

A DOCTORAL THESIS

PANCHROMATIC SPECTRAL ENERGY
DISTRIBUTION MODELING OF INFRARED
BRIGHT GALAXIES

by

mgr SUBHRATA DEY

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Supervisors

prof. dr hab. Michał Ostrowski
dr hab. Arti Goyal

Abstract

The field of galaxy formation and evolution has undergone a revolutionary transformation over the past two decades, facilitated by abundant data collected from multiwavelength photometric and spectroscopic surveys. These observations play a crucial role in understanding the star formation history of the Universe, determining the redshift of the first proto-galaxies, and tracing the evolutionary processes of small components into the massive galaxies observed today.

These evolutionary processes leave an imprint on the global and detailed shape of the spectrum, each dominating at different wavelengths. The emission from galaxies in γ -rays to radio wavelength is the outcome of the complex physical interplay between their main baryonic components: stars of all ages and their remnants; molecular, atomic, and ionized gas; dust; and supermassive black holes. A comprehensive approach to panchromatic spectral energy distribution (SED), hence modeling, is an essential tool to advance our understanding of galaxy evolution.

In this thesis, we have focused on bridging the gap between ultraviolet (UV)-infrared (IR) and radio-only SED modeling for galaxies, which traditionally have been pursued independently. By simultaneously incorporating these two regimes, we captured the interconnectedness of the underlying physical processes and gained a more holistic understanding of galaxy evolution. In addition, we performed radio-only SED modeling using densely sampled radio SEDs. Most existing models have primarily focused on frequencies above 1.4 GHz, neglecting the valuable information available at lower frequencies or involving simple physical models with few free parameters. To address this, we incorporate a physically motivated approach into our SED modeling. This approach takes into account the absorption processes at low frequencies along with the complex nature of the radio continuum, considering scenarios where the emission originates from one or two distinct regions characterized by populations of cosmic-ray electrons and varying optical depths.

In our study, SED modeling is performed for infrared bright galaxies, namely, Luminous and Ultra-luminous Infrared Galaxies (U/LIRGs). They are extreme star-forming galaxies, triggered primarily by interactions and mergers between gas-rich galaxies. They play a crucial role, particularly at higher redshifts. U/LIRGs are the primary contributors to the co-moving star formation rate density (SFRD) of the Universe at $z > 1$, making them extremely important sources for studying galaxy formation and evolution.

Further, the bulk infrared emission in these galaxies is due to warm dust heated by active galactic nuclei (AGN), starbursts due to major mergers, or both. This correlates well with the widely accepted evolutionary picture, which places U/LIRGs at a fixed stage in the evolutionary sequence between the transformation of gas-rich galaxies and red-dead elliptical ones. Therefore, they provide excellent nearby laboratories for studying in detail the physical processes associated with the hierarchical transformation of star-forming galaxies into elliptical galaxies. Detailed SED modeling of nearby U/LIRGs are, therefore, important for gaining a better understanding of baryonic processes and developing and testing models can be used to explain statistical studies based on large populations of such galaxies at high redshift.

The thesis presents a detailed analysis of a sample of 11 nearby LIRGs ($z < 0.04$) and 14 nearby ULIRGs ($z < 0.5$). The spectral analysis spans a broad range of wavelengths, from UV through IR to radio frequencies. For UV-IR-radio SED modeling, we used data in 20-30 bands from different ground- and space-based observing facilities in public archives. Moreover, for radio-only SED modeling, we gathered data from archives, including our dedicated GMRT observations and reanalysis of the archival VLA data for a few galaxies. Specifically, we employed the Code Investigating GALaxy Emission (CIGALE) SED fitting tool for UV-IR-radio SED modeling. Since CIGALE only considers the power-law form for the radio SED model, we developed a radio-only SED modeling code to integrate the low-frequency bending as well as the complex forms of the SEDs. We perform radio SED modeling using densely sampled SEDs in a frequency range $\sim 50\text{MHz}$ – 20GHz using the state-of-the-art *UltraNest* package, leveraging its nested sampling algorithm.

For the 11 nearby LIRGs, radio SEDs include our dedicated observations with the GMRT at 325 and 610 MHz alongside publicly available data. Key findings include that the synchrotron spectral indices show a range between -0.5 and -1.7 with the identification of turnovers and bends in the radio SEDs. The turnovers are attributed to free-free absorption, ruling out synchrotron self-absorption (SSA) or the Tsytovitch-Razin effect because the estimated cut-off frequencies for these processes are much lower than the observed one for the typical surface brightness, magnetic field strengths, and electron densities exhibited by our galaxies.

Results from CIGALE analysis reveal properties consistent with galaxies of similar classes, such as infrared luminosity, dust mass, SFRs, stellar mass, dust temperature, and AGN fraction. Our radio-only SED modeling enabled us to decompose the total radio emission into thermal and nonthermal radio components, respectively. Following the SFR calibration relation presented in [Murphy et al. \(2011\)](#), we calculated the total, nonthermal, and thermal SFRs at 1.4 GHz and compared with the SFR_{IR} obtained from SED modeling using CIGALE averaged at 10 and 100 Myrs. A positive correlation is observed between the SFR_{IR} averaged at 10 Myrs (compared to 100 Myrs ago) and the 1.4 GHz radio (total and nonthermal). This is because similar synchrotron lifetimes are expected for typical

magnetic field strengths observed in these galaxies ($\approx 50 \mu\text{G}$).

Following the LIRG study, we extended the sample to 14 nearby U/LIRGs, to study how the physical properties change with high SFR rates. Key findings include that the synchrotron spectral index ranges between ~ -0.6 and ~ -2.0 with the identification of turnovers and bends in the radio SEDs. We note that five ULIRGs in our sample are known to host gigahertz peaked spectrum (GPS)-type AGN and exhibit bent spectra. However, the estimated surface brightness for these galaxies falls within the range $\approx 0.001\text{--}500$, corresponding to cutoff frequencies ranging from $0.11\text{ MHz--}60\text{ MHz}$ for the turnovers to be attributed to SSA. The Tsytovitch-Razin effect was also ruled out, as the calculated turnover frequency didn't match the observed one for the typical electron plasma density.

Moreover, we discuss the global astrophysical properties for a sample of 25 starburst galaxies, combining the SED modeling results of 11 LIRGs and 14 ULIRGs. Key findings are: 1) radio spectra are frequently characterized by bends and turnovers, with no indication of ULIRGs exhibiting more complicated SEDs than LIRGs despite showing more signs of interactions; 2) including radio measurements in UV-radio SED modeling using CIGALE constrained the dust luminosity and SFR estimates by more than one order of magnitude better than previously reported for starburst galaxies; 3) we show that total and nonthermal radio luminosity at 1.4 and 4.8 GHz frequencies can be good estimators of the recent SFR for all LIRGs and those ULIRGs with insignificant AGN influence; 4) a weaker but still significant correlation is observed between radio SFR at 1.4 GHz and old (averaged over 100 Myr) SFR based on SED modeling, indicative of multiple episodes of starburst activity during their lifetime; 5) the thermal radio luminosity at 4.8 GHz is a better tracer of recent star formation than at 1.4 GHz ; 6) we see that the bolometric AGN fraction does not depend on the optical morphological class, consistent with those found in literature; 7) we studied the correlation between the modeled nonthermal radio spectral indices with galaxy properties such as redshift, stellar mass, SFR, specific SFR, and dust mass. We found that they are not statistically significantly correlated.

The findings presented in the thesis are unique in the sense that no other study has performed SED modeling across such an extensive frequency range encompassing the UV, IR, and radio domains. It highlights the advantage of extending UV-IR SED fitting techniques to radio frequencies, especially as we transition into an era where FIR surveys remain constrained and radio data become increasingly abundant, exemplified by initiatives such as the Square Kilometer Array (SKA) and its precursors.

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*my parents, teachers, friends, for their unconditional support
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List of Publications

The results described in this thesis are published in the following two papers:

1. **Subhrata Dey**, Arti Goyal, Katarzyna Małek, Timothy J. Galvin, Nicholas Seymour, Tanio Díaz Santos, Julia Piotrowska, Vassilis Charmandaris.
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2022, The Astrophysical Journal, Volume 938, id.152, 31 pp. [arXiv: 2207.08929](#)
2. **Subhrata Dey**, Arti Goyal, Katarzyna Małek, Tanio Díaz-Santos.
Radio-only and Radio-to-far-ultraviolet Spectral Energy Distribution Modeling of 14 ULIRGs: Insights into the Global Properties of Infrared Bright Galaxies,
2024, The Astrophysical Journal, Volume 966, id.61, 31 pp. [arXiv: 2402.10786](#)

Declaration

I hereby confirm that this thesis was written solely by me and has not been submitted for any other degree or professional qualification, unless otherwise specified. Chapters 5 and 6 are based on work published in Dey et al. (2022) and Dey et al. (2024). Throughout the thesis, the use of ‘we’ indicates that the research was conducted under the guidance of my supervisor and with the collaboration of others. However, all the work presented in this thesis originates from papers where I am listed as the primary author.

“The world is full of magic things, patiently waiting for our senses to grow sharper.” -WB Yeats

1

Introduction

1.1 Building blocks of observable Universe

Within the Λ CDM cosmology paradigm, galaxy formation arises from fluctuations in density during the early universe (Dodelson, 2003; Springel et al., 2005). These fluctuations acted as seeds for matter aggregation under gravity’s influence. Despite the coexistence of both baryonic (normal) and non-baryonic dark matter during this epoch, their immediate condensation was hindered by intense thermal pressure. However, dark matter, unaffected by pressure, gradually collapsed into massive, gravitationally bound structures called haloes through gravitational instabilities.

These dark matter haloes provided the framework for galaxy assembly. As the universe continued to cool, hydrogen gas, the predominant form of baryonic matter, filled these haloes. Under the relentless force of gravity, the gas underwent further condensation, eventually collapsing into dense clouds rich in atomic and molecular hydrogen. Within these collapsing clouds, increasing densities and temperatures sparked the ignition of first stars through nuclear fusion. These first-generation stars, accompanied by surrounding gas and dust, laid the foundation for the earliest galaxies, termed proto-galaxies (Couchman and Rees, 1986; Tsuribe and Inutsuka, 2001).

Following these early phases, formation and evolution of galaxies depends on the local conditions along with properties of gas and interaction/merging with other systems. Proto-galaxies evolved over time by accretion of dark matter from the surrounding cosmic web, a vast structure of filaments and voids. Further, gravitational interactions and mergers with neighbouring galaxies, formation of new stars led to increase of their mass.

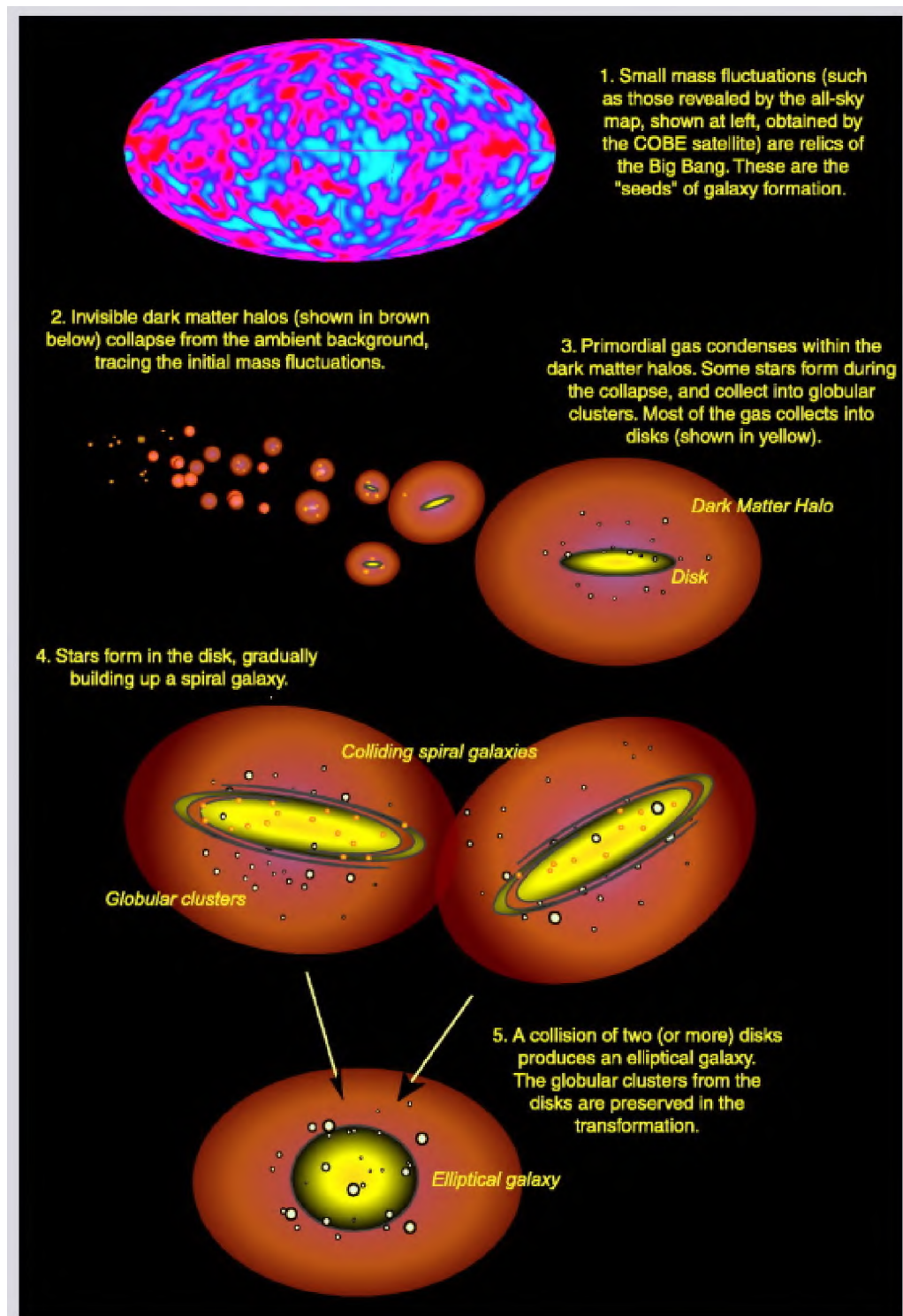


FIGURE 1.1: Schematic illustration of the formation of galaxies in the hierarchical formation model. Image credit: [Abraham and van den Bergh \(2001\)](#).

Eventually formation and evolution of galaxies involve interplay of physical processes between baryonic components (gas, star and dust) of galaxies along with their kinematics, evolution within the expanding universe and gravitational interaction with dark matter. All these processes collectively sculpted the features and diversity of the galaxies observed today, including our own Milky Way. Figure 1.1 shows the schematic illustration of the hierarchical formation model of galaxies.

A fraction of galaxies in the present-day universe exhibit phenomena within their nuclear regions that defy explanation through normal stellar activity. These enigmatic systems are termed “*Active galactic nuclei*” (AGNs). They are associated with the accretion of matter by the central super massive blackhole (SMBH) and also with subsequent feedback processes on the surrounding environment. AGNs within the local universe are recognized to grow by accreting gas, dust, and stars from their vicinity. This process is believed to occur through an accretion disk in which dissipative mechanisms transport matter inward while expelling angular momentum outward (Shlosman et al., 1990). As the accretion disk heats up, it emits radiation across the electromagnetic spectrum and, in certain cases, instigates the formation of twin jets composed of highly collimated, rapid outflows emanating in opposite directions from the disk (Rees, 1984; Blandford et al., 2019). AGNs are detectable across the entire electromagnetic spectrum, ranging from gamma-ray to radio wavelengths, and during their most active phases, they can outshine their host galaxies (Padovani et al., 2017), posing challenges in the retrieval of galaxy properties.

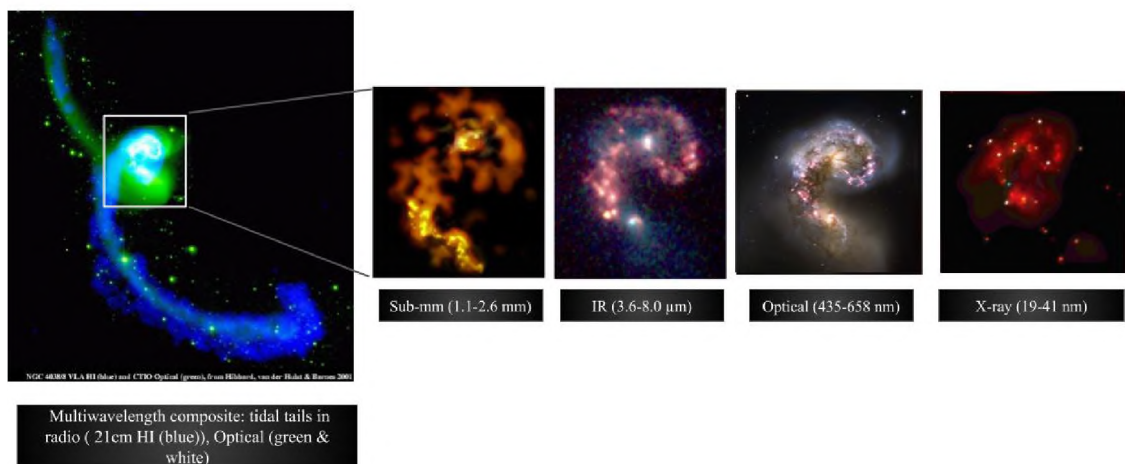


FIGURE 1.2: Multiwavelength radio to X-ray emission of Antennae Galaxies (NGC 4038/NGC 4039). Credit: Radio 21cm HI (blue) from VLA C+D array observations (Hildner et al., 2001); Sub-mm from ALMA (ESO/NAOJ/NRAO); IR from Spitzer (NASA/JPL-Caltech/Z. Wang); Optical from VLT (ESO/A. Milani); X-ray from Chandra X-ray observatory (NASA/SAO/CXC/Fabbiano et al. (2003)).

Multiwavelength observations are crucial for unraveling the complexities of galaxy physics. Galaxies emit light across the electromagnetic spectrum, reflecting a complex interplay of various physical processes occurring across different spatial scales. Single-wavelength observations inherently possess biases, as each wavelength preferentially traces specific galactic features, as can be seen in the Figure. 1.2 of interacting Antennae Galaxies (NGC 4038/NGC 4039) across the electromagnetic wavelength. For example, sub-mm unveils dense, cold gas clouds, the sites of nascent stars; optical view reveals blue-hot young stars and pink-hued hydrogen gas, while radio observations depict older stars and gaseous components. IR imagery highlights dust clouds heated by stars, and X-ray imagery showcases hot interstellar gas infused with elements from supernova explosions. Additionally, faint emission from certain galaxy populations at particular redshifts might go undetected at specific wavelengths. This sequence offers a comprehensive insight into galactic dynamics, transitioning seamlessly from radio to submillimeter, infrared, optical, and X-ray regimes. Therefore, a multiwavelength approach provides a complete picture of the underlying physical processes occurring in galaxies.

1.2 Panchromatic nature of galaxies and AGN

A comprehensive understanding of the electromagnetic spectrum emitted by galaxies is facilitated through the analysis of their spectral energy distribution (SED). This distribution portrays the energy spread across various frequencies or wavelengths, typically derived from broadband photometric observations spanning the spectrum. Within the SED lie intricate signatures of all physical processes contributing to a galaxy's radiative output, including emissions from its galactic nuclei and other components (see Figure 1.3).

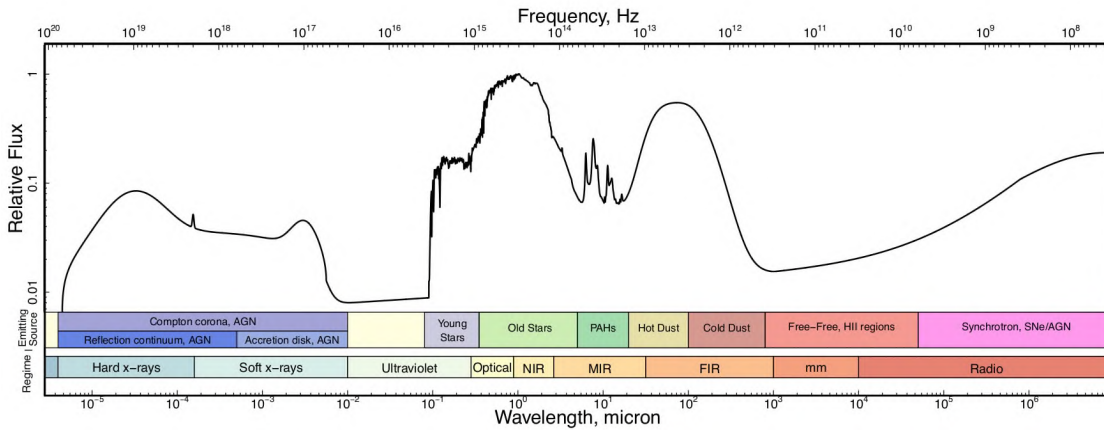


FIGURE 1.3: SED of a mock galaxy emphasizing key physical observables across various wavelength ranges. The dominant emitting sources for each wavelength regime are listed below the SED. Adapted from a graphic made by Luke J. M. Davies.

1.2.1 X-ray emission

The X-ray emission from galaxies is primarily produced by high-energy phenomena and processes including accretion powered object such as AGN, low- and high-mass X-ray binaries. The contributions from fainter discrete sources (including cataclysmic variables, active binaries, young stellar objects, and supernova remnants) are well-correlated with the star formation rate or stellar mass of galaxies. For example, spiral galaxies exhibit a range of $\sim 10^{38} - 10^{42} \text{ erg s}^{-1}$ in the $0.2 - 3.5 \text{ keV}$ spectral range, starburst galaxies emits a much high value of $\geq 10^{41} \text{ erg s}^{-1}$ in the $0.5 - 10 \text{ keV}$ band. Elliptical galaxies fall somewhere in between, with their X-ray luminosity ranging from 10^{40} to $10^{43} \text{ erg s}^{-1}$ (Mathews and Brighenti, 2003). The dominance of low-mass X-ray binaries in elliptical galaxies is a relic of their previous star-formation activity (Zezas and Buat, 2021). AGNs are characterized by intense emission across the electromagnetic spectrum, with X-rays originating from the immediate vicinity of the SMBH, i.e., from the inner parts of accretion disks and corona. Two primary mechanisms are believed to be responsible:

1. Compton Upscattering: high-energy UV photons get upscattered to X-ray energies by thermal electrons in the corona through inverse Compton scattering ((Mushotzky et al., 1993; Reynolds and Nowak, 2003; Fabian, 2006). This mechanism contributes to the broad X-ray continuum observed in AGN spectra.

2. Accretion Disk Emission: At lower X-ray energies, the accretion disk itself may contribute directly to the X-ray emission (Turner and Miller, 2009; Done, 2010).

AGNs hosting powerful jets often exhibit pronounced X-ray continuum emission associated with these energetic outflows (Worrall, 2009). Such intrinsic X-ray emission may undergo interactions with surrounding matter in the nuclear region, leading to the production of distributed X-ray emission through processes such as Compton reflection and scattering. In instances where intrinsic X-rays are obscured, the resulting reflected or scattered emission may dominate the observed luminosity.

Unlike optical or infrared light, X-rays can pierce through dust and gas, allowing us to study the intrinsic properties of AGN even when they are obscured at other wavelengths. Additionally, AGN outshine their host galaxies in the X-ray regime, minimizing contamination from starlight and providing a clear view of the central engine. The intensity of X-ray emission is also closely linked to the rate of matter falling onto the supermassive black hole, making it a valuable tool for tracing accretion activity. Finally, the unique characteristics of X-ray emission make it highly effective in identifying AGN, especially in the distant universe, leading to more complete and reliable samples compared to selections at other wavelengths (see review by Brandt and Alexander, 2015).

1.2.2 Ultraviolet (UV), Optical and Near-Infrared (NIR) emission

The UV-Optical-NIR part of SED is shaped by the physical properties of the stellar populations comprising a galaxy. These properties include star formation history (SFH),

metal content of stars, dust distributions and the interstellar radiation. The analysis of galaxy SEDs commonly employs single stellar population (SSP) modeling which describes the time evolution of the SED of a single, coeval stellar population formed from the same gas cloud with the same metallicity and abundance pattern (Bruzual and Charlot, 2003; Conroy, 2013). The complete galaxy stellar SED is then formulated as a composite of various SSPs, each characterized stellar mass distribution function (initial mass function or IMF), isochrones, and stellar spectral libraries (see Figure 1.4).

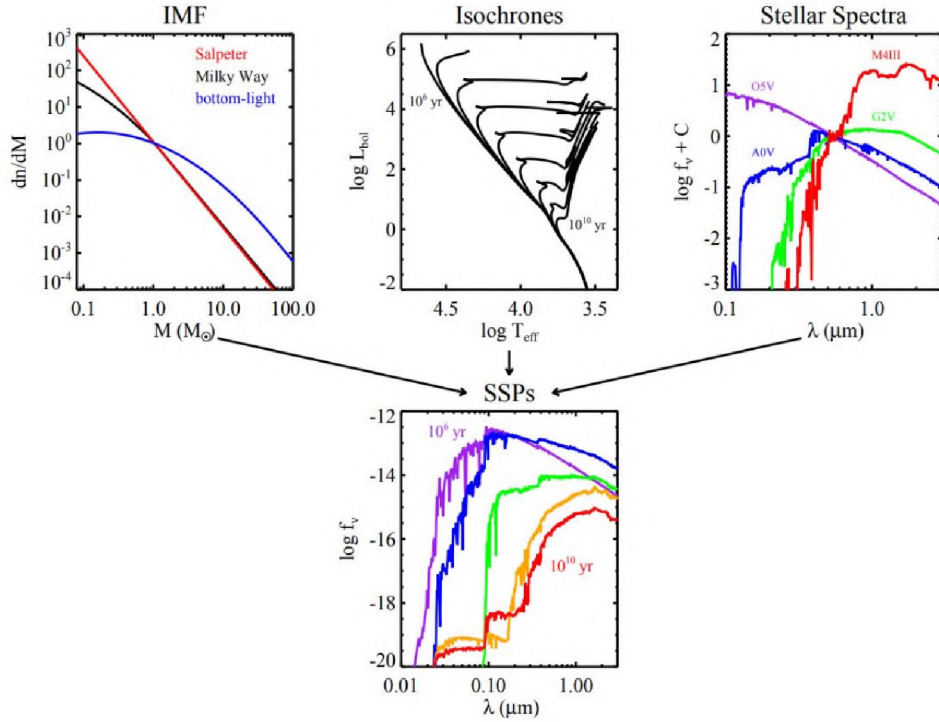


FIGURE 1.4: A schematic depicting the construction of SSPs, showcasing the essential components: the IMF, isochrones, and stellar spectral libraries. The figure is modified from the original in Conroy (2013).

When modeling galaxies, it's crucial to account for the distribution of stellar masses in newly-formed stellar populations. One way to estimate this is through an IMF. Various IMFs are used depending on the galactic environment, ranging from bottom-heavy (favoring more low-mass stars) to top-heavy (favoring more high-mass stars). Recent observations indicate that the IMF varies with metallicity and star-formation density. Commonly used IMF models include those proposed by Salpeter (1955), Kroupa (2001), and Chabrier (2003).

Star formation significantly influences the composition of the Interstellar Medium (ISM) in galaxies. Young ionizing stellar populations, emitting predominantly in the UV range. Young ionizing stellar populations emit most of their energy in the UV regime, acting as a first heating mechanism for the ISM. The production of high-energy photons

leads to the ionization of hydrogen atoms HII, indirectly tracing the star formation rate through the emission from recombined ionized gas.

Young, massive stars have short lifespans, often ending in violent supernova explosions. These events can trigger the collapse of molecular clouds, initiating further star formation and enriching the gas with metals. Approximately 10 Myr after the birth of a new stellar population, young non-ionizing stars become the dominant radiation source, emitting enough UV photons to warm their surroundings. Main sequence stars, especially intermediate and solar mass stars, eventually become the primary sources of radiation, emitting mostly in optical and NIR wavelengths. These long-lived stars act as a secondary heating mechanism for the ISM.

Dust in star-forming regions can absorb and attenuate intrinsic emission from different stellar populations, affecting the optical/UV SED. This attenuated emission is then re-emitted at infrared wavelengths. Uncertainties in correcting for dust attenuation can hamper accurate measurement of young stellar emission, impacting the effectiveness of the optical/UV SED as a star formation tracer. In contrast, the NIR portion of the SED is less affected by obscuration, resulting in more reliable estimates of stellar masses in SED-fitting exercises. However, in galaxies hosting obscured AGN, optical-NIR emission from stellar populations can be contaminated by emission from nuclear host dust, potentially overestimating stellar masses if not properly considered. The SED of obscured AGN exhibits prominent features such as the “infrared bump” at 10-20 μ m, arising from reprocessed dust emission in the torus of UV photons, and an upturn in the optical-UV known as the “big blue bump”, originating from the accretion disk of the SMBH (Elvis et al., 2012; Krawczyk et al., 2013). A widely used strategy involves fitting the SED by utilizing diverse combinations of theoretical models and empirical templates for each specific emission component (e.g., as demonstrated in da Cunha et al., 2008).

1.2.3 Mid-infrared (MIR) and Far-infrared (FIR) emission

The MIR part of the SED is characterized by the hosting of poly-cyclic aromatic hydrocarbons (PAHs) in both star-forming regions and AGN (Díaz-Santos et al., 2010; Magdis et al., 2013; Whitcomb et al., 2020). These large molecules emit prominent emission lines across the spectrum and are a significant component of the MIR emission in galaxies. PAHs are abundant in galaxies with metallicities similar to solar levels and are commonly found in star-forming regions, making them useful tracers of star formation activity. Strong peaks with complex features of PAHs usually fall around 6 - 8 μ m and 11.2 - 12.7 μ m.

In addition, AGN can emit significant portions of their energy in the MIR and NIR wavelengths, originating from the nuclear obscuring torus composed of hot gas and dust within a few parsecs (Fritz et al., 2006; Alonso-Herrero et al., 2011; Ichikawa et al., 2015). The torus is heated by the high-energy accretion disk emission. Although historically believed to be smooth in nature (Fritz et al., 2006), recent findings suggest a clumpy toroidal

structure (Stalevski et al., 2012). The morphology and orientation of this obscuring torus are crucial to the diversity of AGN. The presence or absence of broad emission lines in the optical spectra of AGN, which categorizes them into type 1 and type 2 AGN respectively, is believed to be closely related to the observer’s viewing angle to the torus – face-on or edge-on, respectively.

The FIR and sub-mm range is primarily characterized by the continuum emission from cold dust present in the interstellar medium of star-forming regions. This emission stems from dust heated by UV and optical stellar radiation, particularly by the young and short-lived population of red giant stars. Consequently, FIR emission serves as an indirect indicator of recent star formation activity and is commonly utilized as a reliable tracer of the SFR. The FIR SED exhibits thermal emission, comprised of a combination of black-body spectra at various temperatures, with their shapes governed by Planck’s law. The temperature of each black-body is influenced by factors such as the distribution of dust surrounding the heating source and the size of dust grains. Generally, smaller dust grains heat up more rapidly, emitting higher-energy thermal radiation compared to larger grains. The total SED typically exhibits a characteristic peak, indicating the mean temperature of the dust in the system, often around 30-40 K (Casey et al., 2014).

1.2.4 Radio continuum emission

While UV is a powerful tracer of SFR, it might miss an appreciable fraction of star formation at early universe due to dust attenuation. (Casey et al., 2018). IR emission from dust-reprocessed starlight overcomes the dust-obscuration problem, however, due to limited sensitivity and resolution of current IR facilities (both ground- and space-based), it is notoriously difficult to probe beyond peak of cosmic star formation (Hodge and da Cunha, 2020). In recent times, highly sensitive observations by Atacama Large Millimeter (ALMA) has enabled us to probe the higher redshifts, its limited field of view makes wide-area FIR observations quite expensive.

The radio emission is an excellent tracer of SFR as it remains unaffected by dust extinction. Observed radio emission serves as a direct probe into the star formation activity in ‘normal’ galaxies (i.e., those without an AGN), with radio luminosity directly proportional to recent SFR (Condon, 1992; Bell, 2003). Moreover, the shape of the radio SED and its slope are used to probe the radiation laws and the heating/cooling mechanism of ISM and AGN activity (e.g., Heesen et al., 2022). The radio-SEDs of galaxies are further complicated by the presence of radio-AGN where the radio emission can be due to relativistic jets or it can be from various sources including star formation, AGN-driven winds, photo-ionized gas, low-power jets, and inner accretion disc coronal activity (Panessa et al., 2019). However, radio SEDs of star-forming galaxies (at 1.4 GHz and higher frequencies) usually result from the combination of two distinct mechanisms: free-free emission and absorption, and synchrotron emission, arising from different physical processes in the galaxy.

Thus, to robustly link observed radio emission to a physical process, such as SFR or AGN mechanism, it is essential to deconstruct them into their respective components.

The synchrotron emission ($F_\nu \propto \nu^{-\alpha}$) results from an interaction of charged particles in a magnetic field that is accelerated in shocks produced by supernova remnants and therefore traces the supernova rate. It dominates radio emissions in normal galaxies at frequencies below approximately 30 GHz. Initially accelerated by supernova shocks, these electrons subsequently lose energy as they diffuse or convect through the ISM. Synchrotron and inverse-Compton energy losses at higher frequencies result in steeper spectral indices $\alpha \sim 0.8$ (Condon, 1992; Niklas et al., 1997). The rate of supernovae in galaxies is closely tied to the birth of high-mass stars, as only stars more massive than approximately $8 M_\odot$ produce the Type II and Type Ib core-collapse supernovae believed to accelerate most of the electrons in normal galaxies (Condon, 1992). The radio emission from galaxies serves as a crucial tool for measuring the SFR over timescales of approximately 10-100 Myrs, assuming a supernova rate and the IMF (Condon et al., 2002).

Thermal free-free emission ($F_\nu \propto \nu^{-0.1}$) is produced by the ionization of HII regions by UV flux from high-mass stars. It has a flatter spectra with spectral index ($\alpha \sim 0.1$) Unlike synchrotron emission, free-free emission provides a direct and near-instantaneous tracer of star formation. However, measuring thermal free-free emission in radio SEDs is complicated by the fact that low-frequency SEDs are dominated by nonthermal synchrotron emission ($\nu \lesssim 30$ GHz; Galvin et al., 2018). Furthermore, radio SEDs are further modified by free-free absorption (FFA) or synchrotron self-absorption (SSA) processes causing bends and turnovers (Clemens et al., 2010; Galvin et al., 2018; Chyży et al., 2018). Therefore, disentangling thermal emission from the total radio continuum requires model fitting using densely sampled SEDs and sophisticated modeling techniques (Clemens et al., 2008, 2010; Galvin et al., 2016, 2018; Dey et al., 2022) or high-frequency (≥ 20 GHz) radio measurements.

1.3 Epoch of extreme galaxy and black hole growth

The star-forming galaxies (SFGs) data across various redshifts allow for the mapping of star formation rate in the universe over time, quantified by the cosmic star formation rate density (cSFRD). In particular, cSFRD, derived from a recent compilation of FUV and IR data by Madau and Dickinson (2014), indicates a peak approximately 3.5 billion years after the Big Bang, around $z \approx 2$, followed by a decline of roughly 20-fold towards the present era (Hopkins et al., 2006; Madau and Dickinson, 2014). It is noteworthy that nearly half of the observable stellar mass in today's universe was formed prior to $z \sim 1.3$. This epoch of galaxy assembly represents a crucial phase of galaxy evolution, since the majority of stars in the current universe are believed to have formed during this period.

Figure 1.5 shows the comparison of the total star formation rate density estimates,

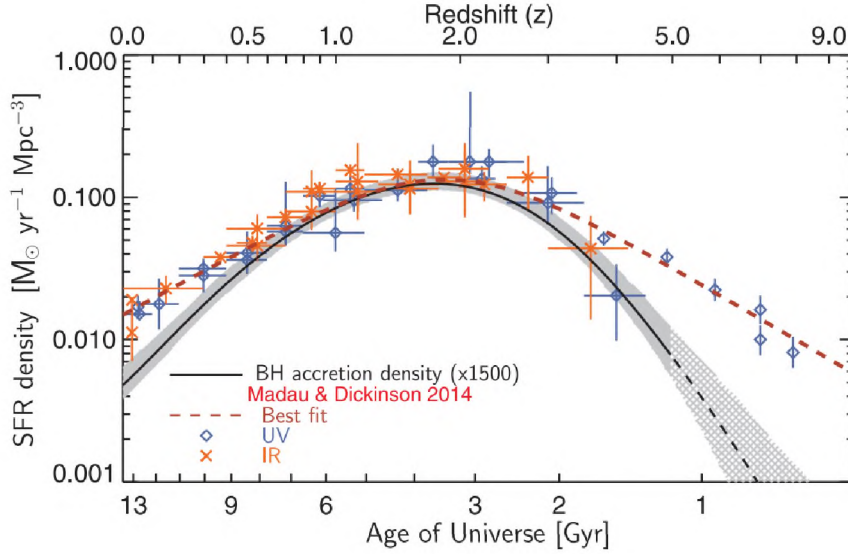


FIGURE 1.5: Comparison of total star formation rate (SFR) density with estimated total supermassive black hole (SMBH) accretion density, adapted from [Aird et al. \(2015\)](#). The dashed dark-red line represents the best-fit evolution of SFR density based on [Madau and Dickinson \(2014\)](#) data. Blue diamonds and orange crosses denote rest-frame ultraviolet and infrared observations, respectively. The solid black line indicates our SMBH accretion density estimate scaled by a factor of 1500. The Shaded regions represent 99% confidence intervals in the model parameters. Dashed black lines and grey shading denote extrapolation beyond the available data. Both galaxy and SMBH growth peak around $z \sim 2$, with SMBH accretion density showing a steeper decline towards higher redshifts.

drawn from [Madau and Dickinson \(2014\)](#), with those of SMBH accretion density, as per [Aird et al. \(2015\)](#). The latter is converted to solar masses per year per cubic megaparsec using consistent bolometric corrections and radiative efficiency assumptions ([Aird et al., 2015](#)). This data is then scaled by an additional factor of 1500. Both the cosmic star formation history and black hole evolution exhibit an evolution with respect to redshift, peaking around $z \sim 2$, before declining in earlier epochs. Furthermore, the observation that the peaks of both processes are coincidental is a strong support for the tight galaxy-blackhole co-evolution scenario, suggesting this epoch to be a good laboratory for the study of the apparent symbiotic relation between the galaxies and their nuclei.

