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Estimation of galaxy SFRs from low radio frequencies

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Abstract

We present a global relation between the low-frequency and infrared (IR) emissions in star-forming galaxies compiled by the Herschel Reference Survey. The GaLactic Extragalactic All-sky MWA (GLEAM) survey operated by the Murchison Widefield Array (MWA) allows us to examine the relation and its frequency dependence with their 20 narrow bands at 72 – 231 MHz. These examinations are important for ensuring the reliability of the radio SFR. In this study, we focus on 18 star-forming galaxies whose radio emission is detected by the GLEAM survey. These galaxies show that a single power-law fitting is valid for understanding how the relation between the radio and IR luminosities varies across MWA frequencies to 1.5 GHz. We also investigate the consistency of the Star Formation Rate (SFR) calculated from the low-frequency emission with that from other indicators. Although this low-frequency emission has an advantage of the extinction-free indicator, the SFR calibration with averaged spectral parameters has a non-negligible uncertainty due to the variety of the radio to IR relation. We propose to use the individual spectral energy distribution for calculating the radio SFR for each star-forming galaxies with less uncertainty.

Acknowledgments

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Chapter 1

Introduction

ABSTRACT

Intro intro intro intro.

1.1 Background

The low-frequency radio emission from star-forming galaxies has been studied for many years. In this paper, we use the term “Low frequency” as the frequency less than a few GHz. The importance of this emission increased after the global log-linear correlation with infrared (IR) had been found. This correlation was discovered by Helou et al. [1985] using integrated far-infrared (FIR; $60\ \mu\text{m}$ and $100\ \mu\text{m}$) and 1.4 GHz radio luminosities in star-forming galaxies, and called the IR-Radio Correlation (IRC). Bell [2003]; Condon et al. [1991]; Yun et al. [2001] have examined this global correlation using a different sample set and found it holds the tightness across more than three orders of magnitude. Recently, the low-frequency survey at around 100 MHz was operated by the LOw Frequency Array (LOFAR; van Haarlem et al. 2013) and the Murchison Widefield Array (MWA; Tingay et al. 2013). With the advent of these telescopes, Calistro Rivera et al. [2017]; Read et al. [2018]; Wang et al. [2019] extend the IRC study to at an order of magnitude lower frequency and find IRC is held at not only 1.4 GHz but $\sim 100\ \text{MHz}$.

Thanks to this correlation, we can regard the low frequency emission as a SFR indicator because IR luminosity is emitted by heated dust grains in a galaxy and can measure the SFR. Since the low-frequency emission is not affected by the dust extinction [Murphy et al., 2011; Yun et al., 2001] and it will be observed from a distant galaxies by the future extended survey, we anticipate its usefulness and need a further investigation of the relation between the radio and IR luminosities, especially its frequency dependence. However, the spatially-resolved studies show that a star-forming galaxy emits the radio emission whose spectral index depends on the galaxy region [For et al., 2018; Heesen et al., 2019; Kapińska et al., 2017]. This means that the radio emission is sensitive to the local density environment of the ISM and it is not guaranteed a simple frequency dependence of the global relation between the integrated radio and IR luminosities.

The integrated radio emission in star-forming galaxies across 100 MHz to 1.4 GHz is supposed to compose of a few percent to 10% free-free and the synchrotron radiations [Condon, 1992]. Each

radiation is emitted by electrons interacted with the electric field of ions in the HII region or the magnetic field in a galaxy. For emitting the synchrotron radiation, an electron needs to be accelerated to the light speed by the supernova remnant. While the synchrotron emission is expected to be dominant at these low frequencies, previous studies find the sign of the free-free absorption and flatter or turnover spectral [Chyžy et al., 2018; Schober et al., 2017]. If the radio emission has a significant turnover among low frequencies, IRC does not have a simple frequency dependence and the radio emission is no longer useful as a SFR indicator.

In this study, we investigate nearby star-forming galaxies from the reference sample for ensuring the reliability of measuring the SFR from the low-frequency emission. For examining the general trend, we use star-forming galaxy samples from Herschel Reference Survey (HRS; Boselli et al. 2010) catalog which are supposed to represent the galaxy samples and the low-frequency emission from The Galactic Extragalactic All-sky MWA (GLEAM; Hurley-Walker et al. 2017) Survey which observes the mJy scale radio emission from large areas with their 20 narrow bands.

This paper is organized as follows. In Section ??, we introduce our galaxy samples and the low-frequency emissions used in this study. In Section ??, we introduce the IR-Radio Correlation with the q_ν value defined for evaluating the correlation quantitatively. Here, we also mention the way to investigate its frequency dependence and derive the radio SFR. In Section ??, we show our results about the frequency dependence of IRC and the consistency of the radio SFR. In Section ??, we compare our results with previous studies. Finally, we summarize our study in Section ??.

Chapter 2

Theoretical Background

ABSTRACT

Intro intro intro intro.

Here, I will describe synchrotron emissions?

Chapter 3

Data

ABSTRACT

In this chapter, I describe the dataset used for our study.

3.1 Herschel Reference Survey (HRS)

In this section, I introduce the Herschel Reference Survey (HRS) catalog [Boselli et al., 2010]. This survey is one of the Herschel guaranteed time key projects and originally it was compiled for understanding dust properties and interstellar medium in nearby galaxies. The catalog contains 322 galaxies selected with the three following criteria.

1. Volume-limited:

They choose galaxies whose distance from the earth is between 15 and 25 Mpc. This limitation reduce the distance uncertainty due to the galaxy peculiar motions and the selection effect due to the high-z galaxies. The lower limit (15 Mpc) also helps us to observe sources within the reasonable exposure time because galaxies too close to us are extended and we need too much time for the observation.

2. *K*-band selection:

They choose galaxies whose 2MASS *K*-band total magnitudes are less than 12 mag for star-forming and peculiar galaxies (Sa-Sd-Im-BCD), and 8.7 mag for quiescent galaxies (E, S0, S0a). If there are galaxies whose *K*-band magnitude more than those values, their measurements are not regarded as an accurate photometry because of not enough exposure time. The reason why they have selected quiescent galaxies with the more stringent *K*-band selection criteria is these galaxies are expected to have low dust contents, and it is difficult to detect within the reasonable exposure time.

3. High galactic latitude:

They choose galaxies whose galactic latitude is high enough to minimize the contamination from the galactic center ($b > +55^\circ$). Also, they have selected galaxies with the low galactic extinction ($A_B < 0.2$; Schlegel et al. 1998).

The selected galaxies located in the sky region between $10^{\text{h}}17^{\text{m}} < \text{R.A.(2000)} < 14^{\text{h}}43^{\text{m}}$ and $-6^{\circ} < \text{decl.} < 60^{\circ}$ (Figure 3.1) HRS galaxies spans a large range of the galaxy density environment from the center of Virgo cluster to the isolated region. As a definition, we can regard the HRS sample as a ideal one for studying the galaxy environment.

