectroscopic redshifts are therefore more reliable than photometric redshifts. Targeting carbon-monoxide (CO) is a relatively efficient method for obtaining spectroscopic redshifts for radio sources with photometric redshifts. CO is the second most abundant molecule present in the cold gas and dust that fills the space between stars, the *interstellar medium*. The rotational transitions of CO have a very low excitation temperature meaning CO gets easily excited and emits emission even in cold molecular clouds. The CO transitions emit radiation at specific sub-millimeter wavelengths. The *Atacama Large Millimeter/sub-millimeter Array* (ALMA) in the Atacama desert, Chili, is an interferometer comprised of 66 antennae with a frequency coverage and sensitivity which enables it to target CO transitions and thus obtain spectroscopic redshifts for gas/dust-rich sources at high redshift.

A sample of radio sources with determined redshifts and for which radio emissions solely result from star formation can be used to determine the evolution of star formation throughout the history of the Universe. Radio observations probe recent star formation and are especially valuable for probing dust-obscured star formation as even the most extreme star-forming galaxies enshrouded in dust can be observed. However, it is not trivial to use radio observations to determine star formation rates. The processes which link supernova remnants to synchrotron emission are complex and involve taking account of many key factors. Fortunately, the *far-infrared-radio-correlation* can be used. This correlation describes the 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. Since infrared luminosity is proportional to star formation rate, the far-infrared-radio-correlation can be used to convert synchrotron luminosities to star formation rates.

With the help of the far-infrared-radio-correlation, radio observations can be used to study the evolution of the star formation rate per unit volume, or the *cosmic star formation rate density*, as a function of redshift. This parameter is one of the most fundamental tools for understanding how star formation proceeds globally across cosmic time. Previous studies have shown that about 10 billion years ago, eight times more stars were formed in the Universe than today. This can be seen in Figure 1.4, which shows the cosmic star formation rate density as a function of redshift. However, most studies measuring the cosmic star formation rate density at high redshift use ultraviolet observations, a wavelength range prone to dust attenuation. This motivates the work presented this thesis. The first two chapters outline how we obtain our radio observations and use them to measure the cosmic star formation rate density with a dust-unbiased tracer. These radio observations are also used to uncover the *'optically dark'* population: extremely dust-obscured sources that are invisible even in deep ultraviolet imaging. Different studies have examined the contribution of these sources to the cosmic star formation rate density, yet have found constraints that still span more than an order of magnitude in range. The work in chapters three and four provides constraints on the contribution of 'optically dark' sources selected from our radio observations to the cosmic star formation rate density.

The COSMOS-XS survey

In this thesis the dust-obscured star formation is studied using the sensitive COSMOS-XS survey. Carried out with the upgraded VLA, COSMOS-XS provides some of the deepest radio observations to date at two frequencies: 10 GHz and 3 GHz (i.e., X- and S-bands). The survey was conducted in the COSMOS field, a 2 deg^2 field which has been observed with all leading ground-based and satellite facilities, yielding a rich multi-wavelength data set. Combining all these sources, the COSMOS-XS survey presents a unique data set that allows us to study the faintest radio populations that can currently be probed. The COSMOS-XS survey also reaches very faint flux densities which gives the ability to trace 'normal' galaxies over the epoch at which star formation in the Universe peaked, 10 billion years ago. Analysis of the COSMOS-XS survey and our resulting conclusions regarding the dust-obscured star formation rate are the subject of this thesis. The chapters of the thesis are summarized below.

This thesis

In this thesis, we present the radio observations from the VLA COSMOS-XS survey and use them to trace dust-unbiased star formation over cosmic time. **Chapter One** introduces the current state of the field and additionally provides the necessary background for the subsequent chapters.

In **Chapter Two**, we discuss the details of the COSMOS-XS survey and present the radio catalogs with the observed radio sources. Counting the number of galaxies or, in other terms, constraining the source counts, is the simplest statistical analysis that can be performed with a flux-limited radio survey. It provides information on the evolutionary properties of sources. The deep 10 and 3 GHz observations enable us to investigate the Euclidean-normalized source counts down to faint flux densities. We show that our observations are consistent within uncertainties with other results at 3 and 1.4 GHz, but extend to fainter flux densities than previous direct detections.

In **Chapter Three**, we use the COSMOS-XS survey to select star-forming galaxies with the far-infrared-radio-correlation. These galaxies are used to constrain the radio luminosity function. The luminosity function gives the cosmic density of sources in bins of luminosity. It can be used to constrain the evolutionary path of star-forming galaxies. We present evidence for significant density evolution over the observed redshift range. We use the radio luminosity functions to derive the dust-unbiased star formation rate density out to $z \sim 4.6$. Using this dust-unbiased survey, we present evidence for a significant underestimation of the star formation rate density based on the ultraviolet luminosity functions at high redshift.

In **Chapter Four**, the focus shifts to 'optically dark' galaxies. We use the 3 GHz radio map from the COSMOS-XS survey to identify these sources. We utilize the new 'Super-deblended' far-infrared catalog to find the photometric redshifts of the 'optically dark' sources. The far-infrared catalog adopts a novel deblending technique to address sources that are blended together. This catalog takes the positions of the sources detected in the COSMOS-XS survey as priors. Using the 'Super-deblended' catalog, we derive the far-infrared-based photometric redshifts of the sources to be between $z = 2$ and $z = 5$. We then quantify the contribution of 'optically dark' sources to the total star formation rate density using the method described in chapter three, and find that they play a non–negligible role at high redshift.

Building on the results of chapter four, we present new ALMA observations of 'optically dark' sources in **Chapter Five**. These ALMA observations comprise a scan of the frequency range 84–108 GHz. In this way the observations are sensitive to CO emission in the cosmic volume without specifically targeting CO lines. With the ALMA scans we can determine the spectroscopic redshifts for a sub-sample of 10 radio-selected 'optically dark' galaxies. We find CO-based redshifts that confirm that the 'optically dark' sources targeted lie at $z \gtrsim 3$. By integrating the luminosity functions found in chapter four to the flux limit of the targeted sub-sample, we determine that the star formation rate density is in agreement with the star formation rate density found for the 10 ALMA detected 'optically dark' sources. This confirms the cosmic importance of 'optically dark' sources at high redshift.