1.4 U/LIRGs in context of galaxy evolution

When considering the breakdown of contributions to cosmic star formation by luminosity class, it becomes evident that U/LIRGs play a crucial role, particularly at higher redshifts (see Figure 1.6). ULIRGs exhibit a notable evolution in their contribution, being relatively insignificant in the present-day universe but contributing approximately 10% at $z \sim 1$ and around 50% at $z \sim 2$. Similarly, slightly less luminous LIRGs, peak in their contribution around $z \sim 1$, accounting for approximately 50% of all star formation at that epoch.

U/LIRGs are hence the primary contributors to the co-moving SFRD of the universe at $z > 1$ making them extremely interesting sources to study galaxy formation and evolution. As the name suggests, U/LIRGs are characterized by a prodigious amount of emission at infrared (IR) wavebands (IR = 8 – 1000 μm) than at all other wavelengths combined. These galaxies are classified as luminous infrared galaxies (LIRGs; $L_{\text{IR}} \lesssim 10^{11-12} L_{\odot}$) and ultra luminous infrared galaxies (ULIRGs; $L_{\text{IR}} \gtrsim 10^{12} L_{\odot}$).

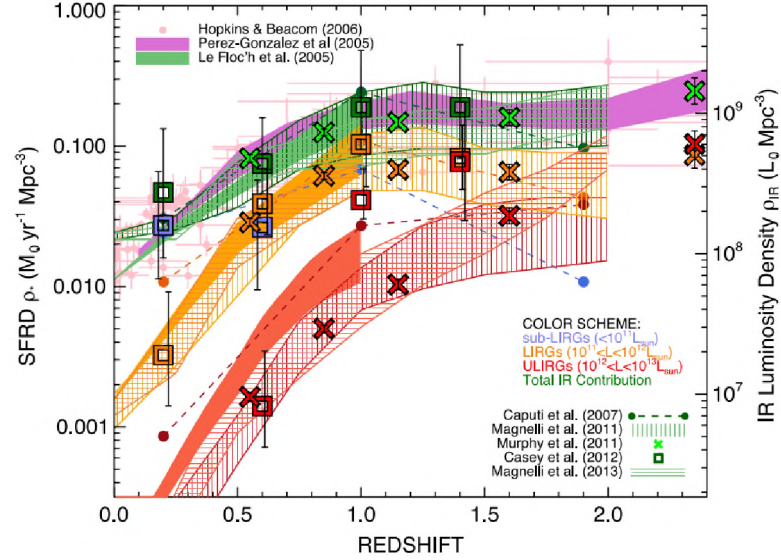


FIGURE 1.6: Estimates of the contribution of dusty star forming galaxies (DSFGs) to cosmic star formation and IR luminosity densities. IR luminosity densities are given by decade in luminosity. The overall color scheme adopted is that the total integrated infrared contribution is shown in green, the sub-LIRG population (i.e. $L_{\text{IR}} \lesssim 10^{11} L_{\odot}$) in blue, the LIRG population ($L_{\text{IR}} \lesssim 10^{11-12} L_{\odot}$) in yellow-orange, and the ULIRG population ($L_{\text{IR}} \gtrsim 10^{12} L_{\odot}$) in red. Image adapted from Casey et al. (2014).

The bulk infrared emission in these galaxies is due to warm dust heated by active galactic nuclei, starbursts due to major mergers, or both. This correlates well with the widely accepted evolutionary picture proposed by Sanders et al.; Hopkins et al. placing U/LIRGs at a fixed stage in a larger evolutionary sequence between collision of gas-rich galaxies and red-dead elliptical ones, represented in schematic diagram Figure 1.7. The collision of gas-rich disk galaxies ignites the phase of star formation by rapid compression and cooling of gas, which in turn creates a prolific amount of dust. The dust absorbs rest-frame optical and ultraviolet emission from young, blue stars and reradiates that light at infrared/submillimeter wavelengths during the U/LIRG phase (Rigopoulou et al., 1999; Lonsdale et al., 2006). Further, when the two galaxy cores and SMBHs undergo the final merging state, an AGN is formed. This AGN is fed by an accretion disk of material, further fuelled by the infall from the outer region of the galaxy merger (Hopkins et al., 2006, 2012). The U/LIRG phase is short-lived due to limited gas supply, high

star formation, and winds due to AGN feedback. However, the resultant galaxy might shine bright due to the formation of an obscured/unobscured AGN or quasar. Eventually, this system approaches a virialized state from the merger, leading to the formation of an elliptical galaxy characterized by an old stellar population and no recent formation of young stars. These evolutionary stages have been extensively studied by [Hopkins et al.](#); [Armus et al.](#); [Spoon et al.](#); [hoon Kim et al.](#); [Hayward et al.](#) and others.

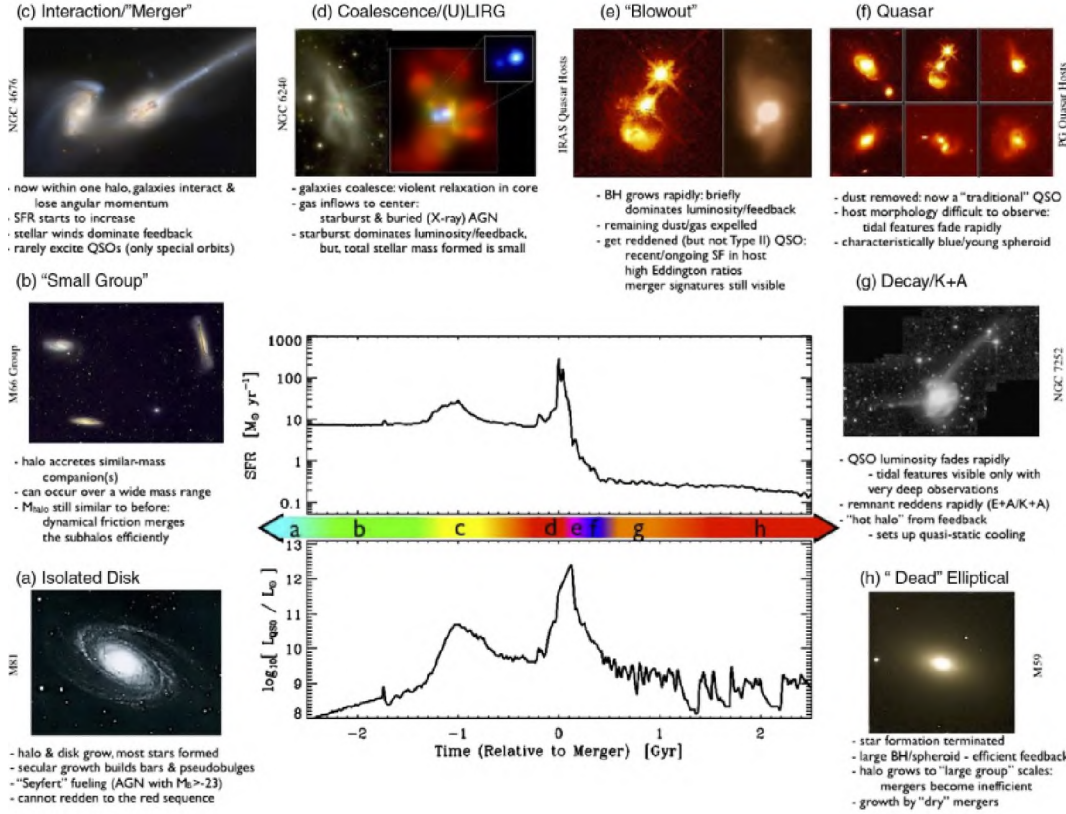


FIGURE 1.7: A schematic diagram of the evolution of a galaxy undergoing a major merger of gas-rich disks during its lifetime. Image adapted from [Hopkins et al. \(2008\)](#).

Nearby U/LIRGs offer unique laboratories allowing multiwavelength studies of the interstellar medium, star formation, and nuclear activity across a broad range of physical conditions. Hence, detailed studies of individual local U/LIRGs are crucial for gaining a better understanding of these processes and for developing and testing models that explain statistical studies of large populations of such galaxies at high redshift for which it is currently impossible to reach a sufficient physical resolution.

1.5 Thesis objectives and outline

This thesis presents the most detailed updated studies on the panchromatic emission of a sample of infrared bright galaxies in our local Universe. Using state-of-the-art statistical methods, this thesis builds upon the current knowledge presented above to expand the parameter space covered by current multiwavelength studies. The remainder of this thesis consists of the following chapters.

2. Data

In Chapter 2, we present details of UV-FIR and radio photometric data that we obtained from our dedicated observations as well as public archives of several ground- and space-based telescopes.

3. Radio-only SED modeling

In Chapter 3, we present the details of the radio-only SED modeling considered in our analysis. We discuss the details of the state-of-the-art SED modeling code we developed using *UltraneSt Package*.

4. UV-IR-Radio SED modeling with CIGALE

In Chapter 4, we present the details of open-source Code Investigating GALaxy Emission (CIGALE)¹ SED modeling tool that we used for our UV-IR-Radio SED.

5. Low-frequency radio continuum imaging and SED modeling of 11 LIRGs: radio-only and FUV to radio bands

In Chapter 5, we present the results of a detailed analysis of a sample of 11 LIRGs. This includes radio-only and UV-IR-radio SED modeling. We employ the CIGALE SED fitting code to model the UV-IR-radio SED. For the radio-only SED modeling, we use the UltraNest package, leveraging its nested sampling algorithm. We compared the results obtained from the UV-IR-radio SED modeling using CIGALE with that for the same class of galaxies in the literature for the sanity check of the analysis methods used by us. Furthermore, benefiting from the decomposition of radio SEDs into thermal and nonthermal components, we obtained the respective SFRs at 1.4 GHz using the calibration relations presented in [Murphy et al. \(2011\)](#). These radio SFRs estimates at 1.4 GHz were compared with infrared SFRs (SFR_{IR}) averaged over the last 10 and 100 Myr, respectively, from the CIGALE analysis. The results presented in this chapter are published in [Dey et al. \(2022\)](#).

6. Radio-only and Radio to far-ultraviolet Spectral Energy Distribution Modeling of 14 ULIRGs: Insights into the Global Properties of Infrared Bright Galaxies

In Chapter 6, we extend our approach to simultaneously model UV-IR-radio SEDs

¹<https://cigale.lam.fr/>

using CIGALE and densely sampled radio SEDs ($\sim 54\text{ MHz} - 30\text{ GHz}$) to a sample of 14 ULIRGs. We study the astrophysical properties of individual ULIRGs obtained from SED modeling. Moreover, by combining results from our previous study on 11 LIRGs in [Dey et al. \(2022\)](#), we discuss the global astrophysical properties for a total sample of 25 starburst galaxies ($z < 0.5$). The results presented in this chapter are published in [Dey et al. \(2024\)](#).

7. Summary and future prospects

We conclude with Chapter 7 providing a summary of the key scientific insights gained from Chapters 5 and 6. We outline the relevance of these findings to current and upcoming telescope facilities and outline the future research directions.

This chapter originally appeared in the *Multiwavelength Data Sets: Radio to FUV* section of two publications:

“Low-frequency Radio Continuum Imaging and SED Modeling of 11 LIRGs: Radio-only and FUV to Radio Bands” **Subhrata Dey, Arti Goyal, Katarzyna Małek, Timothy J Galvin, Nicholas Seymour, Tanio Díaz-Santos, Julia Piotrowska, Vassilis Charmandaris**; 2022, *The Astrophysical Journal*, Volume 938, Issue 2, id.152, 31 pp. (Dey et al., 2022).

“Radio-only and Radio to far-ultraviolet Spectral Energy Distribution Modeling of 14 ULIRGs: Insights into the Global Properties of Infrared Bright Galaxies” by **Subhrata Dey, Arti Goyal, Katarzyna Małek, Tanio Díaz-Santos**; 2024, *The Astrophysical Journal*, Volume 966, Issue 1, id.61, 31 pp. (Dey et al., 2024).

2

Data

In this chapter, we present the details of multiwavelength ancillary photometric data sourced from public archives of various ground- and space-based telescopes. Further, we outline the specifics of the data obtained through our dedicated observations utilizing the Giant Metrewave Radio Telescope (GMRT) for our sample of LIRGs. Moreover, we present details of the reanalysis of archival data obtained from the Karl G. Jansky Very Large Array (VLA) telescope for our selected sample of LIRGs and ULIRGs. Our data compilation spans across the panchromatic waveband, including UV, optical, IR, and radio frequencies. However, for SED modeling, emphasis is placed on two primary spectral windows: radio-only (see Section 2.1) and UV-optical-IR-radio (see Section 2.2). Additionally, Chapter 5 and Chapter 6 provide the details of the specific datasets utilized for individual galaxies within our study.

2.1 Radio waveband

To construct the integrated radio SED for modeling, we utilized data spanning ~ 50 MHz to ~ 30 GHz frequency range. We obtained dedicated continuum observations at 325 and 610 MHz conducted for our sample of LIRGs using the GMRT¹ (Proposal ID: 23_051, PI: Arti Goyal). Further, we also reanalyzed the high-frequency radio continuum datasets for our sample of LIRGs and ULIRGs at 4.8, 8.4, and 14.5 GHz from the publicly available archives of (VLA²), operated by the National Radio Astronomical Observatory, USA.

¹<http://www.gmrt.ncra.tifr.res.in/>

²<https://public.nrao.edu/telescopes/vla/>

Further details on observations and analysis are provided below.

2.1.1 New GMRT data at 325 and 610 MHz

We performed radio continuum imaging of our sample of LIRGs using the GMRT at 325 MHz and 610 MHz. The primary and phase calibrators used in our observations are provided in Table A1. We observed each target with 32 MHz bandwidth divided into 256 spectral channels. We observed standard flux calibrators at the beginning and end of the observation to calibrate the antenna gains. Phase calibrators were selected from the NRAO VLA calibrator manual list and were within 20 deg. Phase calibrators were observed every 30 minutes for a typical duration of 4-5 minutes to correct for antenna gain drifts, atmospheric and ionospheric gain, and phase variations. Each source was observed for a total duration of 32 minutes in two scans consisting of 16 minutes each to enable better U-V coverage.

2.1.2 Archival VLA data at 1.4, 4.8, 8.4, and 14.9 GHz

We analyzed the archival VLA data for our sample of LIRGs and ULIRGs where possible. Most galaxies in our sample were observed for a few minutes of integration time with different array configurations and different central frequencies. The dataset with the largest on-source integration time was reduced when several observations were made with the same configuration and central frequency.

2.1.3 AIPS analysis

The interferometric observations from both the GMRT and the VLA were analyzed using NRAO AIPS³. Data reduction was carried out in a standard fashion. The flux density scale of Baars et al. (1977) was used to obtain the flux densities of the primary (flux) calibrator, the secondary (phase) calibrator, and the target source. Antennas and baselines affected with strong radio frequency interference (RFI) and non-working antennas were removed after visual inspection. For the GMRT datasets, bandpass calibration was determined using the phase calibrator, and the spectral channels were collapsed to generate the continuum database. Usually, spectral channels below ten and above 200 were discarded before collapsing the data. Images were produced using task IMAGR on the channel collapsed data. To correct for distortions in the imaging, the large field of view with noncoplanar baselines (GMRT at frequencies <1 GHz), polyhedron imaging was employed where the field of view was divided into smaller fields (facets). These were 5×5 facets that covered the entire field of view up to the half power beam width (HPBW). Usually, 3-5 rounds of phase-based self-calibration were performed iteratively by choosing point

³The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under a cooperative agreement by Associated Universities, Inc.

sources in the field such that the flux density is $>3\sigma$ with one synthesized beam. The final images were made with full UV -coverage and robust weighting of 0 to weight the UV data (Briggs, 1995). Facets were combined using the task FLATN. The same steps were followed for the VLA observations, except that the data were obtained in two intermediate frequency (IF) channels calibrated for antenna gains before averaging them together for imaging. We did not apply bandpass calibration since the data were obtained in a single spectral channel of 50 MHz bandwidth (BW). The final images were corrected for the reduction in sensitivity due to the shape of the antenna beam using task PBCOR with the specified parameters for the GMRT⁴ and the VLA⁵.

Integrated flux densities (and uncertainty) were obtained using the task TVSTAT in AIPS for the GMRT and VLA images. We note that the synthesized beam sizes range from ~ 0.6 – $38''$. Assuming a typical resolution of $5''$, the linear scale is be 0.5–4 kpc at the galaxy distance ($z = 0.007$ – 0.048). Therefore, it is reasonable to state that we obtain emissions from extended regions in most galaxies.

2.1.4 Radio fluxes from the literature

In order to construct dense radio SEDs for the selected targets, we further searched for flux measurements in the literature. This section provides a comprehensive overview of the archival radio data used in our studies.

- LOFAR LBS Sky Survey II (LoLSS): 54 MHz.
- VLA Low-Frequency Sky Survey (VLSSr): 74 MHz.
- GaLactic and Extragalactic MWA Survey (GLEAM): 74 - 231 MHz.
- LOw-Frequency ARray Two-metre Sky Survey (LoTSS) data release 2: 150 MHz.
- TIFR GMRT Sky Survey (TGSS) alternate data release 1 (TGSS ADR1): 150 MHz.
- Westerbork Northern Sky Survey (WENSS): 327 MHz
- Westerbork In the Southern Hemisphere (WISH): 352 MHz.
- Texas survey: 365 MHz.
- Molonglo Reference Catalog (MRC): 408 MHz.
- Sydney University Molonglo Sky Survey (SUMSS): 843 MHz.
- Rapid ASKAP Continuum Survey (RACS): 889 MHz.
- NRAO VLA Sky Survey (NVSS): 1. 4 GHz.

⁴<http://www.ncra.tifr.res.in:8081/~ngk/primarybeam/beam.html>

⁵<http://www.aips.nrao.edu/cgi-bin/ZXHLP2.PL?PBCOR>

- VLA Sky Survey (VLASS): 3 GHz.
- ATCA: 2.1 - 5.5 GHz.
- VLA: 1.4, 4.85, 8.4, 15.0, 32.5 GHz
- Toruń 32-m telescope: 32 GHz

For radio SED modeling, we further upscaled the errors to account for variations in uncalibrated system temperature. In particular, we added in quadrature to the flux density errors an additional calibration error (see Eq. 1 of Żywucka et al., 2014): 6% for LoLLS (de Gasperin et al., 2023), 5% for VLSSr (Cohen et al., 2007), 10% for 150 MHz TGSS ADR1 (Intema et al., 2017), 10% for 150 MHz LoTSS (Shimwell et al., 2022), 5% for 325 and 610 MHz GMRT (Żywucka et al., 2014; Mhlahlo and Jamrozy, 2021), 5% for 327 MHz WENSS (Hardcastle et al., 2016), 13% for 352 MHz WISH (De Breuck et al., 2002), 365 MHz Texas survey (Douglas et al., 1996), 5% for 1.28 GHz data from Nandi et al. (2021), 10% for ASKAP (Hale et al., 2021), 3% for 1.4, 4.8, 8.4, 14.9, and 32.5 GHz VLA (Perley and Butler, 2017), 3% for NVSS (Condon et al., 1998), 10% for VLASS (Lacy et al., 2020), 10% for GLEAM (Mhlahlo and Jamrozy, 2021), 5% for SUMSS (Mauch et al., 2003; Galvin et al., 2018), 15% for Effelsberg measurements (Impellizzeri et al., 2008), 10% for S-PASS (Meyers et al., 2017), and 5% for ATCA (Galvin et al., 2018) measurements, 0.2% for 32.0 GHz (Lowe et al., 2007) measurements from Toruń 32-m telescope respectively.

TABLE 2.1: Basic information of the radio surveys used for radio-only SED modeling

Instrument	Central Frequency (MHz)	Resolution ($''$)	Sensitivity (mJy/beam)
(1)	(2)	(3)	(4)
LoLSS ^a	54	<15	<1
VLSSr ^b	74	75	0.1
GLEAM ^{c,d}	87, 118, 154, 185, 215	~100	6-10
LoTSS ^e	144	6	0.083
TGSS ADR1 ^f	150	25 × 25	<5
WENSS ^g	327	54 × 54 cosec(<i>Dec</i>)	~18
WISH ^h	352	54 × 54 cosec(<i>Dec</i>)	~18
Texas Survey ⁱ	365	30	0.5
MRC ^j	408	157 × 171.6 sec(<i>Dec</i> +35°)	0.8-1.0
SUMSS ^k	843	43 × 43 cosec(<i>Dec</i>)	~1
RACS ^l	889	~15	~0.25
NVSS ^m	1400	45	~0.45
VLASS ⁿ	3000	~2.5	~0.07

Columns: (1) name of the instrument/satellite (references for the instrument are given as superscript). ^ade Gasperin et al. (2023), ^bLane et al. (2014), ^c(Wayth et al., 2015),

^d<https://www.mwatelescope.org/science/galactic-science/gleam/>,

^ehttps://lofar-surveys.org/dr2_release.html, ^fIntema et al. (2017), ^gRengelink et al. (1997), ^hDe Breuck et al. (2002), ⁱDouglas et al. (1996), ^jLarge et al. (1981), ^kBock et al. (1999),

^lMcConnell et al. (2020), ^mCondon et al. (1998), ⁿLacy et al. (2020), (2) central frequency, (3) Resolution, (4) Sensitivity

2.2 UV-Optical-IR wavebands

To construct densely sampled UV-IR SEDs, we compiled photometric measurements from several instruments, both ground- and space-based facilities. We cross-matched the optical positions of our galaxies with those provided in public databases such as NED ([NASA/IPAC Extragalactic Database \(NED\), 2019](#)), SIMBAD ([Wenger et al., 2000](#)), VizieR ([Ochsenbein, 1996](#)), and NASA/IPAC Infrared Science Archive (IRSA)⁶ using a matching radius of $5''$ – $15''$. This matching radius was chosen to ensure that there exists a counterpart, depending on the instrument’s resolution. Specifically, the UV and optical data were collected from the NED and VizieR photometry viewer, while the infrared data were obtained from the IRSA database. Approximately 20–30 bands of UV–IR broadband photometry are available for these sources. When multiple flux measurements were available at a specific wavelength, we selected the one encompassing the entire galaxy. In the case of interacting- or merging-type galaxies, the fluxes used in modeling include emission from the companion, too, depending on the wavelength used and the resolution of the survey.

These photometric measurements gathered from a diverse set of space- and ground-based missions were crucial for constructing densely sampled SEDs, the details of which are explained below.

- **Galaxy Evolution Explorer (GALEX):** FUV ($0.152\ \mu\text{m}$) and NUV ($0.227\ \mu\text{m}$).
- **X-ray Multi-Mirror Observatory Optical Monitor (XMM-OM):** UVW2 ($0.212\ \mu\text{m}$) and UVW1 ($0.291\ \mu\text{m}$) bands.
- **Swift:** UVW2 ($0.193\ \mu\text{m}$), UVM2 ($0.225\ \mu\text{m}$), and UVW1 ($0.260\ \mu\text{m}$), u ($0.346\ \mu\text{m}$), b ($0.439\ \mu\text{m}$) and v ($0.547\ \mu\text{m}$).
- **SkyMapper Southern Survey (SMSS):** u ($0.35\ \mu\text{m}$), v ($0.38\ \mu\text{m}$), g ($0.51\ \mu\text{m}$), r ($0.62\ \mu\text{m}$), i ($0.78\ \mu\text{m}$) and z ($0.92\ \mu\text{m}$).
- **Sloan Digital Sky Survey Data Release 16 (SDSS DR16):** u ($0.354\ \mu\text{m}$), g ($0.477\ \mu\text{m}$), r ($0.623\ \mu\text{m}$), i ($0.762\ \mu\text{m}$), and z ($0.913\ \mu\text{m}$).
- **Two Micron All-Sky Survey (2MASS):** J ($1.25\ \mu\text{m}$), H ($1.65\ \mu\text{m}$), and Ks ($2.17\ \mu\text{m}$).
- **Infrared Array Camera on Spitzer (Spitzer-IRAC):** $3.6\ \mu\text{m}$, $4.5\ \mu\text{m}$, $5.8\ \mu\text{m}$, and $8\ \mu\text{m}$.
- **Spitzer’s Multiband Imaging Photometer (MIPS):** $24\ \mu\text{m}$, $70\ \mu\text{m}$, and $160\ \mu\text{m}$.

⁶<https://irsa.ipac.caltech.edu/>

- **Wide-Field Infrared Survey Explorer (WISE)**: 3.4 μm , 4.6 μm , 12 μm , and 22 μm .
- **Infrared Astronomical Satellite (IRAS)**: 12 μm , 24 μm , 60 μm , and 100 μm .
- **AKARI**: N60 (65 μm), WIDE-S (90 μm), WIDE-L (140 μm), and N160 (160 μm).
- **Photoconductor Array Camera and Spectrometer on Herschel (Herschel-PACS)**: Blue (70 μm), green (100 μm), and red (160 μm).
- **Spectral and Photometric Imaging Receiver on Herschel (Herschel-SPIRE)**: PSW (250 μm), PMW (350 μm), and PLW (500 μm).

Table 2.2 lists the basic information on the instruments used to gather multiwavelength FUV–IR data sets.

TABLE 2.2: Basic information on the instruments/satellites used for UV-IR measurements in the CIGALE modeling

Instrument	Passbands	Central Wavelength (μm)	Resolution ($''$)
(1)	(2)	(3)	(4)
GALEX ^a	FUV, NUV	0.15, 0.227	4.2, 5.3
XMM-OM ^b	UVW2, UVM1	0.212, 0.291	1.98, 2
Swift ^c	UVW2, UVM2, UVM1,	0.193, 0.225, 0.260,	
Swift ^c	u, b, v	0.346, 0.439, 0.547	2.5 (at 350nm) [†]
SMSS ^d	u, v, g, r, i, z	0.35, 0.38, 0.51, 0.62, 0.78, 0.92	3.1, 2.9, 2.6, 2.4, 2.3, 2.3
SDSS DR16 ^e	u' , g' , r' , i' , z'	0.354, 0.477, 0.623, 0.762, 0.913	1.53, 1.44, 1.32, 1.26, 1.29
2MASS ^f	J, H, Ks	1.235, 1.662, 2.15	2
WISE ^g	W1-W4	3.4, 4.6, 12, 22	6.1, 6.4, 6.5, 12
Spitzer-IRAC ^h	IRAC1 - IRAC4	3.56, 4.52, 5.73, 7.91	1.66, 1.72, 1.88, 1.98
IRAS ⁱ	IRAS1 - IRAS4	12, 25, 60, 100	45, 45, 90, 180
AKARI ^{j,k}	N60, WIDE-S, WIDE-L, N160	65, 90, 140, 160	37, 39, 58, 61
Herschel-PACS ^l	Blue, Green, Red	70, 100, 160	6, 7, 12
Herschel-SPIRE ^{m,n}	PSW, PMW, PLW	250, 350, 500	17.9, 24.2, 35.4

Columns: (1) name of the instrument/satellite (references for the instrument are given as superscript). ^aBianchi and GALEX Team (1999), ^bMason et al. (2001), ^c(Poole et al., 2008), ^d(Wolf et al., 2018), ^ehttps://www.sdss.org/dr16/imaging/other_info/, ^fJarrett et al. (2000), ^gWright et al. (2010), ^hFazio et al. (2004), ⁱNeugebauer et al. (1984), ^jMurakami et al. (2007), ^kDoi et al. (2015), ^lPoglitsch et al. (2010), ^mGriffin et al. (2010), ⁿSmith et al. (2017), (2) name of the passband/filter used for observation, (3) central wavelength of the passband, (h) resolution (full width at half maximum). [†]https://swift.gsfc.nasa.gov/about_swift/uvot_desc.html

This chapter originally appeared in the SED modeling section of “Low-frequency Radio Continuum Imaging and SED Modeling of 11 LIRGs: Radio-only and FUV to Radio Bands” by Subhrata Dey, Arti Goyal, Katarzyna Małek, Timothy J Galvin, Nicholas Seymour, Tanio Díaz Santos, Julia Piotrowska, Vassilis Charmandaris; 2022, The Astrophysical Journal, Volume 938, Issue 2, id.152, 31 pp. (Dey et al., 2022)

3

Radio-only SED modeling

In this chapter, we present the integrated radio SEDs considered in our analysis which are modeled with physically motivated scenarios taking place in galaxies. In particular, we assume that the radio continuum emission originates from either a single or two emission regions characterized by the same or different populations of CRe with spectral indices α_1 ($=\alpha$, either, in case of single emission region or single population of electrons in both regions) and α_2 , and optical depths (τ_1 and τ_2). For the radio-only SED, we developed a code utilizing the state-of-the-art Bayesian inference method, leveraging the nested sampling algorithm. All modeling was performed in the observers’ frame with a reference frequency, $\nu_0 = 1.4$ GHz.

3.1 Radio continuum models

3.1.1 Single power-law (PL)

A single PL model with emission characterized by synchrotron processes, following the form:

$$S_\nu = A \left(\frac{\nu}{\nu_0} \right)^\alpha \quad (3.1)$$

where A and α are the normalization and spectral index, respectively, treated as free parameters.

3.1.2 Synchrotron and Free-Free Emission (SFG NC)

A radio continuum is a sum of optically thin (no-curvature) synchrotron and free-free emission processes, following the form:

$$S_\nu = A \left(\frac{\nu}{\nu_0} \right)^\alpha + B \left(\frac{\nu}{\nu_0} \right)^{-0.1} \quad (3.2)$$

where A and B are the nonthermal and thermal normalization components, respectively, treated as free parameters. The free parameter, α , is the synchrotron spectral index.

3.1.3 Synchrotron and Free-Free Emission with free-free absorption (C)

A radio continuum is defined as a sum of synchrotron and free-free emission processes where the synchrotron emission can be suppressed due to FFA. If the frequency of this turnover due to FFA is parametrized by $\nu_{t,1}$, then the optical depth, τ , can be defined as $(\nu/\nu_{t,1})^{-2.1}$. This model has the following form:

$$S_\nu = (1 - e^{-\tau}) \left[B + A \left(\frac{\nu}{\nu_{t,1}} \right)^{0.1+\alpha} \right] \left(\frac{\nu}{\nu_{t,1}} \right)^2 \quad (3.3)$$

Where A and B are the nonthermal and thermal normalization components and are treated as free parameters. The free parameters, $\nu_{t,1}$ and α are the turnover frequency and the synchrotron spectral index, respectively. To reduce the degeneracy of the model, we replace the term ν_0 with the turnover frequency parameter for each component. A key point here is that the models assume that the synchrotron emission is completely commingled within the extended plasma, which causes the free-free absorption (a plasma will exhibit FFA regardless of the physical origin of the radio photon - i.e., it does not matter what causes a radio photon to be there; it will get absorbed by the plasma).

3.1.4 Multiple Free-Free absorption (FFA) components

Multiple (two) components with emission and absorption representing two star-forming regions with different orientations or compositions. The radio continuum could be complex in these cases, as these regions are integrated by large synthesized beams for unresolved galaxies. We distinguish five scenarios in the multiple components framework, which are described below:

(a) Radio continuum originating from two different relativistic electron populations, characterized by synchrotron spectral indices, α_1 and α_2 in two distinct star-forming regions without FFA turnovers, labeled as SFG NC2, following the form:

$$S_\nu = A \left(\frac{\nu}{\nu_0} \right)^{\alpha_1} + B \left(\frac{\nu}{\nu_0} \right)^{-0.1} + C \left(\frac{\nu}{\nu_0} \right)^{\alpha_2} + D \left(\frac{\nu}{\nu_0} \right)^{-0.1} \quad (3.4)$$

Where, A and C are the nonthermal normalization components, respectively, while B and D are the thermal normalization components, respectively. A, B, C, D, α_1 , and α_2 are treated as free parameters.

(b) Radio continuum characterized by the same (single) relativistic electron population, α , in two distinct star-forming regions having different optical depths, τ_1 and τ_2 , respectively, labeled as “C2 1SA”:

$$S_\nu = (1 - e^{-\tau_1}) \left[B + A \left(\frac{\nu}{\nu_{t,1}} \right)^{0.1+\alpha} \right] \left(\frac{\nu}{\nu_{t,1}} \right)^2 + (1 - e^{-\tau_2}) \left[D + C \left(\frac{\nu}{\nu_{t,2}} \right)^{0.1+\alpha} \right] \left(\frac{\nu}{\nu_{t,2}} \right)^2 \quad (3.5)$$

Where A and C are the nonthermal normalization components and B and D are the thermal normalization components, respectively. A, B, C, D, α , τ_1 and τ_2 are treated as free parameters.

(c) Radio continuum characterized by the same (single) relativistic electron population, α , in two distinct star-forming regions, one without a turnover while the other characterized by optical depth, τ_2 , respectively, labeled as “C2 1SAN”:

$$S_\nu = \left(\frac{\nu}{\nu_0} \right)^{-2.1} \left[B + A \left(\frac{\nu}{\nu_0} \right)^{0.1+\alpha} \right] \left(\frac{\nu}{\nu_0} \right)^2 + (1 - e^{-\tau_2}) \left[D + C \left(\frac{\nu}{\nu_{t,2}} \right)^{0.1+\alpha} \right] \left(\frac{\nu}{\nu_{t,2}} \right)^2 \quad (3.6)$$

Where A and C are the nonthermal normalization components and B and D are the thermal normalization components, respectively. A, B, C, D, α , and τ_2 are treated as free parameters. This model is most suited to explain the high-frequency kinks, elaborated in [Condon and Yin 1990](#) and [Clemens et al. \(2010\)](#).

(d) Radio continuum characterized by the two different relativistic electron populations, α_1 and α_2 , in two distinct star-forming regions, one without a turnover while the other characterized by optical depth, τ_2 , respectively, labeled as “C2 1SAN2”:

$$S_\nu = \left(\frac{\nu}{\nu_0}\right)^{-2.1} \left[B + A \left(\frac{\nu}{\nu_0}\right)^{0.1+\alpha_1} \right] \left(\frac{\nu}{\nu_0}\right)^2 + (1 - e^{-\tau_2}) \left[D + C \left(\frac{\nu}{\nu_{t,2}}\right)^{0.1+\alpha_2} \right] \left(\frac{\nu}{\nu_{t,2}}\right)^2 \quad (3.7)$$

Where A and C are the nonthermal normalization components and B and D are the thermal normalization components, respectively. A, B, C, D, α_1 , α_2 , and τ_2 are treated as free parameters.

(e) Radio continuum characterized by the two different relativistic electron populations, α_1 and α_2 , in two distinct star-forming regions, characterized by optical depths, τ_1 and τ_2 , respectively, labelled as “C2”.

$$S_\nu = (1 - e^{-\tau_1}) \left[B + A \left(\frac{\nu}{\nu_{t,1}}\right)^{0.1+\alpha_1} \right] \left(\frac{\nu}{\nu_{t,1}}\right)^2 + (1 - e^{-\tau_2}) \left[D + C \left(\frac{\nu}{\nu_{t,2}}\right)^{0.1+\alpha_2} \right] \left(\frac{\nu}{\nu_{t,2}}\right)^2 \quad (3.8)$$

Where A and C are the nonthermal normalization components and B and D are the thermal normalization components, respectively. A, B, C, D, α_1 , α_2 , τ_1 and τ_2 are treated as free parameters.

Models labeled as SFG NC2, C2 1SAN2 and C2 are motivated by galaxy merger scenario where two distinct systems with distinct electron populations drives a new burst of starformation.

3.2 Radio continuum model fitting and selection

3.2.1 Model fitting

For model fitting and selection, we applied the Bayesian inference package called UltraNest (Buchner, 2021). UltraNest works on the principle of the Monte Carlo technique called nested sampling (Skilling, 2004). The advantage of nested sampling is that it allows Bayesian inference on arbitrary user-defined likelihood and provides posterior probability distributions on model parameters and marginal likelihood (*evidence*) Z . The likelihood function used in UltraNest is given as

$$\ln \mathcal{L}(\theta) = -\frac{1}{2} \sum_n \left[\frac{(D_n - f(\theta))^2}{\sigma_n^2} + \ln(2\pi\sigma_n^2) \right], \quad (3.9)$$

where D_n and σ_n are the vectors at n different frequencies that contain flux densities

and uncertainties. $f(\theta)$ represents the model fitted with the data and the parameter vector θ . For model fitting, we assume independent flux measurements with normally distributed errors, which is a prerequisite for the likelihood function used by the UltraNest. Within the Bayesian framework, the posterior distribution of any model parameter requires a prior distribution along with a likelihood function, which gives the confidence interval on the derived parameter. In our analysis, we consider a uniform prior distribution of model parameters. We constrain the priors for the normalization parameters, A, B, C, and D as positive, spectral index parameters α and α_2 in the range -0.2 and -2.0 , and turnover frequencies are between 1 MHz and 50 GHz.