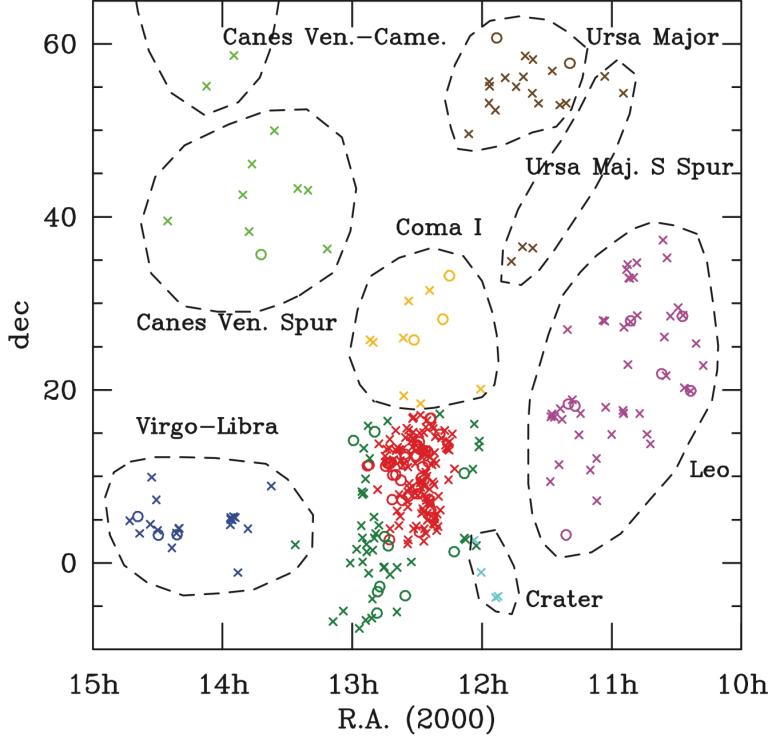


Figure 3.1: (Reprint from Boselli et al. 2010, Figure 1)

This figure shows the sky distribution of HRS galaxy samples. They show the early-type galaxies (E, S0, S0a) and late-type galaxies with circles and crosses, respectively. Dashed circles represents the different cloud regions. Each name of the cloud is shown close to each region. The red and dark green markers are Virgo galaxies (red: Virgo center, dark green: its outskirts).

In addition to a large range of the environment, the HRS galaxies distribute a wide range of the galaxy morphology (Figure 3.2).

Since HRS galaxies are supposed to be well-represented for the whole galaxy population located in the local universe, understanding their physical properties is a critical study. After Boselli et al. [2010] published the HRS sample, many studies investigating the physical properties for HRS galaxies have been done until now. Here, I introduce some of the studies for the HRS sample. Cortese et al. [2012] investigated their UV and optical properties using the Galaxy Evolution Explorer (GALEX; Martin et al. 2005) and SDSS-DR7 [Abazajian et al., 2009]. Boselli et al. [2014] studied their cold gas properties with ^{12}CO ($1 - 0$) observed by the Kitt Peak 12m radio telescope and obtained from the literature data. They also investigate the HI gas obtained from The Arecibo Legacy Fast ALFA (ALFALFA; Giovanelli et al. 2005; Haynes et al. 2011) Survey. Ciesla et al. [2014] executed the SED fitting for HRS galaxies with Code Investigating GALaxy Emission (CIGALE; Noll et al. 2009).

Thanks to all of previous research about the HRS sample, they are well-studied among the wide range of the wavelength from the X-ray to the radio emission at 1.5 GHz. However, the low-frequency around 100 MHz is not examined so far. In this study, we focus on a subsample of HRS galaxies,

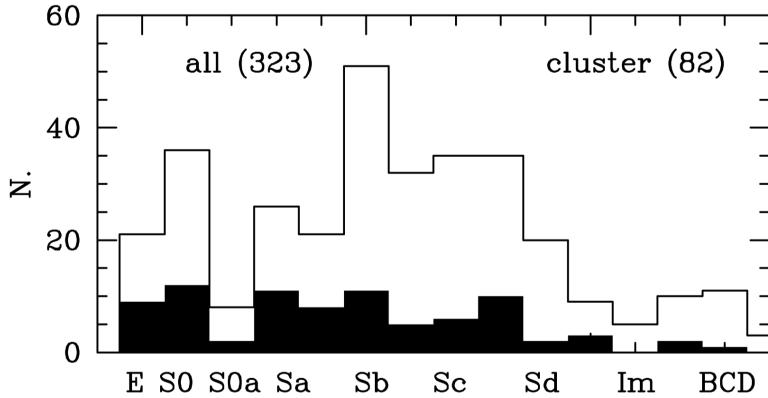


Figure 3.2: (Reprint from Boselli et al. 2010, Figure 2)

This figure shows the distribution in the morphology-type of HRS galaxies. The shaded histogram represents the distribution in it of only the cluster sample. Here, the cluster sample composed of HRS galaxies located in the Virgo A and B clouds.

whose counterpart is detected by the latest low-frequency survey (Section 3.2).

3.2 GLEAM survey

In this section, I introduce the GaLactic Extragalactic All-sky MWA (GLEAM) survey [Hurley-Walker et al., 2017]. This survey was operated by the Murchison Widefield Array (MWA) telescope [Tingay et al., 2013] in Western Australia. It observed a whole southern sky and a northern sky up to $+30^\circ$ ($\sim 25,000$ deg 2 ; Figure 3.3). The catalog from this survey is a publicly-available and contains 307,455 detected radio sources with fluxes at 20 narrow bands between 72 and 231 MHz (each band has 7.68 MHz band width). The sensitivity and angular resolution at 200 MHz are ~ 7 mJy and ~ 2 arcmin respectively. The completeness of this survey at 200 MHz is 90% at ~ 170 mJy. Since this survey allows us to examine the low-frequency spectral energy distribution accurately with their 20 narrow bands, we adopt the radio source catalog for our study.

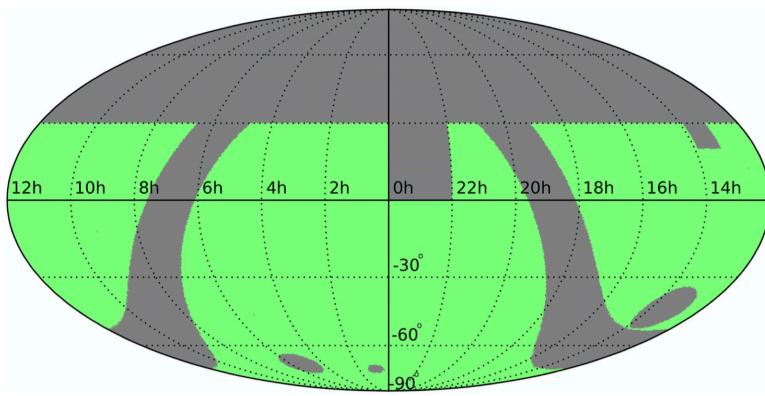


Figure 3.3: (Reprint from Hurley-Walker et al. 2017, Figure 11)

This figure shows the observed area by the GLEAM survey (green shaded region). They exclude several regions intentionally to minimize the contamination: Galactic plane (Absolute Galactic latitude $< 10^\circ$), Ionospherically distorted ($0^\circ < \text{Dec} < +30^\circ$ and $22^\text{h} < \text{R.A.} < 0^\text{h}$), Centaurus A ($13^\text{h}25^\text{m}28^\text{s} - 43^\circ01'09''$, $r = 9^\circ$), Sidelobe reflection of Cen A ($20^\circ < \text{Dec} < +30^\circ$ and $13^\text{h}07^\text{m} < \text{R.A.} < 13^\text{h}53^\text{m}$), Large Magellanic Cloud ($05^\text{h}23^\text{m}35^\text{s} - 69^\circ45'22''$, $r = 5.5^\circ$) and Small Magellanic Cloud ($00^\text{h}52^\text{m}38^\text{s} - 72^\circ48'01''$, $r = 2.5^\circ$).

Chapter 4

Methods

ABSTRACT

Intro intro intro intro.