3.2.2 Model comparison and selection

The evidence value is used to predict the most preferred model by calculating the Bayes odds ratio as follows:

$$\Delta\mathcal{Z} = e^{\mathcal{Z}_1 - \mathcal{Z}_2} \quad (3.10)$$

where $\mathcal{Z}_1$ and $\mathcal{Z}_2$ are the evidence values for models M_1 and M_2 , respectively. The strongest evidence supporting M_1 over M_2 is when $\Delta\mathcal{Z} > 150$ while for $150 > \Delta\mathcal{Z} > 20$ and $20 > \Delta\mathcal{Z} > 3$, respectively, it is either strong or positive evidence. For $\Delta\mathcal{Z} < 3$, the models are considered indistinguishable. This scale is given by (Kass and Raftery, 1995). Among all the examined models, the one with the Bayes odds ratio value equal to 0 (corresponding to natural $\log_e(1)=0$) is considered as the best model given the data. However, the models are indistinguishable when the ratio is less than $\log_e(3) = 1.1$. Therefore, we select the best-fit model as the one with the least number of free parameters if two or more models turn out to be indistinguishable from each other. Table 3.1 summarizes the natural logarithm of the Bayes odds ratio between each model and the most preferred model for galaxy UGC 08058 in given in Figure 3.1. This means that for a given model, $\log_e(1) = 0.0$ indicates the most preferred model. The least preferred model will have the most negative value in this representation. To assess the degeneracy caused by the number of free parameters in the best-fit model, we give a corner plot in Figure 3.2.

TABLE 3.1: An overview of the natural log of the Bayes odds ratio from the UltraNest fitting of each model to an example UGC 08058. We present the most preferred model with the highest evidence value corresponding to $\log_e(1)=0$ (shown in boldface). Models which are indistinguishable from the most preferred model corresponds to $\log_e(3)=1.1$ (shown in italics type-faced). Less preferred models are given by larger negative values.

Name	PL	SFG NC	C	SFG NC2	C2 1SA	C2 1SAN	C2 1SAN2	C2
UGC 08058	-636.75	-87.51	-839.90	-351.81	-5.70	-3.24	0	-12.84

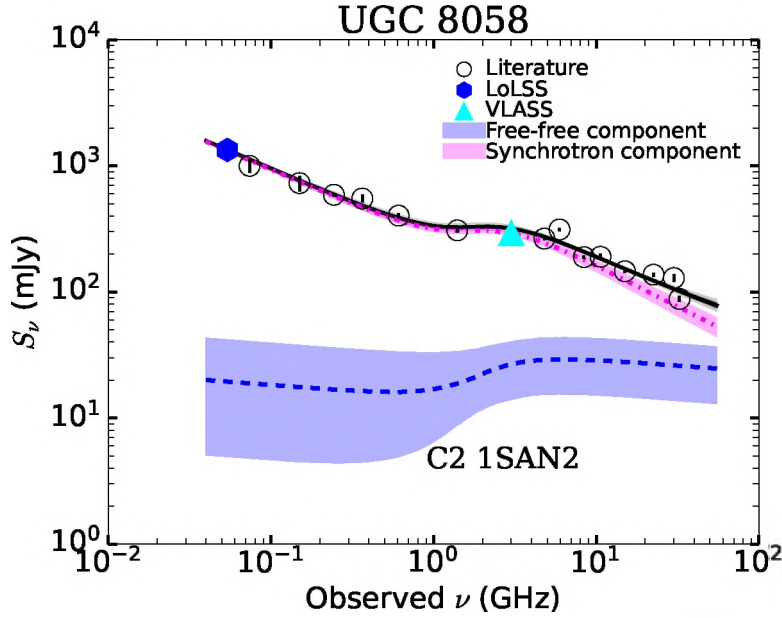


FIGURE 3.1: Radio SED for galaxy UGC 08058. The solid black line represents the best-fit model, while the gray-shaded region represents the 1σ uncertainties sampled by the UltraNest package. The dot-dashed magenta and dotted blue lines show the decomposed synchrotron and free-free components. The pink and blue shaded regions represent the 1σ uncertainties in the synchrotron and free-free components, respectively. The flux densities obtained from the LoLSS and VLASS surveys are shown with blue diamond and cyan triangles, respectively, while open black circles mark the fluxes taken from the literature.

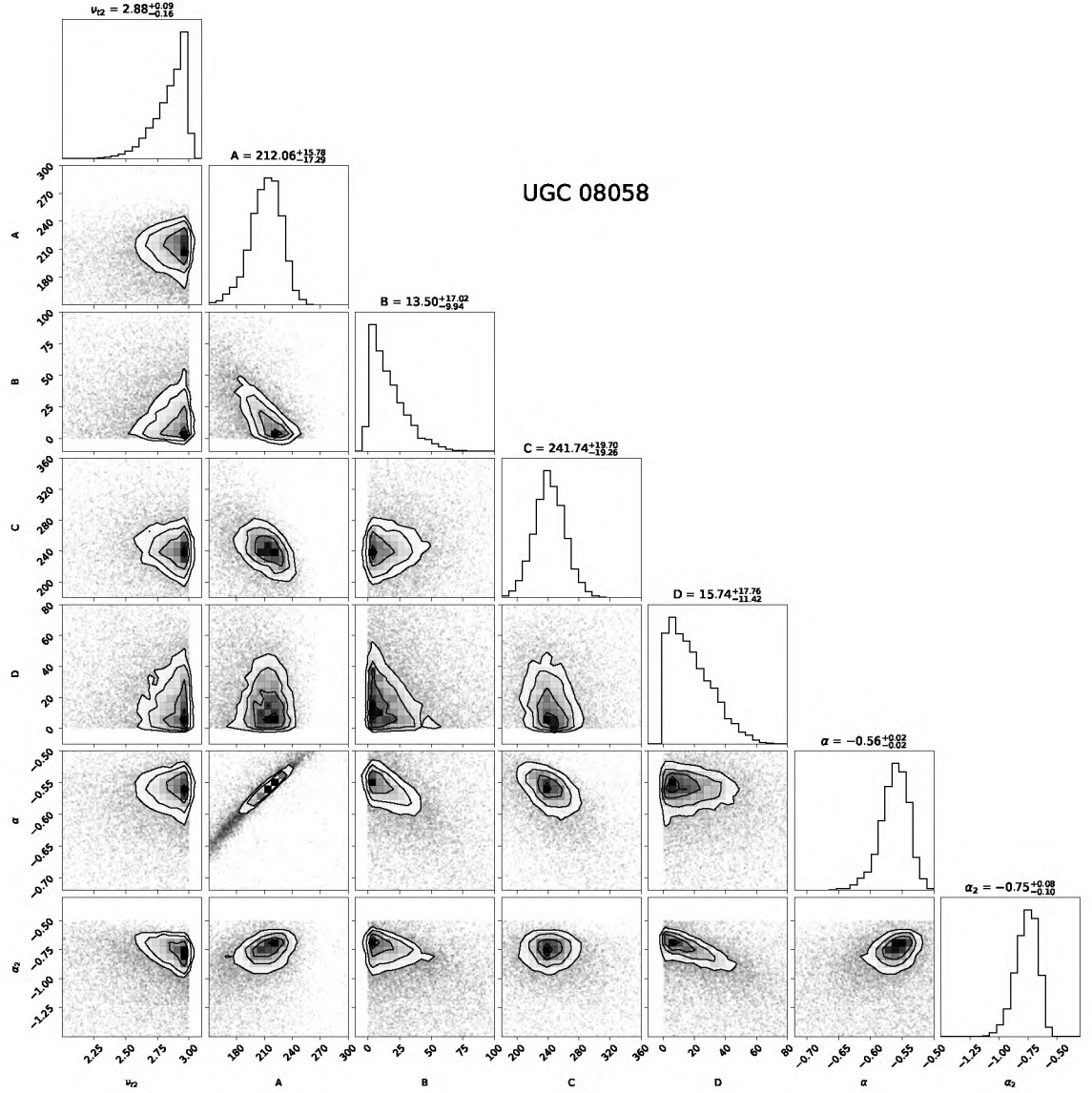


FIGURE 3.2: Corner plots showing the one and two-dimensional posterior probability distribution of the estimated parameters in the radio SED modeling for galaxy UGC 8058.

4

UV-IR-Radio SED modeling with CIGALE

In this chapter, we present the details of Code Investigating GALaxy Emission (CIGALE) SED modeling code used for UV-IR-Radio SED modeling. Specifically, we outline the guiding principles and architecture of the code along with the details of the modules that we used to construct the SED and carry out the analysis.

4.1 Introduction

Code Investigating GALaxy Emission (CIGALE)¹ is an open-source panchromatic SED modeling code. It works on the principle of energy balance, i.e., the energy absorbed by dust in the UV-optical range is self-consistently emitted by dust in the mid- and far-IR range (Noll et al., 2009; Ciesla et al., 2015; Boquien et al., 2019). It further extends the spectrum to radio wavelength by modeling the thermal and nonthermal emission. (Boquien et al., 2019; Yang et al., 2020, 2022). CIGALE is parallelized and modular in nature. The code creates millions of models to be compared with the observations and estimates physical parameters of galaxies (such as SFR, stellar mass, dust luminosity, dust attenuation, AGN fraction, etc) by applying a Bayesian statistical analysis approach. Models corresponding to the physical processes, such as stellar populations, nebular emission, attenuation and emission by dust, etc, are systematically developed by a series of independent modules.

The sequence of building the model is the following.

¹<https://cigale.lam.fr/>

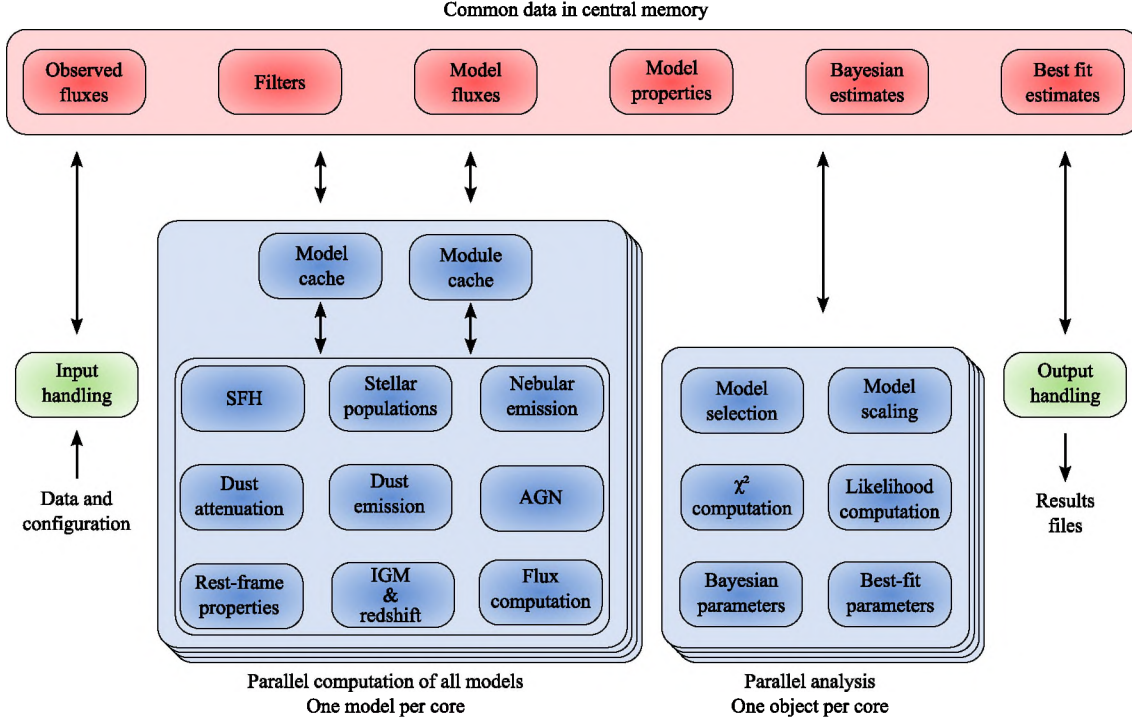


FIGURE 4.1: Schematic illustration of the workflow of CIGALE for SED fitting and parameter estimation. Image Credit: [Boquien et al. \(2019\)](#)

1. **Star-formation history (SFH)** of the galaxy is computed by analytical SFH recipes such as `sfh2exp`, `sfhdelayed`, `sfhperiodic` ([Boquien et al., 2019](#)) or `sfhdelayedplusexp` ([Małek et al., 2018](#)) modules.
2. **Stellar spectrum** is derived from the single stellar population models such as [Bruzual and Charlot \(2003\)](#) or [Maraston \(2005\)](#) considering [Salpeter \(1955\)](#) or [Chabrier \(2003\)](#) initial mass function (IMF) and SFH computed in the above step.
3. **Nebular emission** (series of lines and continuum extending to radio) from the HII region ionized by Lyman continuum photons is obtained following [Inoue \(2011\)](#).
4. **Attenuation** of the stellar and nebular emission is determined following a modified dust attenuation law given by [Calzetti et al. \(2000\)](#) or [Charlot and Fall \(2000\)](#).
5. **Dust emission** in the mid-IR and far-IR wavelengths is obtained following the models by [Draine and Li \(2007\)](#); [Draine et al. \(2014\)](#); [Dale et al. \(2014\)](#); [Jones et al. \(2017\)](#).
6. **AGN emission** in UV, optical, and IR wavelengths is obtained following the model given by [Fritz et al. \(2006\)](#) or [Stalevski et al. \(2012\)](#).
7. The **nonthermal radio emission** (synchrotron emission from the SF and AGN) is obtained using the radio-IR correlation (q_{IR}) ([Helou et al., 1985](#)) and radio-loudness

(Ballo et al., 2012).

8. **Redshifting** of the model and computation of the absorption by the intergalactic medium (IGM).

Figure 4.1 illustrates the overall workflow of CIGALE, describing the process of performing the SED fitting and determining the integrated parameters.

The interpretation of the observed SED relies on comparing various modeled SEDs derived from a fixed parameter grid employed in the modeling process. Initially, each model is adjusted and normalized to the data by minimizing the χ^2 value. Subsequently, the likelihood is employed to quantify the probability that a particular model aligns with the observed data, expressed as $e^{-\chi^2/2}$. These likelihoods serve as weights for determining the physical parameters, with likelihood-weighted means providing estimates along with likelihood-weighted standard deviations indicating uncertainties. Models with low probability are then excluded, retaining only the best-fit models to ascertain the physical parameters. This approach ensures symmetry in the calculated uncertainties. Additionally, the selection of the best-fit model addresses parameter degeneracies, as only the parameter value with the highest probability in the probability density function (pdf) is considered for the best-fit SED.

4.2 SED fitting models

In the following sections we will discuss the different models that we adopted for the SED fitting using CIGALE.

4.2.1 Star-formation history

Modeling of star formation history is very crucial to correctly model the amount of stellar mass with the right age distribution. In literature, there are two approaches to constrain the SFH: parametric and non-parametric (C. et al., 2015; Carnall et al., 2019; Lower et al., 2020). The parametric SFH assumes functional forms such as exponentially declining, delayed-exponentially declining, double power laws, and exponentially increasing (Lee et al., 2009; Maraston et al., 2010; Ciesla et al., 2015; Boquien et al., 2019). To these, it is possible to add a burst and/or a truncation and a constant component. Non-parametric SFH models the SFR as a function of time using piecewise constant functions (i.e., a step function; see Cid Fernandes et al. (2005); Leja et al. (2017)). CIGALE adopts a parametric approach to model the SFH.

To model the SFH, we adopted a delayed SFR with an additional exponential burst with the functional form presented in Eq. 4.1 representing the latest episode of star formation (Malek et al., 2018; Riccio et al., 2021). The selection was made considering the

bursty nature of (U)LIRGs. This form of SFH provides good estimates of the $\text{SFR}-M_\star$ relation compared to observations (Ciesla et al., 2015). The SFH is defined as:

$$\text{SFR}(t) \propto \begin{cases} \text{SFR}_{\text{delayed}}(t) & : \text{if } t < t_0. \\ \text{SFR}_{\text{delayed}}(t) + \text{SFR}_{\text{burst}}(t) & , : \text{if } t \geq t_0. \end{cases} \quad (4.1)$$

where t_0 is the age since the onset of the second episode (burst) of star formation, $\text{SFR}_{\text{delayed}}(t) \propto t e^{-t/\tau_{\text{main}}}$, and $\text{SFR}_{\text{burst}}(t) \propto f_{\text{burst}} e^{-(t-t_0)/\tau_{\text{burst}}}$ if $t > t_0$, and $\text{SFR}_{\text{burst}}(t) = 0$ if $t < t_0$. The factor τ_{main} represents the e-folding time of the main stellar population, and τ_{burst} represents an e-folding time of the late starburst population. This functional form allows for a linear increase of the SFR since the onset of star formation until its peak at τ_{main} followed by an exponential decline. Furthermore, it allows us to add a recent burst occurring for time τ_{burst} with constant amplitude quantified by f_{burst} . The f_{burst} is defined as the ratio of the mass of stars formed during the burst to the total mass of stars. Considering the bursty nature of galaxies, we have given a wide range of f_{burst} , setting an upper limit of 0.9.

4.2.2 Single stellar population (SSP)

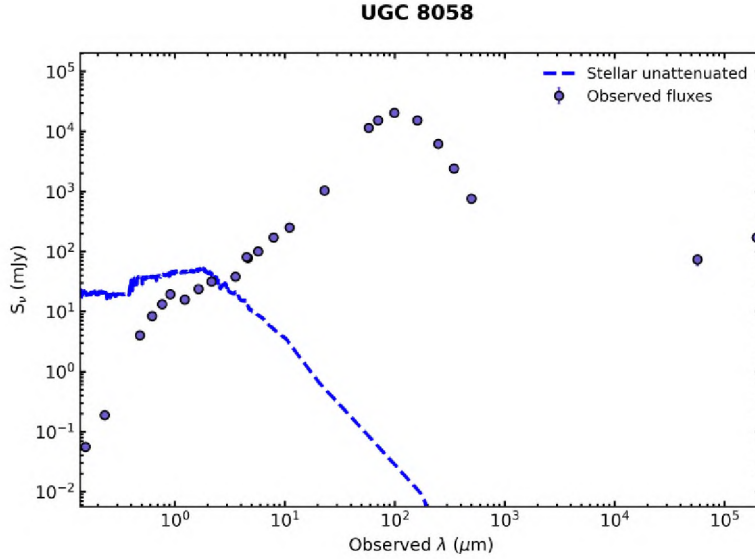


FIGURE 4.2: SED of galaxy UGC 8058 illustrating the contribution of stellar emission (in blue) resulting from the combination of selected SFH (delayed SFR with an additional exponential burst module) with an SSP of Bruzual and Charlot (2003).

The stellar spectrum of the galaxy is calculated by convolving SSP with SFH. To model the stellar component, we used the SSP of Bruzual and Charlot (2003) considering Salpeter (1955) IMF. This stellar library computes the direct stellar contribution to the spectrum (UV to near-IR range) by populating the galaxy with young and old stars of different

masses, as well as the required gas mass that will produce such a population. This model was developed based on observations of nearby stellar populations, and it describes the various stellar emissions that are expected in encounters within any galaxy. These models depend on the metallicity and the separation age. We used a solar-like metallicity of $Z = 0.02$. The spectrum of the composite stellar populations was calculated by convolving the SFH with the grid containing the evolution of the spectrum of an SSP with steps of 1 Myr. Figure 4.2 shows the contribution of stellar emission resulting from the combination of a selected SFH module with an SSP in CIGALE.

4.2.3 Nebular emission

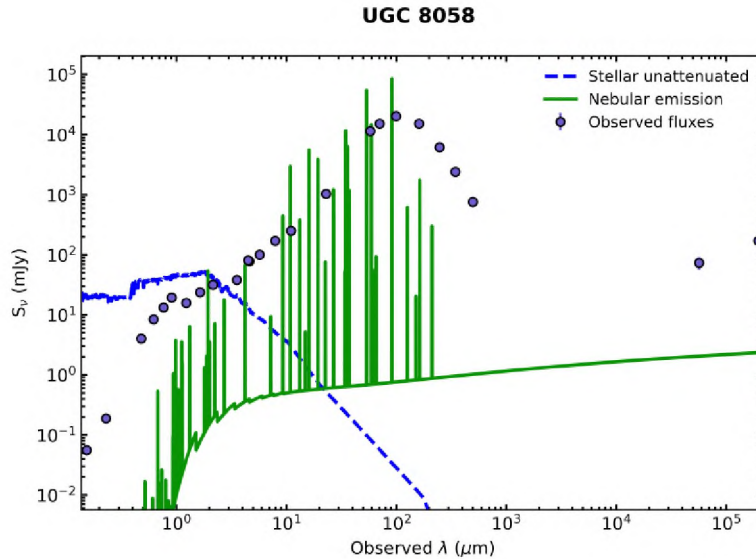


FIGURE 4.3: SED of galaxy UGC 8058 illustrating the contributions of emission (in green) due to the interstellar medium gas being ionized by the stellar light. The lines are modeled from an improved version of the CLOUDY templates computed in Inoue (2011). Stellar emission is shown in blue.

The nebular template in CIGALE is based on Inoue (2011) as shown in Figure 4.3. These templates are generated using the CLOUDY 13.01 and predict the relative intensities of 124 different spectral lines emitted by HII regions. These lines range from HeII at 30.38 nm to [N II] at a wavelength of 205.4 μm . The nebular emission model has four parameters that we kept fixed at default values. These are the ionization parameter, fraction of Lyman continuum photons escaping the galaxy, fraction of Lyman continuum photons absorbed by dust, and line width. The ionization parameter $\log(U)$ is given as $\log(n_\gamma/n_H)$, where n_γ is the number density of photons capable of ionizing hydrogen and n_H the number density of hydrogen. Further, not all photons from the Lyman-continuum ionize the surrounding gas. A fraction of photons can escape the galaxy and a fraction can be absorbed by the dust. Therefore, a correlation factor k is applied to take these two

processes into account.

$$k = \frac{1 - f_{\text{esc}} - f_{\text{dust}}}{1 + \alpha_1 (T_e) / \alpha_B (T_e) \times (f_{\text{esc}} + f_{\text{dust}})}, \quad (4.2)$$

with α_B being the case B recombination rate in $\text{m}^3 \text{s}^{-1}$, $\alpha_1 = \alpha_A - \alpha_B$, the recombination rate at the ground level, T_e the electron temperature in K, f_{esc} the Lyman continuum escape fraction and f_{dust} the partial absorption by dust before ionization. Numerically, for $T_e = 10^4 \text{ K}$, we take $\alpha_B = 2.58 \times 10^{-19} \text{ m}^3 \text{s}^{-1}$ $\alpha_1 = 1.54 \times 10^{-19} \text{ m}^3 \text{s}^{-1}$ (Ferland, 1980).

We have kept these factors at 0, considering that there is no loss of ionizing photons in our nearby galaxies. Each line has a Gaussian shape with a user-defined line width to take gas motion into account, which can be especially important for narrow-band filters and high-redshift objects because of the apparent line broadening with redshift in the observed frame. Figure. 4.3 represents the best-fit SED of galaxy UGC 8058 with a nebular contribution based on Inoue (2011).

4.2.4 Dust attenuation

Aligning with the energy balance principle followed by CIGALE, the dust efficiently absorbs short-wavelength radiation and reemits it in the mid-infrared (MIR) and far-infrared (FIR) spectra. Two models are available in CIGALE to compute dust attenuation: (1) the age-dependent attenuation model of Charlot and Fall (2000), and (2) a flexible attenuation law inspired by the starburst curve of Calzetti et al. (2000). In our studies, we considered the power-law modified starburst attenuation curve following Calzetti et al. (2000). It extends the original Calzetti attenuation law to account for variations in the attenuation curve by varying the steepness of the curve in the UV-optical range and by adding a bump centered at 2175 Å using a Lorentzian-Drude profile (D_λ) according to the following formalism

$$A_\lambda = \left(A_\lambda^{\text{starburst}} \times (\lambda/550 \text{ nm})^\delta + D_\lambda \right) \times \frac{E(B-V)_{\delta=0}}{E(B-V)_\delta}, \quad (4.3)$$

The last term in the Equation 4.3 renormalizes the curve when $\delta \neq 0$

For our sample, we kept the $\delta = 0$ characterizing the attenuation curve of a starburst galaxy. CIGALE allows the user to change the slope of the attenuation curve and/or add a UV bump centered at 217.5 nm. We have kept the amplitude of the UV bump at 0 following studies by Giovannoli et al. (2011), who performed SED-fitting with CIGALE for a sample of 181 LIRGs. The reddening of the emission lines $E(B-V)_{\text{lines}}$ along with reduction factor f scales the curve affecting the stars and the emission lines. The reduction factor f is defined as

$$f = \frac{E(B-V)_{\text{continuum}}}{E(B-V)_{\text{lines}}}, \quad (4.4)$$

Following studies of local (U)LIRGs by [Paspaliaris et al. \(2021\)](#), we keep the $E(B-V)_{\text{lines}}$ and f free.

4.2.5 Dust emission

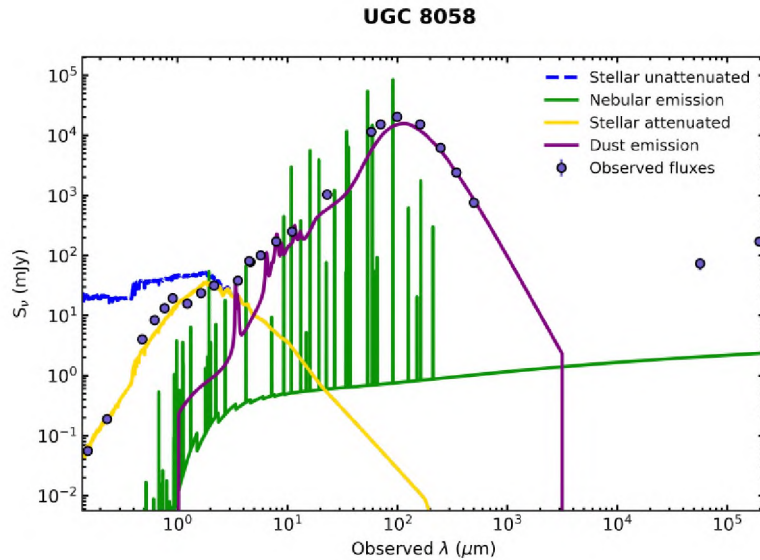


FIGURE 4.4: SED of a galaxy UGC 8058 illustrating the emission from dust. Part of the emissions due to the stellar population is attenuated at low wavelengths (in yellow) following [Calzetti et al. \(2000\)](#) module and re-emitted by the dust at higher wavelengths (in purple) based on THEMIS ([Jones et al., 2017](#)) module. Nebular emission and stellar components are shown in green and blue, respectively.

Two widely used interstellar dust models are (1) the silicate-graphite-PAH model ([Desert et al., 1990](#); [Draine and Li, 2001, 2007](#); [Draine et al., 2014](#)) and (2) the silicate-core carbonaceous-mantle model ([Desert et al., 1990](#); [Jones et al., 1990](#); [Li and Greenberg, 1997](#)). In our studies, we use the THEMIS² model ([Jones et al., 2017](#)) which is an updated version of the latter. THEMIS successfully explains the observed FUV to near-IR extinction and the shape of the IR to millimeter dust thermal emission. Furthermore, it predicts the observed relationship between the $E(B-V)$ color excess and the inferred sub-millimeter opacity derived from the Planck observation (for information see [Jones et al., 2017](#); [Nersesian et al., 2019](#)).

The average starlight intensity U is computed using a δ function component and a power-law distribution:

²https://www.ias.u-psud.fr/themis/THEMIS_model.html

$$\begin{aligned} \langle U \rangle = & (1 - \gamma) \int_{U_{\min}}^{U_{\min} + \Delta U} U \times \delta(U_{\min} - U) dU \\ & + \gamma \int_{U_{\min}}^{U_{\min} + \Delta U} U^{1-\alpha} \times \frac{\alpha - 1}{(U_{\min}^{1-\alpha} - U_{\max}^{1-\alpha})} dU, \text{ for } \alpha \neq 1, \end{aligned} \quad (4.5)$$

where γ represents the fraction of the dust heated in photo-dissociation regions. The THEMIS module consists of three parameters:

The THEMIS module includes three key parameters. These include the mass fraction of small, a-C(:H) grains that emit aromatic features (q_{hac}), the minimum intensity value of the starlight that heats the dust ($U_{\min}$), and the power-law index, α . $U_{\min}$ falls within the 0.1-50, however, an upper limit of $U_{\min} = 80$ is added to account for extreme cases. The value of α and γ are kept at 2 and 0.02. The maximum cutoff for the starlight intensity distribution, $U_{\max}$, is set at 10^7 .

Figure. 4.4 depicts the attenuated emissions from the stellar population, represented in yellow, following to the Calzetti et al. (2000) model. Subsequently, these attenuated emissions are re-emitted by the dust at longer wavelengths, shown in purple, as per the THEMIS model (Jones et al., 2017). Further, the SED also incorporates contributions from stellar and nebular models.

4.2.6 AGN

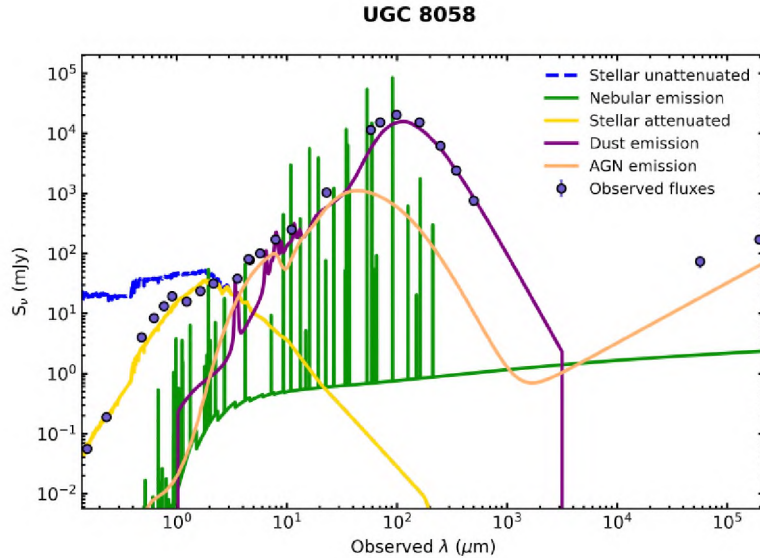


FIGURE 4.5: SED of galaxy UGC 8058 illustrating the contribution due to AGN (in orange) based on SKIRTOR module [Stalevski et al. \(2012\)](#). Dust (in yellow), nebular (in green), and stellar (in blue) emission components are also shown.

To incorporate the AGN component in the SED as shown in Figure 4.5, we selected the SKIRTOR module based on clumpy two-phase torus model of [Stalevski et al. \(2012, 2016\)](#). SKIRTOR utilizes the 3D radiative transfer code SKIRT ([Baes et al., 2011](#)). It includes obscuration by high density clumps (mass fraction = 97 %) of dust in the torus and obscuration by the polar dust component modelled as a dust screen absorption and gray-body emission. The clumpy structure of the torus allows us to observe both types of AGN (type I and type II) at any viewing angle, which was not the case in “smooth” torus model considered in [Fritz et al. \(2006\)](#). Further, the introduction of polar-dust extinction allows us to account for extinction in type I AGNs. SKIRTOR assumes the anisotropic nature of the power source and AGN disk emission ([Yang et al., 2020](#)).

We adopted the Small Magellanic Cloud (SMC) extinction curve, keeping $E(B-V)$ at default value. Further, the grey-body dust re-emission is parametrized with a temperature of 100 K and an emissivity index of 1.6. The AGN fraction (f_{AGN}) quantifies the contribution of the emission from the AGN to the total SED, which is kept free with a large number of input values. 30° and 70° are the two viewing angles considered representing the type I and type II AGNs, respectively. A variety of edge-on optical depth (τ) at 9.7 nm are also considered to account for the very high obscuration by the clumpy torus.

4.2.7 Radio

While the nebular module models the thermal radio continuum, it lacks nonthermal synchrotron emission. The exact shape and intensity of the synchrotron spectrum depend on various parameters such as the magnetic field strength, the energy of the relativistic electrons propagating through it, and so on.

The radio module in CIGALE follows a simplistic approach. It relies on the radio-IR correlation q_{IR} of [Helou et al. \(1985\)](#), a free power-law spectral slope α , and on the assumption that at 21 cm the spectrum is largely dominated by nonthermal emission. In effect, knowing the IR emission, q_{IR} directly provides the luminosity density at 21 cm. Figure 4.6 represents the best-fit radio model for galaxy UGC 8058.

In addition, the radio module of the updated version of CIGALE (CIGALE 2022.1) includes synchrotron emission from both the starforming and the AGN component of the galaxy, compared to its predecessors. The addition of the AGN component to the radio module of CIGALE 2022.1 allowed us to estimate the Radio loudness parameter, R_{AGN} , defined as a ratio of rest-frame AGN luminosities at 5 GHz and 2500. The radio emission from AGN is assumed isotropic and follows a single power-law form ([Yang et al., 2022](#)) as seen in Figure 4.5.

CIGALE assumes the single power-law form only to model the radio part of SED. However, radio SEDs are rarely characterized by single-PL forms. Therefore, while including radio measurements in CIGALE modeling improves the accuracy of derived parameters; it does not fully compensate for the need for radio-only SED modeling (3) using densely

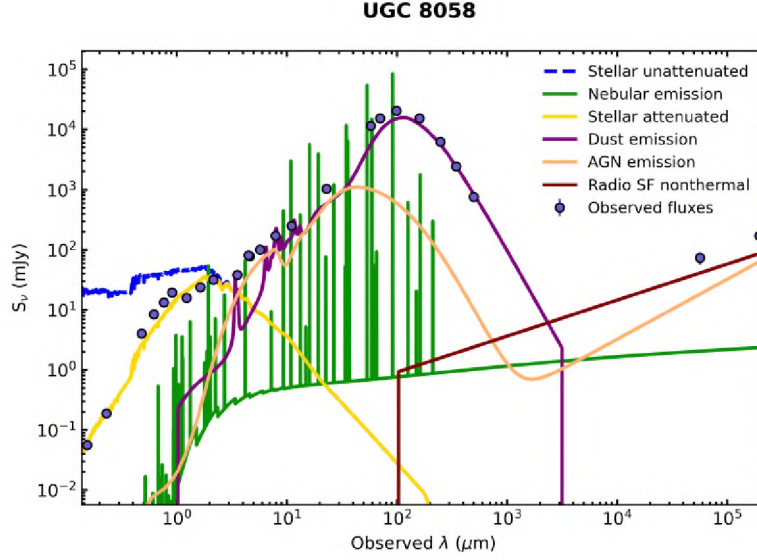


FIGURE 4.6: SED of galaxy UGC 8058 illustrating the radio nonthermal contribution. AGN (in orange), dust (in yellow), nebular (in green), and stellar (in blue) emission components are also shown.

sampled radio SEDs, which is crucial for understanding galaxies' emission and absorption processes.

Figure 4.7 represents the total best-fit SED for galaxy UGC 8058 after summing up the contributions from all the emission components of the galaxy, considered in the UV–radio SED modeling using CIGALE.

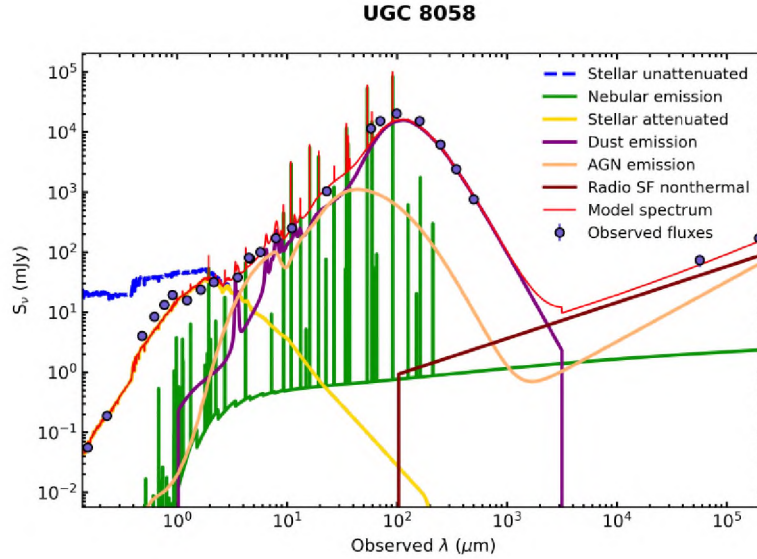


FIGURE 4.7: Best-fit UV-radio SED of galaxy UGC 8058 (in red) after combining the emission from AGN (in orange), dust (in yellow), nebular (in green), and stellar (in blue) components.

4.2.8 Influence of aperture mismatch on modeling

An important issue to address here is the effect of different aperture sizes taken for flux measurements at different wavelengths for the SED modeling. It's worth noting that the apertures employed do not necessarily correspond for all galaxies within our sample. The resulting SED fitting can be affected by the decrement in the flux when the beam size is smaller than the galaxy itself or by a larger aperture, which can result in measuring a partial flux from a nearby galaxy. However, for our sample of galaxies, we tried to use an aperture size that corresponded well to the size of the galaxy. It is not possible to match it perfectly without re-measurement of the fluxes, and we have not done so in our analysis (for improvement in SED quality, see, [Ramos Padilla et al., 2020](#)). Moreover, the parameters derived from the SED fitting tools agree when the apertures are matched with those obtained without matching the apertures ([Ramos Padilla et al., 2020](#)). During SED modeling, CIGALE adds an additional error of 10% of the flux in quadrature together with existing errors. This additional 10% uncertainty counts for all possible uncertainties, for example aperture, that are not included by default in the photometric error bars. Considering the wavelength coverage of the analyzed U/LIRGs, we are confident that even with small aperture problems for selected bands, the final fitted SED mimics the overall estimated physical parameters very well.