4.1 Cross Matching

Although HRS galaxies have been studied in multi-wavelength observations, their spectral energy distribution around 100 MHz is not well-understood, where the contribution from synchrotron radiation is much more significant than from free-free emission [Condon, 1992]. Here, I provide a procedure to cross-matching with two different catalogs we have mentioned in previous sections. Cross-matching is the method widely used in astronomy to obtain additional information from other surveys or catalogs by matching coordinates of each galaxy or blob source within a specified error range. For executing this method for HRS galaxies and the GLEAM survey catalog, we use Tool for Operations on Catalogues And Tables (TOPCAT; Taylor et al. 2009). TOPCAT is a convenient tool for dealing with catalogs and tables, and it allows us to do the cross-matching easily, even more than two catalogs.

Initially, we assume a 10 arcsec error radius for the cross-matching since it is equivalent to the value of 95% error for the astrometry in the GLEAM survey (Section 4.5.5 in Hurley-Walker et al. 2017). This matching results in a total of 18 galaxies which are identified to have a radio counterpart. To assess the matching, we compare a separation of counterparts from the center of galaxies with coordinate uncertainties in the GLEAM catalog. For these galaxies, we find 15 of them have a separation within a 95% error radius, and others do not. Although three of them have a larger separation compared to the error radius, we conclude that the matching for all 18 galaxies is correct by the checking of galaxy images (Appendix ??). In this paper, we regard a radio blob as a counterpart if the brightest part of each blob where the inside of the contour nearest to the center, is surrounded by the D25 radius.

Next, we extend the error radius up to 120 [arcsec], which is corresponding to the angular resolution of the GLEAM survey at 200 MHz. This is because the radio sources are blurred due to the angular resolution of the GLEAM survey and the location of the radio source might be shifted. We know 120 arcsec error radius is quite big for the matching, but this trial gives us the inspiration for the cross-matching with blurred radio sources in the future study. The cross-matching with the error of 120 arcsec suggests that there are 25 new galaxies have a potential counterpart. To assess these

matching, we look at galaxy images one by one (All galaxy images are in Appendix ??). With the same condition mentioned above, we identify 21 matches for these galaxies.

Although we have identified a total of 39 matches in the same way, there are six suspicious matches because of interacting counterparts (HRS4, 216, 244, 284) and quite large separations (HRS200, 295) (Figure ??). For these galaxies, we flag them as suspicious matches, and we do not use them for further analysis. The distribution of separations for galaxies showed in Figure 4.1.

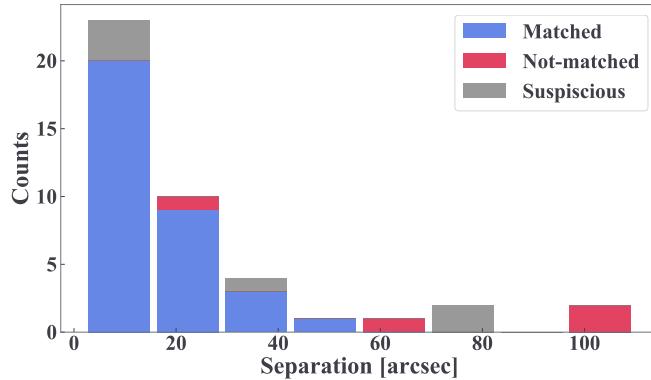


Figure 4.1: This figure shows the distribution of separations. Here we put 43 galaxies and color sorted based on the result. The blue bar shows galaxies identified to have a radio counterpart, red one does galaxies determined not to have a counterpart, and gray for the suspicious galaxies. Most of the matched samples are distributed within a 40 arcsec error radius.

We summarize as the table for 39 galaxies identified to have a radio counterpart in Appendix ?? and put all galaxy images cross-matched within 120 arcsec in Appendix ??.

4.2 Reduce galaxy samples for the secure analysis

In this section, we show some steps for selecting galaxies to do a secure analysis. Since we focus on the relation of galaxy radio emission with star formation activities, we should clarify the radio source and be sure that they are not originally from other sources rather than the star formation. The synchrotron radiation arisen from the star formation activities should be proportional to the SFR in a galaxy. Therefore, the radio emission from elliptical galaxies, which are thought to have no more star formation, would trace other radio sources unrelated to the star formation. These radio sources are considered as Active Galactic Nuclei (AGN), which emits strong radio emission due to the baryon accretion into the supermassive black hole at the center of galaxies irrelevant to the star formation. According to the morphology of galaxies [Cortese et al., 2012], we identify four elliptical galaxies (HRS49, 138, 178, 241) and not use for further calculation and discussion.

After this galaxy selection, we obtain 29 galaxies with a reliable radio counterpart arisen from the star formation activity.

As a next step, we evaluate the signal to noise ratio (SNR) of radio emission at each MWA band. For reducing the uncertainty caused by observation errors, we assess the peak flux at each narrow band by comparing it to the local noise level and adopt flux values whose SNR is higher than five. This

analysis results in a total of 11 galaxies have no radio fluxes whose SNR is higher than the criterion. The reason why these radio sources are detected, although they do not have any fluxes with higher SNR, is Hurley-Walker et al. [2017] determine the detection based on the SNR in the stacking images (170 – 231 MHz).

Finally, after the cross-matching and these procedures, we confirm 18 HRS galaxies are the samples available for further analysis.

4.3 Calculating the q parameter

In this section, we introduce the method to calculate the q parameter for each galaxy. The definition of this parameter here is given on the following equation [e.g. Bell, 2003; Calistro Rivera et al., 2017; Helou et al., 1985]:

$$q_\nu \equiv \log \left(\frac{L_{8-1000\mu\text{m}} / 3.75 \times 10^{12}}{\text{erg s}^{-1} \text{Hz}^{-1}} \right) - \log \left(\frac{L_{\text{Radio}, \nu}}{\text{erg s}^{-1} \text{Hz}^{-1}} \right) \quad (4.1)$$

where $L_{8-1000\mu\text{m}}$ is the total rest-frame infrared luminosity among 8 – 1000 μm , which reflects the total dust luminosity, and 3.75×10^{12} is equivalent to the frequency of 80 μm for correcting the dimension.

Although Ciesla et al. [2014] have already derived the total IR luminosity for most HRS galaxies using the SED fitting method, one of our galaxy samples (HRS163) does not have the value because of the lack of the reliable mid IR flux from the Spitzer telescope. For consistency, we adopt the total IR luminosity calculated from the same method for all galaxy samples. To calculate the total IR luminosity, we refer to Galametz et al. [2013], which derived the calibration relation between combining monochromatic IR luminosity and the total IR dust luminosity. We show the procedure to calculate total IR luminosity in the following section.

4.3.1 Total IR luminosity

In this section, we show how to calculate the total IR luminosity. For the method of calculating total IR luminosity, we refer to Galametz et al. [2013], which shows the empirical relations to estimate TIR from Spitzer bands (24, 70 μm), and the Herschel band (100, 160, 250 μm). HRS galaxies have the flux data from the Multiband Imaging Photometry for Spitzer (MIPS; Bendo et al. 2012; Rieke et al. 2004), the Herschel/PACS [Cortese et al., 2014] and the Herschel/SPIRE [Ciesla et al., 2012].