Data ranging from the near-UV to the optical, infrared, and radio ensure that the obtained models describe the galaxy very well, without any possible miss-classification between passive/star-forming, non-AGN/AGN, etc. Bayesian analysis, based on millions of templates generated by the SED fitting method, gives us not only the uncertainty of the estimated parameters but also their probability distribution function (PDF; [Boquien et al., 2019](#)). A PDF check of the physical parameters estimated in the analysis is a crucial method that indicates the robustness of the estimates ([Boquien et al., 2019](#)). In our CIGALE analysis, we checked all PDFs for estimated physical properties such as stellar masses, SFR, dust mass and dust temperature, which showed a single peak profile indicative of their robust estimates ([Boquien et al., 2019](#)). Indeed, the aperture problem with very limited photometric coverage of the galaxy spectra can affect the final result (see [Małek et al., 2018](#)). However, in the case of 25 selected U/LIRGs with very dense coverage of the spectra, the aperture inhomogeneity can affect the uncertainty but not the main physical parameters analyzed in this thesis.

This chapter originally appeared as “Low-frequency Radio Continuum Imaging and SED Modeling of 11 LIRGs: Radio-only and FUV to Radio Bands” by **Subhrata Dey, Arti Goyal, Katarzyna Małek, Timothy J Galvin, Nicholas Seymour, Tanio Díaz Santos, Julia Piotrowska, Vassilis Charmandaris**; 2022, *The Astrophysical Journal*, Volume 938, Issue 2, id.152, 31 pp. (Dey et al., 2022)

5

Low-frequency radio continuum imaging and SED modeling of 11 LIRGs: radio-only and FUV to radio bands

5.1 Introduction

Characterized by a prodigious amount of emission at infrared (IR) wavebands, luminous and *ultraluminous* infrared galaxies (U/LIRGs) dominate the infrared sky. LIRGs and ULIRGs have infrared luminosity in the wavelength range $8\mu\text{m} < \lambda < 1000\mu\text{m}$, $L_{\text{IR}}, \sim > 10^{11} L_{\odot}$ and $\sim > 10^{12} L_{\odot}$, respectively, where $L_{\odot}$ is the solar luminosity (Helou et al., 1988). As the name suggests, these galaxies bridge the gap between underlying astrophysical processes contributing to emission in normal star-forming galaxies and the active galactic nuclei (AGN) activity (see, for a review Sanders and Mirabel, 1996; Pérez-Torres et al., 2021). Their spectral energy distribution (SED), although dominated by emission at infrared wavebands, ranges from radio to UV/X-rays frequencies (Yun et al., 2001; Pereira-Santaella et al., 2011), containing imprints of different astrophysical processes such as star formation, stellar evolution, chemical enrichment, processes in the interstellar medium, and the AGN (e.g., Conroy, 2013). Therefore, a detailed and broadband SED modeling provides not only important constraints on astrophysical properties shaping SEDs, but also the evolutionary history of a galaxy, providing insights into the cosmic evolution of the galaxy population (Lonsdale et al., 2006).

As the radio waves remain unaffected by dust, the study of the radio continuum offers

a promising approach to studying the astrophysical properties of galaxies. The q_{IR} parameter, defined as the ratio of infrared (60-100 μm) to radio (1.4 GHz) luminosities, shows a surprisingly tight correlation for normal galaxies because emission at these wavebands is ascribed to a common origin and interpreted as calorimetric models (Helou et al., 1988; Condon, 1992; Yun et al., 2001; Murphy, 2009). In this framework, the galaxies are optically thick to UV radiation from young massive stars that are absorbed by the dust in the interstellar medium and reradiated in the far-infrared (FIR) regime. Later on, these stars explode to form type II supernovae and accelerate cosmic-ray electron (CRE) that produces radio emission via a synchrotron process before escaping the galaxy (Voelk, 1989). Helou et al. (1985) suggested that galaxies can be optically thin to both UV photons and cosmic rays, but coupling between gas and magnetic field should exist to maintain the radio-IR correlation (see also, Lacki et al., 2010; Tabatabaei et al., 2013). Furthermore, a secondary component of the radio continuum emission due to free-free interactions between charged particles, i.e., free-free radiation, is also produced by ionization of gas in H II regions. In general, synchrotron emission is characterized by a power-law emission spectrum, $f_\nu \propto \nu^\alpha$ ($\alpha \simeq -0.8$) dominating the 1–10 GHz frequency range, whereas free-free emission has almost a flat spectrum with flux proportional to $\nu^{-0.1}$, dominating in frequency range ≥ 10 GHz (Condon, 1992). The radio spectra of galaxies bend (or flatten) at lower frequencies $< 1\text{GHz}$ due to absorption processes such as free-free absorption (FFA), synchrotron self-absorption (SSA) or the Tsytovitch-Razin effect (Israel and Mahoney, 1990; Condon, 1992; Clemens et al., 2010; Marvil et al., 2015).

The exact shape of the radio spectra between the MHz to GHz range depends on either the quantity and distribution of ionized (thermal) gas in galaxies (Vardoulaki et al., 2015; Clemens et al., 2008; Chyży et al., 2018; Galvin et al., 2018) or due to the presence of the AGN (Clemens et al., 2010). Typically, the thermal fraction, TF , defined as the ratio of thermal to total emission, ranges between 0.1 and 10% at 1.4 GHz for normal star-forming galaxies and LIRGs (see, Galvin et al., 2018). Therefore, constraining the radio spectrum to low frequencies is essential to understand the absorption models for these galaxies.

Multiwavelength SED modeling, from UV to IR, provides information about the light emitted by stars, either directly or through reprocessing by the gas (emission and absorption features in the SED) and dust in the interstellar medium, while radio SED probes the nonthermal and thermal processes in galaxies (see, for a review, Walcher et al., 2011; Tabatabaei et al., 2017; Pérez-Torres et al., 2021). Different regimes of the broad SED provide critical insight into the nature, origin of emission, and factors that establish the energy balance. The astrophysical properties of galaxies using the Code Investigating GALaxy Emission (CIGALE) model set for main-sequence (normal) star-forming galaxies (Ciesla et al., 2017; Vika et al., 2017; Pearson et al., 2018; Riccio et al., 2021; Shirley et al., 2021), LIRGs, and ULIRGs have been characterized (Małek et al., 2017, 2018; Paspaliaris et al., 2021). As these galaxies can host AGNs, the CIGALE code includes the

AGN component in the modeling. In particular, the AGN fraction (defined as the ratio of IR luminosity due to AGN and a sum of IR luminosity due to AGN and starburst), stellar mass (M_*), star formation rate (SFR_{IR}), dust luminosity (L_{IR}), dust temperature (T_{dust}) have been obtained. The most significant finding of these studies is that LIRGs are characterized by a relatively higher SFR_{IR} , L_{IR} , T_{dust} , AGN fraction compared to normal star-forming galaxies and lower than those obtained by ULIRGs (Malek et al., 2017). However, detailed radio-SED analyses of a large sample of galaxies are rare, primarily due to the lack of wide-area multifrequency radio surveys and targeted follow-up of suitable samples.

In this chapter, we discuss the results of SED modeling of a sample of 11 LIRGs at radio-only and far-ultraviolet (FUV) to radio bands, including our new measurements at 325 and 610 MHz frequencies using the Giant Metrewave Radio Telescope (GMRT; Swarup, 1990)¹, operated by the National Centre of Radio Astronomy-Tata Institute of Fundamental Research, India. We report the results of detailed radio SED modeling covering ~ 80 MHz to ~ 15 GHz and CIGALE SED modeling covering GHz band radio frequencies up to UV frequencies. As the CIGALE modeling cannot capture the complex shapes of low-frequency radio spectra exhibited by LIRGs and ULIRGs (e.g., Clemens et al., 2008, 2010; Galvin et al., 2018), therefore, we include >1.4 GHz band radio fluxes to cover the five decades of the spectral range. Furthermore, an essential aspect of CIGALE modeling is that it works on the energy balance between UV and IR, which is ultimately related to radio luminosity; hence, including radio fluxes in CIGALE modeling is essential for better constraining the model parameter space (in particular, the L_{dust}).

One of the primary goals of this work is to compare the astrophysical properties resulting from SED modeling at radio-only and FUV to radio bands. The shapes of SEDs reflect the radiation laws and their parameters (such as power-law energy index or emissivity) and the physical processes affecting those parameters, such as cooling or heating mechanisms in the medium. Moreover, integrated SEDs provide total energetics from different frequency regimes, and comparing those offers key information on the nature of emission and general factors that determine their energy balance principle. Furthermore, our radio SED modeling allowed us to decompose the nonthermal and thermal emission components and estimate the star formation rate (SFR) using the basic nonthermal and thermal radio SFR calibration presented in Murphy et al. (2011) and compare them with the SFR_{IR} estimated from CIGALE SED modeling.

We perform detailed SED modeling of a sample of 11 nearby LIRGs (median redshift equal to 0.0181), focusing separately on radio-only and FUV-radio spectral bands. The chapter is organized as follows. Sample selection is given in Section 5.2, Section 5.3 describes data collection and analysis. Section 5.4 gives details of the radio-only and panchromatic (FUV to radio) SED modeling procedures. Section 5.5 gives the results

¹<http://www.gmrt.ncra.tifr.res.in/>

of model fitting, i.e., characterization of astrophysical properties of our sample. The discussion of the results obtained is given in Section 5.6, and the conclusion is given in Section 5.7.

5.2 Sample selection

TABLE 5.1: Basic information on our sample of LIRGs

Name	R.A.(J2000)	Dec.(J2000)	z	$\log_{10}(L_{\text{IR}})$
	(h m s)	($^{\circ}$ ' ")		($L_{\odot}$)
(1)	(2)	(3)	(4)	(5)
ESO 500-G034	10 24 31.4	−23 33 10	0.0122	10.77
NGC 3508	11 02 59.7	−16 17 22	0.0128	10.65
ESO 440-IG058	12 06 51.9	−31 56 54	0.0232	11.18
ESO 507-G070	13 02 52.3	−23 55 18	0.0217	11.34
NGC 5135	13 25 44.0	−29 50 01	0.0136	11.12
IC 4280	13 32 53.4	−24 12 26	0.0162	10.85
NGC 6000	15 49 49.6	−29 23 13	0.0070	10.92
IR 16164-0746	16 19 11.8	−07 54 03	0.0271	11.29
ESO 453-G005	16 47 31.1	−29 21 22	0.0209	11.69
IR 18293-3413	18 32 41.1	−34 11 27	0.0181	11.62
ESO 593-IG008	19 14 31.1	−21 19 09	0.0485	11.77

Columns : (1) source name, (2) right ascension, (3) declination, (4) spectroscopic redshift from the NASA/IPAC Extragalactic Database (NED)²; (5) absolute far-IR luminosity from Table 1 of Condon et al. (1996), except for NGC 3508 which is taken from Table 1 of Condon et al. (1990).

In this study, we have assembled a sample of 10 LIRGs with the selection criteria $\log_{10}(L_{\text{IR}}) > 10.75 L_{\odot}$ from the 1.425 GHz Atlas of the IRAS Bright Galaxy Sample catalog (Condon et al., 1996) and one galaxy, NGC 3508 from the 1.49 GHz Atlas of the IRAS Bright Galaxy Sample (Condon et al., 1990) of with flux densities greater than 5.24 Jy at 60 μm . These galaxies were selected based on the availability of 150 MHz data in the original release of the TIFR GMRT Sky Survey (TGSS) Data Release (DR) 4, covering 1 sr of the sky, using the GMRT (see, for a basic description of the survey; Sirothia et al., 2014). We note that Intema et al. (2017) presented the entire TGSS data in their alternate data release (TGSS ADR1). Although we selected our sample from the original TGSS DR4 release, which had slightly better sensitivity for extended emission (rms error $\sim 7\text{--}9 \text{ mJy beam}^{-1}$) as compared to the TGSS ADR1 (Intema et al., 2017), we use TGSS ADR1 integrated fluxes for radio SED fitting as its reduction and calibration

methodology is fully described. The basic properties of the LIRG sample are listed in Table 5.1.

5.3 Multi-wavelength datasets: Radio to FUV

5.3.1 Radio data

In chapter 2, we provide an overview of the radio data collected from various sky survey programs along with our dedicated radio observations using the GMRT and reanalysis of the VLA data for some of the galaxies, wherever required. However, in order to construct densely sampled radio SEDs, we also obtained flux density measurements from targeted studies. These are: LIRGs ESO440-IG080 and ESO500-G034 at 10.0 GHz (Hill et al., 2001), NGC 5135 at 6.7 GHz (Impellizzeri et al., 2008).

Table A2 summarizes the GMRT and VLA datasets analyzed by us, while Figure A.1 provides total intensity radio maps overlaid on Digital Sky Survey (DSS)2-*R*-band images in Appendix A.1. As can be seen from Table A2 that the synthesized beam sizes for our continuum images range between a few arcseconds and $10\times$ a few arcseconds. Because we analyzed datasets taken mostly at the B, C, and D array configurations of the VLA, it is unlikely that our galaxies are missing flux due to the lack of short U-V spacing data. To establish this, we compared the 1.4 GHz fluxes from Table A2 with the NVSS fluxes, obtained at a resolution of $45''$. The two measurements are comparable within the measurement uncertainties. Table A3 provides the list of flux measurements used for the radio SED fitting.

5.3.2 UV, Optical, and IR flux densities

In chapter 2, we provide an overview of the data collected from space and ground-based instruments at UV, optical, and IR-bands. We note that with the availability of multiple flux measurements at a given wavelength, we chose the one containing the entire galaxy. Moreover, five galaxies in our sample, namely, ESO 440-IG058, ESO 507-G070, ESO 593-IG008, IR 16164-0746, and IR 18293-3413 are either interacting, merging, or post-merging type; for these, the fluxes used in modeling include emission from the companion too. Table A4 gives the integrated fluxes along with the integration area per band for each source used for SED modeling. For galaxies ESO 440-IG058 and NGC 5135, the IRAC apertures were optimized on a source by source basis to cover individual components when measuring galaxies in merger systems and to contain all the integrated flux in the case of isolated galaxies (Mazzarella et al., in preparation).

5.4 SED modeling

5.4.1 Radio-only SED modeling

A detailed description of radio-only SED modeling is provided in Chapter 3. In this section, we provide the result of the radio-only SED modeling. Table 5.2 summarizes the natural logarithm of the Bayes odds ratio between each model and the most preferred model (Kass and Raftery, 1995).

TABLE 5.2: An overview of the natural log of the Bayes odds ratio from the *UltraNest* fitting of each model to each source. In boldface, we present the most preferred model with highest evidence value (see Equation 3.10).

Name	PL	SFG NC	C	SFG NC2	C2 1SA	C2 1SAN	C2 1SAN2	C2
ESO 500-G034	−68.1	−67.5	−6.3	−76.3	−1.2	0	−1.5	−4.2
NGC 3508	0	−3.5	−7.2	−8.7	−19.3	−4.6	−2.8	−7.1
ESO 440-IG058	−17.2	−14.9	0	−25.7	−3.9	−9.1	−6.8	−2.3
ESO 507-G070	−74.2	−69.9	−159.1	−21.8	−235.1	−1.9	0	−453.1
NGC 5135	−6.5	−3.7	0	−11.8	−13.0	−2.9	−35.4	−6.8
IC 4280	−3.2	−6.1	0	−12.4	−8.8	−1.6	−4.4	−0.7
NGC 6000	−3.4	0	−21.4	−6.1	−11.2	−1.6	−3.1	−408.8
IR 16164-0746	−3.4	0	−1.2	−1.3	−4.1	−0.9	−0.8	−3.0
ESO 453-G005	−2.9	0	−0.6	−3.5	−4.9	−2.1	−2.3	−1.5
IR 18293-3413	−88.7	−86.8	−90.4	−99.5	−4.3	−5.1	0	−5.1
ESO 593-IG008	−3.0	−5.9	0	−7.5	−4.3	−6.8	−3.8	−2.1

The best-fit radio SEDs are presented in Figure 5.1 and Table 5.3 gives the corresponding model parameters, along with the 1σ uncertainties corresponding to the 16th and 84th percentile of the posterior distribution of the parameter. Our radio-only modeling separates the thermal and nonthermal components from the total emission. From the radio-only SED modeling, we see that NGC 3508 shows an excellent fit to the single power law (PL) shape. Three other galaxies, NGC 6000, IR 16164–0746, and ESO 453-G005, are fitted with a single-component model without a turnover (SFG NC). The galaxies ESO 440-IG058, NGC 5135, IC 4280, and ESO 593-IG008 are fitted with the single-component model with low-frequency turnover (C). For galaxies ESO 500–G034 is best-fitted with a multiple component model characterized with a single relativistic electron population in two different star-forming regions (one region with no turnover at low frequencies and the other

characterized by a turnover (C2 1SAN). For galaxies ESO 507–G070 and IR 18293–3413, the best fit model turned out to be multiple components, one characterized by different relativistic electron populations in two different star-forming regions (one region with no turnover at low frequencies and the other characterized by a turnover (C2 1SAN2)). None of our galaxies fits with models described by a single relativistic electron population in two different star-forming regions with different optical depths (C2 1SA) and a multiple component model representing two different electron populations in the two distinct star-forming galaxies with different optical depths (C2).

Using the best-fit model, we estimated total thermal (nonthermal) emission by setting the normalization of the nonthermal (thermal) component(s) to zero. Table 5.4 gives the total, thermal, and nonthermal fluxes at 1.4 GHz, derived from the radio-only SED modeling, along with the 1σ uncertainties corresponding to the 16th and 84th percentile of the posterior distribution of the parameter. To assess the degeneracy caused by the number of free parameters in the best-fit model, we give corner plots for all our galaxies in Appendix (Figure A.2). In Table 5.4, we also provide the 1.4 GHz thermal fraction ($\text{TF}_{1.4}$). The thermal fraction (TF) at a given frequency is the ratio of thermal radio emission to total radio emission (synchrotron and free-free emission).

TABLE 5.3: The most preferred models were selected on the basis of the Bayes odds ratio and the constrained value of the free parameters. The nominal value is taken as the 50th percentile of the posterior distribution of the samples, and the 1 σ uncertainties are provided by the 16th and 84th percentile. Parameters not included in the models are given by “-”.

Name	Model	A	B	α	$\nu_{t,1}$	C	D	α_2	$\nu_{t,2}$	Columns:
		(mJy)	(mJy)		(GHz)	(mJy)	(mJy)		(GHz)	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	
ESO 500-G034	C2 1SAN	$6.33^{+2.15}_{-1.83}$	$3.68^{+2.89}_{-2.45}$	$-1.17^{+0.10}_{-0.11}$	-	$154.57^{+11.34}_{-11.09}$	$3.54^{+3.27}_{-2.41}$	-	$0.52^{+0.06}_{-0.06}$	
NGC 3508	PL	$62.16^{+2.55}_{-2.28}$	-	$-0.73^{+0.02}_{-0.02}$	-	-	-	-	-	
ESO 440-IG058	C	$325.65^{+18.67}_{-16.00}$	$1.83^{+2.30}_{-1.31}$	$-0.82^{+0.03}_{-0.04}$	$0.14^{+0.02}_{-0.02}$	-	-	-	-	
ESO 507-G070	C2 1SAN2	$40.06^{+4.52}_{-4.33}$	$2.11^{+1.75}_{-1.48}$	$-0.77^{+0.05}_{-0.06}$	-	$21.04^{+4.16}_{-4.20}$	$2.11^{+1.75}_{-1.48}$	$-1.50^{+0.39}_{-0.22}$	$7.55^{+1.94}_{-1.97}$	
NGC 5135	C	$1293.06^{+88.51}_{-71.13}$	$7.63^{+8.67}_{-5.59}$	$-0.88^{+0.03}_{-0.05}$	$0.13^{+0.02}_{-0.02}$	-	-	-	-	
IC 4280	C	$359.27^{+43.40}_{-32.10}$	$10.01^{+6.14}_{-5.61}$	$-0.89^{+0.09}_{-0.12}$	$0.14^{+0.04}_{-0.03}$	-	-	-	-	
NGC 6000	SFG NC	$144.55^{+3.18}_{-3.06}$	$0.49^{+0.34}_{-0.34}$	$-0.66^{+0.01}_{-0.02}$	-	-	-	-	-	
IR 16164-0746	SFG NC	$61.54^{+2.15}_{-2.14}$	$0.51^{+0.33}_{-0.34}$	$-0.45^{+0.03}_{-0.03}$	-	-	-	-	-	
ESO 453-G005	SFG NC	$22.32^{+1.06}_{-1.02}$	$0.51^{+0.33}_{-0.34}$	$-0.60^{+0.04}_{-0.04}$	-	-	-	-	-	
IR 18293-3413	C2 1SAN2	$32.74^{+11.58}_{-9.87}$	$4.30^{+3.30}_{-2.86}$	$-1.35^{+0.12}_{-0.15}$	-	$378.89^{+43.90}_{-41.81}$	$4.13^{+3.32}_{-2.70}$	$-1.74^{+0.08}_{-0.04}$	$1.06^{+0.08}_{-0.08}$	
ESO 593-IG008	C	$540.70^{+70.71}_{-47.97}$	$0.49^{+0.35}_{-0.33}$	$-0.87^{+0.03}_{-0.03}$	$0.10^{+0.02}_{-0.02}$	-	-	-	-	

(1) galaxy name, (2) best-fit model, (3) and (7) nonthermal normalization components, (4) and (8) thermal normalisation components, (5) and (9) synchrotron spectral indices, (6) and (10) turnover frequencies.

TABLE 5.4: Total, thermal, and nonthermal fluxes estimated at 1.4 GHz from the radio-only SED fitting and the corresponding thermal fraction estimated at 1.4 GHz. The nominal value is taken as the 50th percentile of the posterior distribution of the samples, and the 1 σ uncertainties are provided by the 16th and 84th percentile.

Name	$S_{1.4}^{\text{total}}$	$S_{1.4}^{\text{th}}$	$S_{1.4}^{\text{nth}}$	$TF_{1.4}$
	(mJy)	(mJy)	(mJy)	
(1)	(2)	(3)	(4)	(5)
ESO 500-G034	59.74 ^{+1.94} _{-1.74}	7.32 ^{+1.82} _{-2.22}	52.57 ^{+3.06} _{-2.74}	0.11 ^{+0.02} _{-0.02}
NGC 3508	61.84 ^{+2.55} _{-2.42}	—	61.84 ^{+2.55} _{-2.42}	0
ESO 440-IG058	49.98 ^{+1.03} _{-1.04}	1.59 ^{+1.79} _{-1.13}	48.39 ^{+1.66} _{-2.24}	0.03 ^{+0.02} _{-0.02}
ESO 507-G070	53.02 ^{+1.59} _{-1.59}	4.75 ^{+3.41} _{-3.11}	48.24 ^{+3.31} _{-3.52}	0.09 ^{+0.04} _{-0.04}
NGC 5135	164.33 ^{+3.58} _{-3.74}	6.04 ^{+7.28} _{-4.43}	158.29 ^{+6.20} _{-9.60}	0.04 ^{+0.02} _{-0.03}
IC 4280	50.32 ^{+1.52} _{-1.73}	8.53 ^{+5.04} _{-5.17}	41.84 ^{+6.12} _{-6.24}	0.12 ^{+0.04} _{-0.04}
NGC 6000	146.98 ^{+3.07} _{-3.21}	0.49 ^{+0.35} _{-0.33}	146.00 ^{+4.00} _{-3.00}	0.003 ^{0.002} _{0.002}
IR 16164-0746	62.04 ^{+2.45} _{-2.59}	0.51 ^{+0.34} _{-0.33}	61.50 ^{+2.50} _{-2.60}	0.008 ^{+0.004} _{-0.004}
ESO 453-G005	23.04 ^{+1.35} _{-1.24}	0.52 ^{+0.33} _{-0.35}	22.50 ^{-1.40} _{+1.40}	0.02 ^{+0.01} _{-0.01}
IR 18293-3413	220.59 ^{+7.18} _{-7.23}	7.76 ^{+2.10} _{-2.15}	212.84 ^{+7.95} _{-7.75}	0.04 ^{+0.01} _{-0.01}
ESO 593-IG008	58.59 ^{+1.72} _{-1.67}	0.36 ^{+0.25} _{-0.26}	58.22 ^{+1.70} _{-1.71}	0.006 ^{+0.003} _{-0.003}

Columns: (1) galaxy name, (2–4) total, thermal, and nonthermal fluxes at 1.4 GHz, (5) thermal fraction at 1.4 GHz

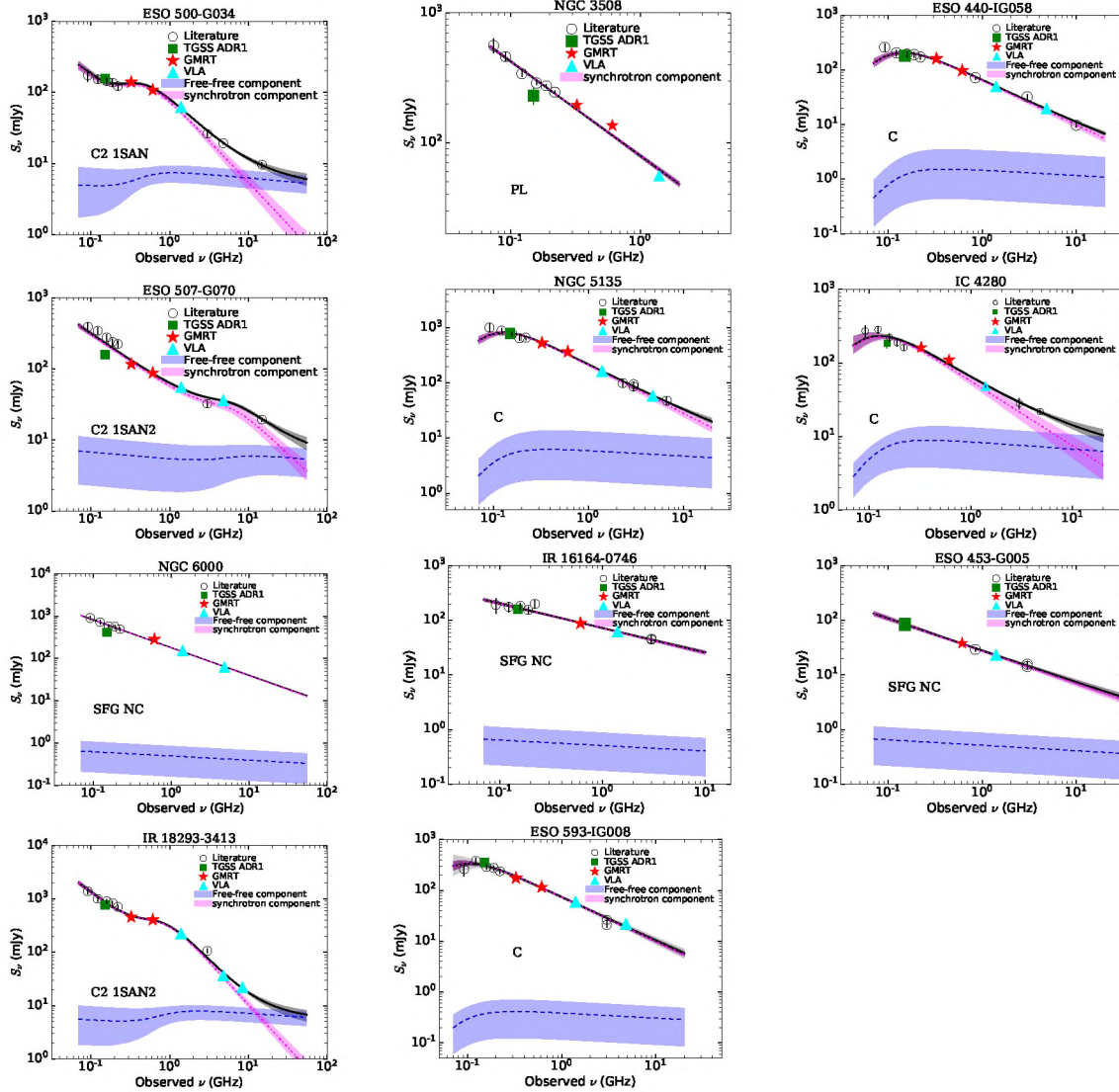


FIGURE 5.1: Radio SED for our sample of LIRGs. Galaxy name and the best-fit radio SED model name are given at the top and inside each panel. The solid black line represents the best-fit model, while the gray shaded region represents the 1σ uncertainties sampled by the UltraNest package. The dot-dashed magenta and dotted blue lines show the decomposed synchrotron and free-free components. The pink and blue shaded regions represent the 1σ uncertainties in the synchrotron and free-free components, respectively. For galaxies fitted with two-component models, the free-free and synchrotron components correspond to the sum of individual free-free and synchrotron components. The flux density measurements obtained with GMRT (365 and 610 MHz) are shown by the filled red star symbol, while the archival VLA data that were reduced and analyzed by us (1.4, 4.8, 8.4, and 14.9 GHz) are shown by the filled cyan triangle. The filled green square indicates the TGSS ADR1 150 MHz fluxes, and the open circle represents the flux density measurements taken from the literature (GLEAM, SUMSS, NVSS, VLASS, ATCA, and Effelsberg telescope) (see Table A2 and A3).

5.4.2 UV to radio SED modeling with CIGALE

A detailed description of SED modeling using CIGALE along with the respective modules is provided in Chapter 4. We estimate astrophysical properties of our galaxies using the SED fitting technique with the CIGALE version 2020.0³ (Noll et al., 2009; Boquien et al., 2019). The SED fitting was performed with a very careful adjustment of the fitting parameters, module by module. Table 5.5 gives the set parameters used to build the SEDs of our galaxies.

TABLE 5.5: List of input parameters for CIGALE modeling.

<i>Parameters</i>		<i>Values</i>
delayed star formation history + additional burst (Ciesla et al., 2015)		
e-folding time of the main stellar population model [Myr]	τ_{main}	300-15000 by a bin of 300
e-folding time of the late starburst population model [Myr]	τ_{burst}	50-1000 by a bin of 50
mass fraction of the late burst population	f_{burst}	0.05, 0.1, 0.3, 0.6, 0.9
Age of the main stellar population in the galaxy [Myr]	age	1000, 2000, 3000, 4500, 5000, 6500, 10000, 12000
Age of the late burst [Myr]	age _{burst}	10.0, 40.0, 80.0, 110, 150, 170
stellar synthesis population (Bruzual and Charlot, 2003)		
Initial mass function	IMF	(Salpeter, 1955)
Metallicity	Z	0.02
Separation age		1 Myr
dust attenuation laws (Calzetti et al., 2000)		
Colour excess of young stars	E(B-V)	0.1-2 by a bin of 0.2
Reduction factor ⁽ⁱⁱⁱ⁾	f_{att}	0.3, 0.44, 0.6, 0.7
dust grain model; THEMIS (Jones et al., 2017)		
fraction of small hydrocarbon solids	q_{hac}	0.02, 0.06, 0.1, 0.17, 0.24
Minimum radiation field	U_{min}	1, 5, 10, 15, 20, 30
power law index of the radiation	α	2
fraction illuminated from U_{min} to U_{max}	γ	0.02, 0.06, 0.1, 0.15, 0.2
active nucleus model; Skirtor (Stalevski et al., 2012, 2016)		
optical depth at $9.7 \mu m$	$\tau_{9.7}$	3.0, 7.0
torus density radial parameter	pl	1.0
torus density angular parameter	q	1.0
angle between the equatorial plan and edge of the torus [deg]	oa	40
ratio of outer to inner radius	R	20
fraction of total dust mass inside clumps [%]	Mcl	97
inclination (viewing angle) [deg]	i	30 (type 1), 70 (type 2)
AGN fraction		0.0-0.4 by a bin of 0.05
extinction law of polar dust		SMC
E(B-V) of polar dust		0.01-0.7 by a bin of 0.5
Temperature of the polar dust	K	100
Emissivity index of the polar dust		1.6
synchrotron emission		
FIR/radio parameter*	q_{IR}	2.3 - 2.9 by a bin of 0.1
Power-law slope (Flux $\propto$ Frequency $^{\alpha_{synch}}$)	α_{synch}	-1.8 to -0.2 by a bin of 0.1

* computed as $\log_{10} L_{IR(8-1000\mu m)} - \log_{10} L_{1.4 GHz}$ where $L_{1.4 GHz}$ is the radio luminosity at 1.4 GHz.

We performed the Probability distribution function (PDF) analysis method to calculate the likelihood function (χ^2) for all possible combinations of parameters (see Section 4.3 of Boquien et al., 2019). We generate the marginalized PDF for every parameter and assess the suitability of the SED model by visual inspection. An example of this method is given

³<https://cigale.lam.fr/>

in Figure 5.2 for the galaxy IC4280 for dust mass.

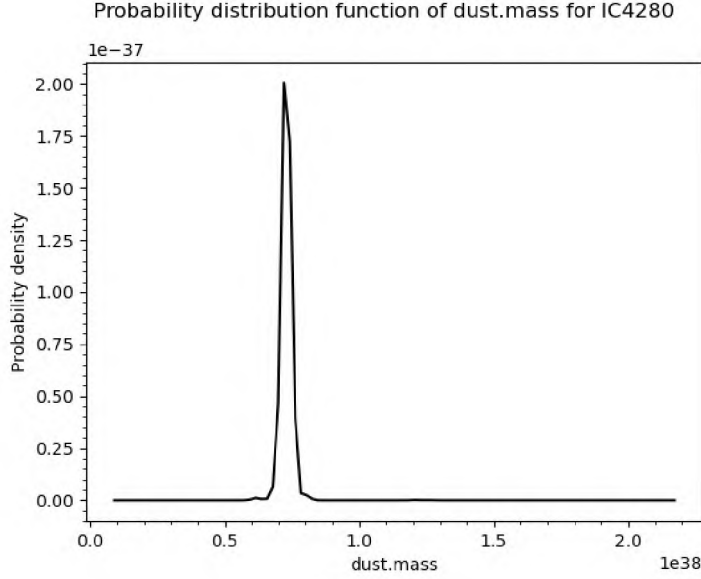


FIGURE 5.2: Probability distribution function (PDF) of the estimated dust mass for galaxy IC 4280 using Bayesian inference.

Figure 5.3 provides the best-fit SED for our sample of LIRGs. We note that some of the photometric data and the best model vary and, for them, the residuals exceed 20-30%. We want to stress that those residuals are often related to strong emission lines, visible for the nebular model. Moreover, this kind of catalog, which includes data from different surveys and instruments, sometimes performed more than 10–20 years ago (GALEX, XMM-OM), reduced with different reduction procedures, can result in heterogeneous photometric coverage of the spectra. In the SED fitting procedure, all measurements are treated with the same weight, and it can happen that the residuals of some of them are not as small as we would expect. The most significant residuals can be found for the g' and r' bands for our galaxies. As fits for the UV part of the spectra look very good, we can assume that the young stellar population was fitted with very good precision. The same observation can be made for i' , z' , and near-IR measurements, which assumes a good estimation of the stellar mass and properties of older stellar populations. The result of SED modeling using CIGALE is provided in Table 5.6.

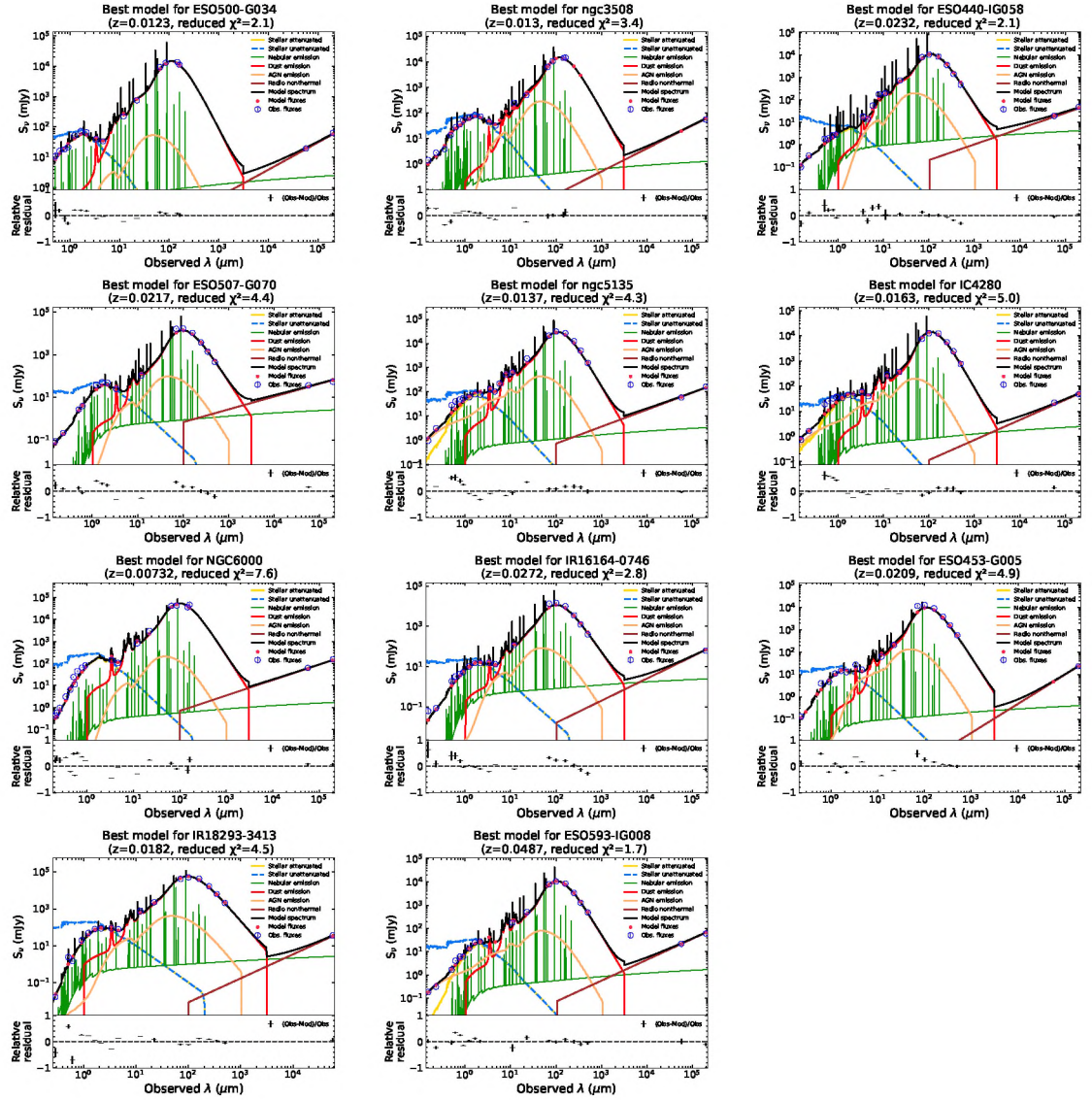


FIGURE 5.3: Best-fit CIGALE SEDs of the 11 LIRGs studied here. The open and filled symbols give the observed and modeled flux densities. The goodness of fit is estimated by reduced χ^2 shown at the top of each panel, along with the name and redshift of the galaxy. In almost all cases, SEDs are well modeled, giving reasonable estimates of astrophysical properties.

TABLE 5.6: CIGALE SED fit results.

Name	$\log_{10}(M_*)$ ($M_\odot$)	$\log_{10}(M_{\text{dust}})$ ($M_\odot$)	T_{dust} (K)	$\log_{10}(\text{SFR}_{\text{IR}})$ ($M_\odot \text{ yr}^{-1}$)	AGN fraction (%)	α_{synch}	$\log_{10}(L_{\text{dust}})$ ($L_\odot$)	q_{IR}	χ^2
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	
ESO 500-G034	10.12 ± 0.07	7.37 ± 0.04	27.55 ± 0.42	0.72 ± 0.14	1.11 ± 0.4	-0.90 ± 0.04	11.86 ± 0.02	2.30 ± 0.01	2.1
NGC 3508	10.32 ± 0.02	7.68 ± 0.02	24.16 ± 0.02	0.59 ± 0.02	6.00 ± 0.001	-0.61 ± 0.03	11.25 ± 0.02	2.43 ± 0.04	3.4
ESO 440-IG058	9.51 ± 0.08	7.82 ± 0.02	27.24 ± 0.002	1.63 ± 0.02	4.53 ± 0.02	-1.20 ± 0.09	10.99 ± 0.02	2.60 ± 0.05	2.1
ESO 507-G070	10.79 ± 0.02	7.61 ± 0.02	30.70 ± 0.003	1.35 ± 0.02	2.00 ± 0.0004	-0.74 ± 0.08	10.93 ± 0.02	2.67 ± 0.05	4.4
NGC 5135	10.34 ± 0.03	7.89 ± 0.08	25.77 ± 1.52	1.05 ± 0.02	6.00 ± 0.04	-0.76 ± 0.09	11.21 ± 0.02	2.50 ± 0.03	4.3
IC 4280	10.44 ± 0.06	7.66 ± 0.04	27.18 ± 0.50	1.07 ± 0.02	6.10 ± 0.60	-0.96 ± 0.15	11.36 ± 0.02	2.30 ± 0.02	5.0
NGC 6000	10.32 ± 0.05	7.39 ± 0.05	28.91 ± 0.50	0.31 ± 0.12	1.06 ± 0.41	-0.90 ± 0.03	10.79 ± 0.02	2.50 ± 0.02	7.6
IR 16164-0746	10.12 ± 0.06	7.82 ± 0.02	29.21 ± 0.003	1.52 ± 0.05	2.24 ± 0.01	-0.80 ± 0.10	10.77 ± 0.02	2.45 ± 0.06	2.8
ESO 453-G005	9.62 ± 0.10	7.69 ± 0.02	27.24 ± 0.05	0.52 ± 0.20	4.72 ± 0.88	-0.82 ± 0.04	10.97 ± 0.02	2.50 ± 0.02	4.9
IR 18293-3413	10.67 ± 0.06	8.06 ± 0.02	30.70 ± 0.06	1.19 ± 0.32	2.55 ± 1.16	-1.19 ± 0.09	11.72 ± 0.02	2.60 ± 0.004	4.5
ESO 593-IG008	10.91 ± 0.19	8.30 ± 0.03	29.55 ± 0.40	1.71 ± 0.16	3.93 ± 2.7	-0.73 ± 0.68	11.18 ± 0.02	2.40 ± 0.001	1.7

Columns: (1) galaxy name, (2) stellar mass, (3) dust mass, (4) dust temperature, (5) instantaneous star formation rate, (6) AGN fraction, (7) slope of power-law synchrotron emission, α , (8) dust luminosity, (9) q_{IR} , (10) reduced χ^2 value for the best-fit model.

5.5 Results

5.5.1 Radio-only and FUV to radio SED modeling

Our main results using detailed radio-only and simultaneous FUV–IR–radio SED modeling using the UltraNest and CIGALE modeling tools, respectively, are given below. The specific notes on individual sources are given in Appendix A.3. Figures 5.1 and 5.3 present the radio-only and FUV–radio SED fits, respectively. Tables 5.3 and 5.6 give the best-fit model parameters and their uncertainties, respectively, for our galaxies. Our main results are the following:

1. The radio continuum SEDs of our galaxies covering ~ 70 MHz– ~ 15 GHz frequency range show a variety of features: (1) single PL model arising from synchrotron emission without thermal contribution, (2) single-component PL models due to synchrotron and free-free emission with and without turnover at low frequencies, and (3) two-component models with distinct emission regions, optical depths, and sometimes different spectral index of the CRe (Figure 5.1). The derived radio synchrotron spectral index ranges between $-0.45^{+0.03}_{-0.03}$ and $-1.74^{+0.04}_{-0.08}$. The turnover frequencies for SEDs fitted with models with absorption features fall in the range between 100^{+20}_{-20} MHz and $7.55^{+1.94}_{-1.97}$ GHz (Table 5.3).
2. Figure 5.3 provides the CIGALE fit for our LIRGs. CIGALE-modeling of the galaxies provides the rest-frame infrared luminosity in the wavelength range of 8–1000 μm ($\log_{10} L_{\text{IR}(8-1000\mu\text{m})}$) as $10.77 \pm 0.02 - 11.86 \pm 0.02 L_{\odot}$. The q_{IR} parameter is $\sim 2.30 \pm 0.02 - \sim 2.67 \pm 0.05$ while the radio spectral index estimated between 1.4 GHz and 5 GHz is in the range of $\sim -0.61 \pm 0.03 - -1.20 \pm 0.09$. The range of estimated stellar mass, dust mass, and dust temperature are $\log_{10} M_{\star} = 9.51 \pm 0.08 - 10.91 \pm 0.19 M_{\odot}$, $\log_{10} M_{\text{dust}} = 7.37 \pm 0.04 - 8.30 \pm 0.03 M_{\odot}$, and $T_{\text{dust}} = 24.16 \pm 0.02 - 30.70 \pm 0.06$ K, respectively. The star formation rate $\log_{10} \text{SFR}_{\text{IR}}$ is $0.31 \pm 0.12 - 1.71 \pm 0.16 (M_{\odot} \text{ yr}^{-1})$. The AGN fraction that contributes to the optical and IR emission ranges between $1.06 \pm 0.41\%$ and $6.10 \pm 0.60\%$ (Table 5.6).
3. Figure 5.4 shows the comparison between the q_{IR} estimated from CIGALE modeling and Equation 5.1. The two estimates are comparable to each other within uncertainties.

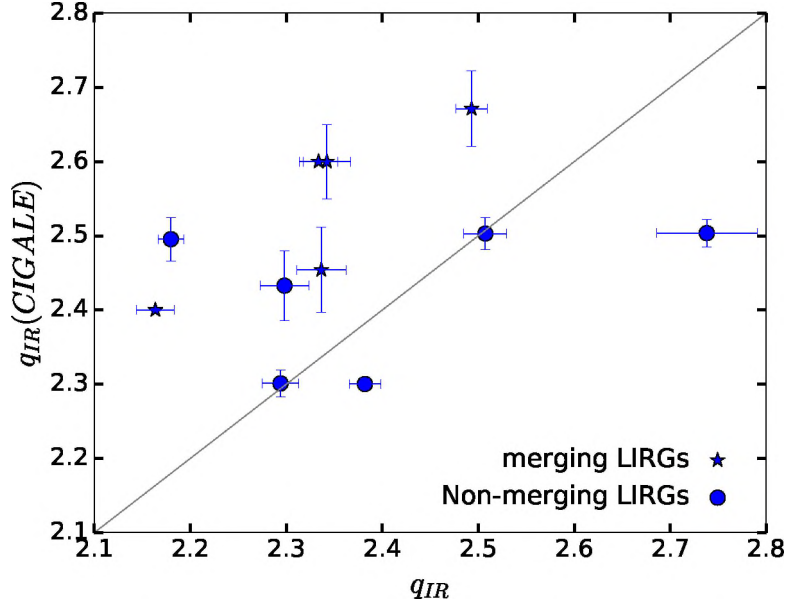


FIGURE 5.4: Comparison of q_{IR} estimated by CIGALE modeling and Equation 5.1. The grey line represents the one-to-one relation.

4. Including the radio measurements in CIGALE modeling allowed us to obtain better constrained L_{dust} values as compared to CIGALE modeling results in the literature, which did not include radio measurements. Although the dust luminosity of our galaxies falls in the range exhibited by galaxies of the same class, we note that our L_{dust} estimates have ~ 1 order of magnitude lower uncertainties than those provided in the literature (Małek et al., 2017).
5. To cross-check the robustness of the CIGALE analysis, we present a comparison of AGN fractions obtained for eight galaxies in our sample to the AGN fractions derived by Díaz-Santos et al. (2017) in Figure 5.5. CIGALE computes the AGN fraction using an AGN template that contributes between UV and IR wavelengths. In contrast, Díaz-Santos et al. (2017) computes the AGN fraction using the mid-IR (MIR) spectral diagnostics, including emission-line ratios, the equivalent width of $6.2\mu m$ polycyclic aromatic hydrocarbon (PAH), the dust continuum slope at 30 and $15\mu m$ as well as spectral template-based diagrams. Except for NGC 5135, we note a close correspondence between our and Díaz-Santos et al. (2017) values, which validates the analysis procedure.

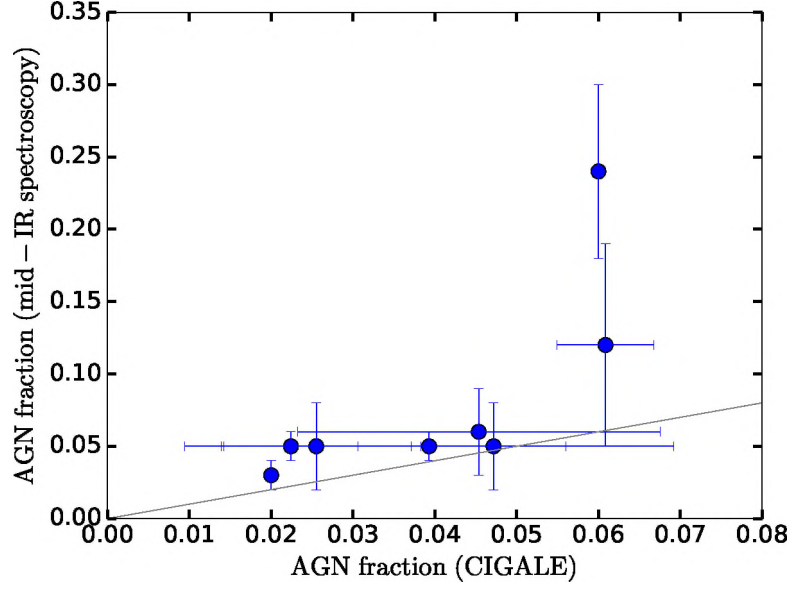


FIGURE 5.5: Comparison of bolometric AGN fractions obtained in this work and [Díaz-Santos et al. \(2017\)](#) for 8 LIRGs in our sample. The grey line represents the one-to-one relation.

5.6 Discussion

5.6.1 q_{IR} parameter

We estimate q_{IR} using far-infrared fluxes at $60\mu\text{m}$ and $100\mu\text{m}$ and 1.4 GHz radio flux to compare with other samples in literature ([Yun et al., 2001](#); [Galvin et al., 2018](#)). That is, we use the following expression given by [Yun et al. \(2001\)](#):

$$q_{\text{IR}} \equiv \log_{10} \left(\frac{\text{FIR}}{3.75 \times 10^{12} \text{ W m}^{-2}} \right) - \log_{10} \left(\frac{S_{1.4\text{GHz}}}{\text{W m}^{-2} \text{ Hz}^{-1}} \right) \quad (5.1)$$

The far infrared luminosity, FIR, is computed using $\text{FIR} \equiv 1.26 \times 10^{-14} (2.58 S_{60\mu\text{m}} + S_{100\mu\text{m}}) \text{ W m}^{-2}$ where $S_{60\mu\text{m}}$ and $S_{100\mu\text{m}}$ are the 60 and $100\mu\text{m}$ band flux densities, in Jy, from IRAS. The error on q_{IR} parameter, computed using Equation 5.1, is derived following standard error propagation. Figure 5.6 shows the distribution of $\log_{10} q_{\text{IR}}$ obtained based on Equation 5.1 with respect to monochromatic infrared luminosity at $60\mu\text{m}$ ($=4\pi d_L^2 \times S_{60\mu\text{m}}$ where d_L is the luminosity distance). To obtain the luminosity distance, we use the cosmological calculator⁴ ([Wright, 2006](#)) with the Hubble constant $H_0 = 69.6 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_{\text{M}} = 0.286$, and $\Omega_{\lambda} = 0.714$ ([Bennett et al., 2014](#)). In this plot, the upper and lower dashed lines represent the 3σ bounds of the mean value. The objects falling above and below the dashed lines are called the “IR excess” (upper dashed line) and the “radio excess” (lower dashed line), respectively. Our sample exhibits typical values of q_{IR} , indicating that radio emission is dominated by star-forming processes without

⁴<http://www.astro.ucla.edu/~wright/CosmoCalc.html>

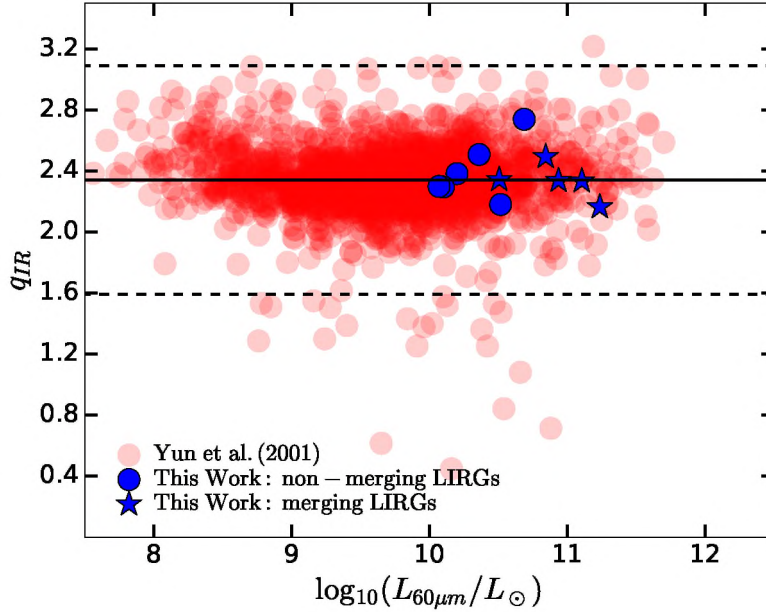


FIGURE 5.6: Distribution of q_{IR} with $60\,\mu\text{m}$ infrared luminosity for our sample of LIRGs. The solid horizontal line marks the mean $q_{\text{IR}} = 2.34$ and the dashed lines represent the upper and lower 3σ bounds (Yun et al., 2001).

any hint of abnormal behavior, such as AGN dominance or unusually high star-forming activity. This supports the results of our UV to IR fitting from CIGALE, where the median AGN fraction is $\sim 2.5\%$, and only for one source ESO 453-G005 it is close to $\sim 10\%$. Furthermore, the distribution of q_{IR} , with respect to $\log_{10} L_{60\mu\text{m}}/(L_{\odot})$ gives comparable results to those obtained for other LIRGs by Yun et al. (2001) and Galvin et al. (2018). According to the plot, the merging and non-merging galaxies take values from the main, most frequent range of q_{IR} values and are indistinguishable in this aspect.

5.6.2 Thermal fraction

From the radio-SED modeling, we computed the thermal fraction at 1.4 GHz, $TF_{1.4\text{GHz}}$, for our sample which range between $0.003^{+0.002}_{-0.002}$ and $0.12^{+0.04}_{-0.04}$ (Table 5.4). We plot the $TF_{1.4\text{GHz}}$ against the rest frame infrared luminosity from CIGALE (Figure 5.7). Our values are similar to those obtained for a different sample of starburst galaxies, including LIRGs and ULIRGs (19 galaxies at median redshift equal to 0.09; Galvin et al., 2018). These values are also compatible with those obtained from normal star-forming galaxy samples (Niklas et al., 1997; Tabatabaei et al., 2017).

5.6.3 Radio spectral indices and spectral curvature

The integrated radio spectras for our sample of LIRGs show complex forms and are rarely described by single power-laws (Figure 5.1). Eight out of 11 galaxies show bends in their

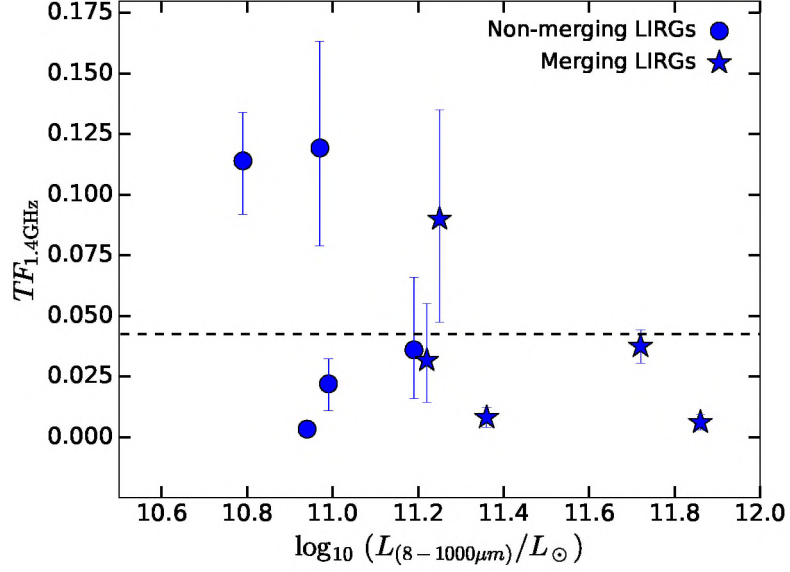


FIGURE 5.7: Thermal fraction (TF) at 1.4 GHz plotted against the rest-frame infrared luminosity obtained from our CIGALE modeling. The dashed line marks the average thermal fraction = 0.042 for our sample.

spectra which we model as arising due to free-free absorption. Here we mention that curvatures in radio SEDs can also occur if the ISM is optically thin to thermal emission and if the refractive index of the medium is less than unity (Tsytovitch-Razin effect; [Israel and Mahoney, 1990](#)), and due to synchrotron self-absorption (SSA; [Israel and Mahoney, 1990](#)). For our galaxies, the radio surface brightness ($=\text{Peak flux}/\theta^2$, where flux is in Jy and θ is the size in arcsec of the source; for unresolved sources, we take the synthesized beam size as the upper limit for the size) is of the order of 10^{-2} (Table A1). For the SSA mechanism to be important at 100 MHz frequencies for our sources, unreasonably high magnetic field strengths >1000 G are needed ([Kellermann and Pauliny-Toth, 1969](#)). Therefore, SSA as a cause of turnover can be safely ruled out for our sample. The Razin turnover frequency is given as $20 \times n_e/B(\text{MHz})$, where n_e is the electron density (cm^{-3}) and B is the magnetic field strength in μG ([Ginzburg and Syrovatskii, 1965](#)). In ISM, for the typical CRe density ~ 1 (cm^{-3}) ([Ferrière, 2001](#)) and the typical magnetic field strength of $50\mu\text{G}$ ([Crocker et al., 2010](#)), the Razin turnover frequency turns out to be 0.4 MHz. Therefore, we can safely rule out the Razin effect as a cause of low-frequency spectral turnover.

The synchrotron spectral index ranges between ~ -0.5 and ~ -1.7 . The galaxies IR 16164–0746 and ESO 453-G005 have relatively flatter spectra, ~ -0.5 , compared to the canonical value of -0.75 ([Condon, 1992](#)). For these galaxies, the spectral flattening can be ascribed to a change in the CRe spectrum (electron energy index = 2.1) because of ionization losses ([Lacki et al., 2010](#); [Ramírez-Olivencia et al., 2022](#)). Galaxies NGC 3508,

ESO 440-IG058, NGC 5135, IC 4280, NGC 6000, and ESO 593-IG080 exhibit typical values of synchrotron spectral slope, ranging between -0.7 and -0.9 . The remaining three galaxies, ESO 500-G034, ESO 507-G070, and IR 18293-3413, show steeper spectral slopes ranging between -1.17 and -1.74 . Interestingly, galaxies showing steeper synchrotron spectral indices are fitted with two-component emission models. On the assumption that the ejection indices of the electron energies are all similar but steepen due to physical processes. Normal synchrotron losses cause a 0.5 steepening in spectral index (Marvil et al., 2015). Therefore, within uncertainties, our spectral indices are consistent with a typical $\alpha \sim -0.75$ and a value of $\alpha \sim -1.25$. The slightly flatter values are almost within the errors, which could be due to the complexity of the radio SED. We cannot evaluate it due to the poor spectral resolution achieved in our images. We speculate along the lines of Galvin et al. (2018), who also modeled the radio SED LIRGs, that the CRe energy spectrum is intrinsically steep for these galaxies. We remark that, unlike frequent assumptions, the nonthermal spectral index is not fixed, and it changes between -0.45 and -1.75 , which could be due to the influence of star formation on the energetics of CRe as discussed in Tabatabaei et al. (2017).

5.6.4 Emission measure

The emission measure (EM) is an integral of the electron density along the line of sight. EM is calculated by assuming that the emission originates from a cylindrical geometry with constant temperature and electron density (Condon, 1992). From the spectral turnover frequency, one can estimate the EM from the formula of the optical depth, τ_ν :

$$\tau_\nu = 3.28 \times 10^{-7} \left(\frac{T_e}{10^4 \text{ K}} \right) \left(\frac{\nu}{\text{GHz}} \right)^{-2.1} \left(\frac{EM}{\text{pc cm}^{-6}} \right) \quad (5.2)$$

where T_e is the electron temperature of the H_{II} emitting region and EM is the emission measure of depth s . τ_ν is the optical depth, set at unity at turnover frequency measured from our SED modeling. The EM is given by the integral of the electron density, N_e , along the line of sight of the H_{II} region of depth s :

$$\frac{EM}{\text{pc cm}^{-6}} = \int_{los} \left(\frac{N_e}{\text{cm}^{-3}} \right)^2 d \left(\frac{s}{\text{pc}} \right) \quad (5.3)$$

We compute the EMs for our sources using the turnover frequencies obtained from our modeling (Table 5.3) and assuming a typical electron temperature 10^4 K (Clemens et al., 2010; Galvin et al., 2018). Table 5.7 provides the emission measures for our sample. Our EM values cover the same range as that obtained by Galvin et al. (19 LIRGs; 2018). Furthermore, our EM values are also consistent with those obtained by Clemens et al. (20 LIRGs and ULIRGs; 2010).

TABLE 5.7: Emission Measure (EM) is derived from the model most supported by the evidence value for each source. Sources without constrained EM are marked by ‘–’

Name	EM ₁ (10 ⁶ cm ⁻⁶ pc)	EM ₂ (10 ⁶ cm ⁻⁶ pc)
ESO 500-G034	–	0.77
NGC 3508	–	–
ESO 440-IG058	0.05	–
ESO 507-G070	–	269.5
NGC 5135	0.04	–
IC 4280	0.05	–
NGC 6000	–	–
IR 16164-0746	–	–
ESO 453-G005	–	–
IR 18293-3413	–	3.44
ESO 593-IG008	0.02	–

5.6.5 Thermal fraction vs. q_{IR}

In star-forming galaxies the radio spectral index is expected to be correlated with TF and q_{IR} with the star formation history playing a key role (Marvil et al., 2015). This is because in young star forming galaxies ($< 10^8$ yr; Condon (1992)) the radio emission is mainly due to free-free emission with a relatively flatter spectrum ($\alpha \sim -0.1$) leading to relatively higher values of TF and q_{IR} (Marvil et al., 2015). As the starburst ages, TF and q_{IR} are expected to decrease as the time-delayed nonthermal emission increases with time. This is mainly because the nonthermal emission originates from relatively old ($> 10^7$ yr; the average lifespan of $> 8 M_{\odot}$ OB type stars) relativistic electrons considering the time taken for the diffusion ($\sim 10^4$ yr) of these electrons across the galaxy is negligible (Clemens et al., 2010; Galvin et al., 2018). Figure 5.8 shows the relation between TF and q_{IR} (computed using Equation 5.1) as a function of the SFR ratio obtained at time intervals 10 Myr and 100 Myr ago from the CIGALE analysis. This representation is informative in order to understand the evolution of the thermal fraction and q_{IR} with the age of star formation. The large scatter observed in the plot can be explained by the following reasons: (i) ceasing of star formation before nonthermal emission commences, (ii) early contribution of nonthermal emission to the radio continuum while star formation is still ongoing, and (iii) due to limited sample size.

5.6.6 M_{dust} vs. SFR

In Figure 5.9 we show the relation of SFR_{IR} with dust mass for our sample, including data from the literature for normal star-forming galaxies in the local Universe (da Cunha et al., 2010b), LIRGs at low ($z < 0.5$) and high ($z > 0.5$) redshifts (Vega et al., 2008; Lo Faro et al., 2013; Pereira-Santaella et al., 2015; da Cunha et al., 2015; Małek et al., 2018; Paspaliaris et al., 2021), and ULIRGs at low and high redshifts (Vega et al., 2008; da Cunha

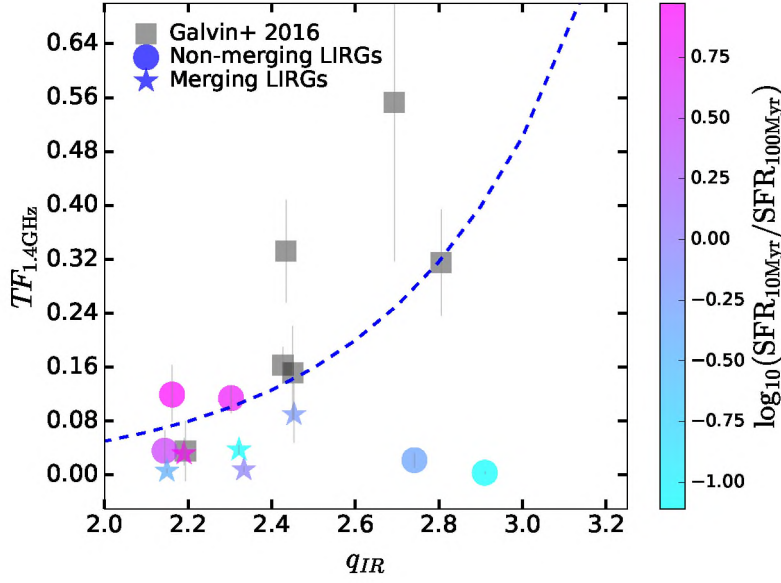


FIGURE 5.8: Distribution of thermal fraction with q_{IR} (Equation 5.1) for our sample of LIRGs. The color bar indicates the SFR_{IR} obtained for a time interval of 10 Myr ago from the CIGALE analysis. The dashed line marks the relation between thermal fraction and q_{IR} given by $TF = 1.7 \times 10^{q_{\text{IR}} - 3.53}$ (Marvil et al., 2015).

et al., 2015; Małek et al., 2017, 2018). Our sample of LIRGs lies essentially in between the two sequences of normal and starburst galaxies defined by Rowlands et al. (2014), in excellent agreement with the behavior shown by starburst galaxies. This is because our IR selection $S_{60\mu\text{m}} \geq 5 \text{ Jy}$ selects sources to have high SFRs. Moreover, our merger-type galaxies (filled star symbol) lie systematically higher in SFR than the nonmergers (filled circle) and at the same time lie systematically below the high redshift LIRGs (diamonds) and ULIRGs (plus), while the normal star-forming galaxies (cross symbol) occupy the region characterized by a lower star formation rate and dust mass. This can be understood as follows. With an increase in the SFR, there is also an increase in the supernova rate, leading to a more efficient enrichment of the ISM with dust. Since SFR is correlated with dust mass, and the dust relates to the gas content in galaxies (Kennicutt relation links SFR and gas mass), therefore, a positive trend in the evolution of SFR with dust mass is expected with our LIRGs when compared with local star-forming galaxies and ULIRGs (Rowlands et al., 2014; Donevski et al., 2020a). High SFR values are seen for interacting/merging LIRGs galaxies as compared to nonmergers (see also, Paspaliaris et al., 2021).

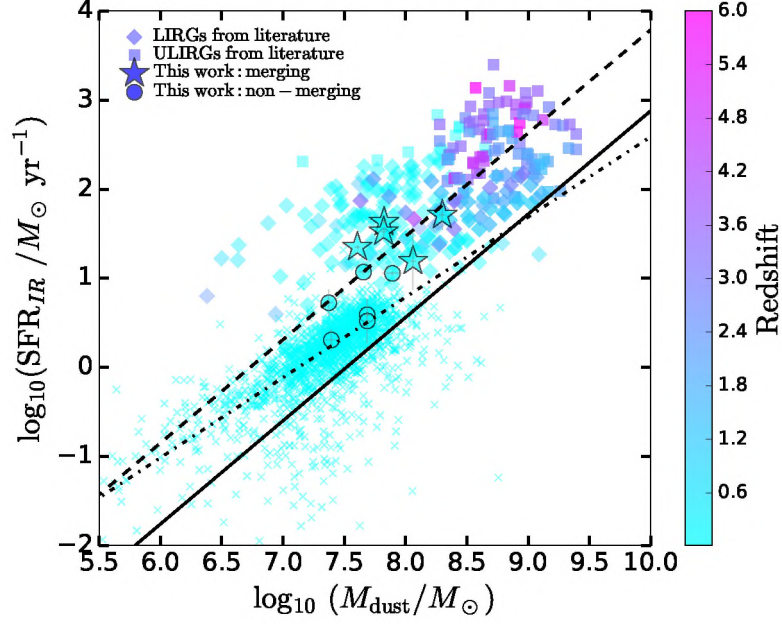


FIGURE 5.9: SFR_{IR} vs M_{dust} for our sample of LIRGs obtained from CIGALE modeling. The solid and dashed lines, respectively, are the relations derived from low- z dusty galaxies (H-ATLAS) and starburst galaxies (local ULIRGs and $z > 2$ submillimeter galaxies) by Rowlands et al. (2014). The dot-dashed line represents the best-fit line to the SDSS-IRAS selected local star-forming galaxies of infrared luminosities ($10 \leq \log_{10}(L_{\text{dust}}/L_{\odot}) < 12$) given by da Cunha et al. (2010b).

5.6.7 SFR vs. stellar mass and nonthermal fraction

Figure 5.10 explores the relation of stellar mass with the CIGALE estimated star formation rate (SFR_{IR}) for our galaxies, including the data for normal star-forming galaxies and the ULIRGs from the literature. As shown, our sample of LIRGs lies systematically above the main galaxy sequence represented by the parametric relation (solid line with 0.4 dex error denoted by dashed lines; Saintonge et al., 2016) along with local star-forming galaxies from the sample of da Cunha et al. (2010b). There is no evidence of a correlation between stellar mass and SFR_{IR} for LIRGs and ULIRGs, including our sample (star symbol), which is explained by reaching saturation in SFR_{IR} and stellar mass for these types of galaxies (da Cunha et al., 2010b; Paspaliaris et al., 2021). Figure 5.11 explores the relationship between the 1.4 GHz nonthermal fraction, nTF ($=$ nonthermal luminosity/total luminosity), and the SFR_{IR} for our galaxy sample. All galaxies, including merger and non-merger types in our sample, exhibit high nTF values at 1.4 GHz, as expected. As we see a clear distinction between the SFR_{IR} values for merger- and non-merger-type galaxies, with the higher SFR_{IR} values being exhibited by merger-type galaxies, one would expect stronger magnetic fields B in these objects due to strong turbulence created by the merger process. For a given synchrotron lifetime of CRe, $\tau_{\text{synch}} \propto B^{-1.5}$, the CRe have a good chance to efficiently lose their energy via synchrotron radiation before escaping the star-forming regions.

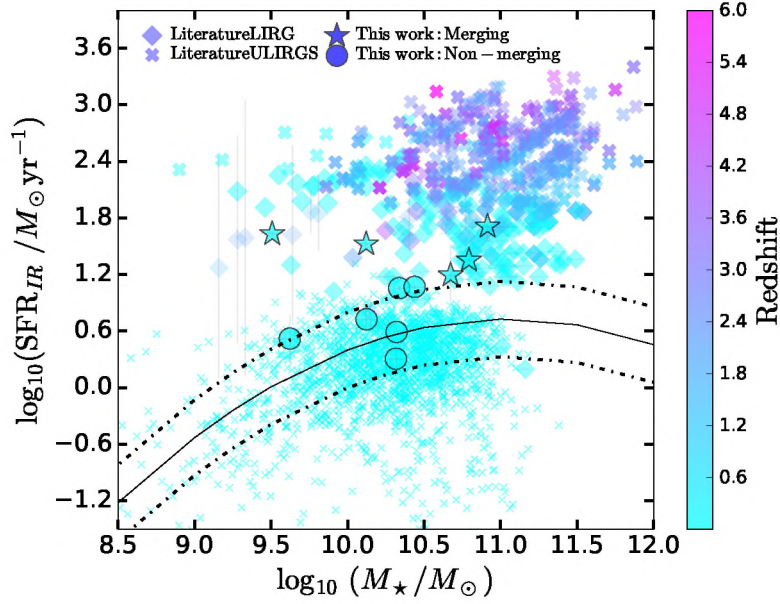


FIGURE 5.10: SFR_{IR} vs $M_{\star}$ for our sample of LIRGs obtained from CIGALE modeling. The solid line represents the relation between $M_{\star}$ - SFR_{IR} for the main sequence galaxies given by [Schreiber et al. \(2015\)](#) for a redshift range of 0.02. The dotted and dashed-dotted lines show the range of the main sequence spreading ± 0.4 dex above and below the solid line.

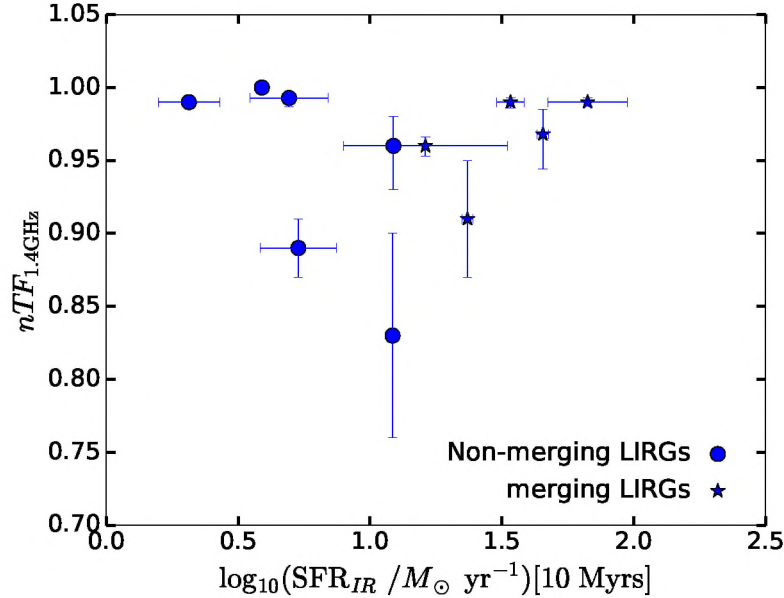


FIGURE 5.11: 1.4 GHz non-thermal fraction, nTF , as a function of SFR_{IR} for a time interval of 10 Myr. The nonthermal fraction is estimated in the same manner as that of the thermal fraction (see Section 5.6.2).

In this regard, we note that resolved studies show that the radio spectral index is flatter in star-forming regions (Fletcher et al., 2011; Tabatabaei et al., 2007, 2013; Hassani et al., 2022), which contradicts the claimed argument of complete synchrotron cooling of CRe before escape from star-forming regions. Moreover, in star-forming regions, there is also a strong chance of CRe escape due to star formation feedback (Murphy et al., 2008). A fine balance between gas and magnetic fields/CRe can more realistically explain the nTF-SFR_{IR} correlation observed in normal star-forming galaxies (Tabatabaei et al. (2013) and Lacki et al. (2010)).