Galametz et al. [2013] derived the calibration equation as follows:

$$L_{3-1100\mu\text{m}} = \sum c_i \nu L_\nu (i) \quad (4.2)$$

where $L_{3-1100\mu\text{m}} L_\odot$ is the total IR luminosity in the frequency range 3 to 1100 μm , c_i is the coefficients at $i = 24, 70, 100, 160, 250 \mu\text{m}$, and $L_\nu L_\odot \text{Hz}^{-1}$ is the luminosity at the frequency ν corresponds to a specific wavelength i . For deriving $L_\nu L_\odot \text{Hz}^{-1}$, we calculate it from flux values and the distance to each galaxy. We referred to Cortese et al. [2012] for obtaining galaxy distances.

They have derived the conversion equation with at least two bands. Therefore, we could estimate total IR luminosities even if galaxies are lack of a few flux data. Since several calculations in the

following sections require the total IR luminosity among $8 - 1000 \mu\text{m}$ ($L_{8-1000\mu\text{m}}$), we recalibrate this luminosity by multiplying the constant value (0.88) in Takeuchi et al. [2005].

The total IR luminosity calculated here is almost consistent with that of Ciesla et al. [2014], although there is a little scatters (Figure 4.2).

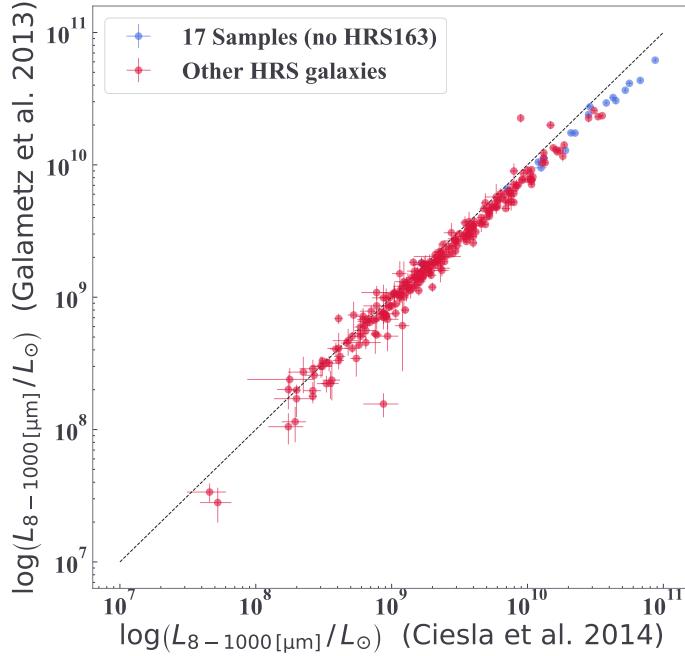


Figure 4.2: This figure shows the comparison of total IR luminosity at $8 - 1000 \mu\text{m}$ from different methods. Here, we show all HRS galaxies which have both luminosities. Blue plots show galaxy samples selected in Section 4.1 and 4.2, and red ones show other HRS galaxies. Although there are some galaxies whose luminosities below $10^9 L_\odot$ have a relatively larger scatters, the difference of luminosities for our samples (blue plots) is smaller than factor 2.

Hereafter, we use $L_{8-1000\mu\text{m}}$ obtained here to calculate the q parameter and SFR in Section ??.

4.4 Fitting to q parameters

Here, we show how to do the fitting for obtaining the spectral index γ which is a principal value to estimate SFR using low-frequency radio emissions. At low frequencies like a few hundred megahertz, the synchrotron emission can be dominant, which emitted from high energy electrons accelerated by the supernova remnant. In this paper, we assume radio emission has a single power-law on the frequency and adopt the following equation

$$q_\nu = -\gamma \log \nu + \beta \quad (4.3)$$

where q_ν a q parameter defined by Equation 4.1 at ν [MHz], and β is the second fitting parameter.

In this paper, we executed two types of fitting:

1. Fitting to only MWA frequencies (72 – 231 MHz)
2. Fitting to MWA frequencies and 1500 MHz

The flux data at 1500 MHz is obtained from Boselli et al. [2015], and here we use only high-quality flux data (flag = 1). These two types of fitting might allow us to judge the correctness of a single power-law assumption. These fitting results are summarized in Section ??.

4.5 Calculating the SFR

In this section, we describe how to derive SFR from low-frequency radio emissions.

In this paper, we estimate this SFR, combining Equation 4.1 with the following equations:

$$\text{SFR}_{\text{IR}} = 3.88 \times 10^{-44} \left(\frac{L_{8-1000\mu\text{m}}}{\text{erg s}^{-1}} \right) \quad (4.4)$$

$$q_{\nu} [\text{MHz}] = q_{1500 [\text{MHz}]} + \log \left(\frac{\nu [\text{MHz}]}{1500 [\text{MHz}]} \right)^{\gamma} \quad (4.5)$$

Equation 4.4 is calculating SFR using the IR emission from Murphy et al. [2011], and Equation 4.5 shows the difference of the q parameter between a certain wavelength ν and 1500 MHz.

Substituting equation 4.1 and 4.5 into equation 4.4 yields the following equation to estimate SFR from radio emission at ν MHz:

$$SFR_{\text{Radio}, \nu} = 1.46 \times 10^{-31} \times 10^{q_{1500\text{MHz}}} \left(\frac{\nu [\text{MHz}]}{1500 [\text{MHz}]} \right)^{-\alpha_{\text{sync}}} \times L_{\text{Radio}, \nu} \quad (4.6)$$

In Section 5.2, we show the results of calculating SFR from low-frequency radio using this equation and comparing it with the SFR from other indicator.

Chapter 5

Results

ABSTRACT

In this chapter, we present our results with figures. Firstly, in Section 5.1, we show the q_ν frequency dependence for each galaxy with the distribution of γ . Secondly, in Section 5.2, we show the result of the comparison between the SFR from a radio emission and other indicators.

5.1 Distributions of γ

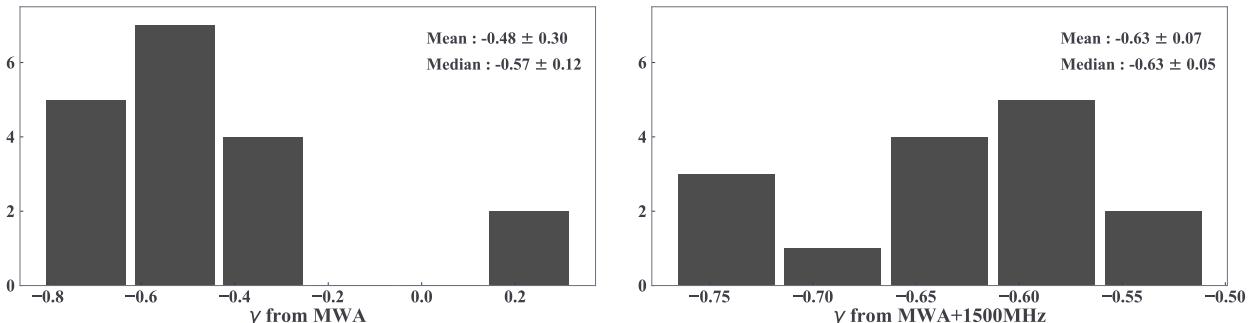


Figure 5.1: This figure shows distributions of γ for each fitting. The left figure indicates the fitting result with only MWA frequencies, and the right one does with 1500 [MHz] besides MWA frequencies.

Here, we show two kinds of fitting results. The left plot in Figure 5.1 is the γ distribution from the fitting only to MWA frequencies, and the right one is to 1500 MHz besides MWA frequencies. We show the mean and median with the standard and quantile deviation in both plots. Since we adopt high-quality flux data at 1500 MHz [Boselli et al., 2015], three samples (HRS 122, 163 and 204) are fitted only in the case with MWA fluxes. Figure 5.2 compares γ from different fitting fluxes for each galaxy.

In these figures, we can find that there are two galaxies (HRS 25 and 144) with a relatively flatter γ fitted only to MWA frequencies. This suggests that there is a critical frequency where the turnover arises between MWA frequencies and 1500 MHz. At low frequencies, the spectral is prone to be flatter due to the free-free absorption [e.g., Calistro Rivera et al., 2017; Chyzy et al., 2018; Schober et al.,

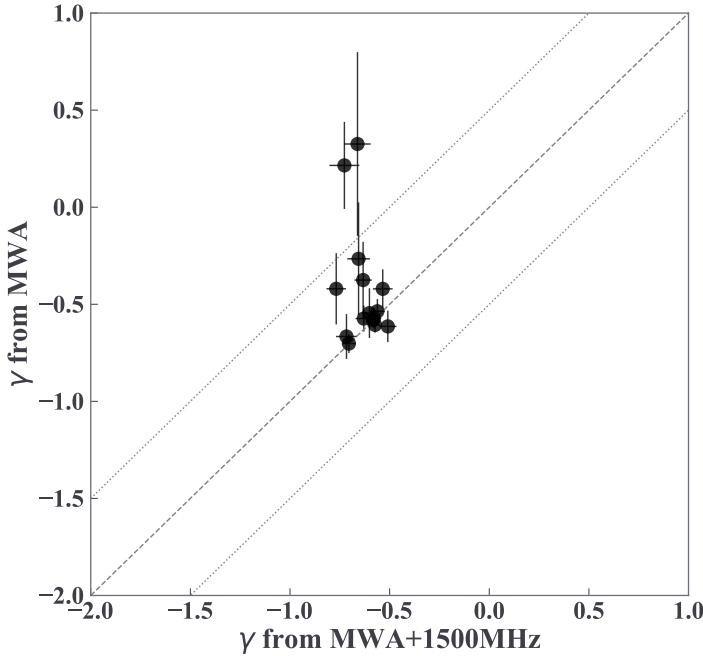


Figure 5.2: This figure is for comparing the difference of γ for each fitting method. The solid line shows the one to one correlation, and dotted lines show 0.5 dex away from the solid line. Each plot shows each galaxy. In this figure, we can see γ fitted to only MWA frequencies are relatively flatter.

2017]. In addition to this, Schober et al. [2017] show that a Milky Way like galaxy (similar SFR) has the critical frequency order of magnitude lower than the MWA frequency. However, HRS 25 and 144 have a Milky Way like SFR [Boselli et al., 2015] and a critical frequency between MWA frequencies and 1500 MHz. This result cannot be explained by Schober et al. [2017]. One possible explanation is that fewer number of fluxes yields less constraint of the fitting and the flatter γ for HRS 25 and the galactic nuclei affects the spectral for HRS 144 identified as a Seyfert galaxy from the BPT diagram [e.g., Baldwin et al., 1981; Kauffmann et al., 2003; Kewley et al., 2001; Schawinski et al., 2007]. For understanding these galaxies, we would need the case study with more data in a wide frequency range.

If we neglect these galaxies, the mean γ changes from -0.48 ± 0.30 to -0.57 ± 0.14 for the fitting without 1500 MHz and from -0.63 ± 0.08 to -0.62 ± 0.08 with 1500 MHz. The mean γ does not vary in any case with 1500 MHz. This means that HRS 25 and 144 do not affect the fitting result among MWA frequencies and 1500 MHz, although they do the mean γ from the fitting only to MWA frequencies. Therefore, in this paper, we adopt the averaged γ obtained from the fitting across the MWA frequency to 1500 MHz for calculating SFR (Section 5.2).

The fitting results are shown in Appendix ??.

5.2 Star Formation Rate (SFR) from the low-frequency emission

Here, we show the result from comparing $SFR_{\text{Radio}, \nu}$ defined by Equation 4.6 with SFR_{IR} (Equation 4.4) and $SFR_{\text{FUV}+24\text{mic}}$ [Boselli et al., 2015].

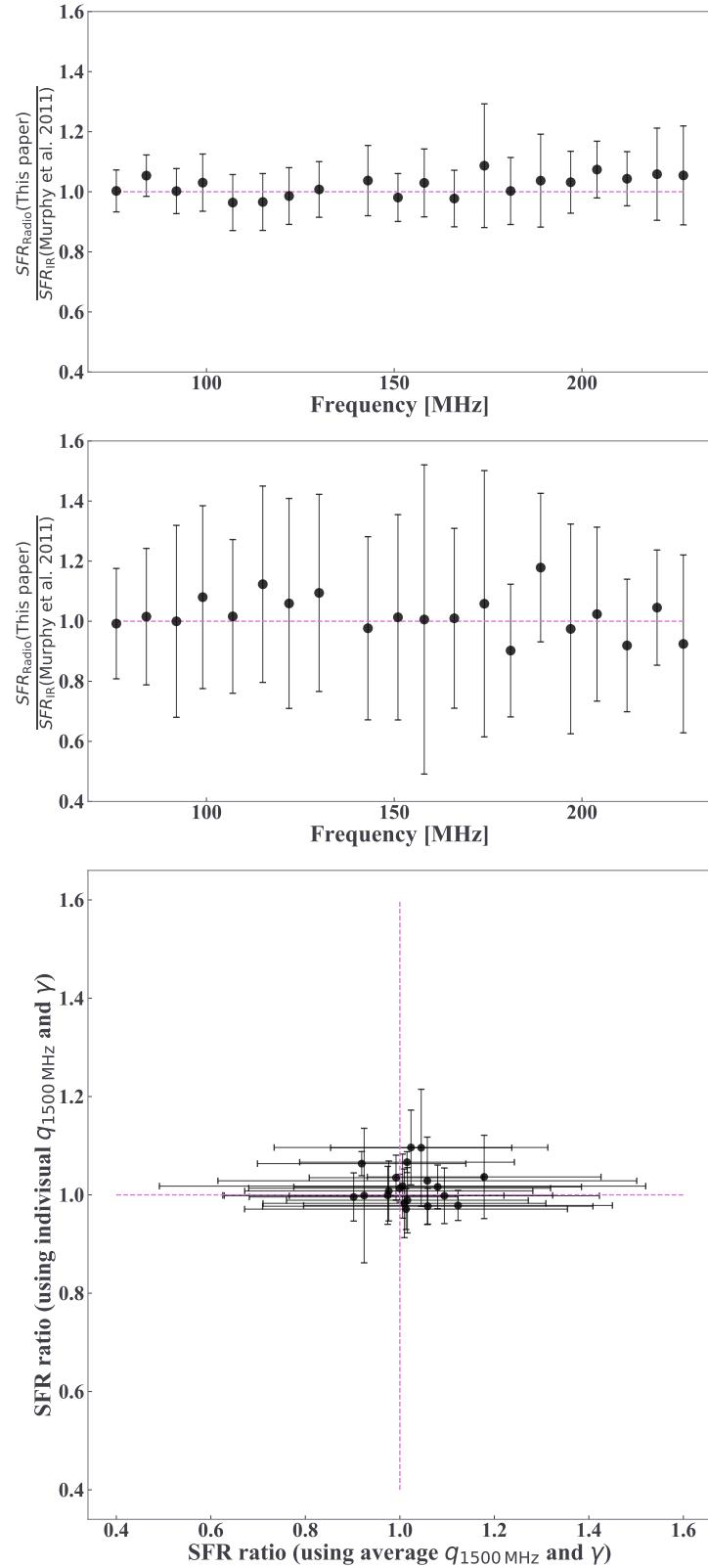


Figure 5.3: This figure shows the SFR ratio between $SFR_{\text{Radio},\nu}$ and SFR_{IR} at each MWA frequency. The difference between the upper and middle plots is the calibration parameters to calculate $SFR_{\text{Radio},\nu}$. Individual or averaged γ and $q_{1500 \text{ MHz}}$ are used for the upper or middle plots, respectively. The bottom plot compares SFR ratios calculated with different calibrations.