5.6.8 Specific star formation rate

Figure 5.12 shows the evolution of specific star formation rate, (sSFR_{IR} defined to be the ratio of SFR and $M_\star$), with respect $M_\star$ (panel (a)), specific dust mass (sM_{dust} defined to be ratio of M_{dust} and $M_\star$; (panel (b)), and T_{dust} (panel (c)), respectively, for our sample of LIRGs including the data from the literature for normal star-forming galaxies along with LIRGs and ULIRGs. The sSFR_{IR} measures the recent star formation activity and is defined as the current star formation over the stellar mass of the galaxy (Donevski et al., 2020a; Paspaliaris et al., 2021). Panel (a) shows an anticorrelation between the sSFR and $M_\star$ for the three samples, indicating that massive galaxies are less efficient in star formation than less-massive ones. This is expected in the ‘downsizing’ scenario of galaxy evolution, where massive galaxies formed most of their stars earlier and on shorter timescales. In comparison, less-massive galaxies evolve on longer timescales (Scodreggio et al., 2009; Popesso et al., 2011; Sobral et al., 2011; Laganá and Ulmer, 2018).

Panel (b) shows a positive correlation between sSFR_{IR} and sM_{dust} for the three samples, with LIRGs and ULIRGs occupying higher sSFR values per unit of specific M_{dust} compared to normal star-forming galaxies. In this plot, the contribution of $M_\star$ to SFR and M_{dust} is normalized, making it ideal for studying gas-to-dust behavior in galaxies (Smith et al., 2012; Hunt et al., 2014; Donevski et al., 2020a). First, the figure shows that there is an increase in dust mass compared to stellar mass on a very short timescale for these galaxies with LIRGs and ULIRGs expected to occupy the top-right corner of the plot (see, Donevski et al., 2020a, and the references therein). The relationship between sM_{dust} and sSFR indicates an evolutionary scenario in which sSFR decreases due to exhaustion of the gas reservoir and therefore causes an inefficient dust production, causing galaxies to occupy the bottom left corner of the plot (Burgarella et al., 2020). As expected, our LIRGs follow the trend, and local and high redshift LIRGs and ULIRGs with normal star-forming galaxies are in a different branch.

Panel (c) shows the distribution of sSFR_{IR} with T_{dust} for our LIRGs and local and high redshift LIRGs and ULIRGs obtained from the literature. We note that the dust temperature obtained for our LIRGs falls in a narrow range. This is most likely due to the discrete nature of the parameter space used in the CIGALE modeling, including the

values provided for the interstellar radiation field needed to heat the dust (Equation 1 of; Paspaliaris et al., 2021). In general, a linear trend is observed between sSFR with T_{dust} , extending to highz galaxies, which is due to the heating of dust surrounding the young stellar population in highly star-forming galaxies (Magnelli et al., 2014; Liang et al., 2019). However, our sample has more homogeneous properties and indicates dust temperature within a limited range of 24 K to 32 K.

This comparison indicates that our galaxies fall in the middle of the parameter space occupied by normal galaxies of the local Universe and distant starburst objects, exhibiting intermediate properties, as expected, between the two extremes of the galaxy evolution.

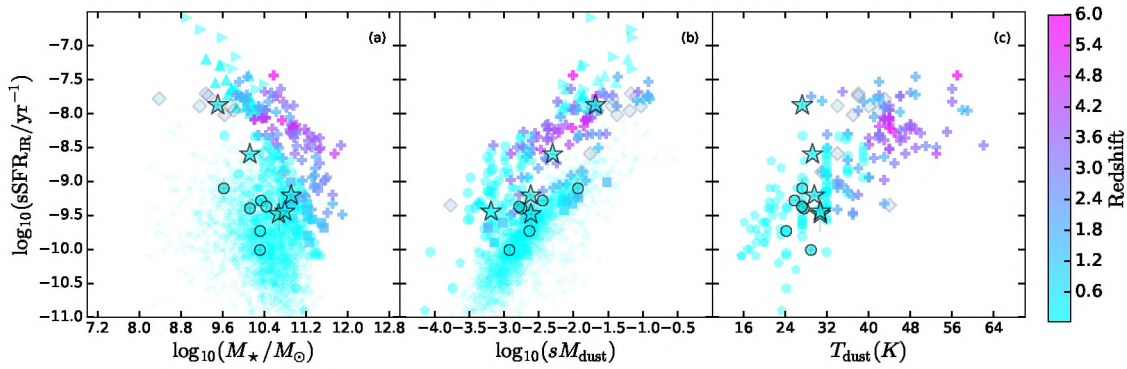


FIGURE 5.12: Distribution of sSFR_{IR} with respect to stellar mass (panel (a)), specific dust mass (panel (b)) and dust temperature (panel (c)) for the 11 LIRGs studied here (star and circle symbols represent the merging and non-merging types). For comparison, we include data from literature for normal star forming galaxies (cross; da Cunha et al., 2010b), LIRGs (upward facing triangle; Vega et al., 2008), (circle; Paspaliaris et al., 2021), (diamond; da Cunha et al., 2015), (square; Lo Faro et al., 2013), and ULIRGs, (right side facing triangle; Vega et al., 2008), (plus; da Cunha et al., 2015).

5.6.9 Calibrating SFR in Radio Wavelength

Our detailed radio SED modeling enabled us to decompose the nonthermal and thermal spectral luminosities and derive the respective SFRs. For this, we use the radio SFR calibration relations given by Murphy et al. (2011). Thermal SFR, SFR_νth is derived using Kroupa initial mass function (IMF; Kroupa, 2001) assuming solar metallicity and continuous star formation:

$$\left(\frac{\text{SFR}_{\nu}^{\text{th}}}{M_{\odot} \text{ yr}^{-1}} \right) = 4.6 \times 10^{-28} \left(\frac{T_e}{10^4 \text{ K}} \right)^{-0.45} \left(\frac{\nu}{\text{GHz}} \right)^{0.1} \times \left(\frac{L_{\nu}^{\text{T}}}{\text{erg s}^{-1} \text{ Hz}^{-1}} \right) \quad (5.4)$$

where L_{ν}^{T} is the thermal spectral luminosity and $T_e=10^4$ K.

The nonthermal SFR, $\text{SFR}_\nu^{\text{nth}}$, is derived using calibration between the supernova rate and the SFR using the output of Starburst99 model (Leitherer et al., 1999), and empirical relation between supernova rate and nonthermal spectral luminosity, L_ν^{NT} , of the Milky Way (Tammann, 1982; Condon and Yin, 1990):

$$\left(\frac{\text{SFR}_\nu^{\text{nth}}}{M_\odot \text{ yr}^{-1}} \right) = 6.64 \times 10^{-29} \left(\frac{\nu}{\text{GHz}} \right)^{\alpha^{\text{NT}}} \left(\frac{L_\nu^{\text{nth}}}{\text{erg s}^{-1} \text{ Hz}^{-1}} \right) \quad (5.5)$$

where, $\alpha^{\text{nth}} = \alpha = \alpha_{\text{synch}}$ is the synchrotron spectral index. For our calculations, we use the values obtained from the radio SED modeling (Table 5.3).

The total SFR at 1.4 GHz, $\text{SFR}_{1.4\text{GHz}}$ is derived using the relation between the IR emission and current SFR resulting from the integration of the output of Starburst99 spectrum over the wavelength range of 912Å – 3646Å, and the q_{IR} relation (see Equation 5.1). We use $q_{\text{IR}} = 2.64$ (Bell, 2003) to arrive at the total $\text{SFR}_{1.4\text{GHz}}$ relation:

$$\left(\frac{\text{SFR}_{1.4\text{GHz}}}{M_\odot \text{ yr}^{-1}} \right) = 6.35 \times 10^{-29} \left(\frac{L_{1.4\text{GHz}}}{\text{erg s}^{-1} \text{ Hz}^{-1}} \right) \quad (5.6)$$

Figure 5.13 shows the comparison of the SFR obtained from the CIGALE SED fitting for two time intervals, 10 and 100 Myr ago, and the 1.4 GHz radio SFR (total, nonthermal, and thermal, respectively). Upon visual inspection, we notice that SFR obtained from IR modeling shows a one-to-one correlation with 1.4 GHz radio SFR. A striking result is that we obtain a much better correspondence of radio emission (total and synchrotron) with the young stellar population of about 10 Myr than with the older population. To check this, we applied Spearman’s rank correlation test, which measures the statistical dependence between the two variables (Spearman, 1904). A null hypothesis of no correlation is tested against the alternate hypothesis of non-zero correlation at a certain significance level ($=0.01$, adopted by us).

Typically, the p -value⁵ < 0.01 means that the null hypothesis of no-correlation is rejected at a confidence level $> 99\%$. For the star formation rate at 10 Myr ago, the obtained p -values are 0.0008 and 0.0002, respectively, rejecting the null hypothesis that the radio (total, nonthermal, and thermal) and IR SFRs are not correlated. At the same time, the ρ -values⁶ are positive, indicating a positive correlation between the two variables (panels (a) and (b) of Figure 5.13). The null hypothesis of no correlation is not rejected for a significance level of 0.01 for thermal SFR and SFR_{IR} at 10 Myr ago (panel (c) of Figure 5.13) and radio and SFR_{IR} at 100 Myr ago (panel (d), (e), (f) of Figure 5.13). This is probably due to the relatively short lifetime of the CRe synchrotron at the 1.4 GHz frequency. At this frequency, in a magnetic field of about 50 μG (Crocker et al., 2010), the synchrotron lifetime is $\approx 3.3 \times 10^5 \text{ yr}$. Therefore, synchrotron emission may be

⁵ p -value is the probability of obtaining the result as extreme as observed by chance

⁶ ρ -value measures the strength and direction of association between two ranked variables

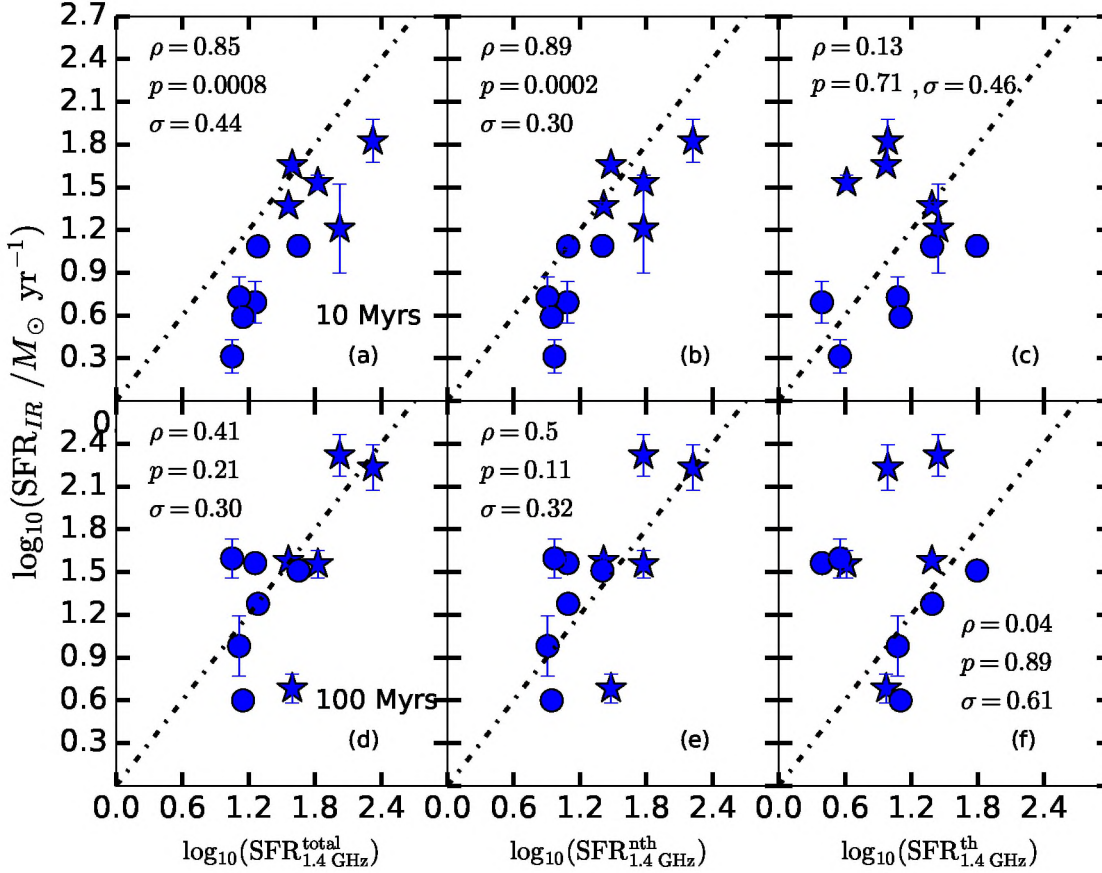


FIGURE 5.13: Comparison of the SFR obtained from the CIGALE SED fitting for two time intervals 10 and 100 Myr ago and the 1.4 GHz radio SFR (total, nonthermal, and thermal, respectively). The mergers and non-mergers are shown with star and circle symbols, respectively. p - and ρ - values are obtained from the application of the Spearman's rank correlation test.

an effective indicator of recent SFR in galaxies. The thermal component appears to be less useful because of visible significant scatter in the predicted SFR. Since thermal emission is much weaker than synchrotron emission at this frequency, this may explain its weaker usefulness than the nonthermal component. Our analysis strengthens that 1.4 GHz radio SFR measurements can be used as a diagnostic tool for high- z galaxies (Murphy et al., 2011; Tabatabaei et al., 2017).

5.6.10 Comparison of radio spectral indices from Radio-only and CIGALE SED Modeling

We emphasize that both radio-only and FUV to radio modeling includes synchrotron emission in the models; however, the direct comparison between the synchrotron spectral index obtained from the two SED fitting techniques is inadequate. This is because the CIGALE modeling (FUV to radio) uses a very simple formulation to compute the radio flux at 1.4 GHz. This is done using the standard q_{IR} relation at 1.4 GHz and the integrated IR

luminosity between 8 and 1000 μm . The radio flux at other frequencies is then computed using a single PL model with an assumed value of the spectral index. However, it is observed that the radio-only SEDs show complex morphologies (flattening or turnovers at lower frequencies and steepening at higher frequencies for some cases). Furthermore, such a direct comparison would only reveal the known scatter in the q_{IR} relation (Wang et al., 2019; Sinha et al., 2022). Furthermore, the limitations of this simple extrapolation in the CIGALE modeling are evident by the discontinuities in the radio wave bands 5.3.

5.7 Conclusion and final remarks

In this study, we have performed joint modeling of SEDs of 11 LIRGs, focusing in radio-only and FUV to radio bands where model parameters are estimated using state-of-the-art Bayesian (radio-only) and Bayesian-like (CIGALE modeling) inference techniques. The radio spectra of LIRGs studied here show complex features. Moreover, the obtained q_{IR} , thermal fraction ($\leq 10\%$) emission measure for our galaxies is comparable to other LIRGs in the literature. CIGALE modeling allows us to fit complex star formation history models, i.e., delayed star formation with an exponential burst (in our case), enabling us to estimate SFR_{IR} at different time intervals. Our main findings are the following:

1. The radio-only SED modeling shows that radio spectra have complex features, showing bends and turnovers. Unlike the frequent assumptions, this shows that the non-thermal spectral index is not fixed, and it changes -0.45 and -1.75 , which could be due to the influence of star formation on the energetics of CRe. The computed 1.4 GHz TF falls between $\sim 0.8\%$ and $\sim 0.12\%$ for our galaxies, similar to that obtained for other LIRGs in the literature.
2. Although many studies have performed FUV-IR SED modeling using CIGALE for star-forming galaxies, LIRGs, and ULIRGs, only a handful have included radio measurements in the SED fitting (e.g., Vega et al., 2008; Shen et al., 2020; Hamed et al., 2021). The inclusion of radio measurements in CIGALE modeling mostly serves to better constrain the derived dust luminosity. Our results indicate that, while the values of L_{IR} , fall in the range exhibited by galaxies of the same class, the uncertainties on them are improved by one order of magnitude as compared to those given in the literature.
3. The $M_{\star}$, T_{dust} , SFR_{IR} , AGN fraction derived using CIGALE modeling for our galaxies fall in the range exhibited by galaxies of the same class. The AGN is not energetically dominant in our sources, as the typical AGN fraction is $\leq 6\%$ similar to those found in other samples. The bolometric AGN fraction obtained by CIGALE is similar to that obtained from spectroscopic methods for the majority of our galaxies, indicating the robustness of the CIGALE analysis.

4. Comparison of the 1.4 GHz radio SFRs obtained using the total, and nonthermal radio emissions show a close correspondence with the CIGALE-obtained SFRIR at 10 Myr ago as compared to 100 Myr ago, strengthening the view that 1.4 GHz SFR estimates are a good indicator of recent star formation.

The comparison of astrophysical properties obtained by radio SED modeling and CIGALE modeling with other samples studied in the literature indicates that our sample belongs to a homogeneous population of LIRGs with respect to their astrophysical properties. Finally, we end by stating an obvious caveat that our findings are based on a SED study of a relatively small sample (11 LIRGs in total and five merger-type galaxies). Therefore, a larger sample with broadband SED coverage is needed to strengthen the tentative findings presented in this study.

This chapter originally appeared as “Radio-only and Radio to far-ultraviolet Spectral Energy Distribution Modeling of 14 ULIRGs: Insights into the Global Properties of Infrared Bright Galaxies” by Subhrata Dey, Arti Goyal, Katarzyna Małek, Tanio Díaz-Santos; 2024, The Astrophysical Journal, Volume 966, Issue 1, id.61, 31 pp. (Dey et al., 2024)

6

Radio-only and Radio-to-FUV SED modeling of 14 ULIRGs: Insights into the Global Properties of Infrared Bright Galaxies

6.1 Introduction

Luminous infrared galaxies (LIRGs; $L_{\text{IR}}[8 - 1000\mu\text{m}] \lesssim 10^{11-12} L_{\odot}$ where $L_{\odot}$ is the solar luminosity) and Ultra luminous infrared galaxies (ULIRGs; $L_{\text{IR}}[8 - 1000\mu\text{m}] \gtrsim 10^{12} L_{\odot}$) are excellent laboratories for studying star formation and active galactic nuclei (AGN) (Sanders et al., 1988). U/LIRGs could be linked with the hierarchical transformation of starforming galaxies into elliptical galaxies, the formation of quasars, and the coevolution of supermassive black holes (SMBH) and stellar bulges (Sanders et al., 1988; Hopkins et al., 2006). The high IR luminosities in U/LIRGs are associated with interactions and mergers between gas-rich galaxies that effectively distort their morphologies. These interactions and mergers funnel gas and material toward the galactic nuclei, which fuels the central starbursts and facilitates the accretion of matter onto SMBH, leading to the growth of the stellar and SMBH masses (for a recent review; U, 2022). The high IR luminosity is a result of the absorption of ultraviolet (UV) emissions generated by enhanced star formation, either by dust (Rigopoulou et al., 1999; Lonsdale et al., 2006) or by the optically thick torus surrounding the AGN. Subsequently, this absorbed energy is reradiated in the infrared wavelength range. The relative contribution of these two processes and their interconnection has been extensively studied (Armus et al., 2007; Spoon et al., 2007;

Veilleux et al., 2009).

The spectral energy distribution (SED) of galaxies is shaped by physical processes occurring within the galaxy with imprints of its components such as stars, dust, AGN, etc. Although different emission mechanisms contribute to different wavelength regimes, a considerable interplay between galaxy components impacts the overall shape of the SED. The FUV–IR SEDs of galaxies probe stellar mass ($M_{\star}$) and star formation rates (SFRs) as the emission in this regime is dominated by stellar processes related to short-lived massive OB stars ($\sim 8M_{\odot}$) and low-mass stars (Taylor et al., 2011; Kennicutt and Evans, 2012). The computation of SFR is further complicated as the intrinsic SEDs are modified by dust, which absorbs the UV-optical photons and re-emits at IR wavebands (Salim and Narayanan, 2020). The presence of an AGN also adds to this complexity, as its SED also spans the entire electromagnetic spectrum, from radio to X-rays to γ -rays (Blandford et al., 2019). It has prominent features such as the “infrared bump” at 10–20 μm and an upturn in optical-UV, the “big-blue bump” (Elvis et al., 2012; Krawczyk et al., 2013). The former is the reprocessed dust emission from the torus of the UV photons, while the latter originates from the SMBH’s accretion disk. Studying the host galaxies’ properties in the presence of an AGN is challenging because the central nuclei often outshine them, making it hard to analyze stellar populations. In an obscured AGN, the host galaxy’s light dominates the optical/near-IR SED, complicating estimates of intrinsic nuclear power. To effectively address this issue, a widely used strategy involves fitting the SED by utilizing diverse combinations of theoretical models and empirical templates for each specific emission component (e.g., as demonstrated in da Cunha et al., 2008).

Radio SEDs probe processes related to star formation as well as the presence of AGN. The radio SED of galaxies is composed of steep spectrum synchrotron emission ($S \propto \nu^{-\alpha}$ where $\alpha = 0.75 \pm 0.1$ (Condon, 1992) is the slope) and flat spectrum thermal free-free emission (FFE; $S \propto \nu^{-0.1}$) processes (Condon, 1992). Moreover, the shape of radio SED and its slope are used to probe the radiation laws and the heating/cooling mechanism of the interstellar medium (ISM) and AGN activity (e.g., Heesen et al., 2022). The radio SEDs of galaxies are further complicated by the presence of radio-AGN, where the radio emission can be due to relativistic jets, or it can be from various sources, including star formation, AGN-driven winds, photo-ionized gas, low-power jets, and inner accretion disc coronal activity (Panessa et al., 2019). It is becoming increasingly common to consider all components while modeling UV-IR-radio SEDs of galaxies in recent times: GRAZIL (Vega et al., 2008), CIGALE (Noll et al., 2009; Boquien et al., 2019), and PROSPECT (Thorne et al., 2023), albeit with simple assumptions such as single power law form of radio SEDs in CIGALE and PROSPECT (Yang et al., 2022; Thorne et al., 2023).

Since the radio luminosity results from two distinct emission mechanisms, we must decompose it into its respective components (synchrotron and FFE) in order to link it to star formation or AGN activity. The synchrotron emission results from an interaction

of charged particles in a magnetic field that is accelerated in shocks produced by supernova remnants and, therefore, traces the supernova rate. The synchrotron emission radio component measures the star formation rate (SFR) over timescales of $\sim 10\text{--}100$ Myr for an assumed supernova rate and the initial mass function (Condon et al., 2002). The thermal free-free emission component is produced by the ionization of H II regions by the UV photons emitted from the same massive stars that eventually produce the supernova associated with the nonthermal synchrotron emission. The thermal free-free emission is a direct near-instantaneous measure of SFR. However, measuring thermal FFE in radio SEDs is complicated by the fact that low-frequency SEDs are dominated by nonthermal synchrotron emission ($\nu \lesssim 30$ GHz; Galvin et al., 2018). Furthermore, radio SEDs are further modified by free-free absorption (FFA) or synchrotron self-absorption (SSA) processes, causing bends and turnovers (Clemens et al., 2010; Galvin et al., 2018; Chyży et al., 2018). Therefore, disentangling thermal emission from the total radio continuum requires model fitting using densely sampled SEDs and sophisticated modeling techniques (Clemens et al., 2008, 2010; Galvin et al., 2016, 2018; Dey et al., 2022) or high-frequency (≥ 20 GHz) radio measurements.

In our initial paper on this subject Dey et al. (2022), we made the first attempt to simultaneously model the UV–IR–radio SEDs using CIGALE and the densely sampled radio SEDs (~ 70 MHz–15 GHz) for a sample of 11 LIRGs. Due to the inclusion of radio data in the SED modeling using CIGALE, we could estimate the dust luminosities with one order of magnitude better accuracy than previously reported (median uncertainties ~ 0.03 dex compared to ~ 0.3 dex in literature). We separated the nonthermal synchrotron and thermal FFE components in our radio SED modeling and obtained the radio 1.4 GHz total, nonthermal and thermal SFRs using the radio luminosity scaling relations of Murphy et al. (2011). We then compared 1.4 GHz radio total, nonthermal, and thermal SFRs at 1.4 GHz with infrared SFRs (SFR_{IR}) averaged over the last 10 and 100 Myr from the CIGALE analysis. We found a good correspondence between the SFR_{IR} averaged over the last 10 Myr with the total and nonthermal radio SFRs, respectively. This indicates that 1.4 GHz total, and nonthermal luminosities are good indicators of recent star formation in LIRGs (on timescales of ~ 10 Myr).

This work extends our approach to simultaneously model UV–IR–radio SEDs using CIGALE and densely sampled radio SEDs (~ 54 MHz–30 GHz) to a sample of 14 ULIRGs. We aim to investigate how high star formation activity impacts the galaxy properties by extending the sample of our LIRGs (11 objects; Dey et al., 2022). We note that many authors have previously studied UV–IR SEDs of large samples of ULIRGs: da Cunha et al. (2010a); Malek et al. (2017); Paspaliaris et al. (2021); Sokol et al. (2023) but only a few have modeled their radio SEDs in detail (see, for exception Clemens et al., 2010; Galvin et al., 2018; Nandi et al., 2021) due to the lack of radio data. Therefore, we restricted our sample to ULIRGs for which densely sampled radio SEDs and UV–IR SEDs are available. This

was done to facilitate the complex modeling of the radio spectra with physically motivated models characterized by multiple free parameters. Section 6.2 provides the selection criteria for our targets which are taken from Clemens et al. (2010), (Galvin et al., 2018), and Nandi et al. (2021). The study presented here improves on previous modeling efforts in the following manner: (1) better coverage of the radio spectra, in particular, the inclusion of low-frequency flux measurements ($\sim 50\text{--}100$ MHz) (2) comparison of physically motivated scenarios (simple and complex models with multiple free parameters) and using Bayesian inference to select the best-fit model and estimation of the model parameters and their uncertainties.

6.2 Sample selection

Our sample consists of 14 ULIRGs compiled from the following three studies:

1. Six galaxies from the sample of 31 galaxies from Clemens et al. (2010). We selected these targets because the rest of them did not have enough data coverage to perform SED modeling using complex models with many free parameters.
2. Three galaxies from the sample of 12 galaxies from Galvin et al. (2016) as they did not perform the radio SED modeling of these galaxies.
3. Five galaxies from the sample of 13 galaxies studied by Nandi et al. (2021). We selected these targets because we could not find enough data for the rest of them to perform complex SED modeling with many free parameters.

These galaxies were selected on the basis of the availability of photometric data with a wide range of wavelength coverage from UV to FIR bands accompanied by two decades of spectral coverage in the radio band. Our sample has a redshift range of 0.03–0.4285 and $\log_{10} L_{\text{IR}} \gtrsim 11.90 L_{\odot}$ justifying a ULIRG classification. The basic properties of our sample of ULIRG, including dust luminosity from the literature, are listed in Table 6.1. We further note that Clemens et al. (2010) used a simple model, i.e., synchrotron+FFE+FFA, or a combination of these to describe the radio SEDs of their sample. Moreover, Nandi et al. (2021) modeled the radio SEDs of these galaxies with the SYNAGE spectral fitting tool, which describes the evolution of a radio AGN continuously replenished by a constant flow of fresh relativistic particles with a power law energy distribution (Murgia et al., 1999). This tool works well for SED modeling of radio galaxies with large-scale structures as it assumes cylindrical geometry of the sources and equipartition of energy between the energetic particles and magnetic field. In addition, the flattening at low frequencies and steepening at high frequencies are interpreted as due to SSA and particle energy losses. We reiterate that our sample is based on the availability of good data coverage at UV–IR range, allowing us to perform simultaneous UV–IR–radio modeling using the CIGALE

TABLE 6.1: Basic information on our sample of ULIRGs

Name	R.A.(J2000)	Dec.(J2000)	z	$\log_{10}(L_{\text{IR}})$	Ref.
	(hms)	($^{\circ} \ ' \ ''$)		($L_{\odot}$)	
(1)	(2)	(3)	(4)	(5)	
IRAS F00183-7111	00 20 34.69	-70 55 26.7	0.3300	12.93 ^(a)	(f)
IRAS F03538-6432	03 54 25.21	-64 23 44.7	0.3007	12.62 ^(b)	(f)
IRAS 08572+3915	09 00 25.39	+39 03 54.40	0.0582	12.09 ^(c)	(g)
UGC 05101	09 35 51.60	+61 21 11.5	0.0393	11.90 ^(c)	(g)
IRAS 10565+2448	10 59 18.12	+24 32 34.46	0.0431	11.98 ^(c)	(g)
IRAS 12112+0305	12 13 46.00	+02 48 38.0	0.0733	12.28 ^(d)	(h)
UGC 08058	12 56 14.23	+56 52 25.2	0.0421	12.49 ^(c)	(g)
IRAS 13305-1739	13 33 16.54	-17 55 10.7	0.1483	12.21 ^(d)	(h)
UGC 8696	13 44 42.11	+55 53 12.7	0.0373	12.09 ^(c)	(g)
IRAS 14348-1447	14 37 38.40	-15 00 20.0	0.0823	12.30 ^(c)	(g)
IRAS 14394+5332	14 41 04.38	+53 20 08.7	0.1050	12.04 ^(d)	(h)
IRAS 17179+5444	17 18 54.40	+54 41 48.5	0.1476	12.20 ^(e)	(h)
IRAS F23529-2119	23 55 33.00	-21 03 08.7	0.4285	12.52 ^(b)	(f)
IRAS 23389+0300	23 41 30.31	+03 17 26.4	0.1450	12.09 ^(e)	(h)

Columns : (1) source name, (2) R.A., (3) decl., (4) spectroscopic redshift from the NASA/IPAC Extragalactic Database (NED)¹, (5) value of the absolute FIR luminosity with reference in superscript; ^(a) [Spoon et al. \(2009\)](#), ^(b) [Braun et al. \(2011\)](#), ^(c) [Clemens et al. \(2010\)](#), ^(d) [Kim and Sanders \(1998\)](#), ^(e) [Veilleux et al. \(1999\)](#) (6) reference for the source selection: (f) [Galvin et al. \(2016\)](#), (g) [Clemens et al. \(2010\)](#), (h) [Nandi et al. \(2021\)](#).

and radio-only SED modeling using dense radio SEDs and comparing the astrophysical properties inferred by these tools.

6.3 Multi-wavelength datasets: Radio to far UV

6.3.1 Radio flux densities from literature

In chapter 2, we provide an overview of the radio data collected from various sky survey programs along with our dedicated radio observations using the GMRT and reanalysis of the VLA data for some of the galaxies, wherever required. However, in order to construct densely sampled radio SEDs, we also obtained flux density measurements from targeted studies. Since all of our galaxies have been targets for dedicated radio continuum monitoring, we included the measurements either with the GMRT (1.28 GHz; [Nandi et al., 2021](#)), or VLA (235 MHz, 610 MHz, 15 GHz, and 22 GHz; [Clemens et al., 2008, 2010](#)) or ATCA (2.1 GHz, 5.5 GHz, and 9 GHz; [Galvin et al., 2016](#)) telescopes. We note that for the three galaxies from [Galvin et al. \(2016\)](#) sample, IRAS F00183-7111, IRAS F0358-6432, and IRAS F23529-2119, the radio measurements at mid-frequency range were provided

by ATCA, centered at 2.1, 5.5, and 9 GHz frequencies with a bandwidth of 2.04 GHz. For some targets, if enough signal-to-noise ratio (>8) was available in a particular point source model of each image, then the corresponding *uv*-data file was divided into two and so on to produce images in subbands and the subsequent flux densities are given (Table A2 of Galvin et al., 2016). For our radio SED modeling, we average the fluxes in a particular band, and those fluxes are used in radio SED modeling.

Additionally, we used flux measurement provided from studies targeting individual sources such as at IRAS F00183-7111 at 1.4 GHz (Drake et al., 2004), IRAS 12112+0305 and IRAS 10565+2448 at 8.4 GHz (Vardoulaki et al., 2015), IRAS F00183-7111 at 4.8 and 8.6 GHz (McConnell et al., 2012), IRAS 23389+0300 at 178 MHz (Gower et al., 1967), IRAS 08572+3915 at 32 GHz (Barcos-Muñoz et al., 2017), UGC 5101 at 325 MHz (Rengelink et al., 1997) and 32.5 GHz (Leroy et al., 2011), and UGC 08058 at 30.0 GHz (Lowe et al., 2007) and 32.5 GHz (Leroy et al., 2011).

6.3.2 Archival VLA data

For two galaxies in our sample, IRAS 14394+5332 and IRAS 23389+0303, we found additional radio archival VLA data at 8.4 GHz. The two targets were observed on 2004 October 19, under the project ID AN 122 in A-array configuration for a total duration of 22 min and 20.25 min, respectively. We calibrated the interferometric data using the NRAO AIPS² package using the standard procedure. The flux density scale of Baars et al. (1977) was used to obtain the flux densities of the primary (flux) calibrator (1331+305), the secondary (phase) calibrator (1419+543 and 2320+052 for IRAS 14394+5332 and IRAS 23389+0303, respectively), and the target source. Antennas and baselines affected with strong radio frequency interference and non-working antennas were removed after visual inspection. The images were produced using the task IMAGR on the data after both frequency channels were calibrated separately and averaged. Usually, 3-5 rounds of phase-only self-calibration were performed iteratively by choosing point sources in the field such that the flux density is $>3\sigma$ with one synthesized beam. The final images were made with full *UV*-coverage and robust weighting of 0 (Briggs, 1995). The final images were corrected for the reduction in sensitivity due to the shape of the antenna primary beam using task PBCOR³. Integrated flux densities (and uncertainty) were obtained using the task TVSTAT in AIPS. Figure B.1 in Appendix B.2 provides the radio optical overlays and preliminary information on the data sets.

²The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

³<http://www.aips.nrao.edu/cgi-bin/ZXHLP2.PL?PBCOR>

6.3.3 UV, Optical, and IR flux densities

In chapter 2, we provide an overview of the data collected from space- and ground-based instruments at UV, optical, and IR-bands. Moreover, we note that with the availability of multiple flux measurements at a given wavelength, we chose the one containing the entire galaxy. Table A4 gives the integrated fluxes along with the integration area per band for each source used for SED modeling.

6.4 SED modeling

6.4.1 Radio SED modeling

A detailed description of radio-only SED modeling is provided in Chapter 3. The best model is selected based on the Bayes odds ratio logarithm is given in Table 6.2 and the corresponding best-fit radio SEDs are given in Figure 6.1 for our sample. Table 6.3 provides the 50 percentile of the posterior distribution of best-fit model parameters and their equivalent 1σ uncertainties corresponding to 16th and 84th percentiles of the posterior distribution of the parameter. To evaluate the degeneracy arising from the multiple free parameters in the best-fit model, we present corner plots for each of our galaxies in the appendix (Figure B.2). The corner plot presented in Figure B.2 represents the one- and two- dimensional projections of the posterior probability distribution of parameters. The Table 6.4 provides total, thermal, and nonthermal radio fluxes from SED modeling, along with thermal fraction at 1.4 GHz ($TF_{1.4\text{GHz}}$).

TABLE 6.2: An overview of the natural log of the Bayes odds ratio from the UltraNest fitting of each model to each source. We present the most preferred model with the highest evidence value corresponding to $\log_e(1)=0$ (shown in boldface). Models that are indistinguishable from the most preferred model correspond to $\log_e(3)=1.1$ (shown in italics typeface). Less preferred models are given by larger negative values.