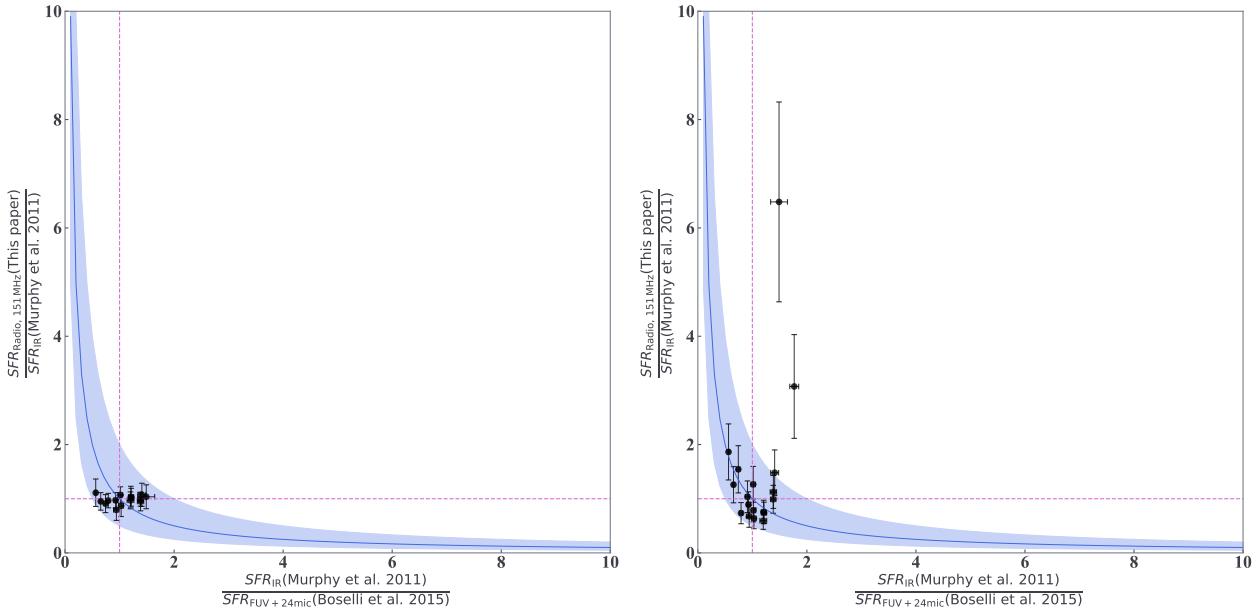


Figure 5.4: This figure shows SFR ratios from different indicators. The vertical and horizontal axes are $SFR_{\text{Radio}, 151 \text{MHz}} / SFR_{\text{IR}}$ and $SFR_{\text{IR}} / SFR_{\text{FUV}+24\mu\text{m}}$ in both plots. Magenta dashed lines indicate the unity for each SFR ratio, and the solid blue lines do for the SFR ratio between $SFR_{\text{Radio}, 151 \text{MHz}} / SFR_{\text{FUV}+24\mu\text{m}}$. The blue shaded region shows the ratio between $SFR_{\text{Radio}, 151 \text{MHz}}$ and $SFR_{\text{FUV}+24\mu\text{m}}$ within factor two ($0.5 \leq SFR_{\text{Radio}, 151 \text{MHz}} / SFR_{\text{FUV}+24\mu\text{m}} \leq 2$). The difference between the upper and middle plots is the calibration parameters to calculate $SFR_{\text{Radio}, 151 \text{MHz}}$.

Figure 5.3 shows the SFR ratio between $SFR_{\text{Radio}, \nu}$ and SFR_{IR} . For drawing the upper figure, we substitute the individual $q_{1500 \text{ MHz}}$ and γ into Equation 4.6. We calculate $SFR_{\text{Radio}, \nu}$ at each MWA frequency and plot the mean value. Note that the number of galaxies taken for the mean at each frequency is different because we use only high-quality fluxes. In this case, we can see it is consistent with SFR_{IR} within a 10% error. For the middle figure, we substitute the averaged $q_{1500 \text{ MHz}}$ and γ instead of individual values. This calibration method yields larger scatters compared to the previous one. However, $SFR_{\text{Radio}, \nu}$ is still consistent with SFR_{IR} . The bottom figure shows the SFR ratio comparison from different calibrations. In this figure, it is clear that SFR calculated from the averaged value has more extensive scatters than from the individual values.

These figures give us the idea that calculating radio SFR needs the spectral energy distribution for less uncertainty. For the spectral, we find that the single power-law assumption yields the radio SFR with the consistency within 10%, even including galaxies that might have a flatter spectral at low frequencies.

Figure 5.4 shows the comparison of SFR ratios. For both plots in the figure, vertical and horizontal axes show the ratio between $SFR_{\text{Radio}, 151 \text{ MHz}}$ and SFR_{IR} , between SFR_{IR} and $SFR_{\text{FUV}+24\mu\text{m}}$, respectively. We use radio emission at 151 MHz because this is the only flux band that all our samples have high-quality data. Here, we check the consistency of the radio SFR with other SFR indicators. While SFR_{IR} traces the only dust emission, $SFR_{\text{FUV}+24\mu\text{m}}$ does the direct young massive stellar emission dust-corrected with the radiation at 24 μm [Kennicutt & Evans, 2012; Murphy et al., 2011]. This figure shows how consistent the radio SFR is with this direct emission tracer.

5.2. STAR FORMATION RATE (SFR) FROM THE LOW-FREQUENCY EMISSION

The difference between these plots is the calibration parameter for calculating $\text{SFR}_{\text{Radio}, 151 \text{ MHz}}$. The individual $q_{1500 \text{ MHz}}$ and γ are used for the left plot and the averaged ones for the right plot. The blue shaded region shows the ratio between $\text{SFR}_{\text{Radio}, 151 \text{ MHz}}$ and $\text{SFR}_{\text{FUV}+24\text{mic}}$ within factor two ($0.5 \leq \text{SFR}_{\text{Radio}, 151 \text{ MHz}} / \text{SFR}_{\text{FUV}+24\text{mic}} \leq 2$). In the figure, we can see that the radio SFR using individual parameters is also consistent with $\text{SFR}_{\text{FUV}+24\text{mic}}$. However, in the other case, there are two galaxies (HRS 306 and 144) whose radio SFR overestimates. This is because these galaxies have stronger radio emission (lower q_ν) than the extrapolated average value at 151 MHz.

Chapter 6

Discussions

ABSTRACT

Intro intro intro intro.

6.1 Comparing the calibration with previous results

Here, we compare our results in Section 5.1 with previous research. From our samples, we obtain the mean $\gamma = -0.63 \pm 0.07$ with MWA frequencies and 1500 MHz. Calistro Rivera et al. [2017] and Chyžý et al. [2018] obtained -0.78 ± 0.24 and -0.56 ± 0.11 , respectively. The difference of these might result from the selection of galaxy samples. While we use nearby galaxies within 25 Mpc, Calistro Rivera et al. [2017] do 758 galaxies up to $z \sim 2$, and Chyžý et al. [2018] do 118 galaxies up to $z = 0.04$.

Chyžý et al. [2018] indicate that the slope is steeper at higher frequencies ($1.3 \sim 5$ GHz), and this might steepen the slope of galaxy samples in Calistro Rivera et al. [2017] which adopt galaxies up to $z \sim 2$. Considering the value and scatter, our result using the Herschel reference sample would be consistent with previous findings. Indeed, the frequency dependence of the low-frequency emission and its relation with IR emission is still uncertain.

6.2 Radio SFR uncertainty

In Section 5.2, we show the consistency of our SFR calibrations using the low-frequency emission. For calculating the more accurate radio SFR, we need its spectral energy distribution for each galaxy, as we have already shown in Section 5.2. Since star-forming galaxies have a wide variety of q_ν at low frequencies (~ 0.53 dex in Figure 14, 15; Calistro Rivera et al. 2017), and still we do not know the physical details, the radio SFR calibration has considerable uncertainty. Substituting averaged γ and $q_{1500\text{MHz}}$ obtained from our sample galaxies into Equation 4.6 yields the following equation:

$$\text{SFR}_{\text{Radio}, 150\text{MHz}} = (1.03 \pm 0.27) \times 10^{-29} \times \left(\frac{L_{\text{Radio}, 150\text{MHz}}}{\text{erg s}^{-1}} \right) \quad (6.1)$$

where we substitute the median values of $\gamma = -0.63$, $q_{1500\text{MHz}} = 2.48$ and $\nu = 150$ MHz into Equation 4.6.

CHAPTER 6. DISCUSSIONS

Calistro Rivera et al. [2017] have obtained the coefficient of 0.76 ± 0.08 at $z = 0$ (Equation 11) from their calibration.

We should keep our mind that the SFR calibration has non-negligible uncertainty, possibly caused by the galaxy selection and the variety of q_ν at low frequencies. We need the radio spectral with multi-band observation for estimating SFR accurately.

Chapter 7

Summary

In this study, we investigate 18 star-forming galaxies in the HRS catalog for their global relation of the low-frequency radio with IR luminosities. We find a single power-law assumption for the frequency dependence of q_ν is valid across MWA frequencies and 1.5 GHz, and their slope γ is consistent with previous studies. We also investigate the consistency of the radio SFR expected to be an extinction-free indicator. Our sample shows that the spectral information for each galaxy is needed to estimate its SFR accurately because of a wide variety of q_ν . These results suggest that future observation with several radio bands is required at low frequencies for measuring accurate SFRs.

For further understanding of the low-frequency properties in star-forming galaxies, we need more samples from multi-band observation. The updated GLEAM survey will reveal physical details with an order of magnitude better angular-resolution and sensitivity than the latest survey.

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Appendix A

Galaxy images

A.1 Matched samples (18 samples used for the analysis)

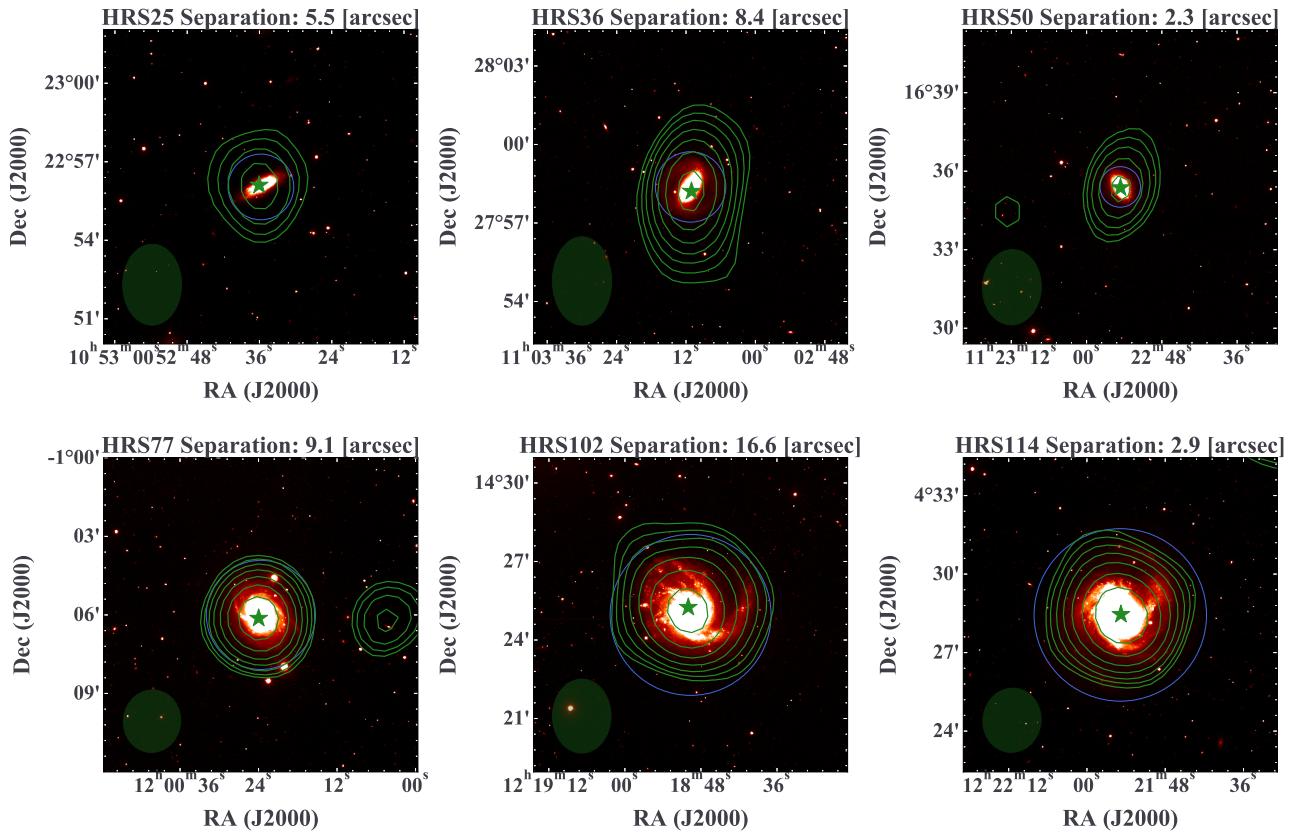


Figure A.1: These are the SDSS [Abolfathi et al., 2018] i-band images with radio contours from the GLEAM survey at 170 – 231 MHz (solid green lines). These galaxies are selected in Section 4.1 and 4.2. I draw the green contours started from the 3σ local noise and increase by a factor of the square root of n (“n” is an integer). The green star marker shows the location of a radio source referred to as the GLEAM catalog. The size of this marker does not mean any feature of observations. The blue circle shows the isophotal optical size at 25 mag arcsec $^{-2}$ from Boselli et al. [2010]. On the bottom left in each plot, we show the beam size of the GLEAM survey.