Name	PL	SFG NC	C	SFG NC2	C2 1SA	C2 1SAN	C2 1SAN2	C2
IRAS F00183-7111	-143.04	-143.91	0	-152.04	<i>-0.24</i>	-10.10	-6.88	-1.52
IRAS F03538-6432	0	-6.72	-17.65	-13.53	-10.21	-13.53	-14.47	-10.91
IRAS 08572+3915	-102.64	<i>-0.35</i>	0	-2.46	-10.00	-14.55	-11.72	-10.69
UGC 5101	-43.89	-51.02	-15.47	-60.13	-2.79	-1.95	0	-2.074
IRAS 10565+2448	-41.32	-48.38	0	-57.07	-7.34	-11.09	-10.24	-7.49
IRAS 12112+0305	-71.61	-52.28	0	-58.88	-8.81	-14.01	-11.49	-9.99
UGC 08058	-636.75	-87.51	-839.90	-351.81	-5.70	-3.24	0	-12.84
IRAS 13305-1739	0	-7.60	-12.19	-24.25	-14.174	-9.67	-6.62	-14.33
UGC 8696	-54.78	-62.43	-19.32	-72.51	-6.49	-29.48	-29.63	0
IRAS 14348-1447	0	-7.29	-20.77	-14.04	-1.65	-3.24	-1.83	-1.78
IRAS 14394+5332	-35.73	-43.64	-38.29	-54.24	-1.75	-65.61	-2.79	0
IRAS 17179+5444	-419.38	-255.02	0	-269.93	-5.85	-23.79	-15.42	-5.99
IRAS F23529-2119	0	-6.58	-7.38	-14.40	-1.93	-4.72	-7.36	-1.67
IRAS 23389+0300	-1143.71	-49.87	0	-56.48	-6.40	-11.60	-9.09	-7.58

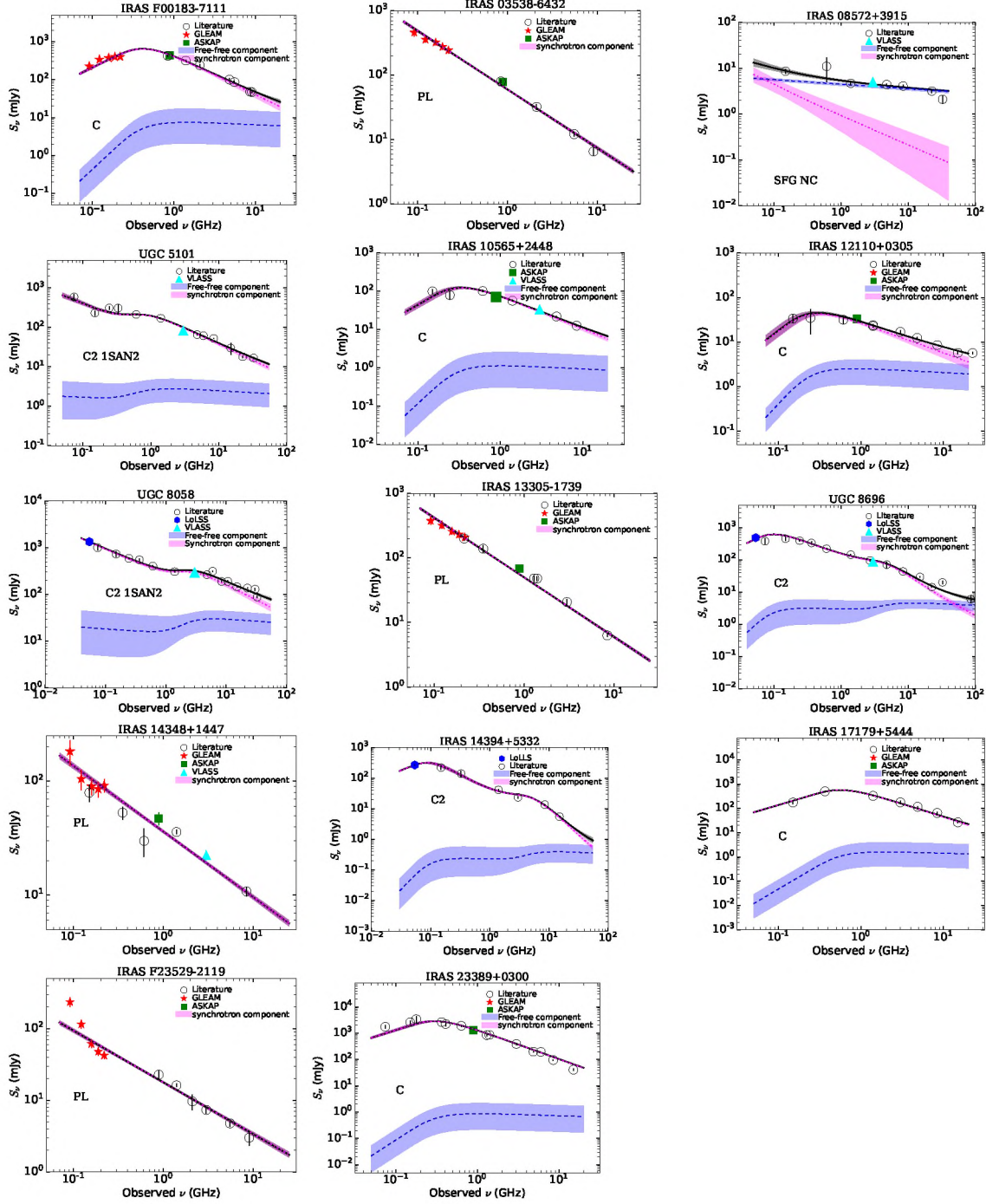


FIGURE 6.1: Radio SEDs for our sample of 14 ULIRGs. Galaxy name and the best-fit radio SED model name are given at the top and bottom left-corner, respectively, of each panel. The solid black line represents the best-fit model, while the gray-shaded region represents the 1σ uncertainties sampled by the UltraNest package. The dot-dashed magenta and dotted blue lines show the decomposed synchrotron and free-free components. The pink and blue shaded regions represent the 1σ uncertainties in the synchrotron and free-free components, respectively. For galaxies fitted with two-component models, the free-free and synchrotron components correspond to the sum of individual free-free and synchrotron components. The flux densities obtained from the GLEAM, ASKAP, and VLASS surveys are shown with red stars, green squares, and cyan triangles, respectively, while open black circles mark the fluxes taken from other sources. (see Table B.1).

TABLE 6.3: The most preferred models were selected based on the Bayes odds ratio and the constrained value of the free parameters. The nominal value is taken as the 50th percentile of the posterior distribution of the samples, and the 1 σ uncertainties are provided by the 16th and 84th percentile. Parameters not included in the models are indicated as “-”.

Name	Model	A	B	$\alpha(=\alpha_1)^*$	$\nu_{t,1}$	C	D	α_2	$\nu_{t,2}$
(1)	(2)	(mJy)	(mJy)	(5)	(GHz)	(mJy)	(mJy)	(9)	(GHz)
IRAS F00183-7111	C	1004.84 ^{+35.52} _{-38.54}	9.60 ^{+12.30} _{-7.00}	-1.05 ^{+0.06} _{-0.09}	0.45 ^{+0.04} _{-0.03}	-	-	-	-
IRAS F03538-6432	PL	44.08 ^{+1.55} _{-1.46}	-	-0.91 ^{+0.02} _{-0.02}	-	-	-	-	-
IRAS 08572+3915	SFG NC	0.80 ^{+0.44} _{-0.43}	4.29 ^{+0.29} _{-0.32}	-0.62 ^{+0.10} _{-0.25}	-	-	-	-	-
UGC 5101	C2 ISAN2	50.67 ^{+13.40} _{-15.95}	1.38 ^{+1.96} _{-1.01}	-0.76 ^{+0.09} _{-0.15}	-	207.63 ^{+34.13} _{-27.67}	1.51 ^{+1.99} _{-1.10}	-0.88 ^{+0.07} _{-0.11}	0.92 ^{+0.13} _{-0.11}
IRAS 10565+2448	C	196.79 ^{+13.89} _{-13.11}	1.25 ^{+1.87} _{-0.92}	-0.86 ^{+0.04} _{-0.05}	0.33 ^{+0.04} _{-0.04}	-	-	-	-
IRAS 12112+0305	C	67.93 ^{+6.72} _{-6.23}	2.93 ^{+1.74} _{-1.75}	-0.67 ^{+0.07} _{-0.10}	0.26 ^{+0.05} _{-0.04}	-	-	-	-
UGC 08058	C2 ISAN2	212.06 ^{+15.78} _{-17.29}	13.50 ^{+17.02} _{-9.94}	-0.56 ^{+0.02} _{-0.02}	-	241.74 ^{+19.70} _{-19.26}	15.74 ^{+17.76} _{-11.42}	-0.75 ^{+0.08} _{-0.10}	2.88 ^{+0.09} _{-0.16}
IRAS 13305-1739	PL	36.78 ^{+0.95} _{-1.03}	-	-0.92 ^{+0.01} _{-0.02}	-	-	-	-	-
UGC8696	C2	932.94 ^{+36.39} _{-34.66}	3.75 ^{+3.37} _{-2.56}	-0.93 ^{+0.04} _{-0.05}	0.10 ^{+0.003} _{-0.002}	61.25 ^{+9.95} _{-9.48}	2.05 ^{+2.09} _{-1.47}	-1.92 ^{+0.15} _{-0.06}	5.87 ^{+0.69} _{-0.69}
IRAS 14348-1447	PL	29.81 ^{+0.92} _{-0.88}	-	-0.58 ^{+0.02} _{-0.02}	-	-	-	-	-
IRAS 14394+5332	C2	452.12 ^{+19.82} _{-20.61}	0.30 ^{+0.41} _{-0.22}	-1.24 ^{+0.09} _{-0.12}	0.10 ^{+0.01} _{-0.01}	25.11 ^{+3.22} _{-3.12}	0.18 ^{+0.25} _{-0.13}	-1.97 ^{+0.05} _{-0.03}	6.30 ^{+0.42} _{-0.43}
IRAS 17179+5444	C	900.09 ^{+23.66} _{-25.39}	2.05 ^{+2.97} _{-1.55}	-1.09 ^{+0.04} _{-0.04}	0.63 ^{+0.04} _{-0.03}	-	-	-	-
IRAS F23529-2119	PL	13.95 ^{+0.47} _{-0.50}	-	-0.72 ^{+0.02} _{-0.02}	-	-	-	-	-
IRAS 23389+0300	C	4513.09 ^{+212.85} _{-181.97}	0.92 ^{+1.38} _{-0.69}	-1.10 ^{+0.01} _{-0.01}	0.32 ^{+0.02} _{-0.02}	-	-	-	-

Columns: (1) galaxy name, (2) best-fit model, (3) and (7) nonthermal normalization components, (4) and (8) thermal normalisation components, (5) and (9) synchrotron spectral indices, (6) and (10) turnover frequencies. * $\alpha=\alpha_1$ for two component models.

TABLE 6.4: Total, thermal, and nonthermal fluxes are estimated at 1.4 GHz from the radio-only SED fitting, and the corresponding thermal fraction is estimated at 1.4 GHz. The nominal value is taken as the 50th percentile of the posterior distribution of the samples, and the 1 σ uncertainties are provided by the 16th and 84th percentile.

Name	$S_{1.4}^{\text{total}}$ (mJy)	$S_{1.4}^{\text{th}}$ (mJy)	$S_{1.4}^{\text{nth}}$ (mJy)	TF _{1.4}
(1)	(2)	(3)	(4)	(5)
IRAS F00183-7111	302.88 ^{+10.87} _{-10.71}	8.59 ^{+6.31} _{-9.84}	293.40 ^{+15.65} _{-13.31}	0.03 ^{+0.02} _{-0.03}
IRAS F03538-6432	44.12 ^{+1.42} _{-1.42}	-	44.12 ^{+1.42} _{-1.42}	-
IRAS 08572+3915	5.07 ^{+0.23} _{-0.23}	4.32 ^{+0.31} _{-0.30}	0.75 ^{+0.45} _{-0.46}	0.86 ^{+0.10} _{-0.09}
UGC 5101	171.31 ^{+5.38} _{-5.26}	3.17 ^{+1.74} _{-2.28}	167.82 ^{+4.94} _{-5.08}	0.02 ^{+0.01} _{-0.01}
IRAS 10565+2448	57.05 ^{+1.76} _{-1.76}	1.10 ^{+0.81} _{-1.46}	55.74 ^{+2.27} _{-2.05}	0.02 ^{+0.01} _{-0.02}
IRAS 12112+0305	23.90 ^{+0.90} _{-0.79}	2.59 ^{+1.48} _{-1.36}	21.28 ^{+1.52} _{-1.62}	0.11 ^{+0.06} _{-0.05}
UGC 8058	281.27 ^{+7.80} _{-8.16}	13.27 ^{+8.23} _{-13.48}	305.27 ^{+14.41} _{-11.96}	0.05 ^{+0.03} _{-0.05}
IRAS 13305-1739	36.77 ^{+1.05} _{-0.98}	-	36.77 ^{+1.05} _{-0.98}	-
UGC 8696	131.82 ^{+4.27} _{-4.36}	0.98 ^{+0.70} _{-1.62}	130.47 ^{+4.55} _{-4.55}	0.007 ^{+0.004} _{-0.008}
IRAS 14348-1447	29.76 ^{+0.91} _{-0.87}	-	29.76 ^{+0.91} _{-0.87}	-
IRAS 14394+5332	39.77 ^{+2.38} _{-2.32}	0.27 ^{+0.19} _{-0.35}	39.42 ^{+2.43} _{-2.35}	0.007 ^{+0.005} _{-0.009}
IRAS 17179+5444	347.11 ^{+13.07} _{-13.08}	1.65 ^{+1.22} _{-2.42}	344.98 ^{+12.94} _{-12.96}	0.005 ^{+0.003} _{-0.007}
IRAS F23529-2119	13.94 ^{+0.45} _{-0.46}	-	13.94 ^{+0.45} _{-0.46}	-
IRAS 23389+0300	881.21 ^{+9.51} _{-10.49}	0.78 ^{+0.58} _{-1.17}	880.12 ^{+9.70} _{-10.50}	0.0008 ^{+0.0006} _{-0.0013}

Columns: (1) galaxy name, (2–4) total, thermal, and nonthermal fluxes at 1.4 GHz, (5) thermal fraction at 1.4 GHz

6.4.2 UV to radio SED modeling with CIGALE

A detailed description of FUV-radio SED modeling using CIGALE is provided in Chapter 4. For simultaneous UV-to-radio SED modeling of our galaxies, we used the recently updated version of the X-CIGALE software (Yang et al., 2020), CIGALE 2022.1 (Yang et al., 2022). The advantage of CIGALE 2022.1 as compared to its predecessors is that here, the radio module includes both the thermal (free-free emission from the nebular emission) and the nonthermal emission (synchrotron emission from the starforming and AGN component) of the galaxy. The addition of a new AGN component to the radio module of CIGALE 2022.1 allowed us to estimate the Radio loudness, R_{AGN} defined as a ratio between AGN luminosities measured at 5 GHz and 2500Å, and then the slope of the power law AGN radiation (assumed isotropic) (Yang et al., 2022). To maintain consistency with our previous study (Dey et al., 2022), we used the same modules. CIGALE 2022.1 takes into account the radio luminosities by star formation and AGN components using the q_{IR} and radio-loudness (R_{AGN}) parameters scaling relations. At 1.4 GHz, the radio luminosity from star formation is dominated by nonthermal synchrotron emission and, therefore, calculated using the q_{IR} parameter. The q_{IR} sets the normalization at this frequency, and a single power-law form describes the synchrotron emission from star formation. The scatter and variations in the q_{IR} parameter itself will contribute to the uncertain modeling of the radio component by the CIGALE. The nonthermal synchrotron emission from the AGN, described by the R_{AGN} parameters, also assumes the single power-law form. However, radio SEDs are rarely characterized by single-PL forms. Therefore, while including radio measurements in CIGALE modeling improves the accuracy of derived parameters, it does not fully compensate for the need for radio-only SED modeling using densely sampled radio SEDs, which is crucial for understanding galaxies' emission and absorption processes. Table 6.5 provides the parameter grid of the models used by us.

TABLE 6.5: List of input parameters for CIGALE modeling

<i>Parameters</i>		<i>Values</i>
delayed star formation history + additional burst (Ciesla et al., 2015)		
e-folding time of the main stellar population model [Myr]	τ_{main}	300-15000 by a bin of 300
e-folding time of the late starburst population model [Myr]	τ_{burst}	50-1000 by a bin of 50
mass fraction of the late burst population	f_{burst}	0.05, 0.1, 0.3, 0.6, 0.9
Age of the main stellar population in the galaxy [Myr]	age	1000, 2000, 3000, 4500, 5000, 6500, 10000, 12000
Age of the late burst [Myr]	age _{burst}	10.0, 40.0, 80.0, 110, 150, 170
stellar synthesis population (Bruzual and Charlot, 2003)		
Initial mass function	IMF	(Salpeter, 1955)
Metallicity	Z	0.02
Separation age		1 Myr
dust attenuation laws (Calzetti et al., 2000)		
Colour excess of young stars	E(B-V)	0.1-2 by a bin of 0.2
Reduction factor ⁽ⁱⁱⁱ⁾	f_{att}	0.3, 0.44, 0.6, 0.7
dust grain model; THEMIS (Jones et al., 2017)		
fraction of small hydrocarbon solids	q_{hac}	0.02, 0.06, 0.1, 0.17, 0.24
Minimum radiation field	U_{min}	1, 5, 10, 15, 20, 30
power law index of the radiation	α	2
fraction illuminated from U_{min} to U_{max}	γ	0.02, 0.06, 0.1, 0.15, 0.2
active nucleus model; Skirtor (Stalevski et al., 2012, 2016)		
optical depth at 9.7 μm	$\tau_{9.7}$	3.0, 7.0
torus density radial parameter	pl	1.0
torus density angular parameter	q	1.0
angle between the equatorial plan and edge of the torus [deg]	oa	40
ratio of outer to inner radius	R	20
fraction of total dust mass inside clumps [%]	Mcl	97
inclination (viewing angle) [deg]	i	30 (type 1), 70 (type 2)
AGN fraction		0.0-0.4 by a bin of 0.05
extinction law of polar dust		SMC
E(B-V) of polar dust		0.01-0.7 by a bin of 0.5
Temperature of the polar dust	K	100
Emissivity index of the polar dust		1.6
Radio		
SF FIR/radio parameter*	q_{IR}	2.3 - 2.9 by a bin of 0.1
SF Power-law slope (Flux $\propto$ Frequency ^{α_{synch}})	α_{SF}	-2.0 to -0.2 by a bin of 0.1
Radio-Loudness parameter**	R_{AGN}	0.01, 0.05, 0.1, 0.5... 1000, 5000
AGN Power-law slope	α_{AGN}	-2.0 to -0.2 by a bin of 0.1

* computed as $\log_{10} L_{IR(8-1000\mu\text{m})} - \log_{10} L_{1.4\text{GHz}}$ where $L_{1.4\text{GHz}}$ is the radio luminosity at 1.4 GHz.

** defined as a ratio between AGN luminosities measured at 5 GHz and 2500 Å,

Figure 6.2 and Table 6.6 give the best-fit parameters and resultant best-fit SED models. We stress here that the large number of photometric data points with uniform sampling across the wavelength range allows us to use a dense grid of parameters without the risk of over-fitting model parameters.

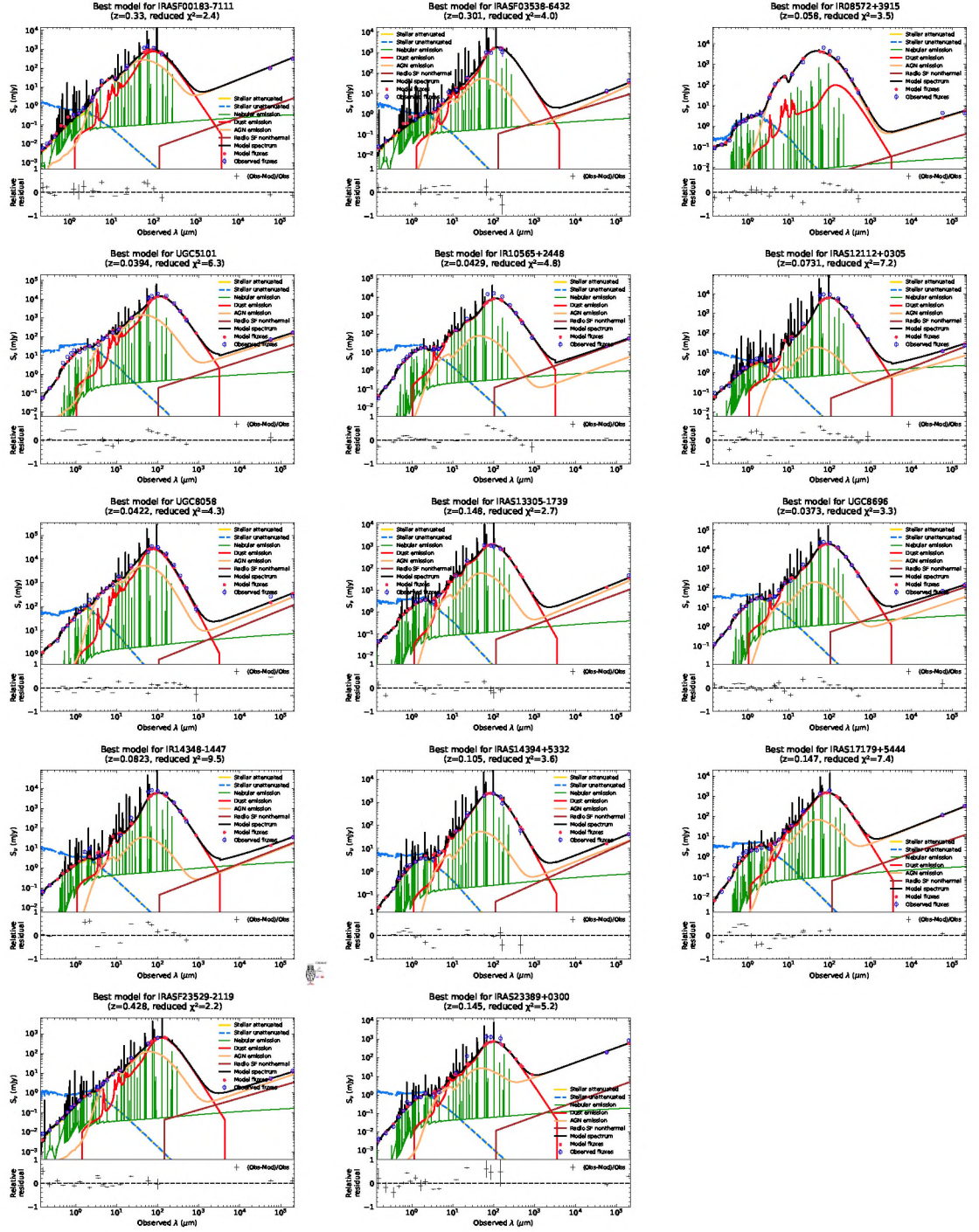


FIGURE 6.2: Best-fit UV-radio SEDs of our sample of 14 ULIRGs obtained using CIGALE. The open and filled symbols give the observed and modeled flux densities. The goodness of fit is estimated by the reduced χ^2 shown at the top of each panel, along with the name and redshift of the galaxy. SEDs are well modeled in almost all cases, giving reasonable estimates of astrophysical properties.

TABLE 6.6: CIGALE SED fitting results.

Name	$\log_{10}(L_{\text{dust}})$ ($L_{\odot}$)	$\log_{10}(M_{\star})$ ($M_{\odot}$)	$\log_{10}(\text{SFR}_{\text{IR}})$ ($M_{\odot} \text{ yr}^{-1}$)	AGN fraction (%)	Rad. Loud. (R_{AGN})	α_{AGN}	α_{SF}	q_{IR}	τ_{V}	χ^2
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
IRAS F00183-7111	12.52±0.02	10.90±0.17	2.95±0.02	49.98±0.45	30.00±0.01	-0.83±0.12	-0.81±0.17	2.37±0.16	2.41±0.01	2.4
IRAS F03538-6432	12.48±0.06	11.09±0.12	2.90±0.10	30.00±0.21	9.93±0.61	-0.82±0.07	-0.81±0.08	2.51±0.09	1.61±0.02	4.0
IRAS 08572+3915	10.19±0.05	10.32±2.51	0.29±0.06	99.00±0.004	0.16±0.01	-0.61±0.03	-0.64±0.04	2.53±0.04	0.38±0.12	3.5
UGC 5101	11.88±0.02	10.74±0.06	2.00±0.02	19.99±0.001	5.00±0.06	-0.92±0.12	-0.75±0.05	2.31±0.05	2.30±0.01	6.3
IRAS 10565+2448	11.73±0.02	10.56±0.04	1.86±0.03	3.00±0.04	1.76±0.75	-0.75±0.05	-0.76±0.05	2.39±0.02	2.28±0.001	4.8
IRAS 12112+0305	11.68±0.02	10.24±0.06	1.90±0.02	8.02±0.18	5.2 ±3.00	-0.79±0.03	-0.75±0.05	2.43±0.02	2.19±0.01	7.2
UGC 08058	12.15±0.02	12.22±0.19	2.41±0.03	40.00±0.09	1.07±0.26	-0.70±0.03	-0.72±0.07	2.48±0.07	1.58±0.01	4.3
IRAS 13305-1739	12.09±0.02	10.84±0.05	2.23 ±0.05	9.90±2.00	15.44±3.73	-0.83± 0.13	-0.83±0.12	2.42±0.11	1.64±0.01	2.7
UGC8696	11.97±0.02	10.56±0.03	2.09±0.04	2.11±0.56	2.54±1.36	-0.75±0.05	-0.75±0.05	2.42±0.05	2.34 ±0.02	3.3
IRAS 14348-1447	12.07±0.02	9.71±0.08	2.45±0.05	1.30±0.46	2.92±1.15	-0.80±0.08	-0.70±0.08	2.37±0.07	2.19±0.03	9.5
IRAS 14394+5332	12.05±0.02	10.50±0.06	2.26±0.03	4.95±0.66	12.50±4.29	-0.75±0.05	-0.75±0.05	2.35±0.11	2.08±0.04	3.6
IRAS 17179+5444	12.18±0.02	10.85±0.04	2.29±0.05	5.31±1.20	199.77±4.72	-0.76±0.05	-0.75±0.05	2.43±0.14	2.35±0.01	7.4
IRAS F23529-2119	12.62±0.02	11.53±0.08	2.91±0.02	30.54±3.2	3.02±0.23	-0.81±0.1	-0.70±0.15	2.46±0.14	1.77 ± 0.003	2.2
IRAS 23389+0300	11.72±0.02	10.21±0.43	1.98±0.03	8.52 ±0.87	799.56±26.12	-1.03±0.09	-0.90 ±0.16	2.58±0.10	2.34±0.01	5.2

Columns: (1) galaxy name, (2) stellar mass, (3) dust mass, (4) dust temperature, (5) instantaneous star formation rate, (6) AGN fraction, (7) slope of power-law synchrotron emission, α , (8) dust luminosity, (9) q_{IR} , (10) V-band optical depth, (11) reduced χ^2 value for the best-fit model.

6.5 Results

Our main results using detailed radio-only and simultaneous FUV–IR–radio SED modeling using the UltraNest and CIGALE modeling tools, respectively, are given below. The specific notes on individual sources are given in Appendix B.3. Figures 6.1 and 6.2 present the radio-only and FUV–radio SED fits, respectively. Tables 6.3 and 6.6 give the best-fit model parameters and their uncertainties, respectively, for our galaxies. Our main results are the following:

1. Radio-only SED modeling of 14 ULIRGs has been carried out in previous studies (Section 6.2); however, in this study, we obtained the best fit radio SED model from the pool of physically motivated models using the state-of-the-art fitting tool (Figure 6.1). Most galaxies are fitted with complex models instead of single power-law forms. The estimated radio spectral index ranges between -0.58 and -1.94 (Table 6.3).
2. Spectral index values between ~ -0.6 and ~ -0.9 can be considered within uncertainty, in agreement with the canonical synchrotron emission spectral index ($\alpha \approx -0.75$ for the frequently assumed value of particle energy index $= -2.5$; Lacki et al. 2010). Values between ~ -1.0 and ~ -1.5 can be considered according to the cooled synchrotron emission spectral index ($\alpha = -1.25$). For two galaxies (UGC 8696 and IRAS 14394+5332), the spectra are best fitted with a two-component model where the derived spectral index of the second component is much steeper, ~ -1.9 . In these galaxies, when we compare the weights of the two CRE populations in model C2, the steep spectrum component is only of the order of 1 to 1.5σ of the flatter spectrum component, and thus the extremely steep spectral index can be easily attributed to uncertainties in the data or flux measurements. Moreover, given that high-frequency observations ($< 7\text{--}8\text{ GHz}$) can often be underestimated due to their lower SNR leading to a steep spectrum, the most likely cause of extremely steep spectra is due to the above-mentioned effects.
3. For the majority of our sample, the computed thermal fraction at 1.4 GHz ($\text{TF}_{1.4\text{ GHz}}$) is < 0.12 (Table 6.4). The ($\text{TF}_{1.4\text{ GHz}}$) is comparable to that found for starforming galaxies (Marvil et al., 2015).
4. CIGALE SED modeling resulted in following range of astrophysical properties: dust luminosity, $\log_{10}(\text{L}_{\text{dust}}) = 10.19\text{--}12.62$, stellar mass, $\log_{10}(M_{\star}) = 9.71\text{--}11.78$, infrared star formation rate $\log_{10}\text{SFR}_{\text{IR}} = 0.29\text{--}2.95$, optical AGN fraction $= 1.3\text{--}99.0$, radio loudness parameter, $(R_{\text{AGN}}) = 0.16\text{--}799.56$, AGN power-law slope, $\alpha_{\text{AGN}} = 0.61\text{--}1.03$, SF power-law slope, $\alpha_{\text{SF}} = 0.64\text{--}0.90$, $q_{\text{IR}} = 2.31\text{--}2.58$, $\tau_{\text{V}} = 0.38\text{--}2.42$ for our sample (Table 6.6). For all galaxies except IRAS 08572+3915, the L_{dust} , $M_{\star}$, SFR_{IR} , and AGN fractions are consistent with those typical for ULIRG-type galaxies (Małek et al., 2018).

5. We found that adding radio data to the CIGALE modeling significantly increases the accuracy of the model fits. The median uncertainties on the derived L_{dust} and SFR_{IR} values from CIGALE modeling are 0.02 dex and 0.03 dex, respectively. These are estimated more than one order of magnitude better than previously reported (0.25 dex, and 0.39 dex, respectively [Małek et al., 2018](#)). A similar improvement in the measurement of L_{dust} and SFR_{IR} for star-forming galaxies was reported by [Thorne et al. \(2023\)](#) using the PROSPECT SED fitting tool, which included the radio module in the SED fitting code.
6. The most recent version of the CIGALE tool decomposes the total radio luminosity into AGN and star formation radio luminosities, allowing us to obtain R_{AGN} and α_{AGN} . Using the classical division between radio-loud and radio-quiet AGNs ([Kellermann et al., 1989](#)), six of our galaxies turn out to be radio-loud (IRAS F00183-7111, IRAS F03538-6442, IRAS 13305-1739, IRAS 14394+5332, IRAS 17179+5444, and IRAS 23389+0300). Five out of six radio-loud ULIRGs have gigahertz peaked spectrum (GPS) type AGN at their center (except for IRAS F03538-6442), which is the cause of radio-loudness. At the same time, we note that α_{AGN} is consistent with that of the canonical synchrotron emission spectral index.

6.6 Discussion

Below, we discuss the global astrophysical properties for our entire sample of infrared bright galaxies consisting of 11 LIRGs (studied in our previous paper; [Dey et al., 2022](#)) and 14 ULIRGs (this work). We performed a similar analysis on both samples of galaxies; hence, the results can be interpreted without any additional assumptions.

6.6.1 q_{IR} parameter

Within the framework of the “calorimetry” model of galaxies, the radio emission follows a tight empirical relation with the IR emission, denoted by q_{IR} parameter (infrared–radio correlation; [Voelk, 1989](#); [Lacki et al., 2010](#)). The origin of this relation lies within the physics of cosmic rays, magnetic fields, and interstellar dust, which are connected through star formation activity. Young OB stars heat their surrounding dust that re-emits the thermal continuum in the IR, and the supernova explosions of the same stars produce CREs that emit the radio continuum ([Draine, 2011](#); [Klessen and Glover, 2016](#)). The galaxies are considered optically thick to radio and UV–IR emission in the sense that CREs lose all their energy via synchrotron radiation within the galaxy and that all UV photons emitted by young stars are absorbed by dust and then re-emitted in the infrared ([Draine, 2003](#)). However, with the advent of *Spitzer* and *Herschel* telescopes, it was noted that galaxies are optically thin to UV–IR emission instead, and radio–FIR relation can be maintained with gas and magnetic field coupling in galaxies ([Helou et al., 1988](#); [Niklas et al., 1997](#); [Lacki](#)

et al., 2010; Tabatabaei et al., 2017). Nevertheless, the radio-FIR correlation holds for four decades in IR luminosities and for different galaxy classes (Yun et al., 2001; Magnelli et al., 2015), as well as within galaxies (Dumas et al., 2011; Tabatabaei et al., 2013).

The q_{IR} parameter is given as (Yun et al., 2001):

$$q_{\text{IR}} \equiv \log_{10} \left(\frac{\text{FIR}}{3.75 \times 10^{12} \text{ W m}^{-2}} \right) - \log_{10} \left(\frac{S_{1.4 \text{ GHz}}}{\text{W m}^{-2} \text{ Hz}^{-1}} \right) \quad (6.1)$$

where far infrared luminosity, FIR, is computed using $\text{FIR} \equiv 1.26 \times 10^{-14} (2.58 S_{60\mu\text{m}} + S_{100\mu\text{m}}) \text{ W m}^{-2}$ where $S_{60\mu\text{m}}$ and $S_{100\mu\text{m}}$ are the 60 and 100 μm band flux densities, in Jy, from IRAS and $S_{1.4 \text{ GHz}}$ is the 1.4 GHz radio luminosity.

Figure 6.3 shows the q_{IR} estimated from Equation 6.1 and plotted against the monochromatic infrared luminosity at 60 μm (panel (a)). panel (b) shows the q_{IR} estimated from CIGALE, $q_{\text{IR}}(\text{CIGALE})$, with the color bar showing the radio-loudness parameter. The $L_{60\mu\text{m}}$ is derived as $4\pi d_L^2 \times S_{60\mu\text{m}}$ where d_L is the luminosity distance. To obtain the luminosity distance, we use the cosmological calculator⁴ (Wright, 2006) with the Hubble constant $H_0 = 69.6 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_M = 0.286$, and $\Omega_\lambda = 0.714$ (Bennett et al., 2014). The color bar represents the radio loudness parameter. We note that $q_{\text{IR}}(\text{CIGALE})$ considers the dust continuum luminosity calculated based on the Bayesian analysis of the used templates in the rest-frame wavelength region 8–1000 μm .

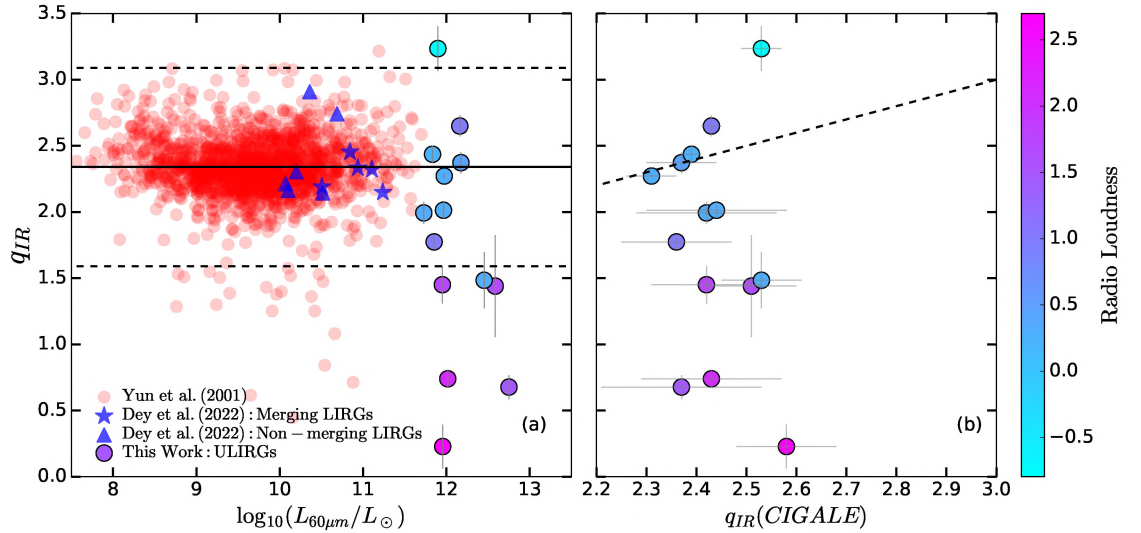


FIGURE 6.3: q_{IR} estimated from Equation 6.1 versus 60 μm dust luminosity. The solid line represents the mean, while the upper and lower dashed lines represent its 3σ bounds (panel a). panel (b) shows the q_{IR} estimated from Equation 6.1 against that from CIGALE. The color bar shows the decimal logarithmic radio loudness. To help guide the eye, a dashed line showing the one-to-one line is plotted in panel (b) to visualize the correspondence between the two q_{IR} estimation methods. All objects with radio-loudness ≥ 10 are considered radio-loud.

In panel (a), the upper and lower dashed lines represent the 3σ bounds of the mean

⁴<http://www.astro.ucla.edu/~wright/CosmoCalc.html>

value with objects designated as “IR excess” and “radio excess” if they fall above and below the 3σ bounds, respectively. Most of our sample exhibits typical values of q_{IR} , indicative of radio emission from star formation processes alone with six ULIRGs being radio excess objects, of which five show kpc-scale double-lobed radio galaxy at their center (IRAS F00183-7111, IRAS 13305-1739, IRAS 14394+5332, IRAS 17179+5444, IRAS 23389+0300), except for one galaxy, IRAS F03538-6432 where the cause of intense radio emission could be enhanced star formation due to merging or a presence of a compact radio AGN. We also note that IRAS 08572+3915 is an IR excess object due to the presence of heavily obscured AGN (Appendix B.3). Furthermore, the distribution of q_{IR} , with respect to $\log_{10} L_{60\mu\text{m}}/(L_{\odot})$ gives comparable results to those obtained for other LIRGs by Yun et al. (2001) and Galvin et al. (2018). Here, LIRGs and ULIRGs (which are either non-merging or merging/interacting) exhibit similar q_{IR} values and are indistinguishable in this aspect. Furthermore, (Yun et al., 2001) obtained a mean value of q_{IR} with 1σ scatter= 2.34 ± 0.26 for a sample of 1809 galaxies that includes IR excess and radio excess objects in a small number ($<2\%$ of the total sample). Bell (2003) obtained a median value of q_{IR} with 1σ scatter= 2.64 ± 0.26 for a sample of 162 galaxies without AGN activity. For our sample of 25 galaxies using Equation 6.1, we get a mean with 1σ scatter= 2.03 ± 0.7 . Within the uncertainties, the q_{IR} obtained for our sample is consistent with these studies.

panel (b) shows the q_{IR} estimated Equation 6.1 plotted against the q_{IR} obtained from UV-radio SED modeling using CIGALE, $q_{\text{IR}}(\text{CIGALE})$. The values of our sample of galaxies lie around a rather uniform value of ~ 2.58 , in contrast to the values found via Equation 6.1, which show a range between ~ 0.2 and ~ 3.2 . This is because CIGALE 2022.1 computes the q_{IR} using the radio module where synchrotron spectral indices from star formation (α_{SF}) and AGN (α_{AGN}) and q_{IR} are provided as an input. The radio module decomposes the total radio emission into that from star formation and AGN using q_{IR} and R_{AGN} as normalizing factor. Since we decompose the modeled star formation and AGN radio emission in our analysis, we obtain $q_{\text{IR}}(\text{CIGALE})$ only from the star-forming component, while the q_{IR} estimated using Equation 6.1 considers the total radio luminosity irrespective of origin. That is why the $q_{\text{IR}}(\text{CIGALE})$ estimates is ~ 2.5 while the range is between ~ 0.2 and ~ 3.2 when q_{IR} is estimated from Equation 6.1. We performed the Spearman rank correlation test between q_{IR} and $q_{\text{IR}}(\text{CIGALE})$ values, which measures the statistical dependence (p -value) and the strength of the correlation (ρ -value) between the two variables (Spearman, 1904). A no-correlation null hypothesis is evaluated against a non-zero correlation hypothesis at a significance level of 0.01. The hypothesis of no correlation is rejected at confidence level $>99\%$ for $p<0.01$. The values of q_{IR} and $q_{\text{IR}}(\text{CIGALE})$ of the ULIRGs sample are not correlated with $p=0.55$ and $\rho=-0.17$. We show that the q_{IR} values for these galaxies lie around 2.5 when the AGN contribution is taken into account.