APPENDIX A. GALAXY IMAGES

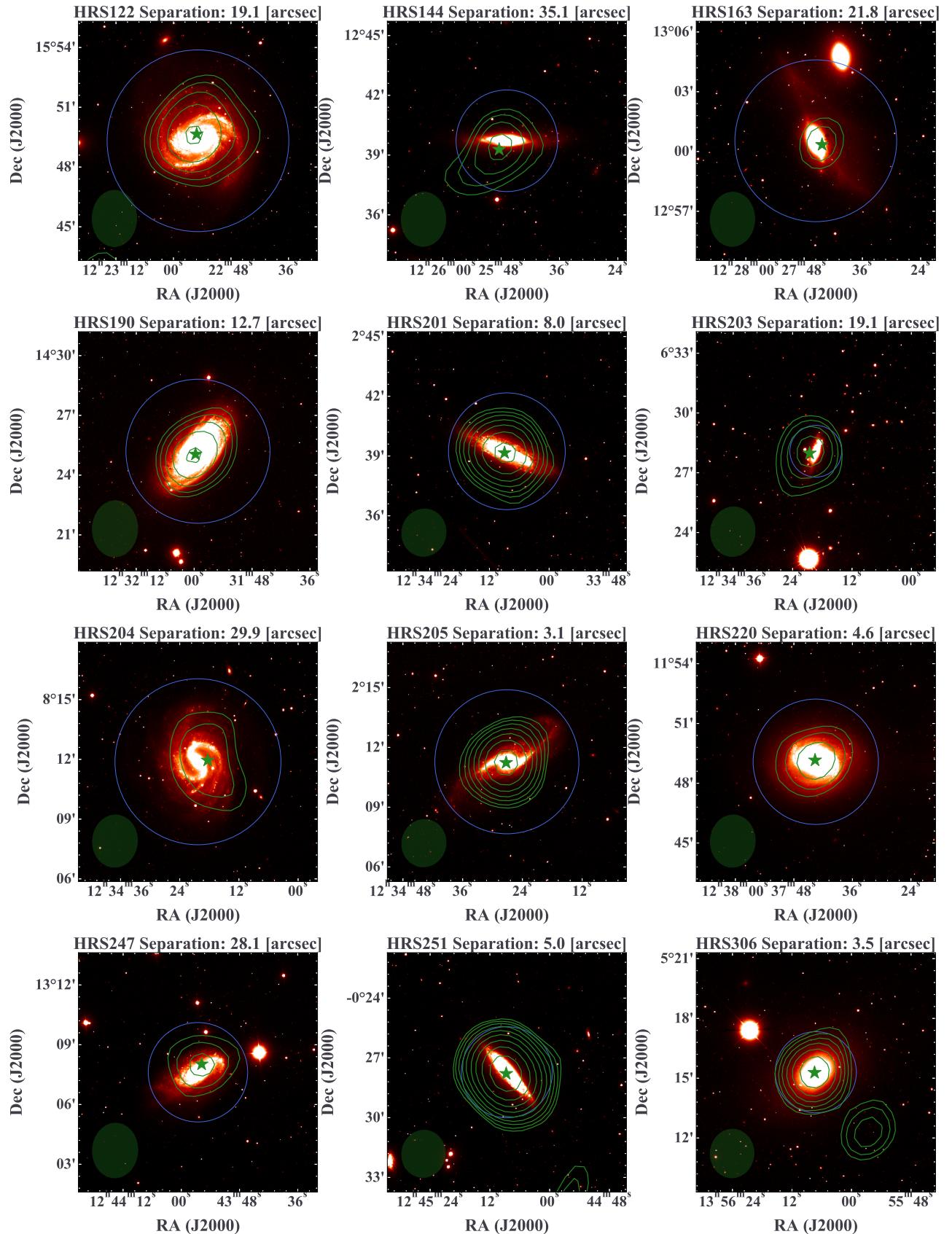


Figure A.2: Continuous.

A.2 Matched samples (not used for the analysis)

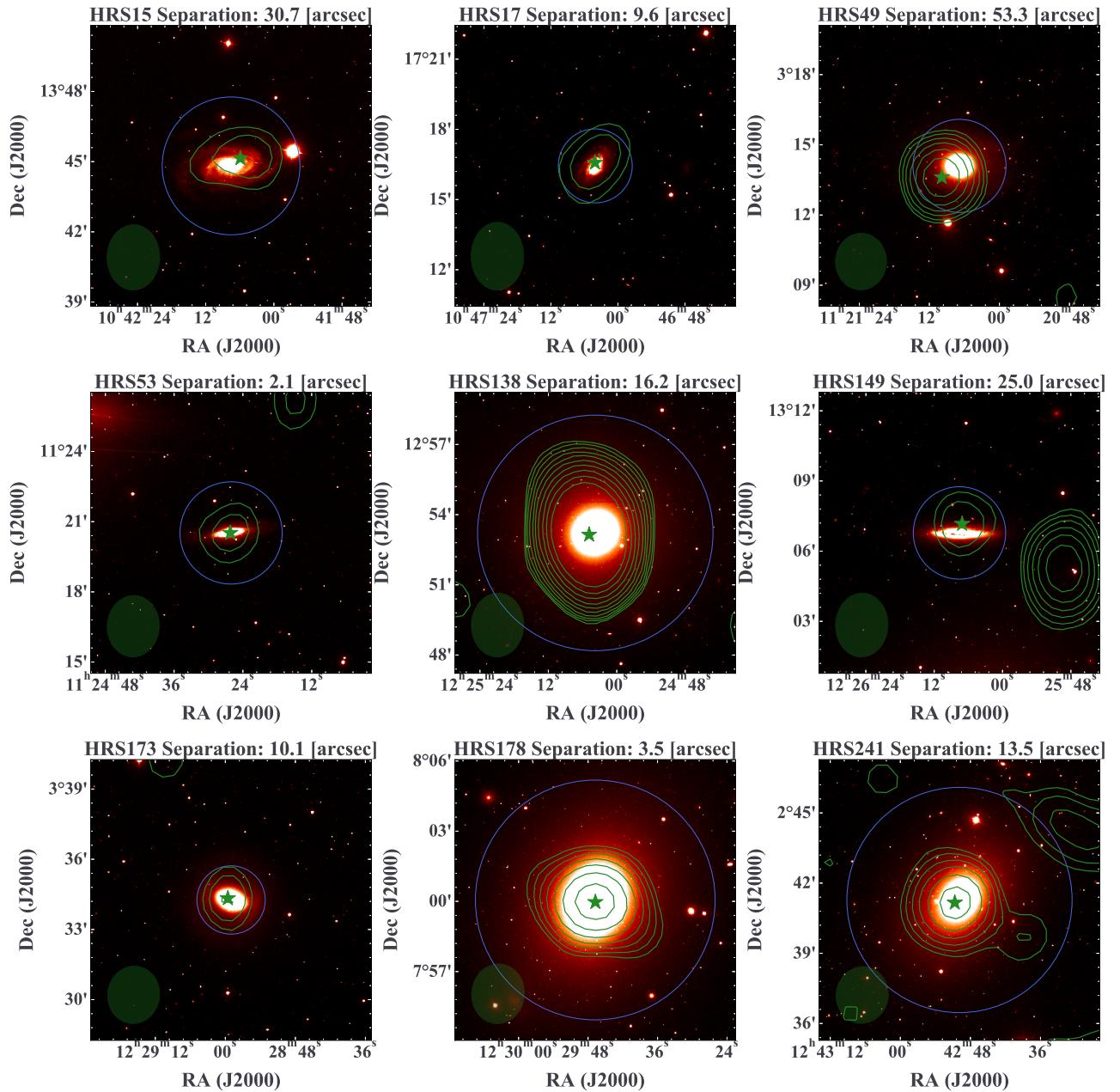


Figure A.3: These galaxies are not used for the analysis labeled in Section 4.2 although they have a radio counterpart in the GLEAM catalog by the cross-matching.