6.6.2 Radio spectral indices and spectral curvature

The integrated radio spectra for our sample of ULIRGs show complex forms and are rarely described by single power-laws; instead, they show multiple low-frequency bends and turnovers (Figure 6.1). Bends in the radio SED can occur not only due to FFA or SSA but also due to the Tsytovitch-Razin effect when the refractive index of the medium is less than unity (Israel and Mahoney, 1990). The cutoff frequency for SSA to be effective is related to the radio surface brightness, which is given as $\text{peak flux}/\theta^2$, where the flux is in Jy, and θ is the size in arcsec (for unresolved sources, we take the synthesized beam size as the upper limit for the size). Typically, it is of the order of 10^{-2} for our sources. For the SSA mechanism to be important at 100 MHz for our sources, unreasonably high magnetic field strengths >1000 G are needed (Kellermann and Pauliny-Toth, 1969). We further note that five ULIRGs in our sample are known to host GPS-type AGN and exhibit bent spectra (Section B.3). The estimated surface brightness for them is $\approx 10^{-3}$ -500 when their VLBI sizes and peak fluxes are considered. The corresponding cutoff frequencies range 0.11 MHz-60 MHz. These estimated cutoff frequencies are smaller than the low-frequency turnovers in our cases; hence, SSA can be safely ruled out (Kellermann and Pauliny-Toth, 1969).

The Tsytovitch-Razin turnover frequency is calculated as $20 \times N_e/B$ (MHz), where N_e is the electron density (cm^{-3}) and B is the magnetic field strength in μG (Ginzburg and Syrovatskii, 1965). In ISM, for the typical CRE density ~ 1 (cm^{-3}) (Ferrière, 2001) and the typical magnetic field strength of $50 \mu\text{G}$ (Crocker et al., 2010), the Tsytovitch-Razin turnover frequency turns out to be 0.4 MHz. This safely rule out the Tsytovitch-Razin effect as a cause of low-frequency turnover for our sources.

The synchrotron spectral index for our sample of galaxies ranges between ~ -0.6 and ~ -2.0 . The relatively flat spectra in galaxies, ~ -0.6 , are comparable to the spectral index of synchrotron emission by electrons accelerated due to diffusive shock acceleration with an energy index in the range of -2 to -2.5 in shock fronts of supernova remnants (see, Lacki et al., 2010, and the references therein). Steeper spectral slopes ranging from -1.0 and -1.5 can be explained by synchrotron/inverse-compton cooling losses, as both are more efficient at higher frequencies (Hummel, 1991; Marvil et al., 2015).

6.6.3 Thermal emission

The thermal emission of an ionized gas depends on the emission measure (EM), which is an integral of the electron density along the line of sight. EM is calculated by assuming that the emission originates from a volume of cylindrical geometry with constant temperature and electron density (Condon, 1992). It is calculated from the optical depth, τ_ν , at the turnover frequency:

$$\tau_\nu = 3.28 \times 10^{-7} \left(\frac{T_e}{10^4 \text{ K}} \right) \left(\frac{\nu}{\text{GHz}} \right)^{-2.1} \left(\frac{EM}{\text{pc cm}^{-6}} \right) \quad (6.2)$$

where T_e is the electron temperature of the H_{II} emitting region and EM is the emission measure of depth s . τ_ν is set to unity at the turnover frequency measured from our radio SED modeling. The EM is given by the integral of the electron density, N_e , along the line of sight of the H_{II} region of depth s , assuming that N_e^2 does not change with s :

$$\frac{EM}{\text{pc cm}^{-6}} = \int_{los} \left(\frac{N_e}{\text{cm}^{-3}} \right)^2 d \left(\frac{s}{\text{pc}} \right) \quad (6.3)$$

We compute the EMs for our sources using the turnover frequencies obtained from our modeling (Table 6.3) and assuming a typical electron temperature 10^4 K. Table 6.7 provides the emission measures for our sample. Our EM values for our LIRGs sample (Dey et al., 2022) and ULIRGs are consistent with those given for galaxies of these classes (Clemens et al., 2010; Galvin et al., 2018).

TABLE 6.7: Emission Measure (EM) and electron density (Ne) is derived from the model most supported by the evidence value for each source. Sources without constrained EM and Ne are marked by ‘—’.

Name	EM ₁ (10 ⁶ cm ⁻⁶ pc)	Ne ₁ (cm ⁻³)	EM ₂ (10 ⁶ cm ⁻⁶ pc)	Ne ₂ (cm ⁻³)
IRAS F00183-7111	0.57	2.98	—	—
IRAS F03538-6432	—	—	—	—
IRAS 08572+3915	—	—	—	—
UGC 5101	—	—	2.56	153
IRAS 10565+2448	0.30	>37	—	—
IRAS 12112+0305	0.18	26	—	—
UGC 08058	—	—	28.11	693
IRAS 13305+1739	—	—	—	—
UGC 8696	0.06	16	210.36	939
IRAS 14348-1447	—	—	—	—
IRAS 14394+5332	0.02	6	145.46	537
IRAS 17179+5444	1.15	83	—	—
IRAS F23529-2119	—	—	—	—
IRAS 23389+0300	0.28	21	—	—

We obtain mean ionized gas densities using emission measures computed from our modeling ($EM=Ne^2 l$ where l is the physical size of the source). For the majority of our sources, the physical sizes are calculated using angular sizes (=deconvolved major axis full width at half maximum) at 8.4 GHz from Condon et al. (1991) and distances computed following

the methodology in Section 6.6.1. IRAS 10565+2448 was unresolved at 8.4 GHz (Condon et al., 1991), we obtain a lower limit on the electron density because we use the resolution ($=0.25''$) as a measure of angular size. For IRAS 14394+5332 and IRAS 23389+0300, we use the synthesized beam size from our radio imaging (Appendix B.1). For IRAS 17179+5444, we take a fitted major axis length as a measure of angular size (Myers et al., 2003). Since the observations rarely resolve the sources, so we do not have a direct measure of the source sizes at turnover frequencies. These could, in principle, be larger than those at 8.4 GHz due to cosmic-ray diffusion, but the synchrotron lifetime are small at these frequencies, so effect on the source size should be negligible, therefore, it is reasonable to use 8.4 GHz source sizes. For the Galvin et al. sources, we use the beam sizes at 9.0 GHz to measure the electron densities. The estimated electron densities are listed in Table 6.7 and are in accord with those found in literature (Clemens et al., 2010).

6.6.4 Thermal Fraction

The thermal fraction(TF) measures the contribution of thermal free-free emission to the observed total radio continuum. It is an excellent indicator of current star formation in galaxies as it probes the H_{II} region. The TF at 1.4 GHz (TF_{1.4}) was computed from the decomposed thermal and nonthermal flux estimated using the radio SED modeling. For our sample of ULIRGs, the TF is less than 0.11, except for galaxy IRAS 08527+3915 whose value is ~ 0.86 (Table 6.4). In Figure 6.4, we plot the TF_{1.4} versus the IR luminosity from star formation processes alone (note that CIGALE gives dust luminosities from the AGN and SF) with a color bar marking the bolometric AGN fraction. The TF values are consistent with those from previous studies (Marvil et al., 2015). We find that both samples of LIRGs and ULIRGs exhibit a similar range of TFs despite the expectation that (U)LIRGs should exhibit high TFs, because they have high SFRs compared to the LIRGs. However, a similar range could be observed due to the absorption of ionizing photons by dust, therefore reducing the amount of gas-ionizing photons in LIRGs and ULIRGs (Valdés et al., 2005; Díaz-Santos et al., 2017).

The ULIRG IRAS 08527+3915 exhibit about 2 orders of magnitude lower dust luminosity as compared to other ULIRGs (Table 6.6), therefore, the high TF shown by this source ($=0.86$) must be due to low absorption of ionizing photons by dust. However, the four ULIRGs showing low TF ($<0.7\%$; Table 6.4) have dust luminosities comparable to other ULIRGs ($\sim 10^{12}L_{\odot}$; Table 6.6), which could be due to the large optical thickness of the thermal ionized gas.

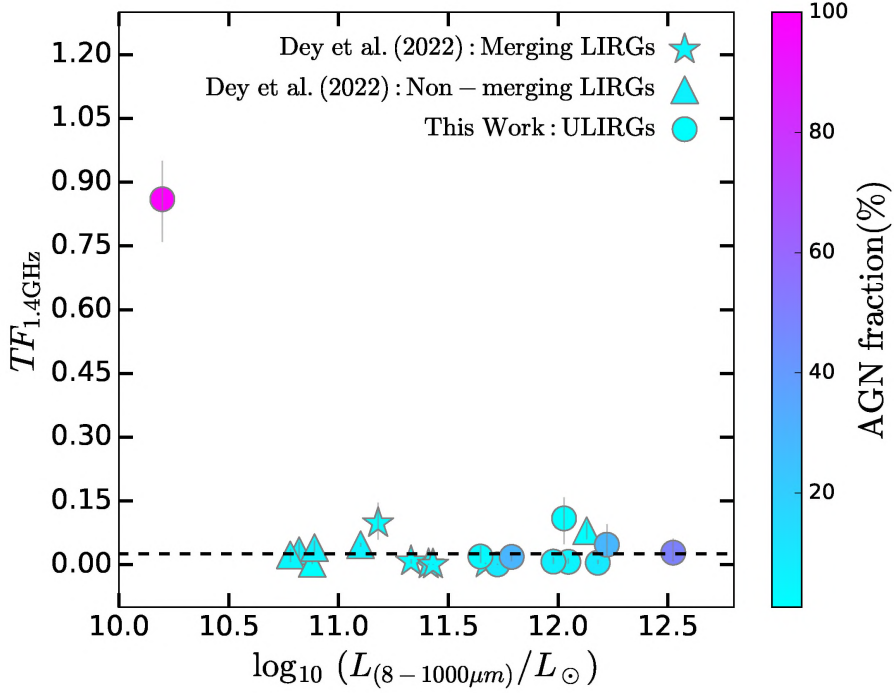


FIGURE 6.4: Thermal fraction (TF) at 1.4 GHz plotted against the dust luminosity obtained from our CIGALE modeling. The dashed line indicates the median $TF = 0.02$ for our sample. The color bar represents the bolometric AGN fraction.

6.6.5 $TF_{1.4}$ vs. q_{IR}

The $TF_{1.4}$ and q_{IR} are good indicators of starburst timescale in star-forming galaxies. The TF is high in regions of recent star formation due to increased thermal emission from accelerated free-free electrons in H_{II} regions. The q_{IR} also shows a similar nature due to the increase in the IR emission and the deficit of nonthermal emission to the total radio continuum. Figure 6.5 compares TF with q_{IR} with a color bar marking the timescale of star formation activity. In addition, we overplot the LIRGs from Dey et al. (2022) and the ULIRGs from Galvin et al. (2016) for comparison. As the starburst ages, we expect the TF and q_{IR} to decrease and the time-delayed synchrotron emission to set in. The LIRGs and ULIRGs do not follow the theoretical line by Marvil et al. (2015) well because many galaxies studied here are interacting and, therefore, undergo multiple bursts of star formation activity. No clear distinction between the young (cyan) and old (magenta) stellar populations is seen. The expectation of high TF in the case of ULIRGs undergoing young star formation (magenta) is not observed, possibly due to the absorption of ionizing photons by dust (Section 6.6.4).

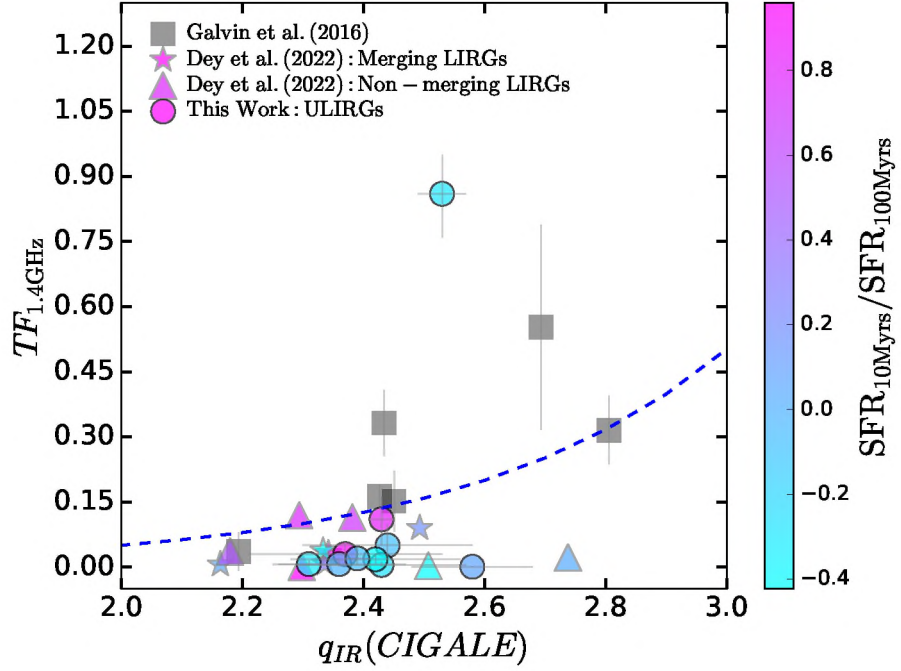


FIGURE 6.5: Distribution of thermal fraction with q_{IR} (Equation 6.1) for our sample of ULIRGs. The color bar indicates the ratio of SFR_{IR} obtained for a time interval averaged over the last 10 Myr and 100 Myr ago from the CIGALE analysis. The solid line marks the relation between TF and q_{IR} given by $\text{TF} = 1.7 \times 10^{q_{\text{IR}} - 3.53}$ (Marvil et al., 2015)

6.6.6 SFR calibration

One of the most important goals of our study is to calibrate radio continuum emission in order to derive radio SFR, which is an excellent extinction-free SFR diagnostic. CIGALE modeling allows us to obtain SFR_{IR} averaged over different time intervals, i.e., 10 and 100 Myr, enabling us to check the validity of the SFR calibration as a function of the SFR history. Since our detailed radio SED modeling provides the decomposed nonthermal and thermal spectral luminosities, we obtain the total, nonthermal, and thermal SFRs following the SFR calibration relations given by Murphy et al. (2011). Thermal SFR, $\text{SFR}_{\nu}^{\text{th}}$ is derived using Kroupa initial mass function (IMF; Kroupa, 2001) assuming solar metallicity and continuous star formation:

$$\left(\frac{\text{SFR}_{\nu}^{\text{th}}}{M_{\odot} \text{ yr}^{-1}} \right) = 4.6 \times 10^{-28} \left(\frac{T_e}{10^4 \text{ K}} \right)^{-0.45} \left(\frac{\nu}{\text{GHz}} \right)^{0.1} \left(\frac{L_{\nu}^{\text{th}}}{\text{erg s}^{-1} \text{ Hz}^{-1}} \right) \quad (6.4)$$

where L_{ν}^{th} is the thermal spectral luminosity and $T_e = 10^4 \text{ K}$.

The nonthermal SFR, $\text{SFR}_{\nu}^{\text{nth}}$, is derived using calibration between the supernova rate and the SFR using the output of the Starburst99 model (Leitherer et al., 1999), an

empirical relation between the supernova rate and the nonthermal spectral luminosity, L_ν^{nth} , of the Milky Way (Tammann, 1982; Condon and Yin, 1990):

$$\left(\frac{\text{SFR}_\nu^{\text{nth}}}{M_\odot \text{ yr}^{-1}} \right) = 6.64 \times 10^{-29} \left(\frac{\nu}{\text{GHz}} \right)^{\alpha^{\text{nth}}} \left(\frac{L_\nu^{\text{nth}}}{\text{erg s}^{-1} \text{ Hz}^{-1}} \right) \quad (6.5)$$

where, $\alpha^{\text{nth}} = \alpha = \alpha_{\text{synch}}$ is the synchrotron spectral index. For our calculations, we use the values obtained from radio SED modeling (Table 6.3).

In Chapter 5 we obtained total SFR, $\text{SFR}_\nu^{\text{total}}$ for the sample of LIRGs, using the radio to infrared scaling with a fixed value of q_{IR} parameter, 2.4 (Bell, 2003; Murphy et al., 2011), however, here we estimate it by combining Equation 6.4 and 6.5.

$$\left(\frac{\text{SFR}_\nu^{\text{total}}}{M_\odot \text{ yr}^{-1}} \right) = 10^{-27} \left[2.18 \left(\frac{T_e}{10^4 \text{ K}} \right)^{0.45} \left(\frac{\nu}{\text{GHz}} \right)^{-0.1} + 15.1 \left(\frac{\nu}{\text{GHz}} \right)^{-\alpha^{\text{nth}}} \right]^{-1} \left(\frac{L_\nu^{\text{total}}}{\text{erg s}^{-1} \text{ Hz}^{-1}} \right). \quad (6.6)$$

Here, the advantage is that the above Equation 6.6 weights the total radio luminosity with the expected thermal fraction at a given frequency. We estimated the $\text{SFR}_\nu^{\text{total}}$ for the LIRG sample using the radio-only SED modeling results from Chapter 5.

Figure 6.6 shows the SFR_{IR} averaged over 10 and 100 Myr ago and total, nonthermal, and thermal radio SFRs obtained at 1.4 GHz (left panel) and 4.8 GHz (right panel). We obtain these radio SFRs from Equation 6.4, 6.5, 6.6 using thermal, nonthermal, and total radio fluxes from our radio SED modeling (see Section. 6.4.1). We note that our CIGALE analysis used Salpeter IMF for estimating the SFR_{IR} while the radio SFRs are obtained using Kroupa's IMFs. This will lead to an offset between the infrared and radio SFR estimates. To correct for this offset, we divide the radio SFRs by a constant factor of 0.67 (Madau and Dickinson, 2014). The dashed line shows one-to-one line to help guide the eye. Most of our sources fall on the line with only few exceptions. These sources have large radio luminosities due to the presence of radio AGN (shown by large radio loudness parameter) and hence they do not follow correspondence between IR and radio nonthermal and total luminosities.

To check for statistical dependence between the two independently estimated SFRs, we performed Spearman's rank correlation test. We obtain a statistically significant correlation with $p \leq 0.01$ for the SFR_{IR} averaged over 10 Myrs and 100 Myrs, respectively, with total and nonthermal SFR at 1.4 GHz respectively (Figure 6.6 (a), (b), (d), (e); top panel), clearly rejecting the null hypothesis of no correlation with confidence $\geq 99\%$. We obtained positive correlations between the two variables indicated by the positive ρ values. Even though some galaxies deviate from the one-to-one line due to high radio loudness (shown by the color bar), the two independent SFR diagnostics are strongly correlated.

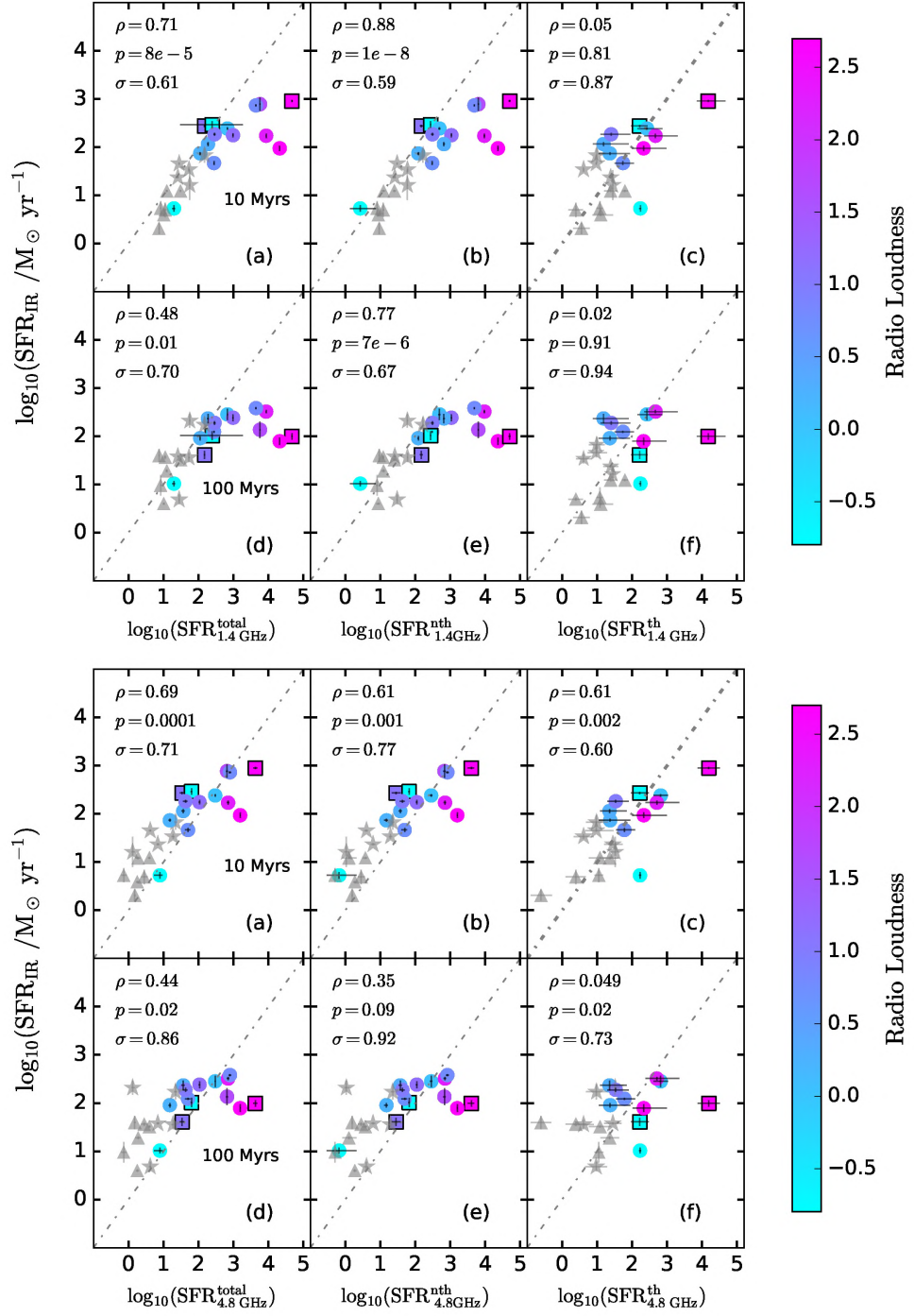


FIGURE 6.6: Comparison of the SFR_{IR} obtained for two time intervals 10 and 100 Myr ago from the CIGALE SED fitting with the radio total, nonthermal, and thermal SFRs, obtained at 1.4 GHz (top panel) and 4.8 GHz (bottom panel), respectively. The color bar shows the decimal logarithmic radio loudness parameter. The circle and square show the burst age greater and smaller than 15 Myr, respectively, derived from the CIGALE modeling. To help guide the eye, a dashed line showing one-to-one line in each panel is plotted.

This is quite puzzling as the typical lifetime of the CRE synchrotron at 1.4 GHz frequency is $\approx 3.4 \times 10^6$ yr (using Equation 18 of [Lacki et al., 2010](#)) for the assumed magnetic field strength of about $50 \mu\text{G}$ ([Crocker et al., 2010](#)). Therefore, a positive correlation between radio SFR and SFR_{IR} for 10 Myr might be expected but not with SFR_{IR} averaged over 100 Myr ago. However, we note that ULIRGs usually undergo multiple episodes of star-burst activity ([Farrah et al., 2003](#)) during their lifetime; therefore, an absence of a clear division between these two timescales with radio SFR is expected. Next, even though the thermal radio luminosity is due to star formation processes alone, we still do not recover a good correlation between the $\text{SFR}_{1.4\text{GHz}}^{\text{th}}$ and SFR_{IR} ($p=0.81$ and 0.91 for 10 and 100 Myrs, respectively, Figure 6.6 (c), (f); top panel). This could be due to the significant statistical uncertainty associated with measuring thermal luminosity at 1.4 GHz where it is dominated by nonthermal processes ([Condon, 1992](#)) and strengthens the view that 1.4 GHz thermal radio luminosity is not a good tracer of recent star formation rate.

Similarly, we obtain a statistically significant correlation $p \leq 0.002$ for the SFR_{IR} averaged over 10 Myrs with total, nonthermal, and thermal radio SFR at 4.8 GHz (Figure 6.6 (a), (b), (c); bottom panel), rejecting the null-hypothesis with confidence $>99.8\%$. We do not recover a statistically significant correlation for the SFR_{IR} averaged over 100 Myrs with total, nonthermal, and thermal radio SFRs at 4.8 GHz ($p \geq 0.02$, Figure 6.6 (d), (e), (f); bottom panel). As the synchrotron lifetimes are about a factor of two smaller for electrons emitting at 4.8 GHz than at 1.4 GHz, similar results are expected while comparing SFR_{IR} s with radio SFRs obtained at these frequencies. As expected, the thermal radio SFR at 4.8 GHz shows a good correlation with SFR_{IR} averaged over 10 Myr ago (Figure 6.6 (c); bottom panel) compared to 1.4 GHz thermal radio SFR (Figure 6.6 (c); top panel). If the optically thin condition holds, the thermal emission differs only slightly at 1.4 and 4.8 GHz (thermal spectral index is -0.1); therefore, our new result of statistically significant correlation with 4.8 GHz thermal radio SFR with SFR_{IR} averaged over 10 Myr ago compared to 1.4 GHz thermal radio SFR with SFR_{IR} averaged over 10 Myr ago points to the fact that free-free emission is optically thick at 1.4 GHz while it is optically thin at 4.8 GHz (also indicated by a low thermal fraction at 1.4 GHz; Section 6.6.4). Furthermore, we note that the SFR_{IR} averaged over 100 Myr ago shows an indication of flattening with total and nonthermal radio SFRs compared to that averaged over 10 Myr due to the low burst age obtained from our CIGALE analysis (shown with circle and square with burst age greater and smaller than 15 Myr, respectively). This indicates that these galaxies have young star formation.

6.6.7 Comparison of optical morphological differences and their relation to attenuation, L_{dust} , SFRs, and bolometric AGN fractions

Our sample of LIRGs consisted of a total of 11 galaxies with 5 merging galaxies and 6 isolated galaxies ([Dey et al., 2022](#)). Instead, all our ULIRGs are interacting, pre-merging,

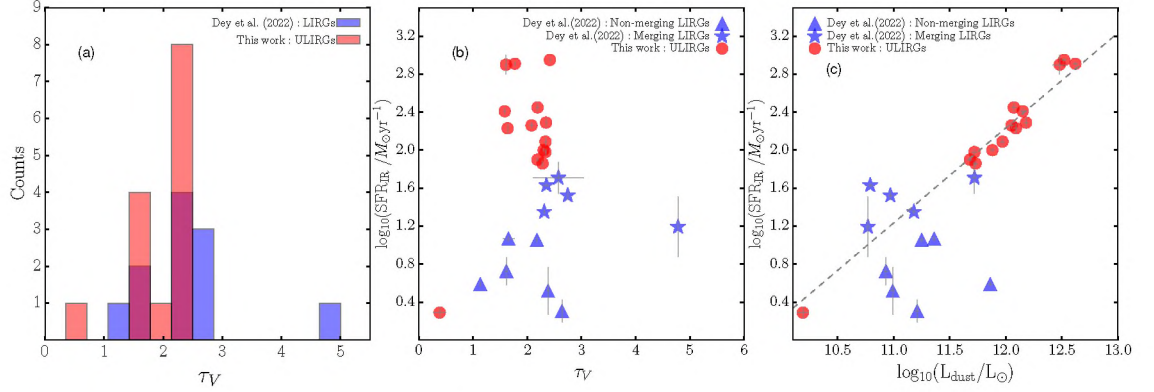


FIGURE 6.7: Histogram of τ_V (panel (a)), relation of τ_V and SFR_{IR} (panel (b)), and relation of L_{dust} with SFR_{IR} (panel (c)).

or in a post-merging stage (Appendix B.3). Figure 6.7(a) shows the histograms of CIGALE estimated V-band optical depth, $\tau_V (=0.921 \times A_V$ where A_V is the attenuation at V-band; Calzetti, 2013). In our CIGALE modeling, we assume a single component dust model by Calzetti et al. (2000). The two-sample Kolmogorov-Smirnov (KS) test fails to reject the null hypothesis that the two data sets are of the same continuous distribution at a significance level of 0.01. Figure 6.7(b) shows the comparison between instantaneous SFR_{IR} and τ_V . Although they show about an order of magnitude higher SFRs than LIRGs, the ULIRGs exhibit the same range of τ_V as LIRGs. For our ULIRGs, this is a selection effect, as these are saturated in the U-band, creating a clustering at $\tau_V \approx 2$. On a separate note, we stress that the depth obtained from the mid-IR spectra of the central kpcs in some ULIRGs tends to be much larger than in LIRGs (see Stierwalt et al., 2013, 2014), and implies τ_V is much higher than what CIGALE can measure in the UV-optical wavebands because the nuclei are very thick. Figure 6.7(c) shows instantaneous SFR and L_{dust} obtained from SED modeling using CIGALE. The dashed lines shows the SFR obtained with the Kennicutt relation of SFR estimation from L_{dust} following $\text{SFR}[M_{\odot} \text{yr}^{-1}] = 4.5 \times 10^{-44} \times L_{\text{dust}} \text{ erg s}^{-1}$ (Kennicutt, 1998). For both samples, the SFRs estimated from the CIGALE analysis show a good correspondence with those from the Kennicutt's relation.

Regarding the bolometric AGN fraction, for LIRGs, it was limited to $<10\%$ (Dey et al., 2022) while for the majority of ULIRGs (11 out of 14), it is $\leq 30\%$ and reaches as high as 99% (Table 6.6). We performed a two-sample KS test to check whether the bolometric AGN fractions depend on the optical morphological class. We divided our total sample into two subsamples: one consisting of isolated galaxies (6 galaxies) and the other of merging or interacting galaxies (19 galaxies). The KS-test returned the $p=0.012$, which does not reject the null hypothesis that the two populations are drawn from the same continuous distribution at a 1% significance level. This supports previous conclusions that bolometric AGN fraction does not depend on the optical morphological class (e.g., Petric et al., 2011;

Paspaliaris et al., 2021).

6.6.8 Comparison of radio spectral indices with redshift, SFR, stellar mass, dust mass, and sSFR

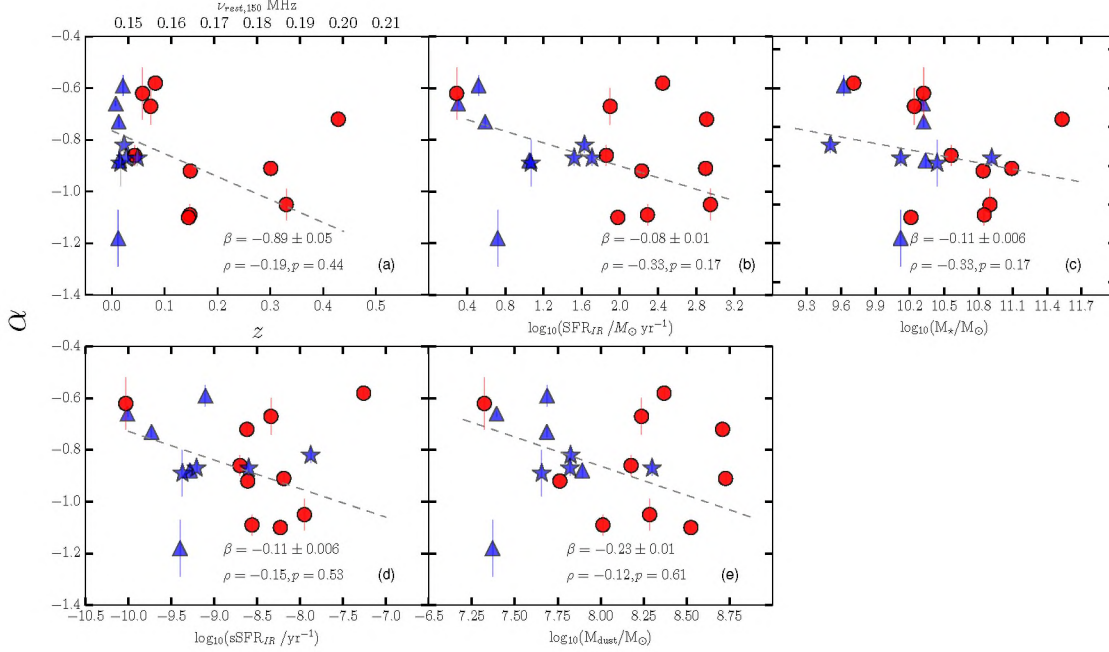


FIGURE 6.8: Variation of synchrotron spectral index, α , obtained from radio SED modeling and redshift (panel (a)); SFR (panel (b)), stellar mass ($M_{\star}$; panel (c)), sSFR (panel (d)), and dust mass (M_{dust} ; panel (e)) for our truncated sample of 19 galaxies. The blue stars and triangles show the merging and non-merging LIRGs, while the red circles represent the ULIRGs, all classified as merging or interacting galaxies. The slope of the weighted linear fit along with 1σ uncertainty and the ρ and p -values from the application of Spearman’s rank correlation test are given inside each panel.

The radio continuum emission from star-forming galaxies is a combination of steep non-thermal synchrotron emission ($S_{\nu} \propto \nu^{-\alpha}$) and flat thermal free-free emission ($S_{\nu} \propto \nu^{-0.1}$) with the emission dominated by synchrotron emission at low frequencies ($\lesssim 10$ GHz; Condon, 1992). For synchrotron emission from continuously injected CREs with a distribution $N \propto E^{-\Gamma}$, the observed radio spectral index is $\alpha = (1 - \Gamma)/2$, where E and Γ are the energy and particle energy index, respectively. When spectral aging is important, the synchrotron spectral index changes by $\Delta\alpha = 0.5$ at high frequencies as the particle distribution steepens to $N \propto E^{-\Gamma-1}$. Various absorption processes, escape of CREs, and adiabatic cooling of electrons further modify the shape of the radio continuum.

Figure 6.8 presents the scatter plots between the modeled synchrotron spectral index, α (Section 6.4.1) and redshift (panel (a)), SFR (panel (b)), stellar mass ($M_{\star}$; , panel (c)), specific star formation rate (sSFR; panel (d)), dust mass (M_{dust} ; panel (e)) obtained from CIGALE modeling (Section 6.4.2) for our truncated sample of 19 galaxies (nine LIRGs

and 10 ULIRGs). We chose these galaxies because, for them, the radio SEDs are best fitted by models where the nonthermal emission is due to a single population of accelerated particles. For this analysis, we exclude the six galaxies that best fit complex radio SEDs where the emission is due to two distinct populations of nonthermal particles. The weighted linear fit in Figure 6.8 is performed by minimizing χ^2 and using the uncertainties of α . The slopes of these linear fits, β , and 1σ uncertainties are given in the right-bottom corner of each panel. Furthermore, we applied Spearman’s rank correlation test. We do not find a statistically significant correlation between the analyzed quantities, as the null hypothesis of no-correlation cannot be rejected.

Theoretically, from the single-zone model of CRE injection, cooling, and escape, one would expect a steepening of the radio spectra with redshift due to increased inverse-Compton losses due to increased CMB density (Lacki et al., 2010; Klein et al., 2018). Our analysis does not reveal such evolution with redshift, possibly due to the low z range ($z \leq 1$;) and small sample size (panel (a); see also Magnelli et al., 2015; An et al., 2021, 2023). We emphasize that we use the modeled spectral index in our analysis, where the flattening due to low frequencies (FFA) and at high frequencies (FFE) is taken care of. An et al. (2023) also noted the steepening of observed two-point spectral index ($\alpha_{150\text{ MHz}}^{610\text{ MHz}}$) with $M_\star$, instantaneous SFR_{IR} . Similarly, Heesen et al. (2022) has also reported higher SFRs showing steeper spectra ($\alpha_{1.4\text{ GHz}}^{150\text{ MHz}}$) in his sample of 76 star-forming galaxies in the SFR range $\sim 10^{-1}$ – $10^1 \text{ M}_\odot \text{ yr}^{-1}$.

One expects galaxies with lower SFRs to show steeper spectra due to the aging of CREs due to ceased acceleration. It is tempting to extend the Heesen et al. results to a higher SFR range as our sample consists of galaxies with the SFR range $\sim 10^{0.4-3.0} \text{ M}_\odot \text{ yr}^{-1}$. We find that α does not have a strong and statistically significant correlation with the SFR (large p -value and small ρ -value; panel (b)), though the normalization of linear fit seems to be a simple extrapolation from that obtained for lower SFR range galaxies (see Figure 5a of Heesen et al., 2022). However, we cannot strictly compare our result with that of Heesen et al. because their spectral index is the observed one and not the clean synchrotron spectral index, used in our analysis. Moreover, their spectral index correlation with SFR cannot be due to the SFR, as the spectral index is flatter in star-forming regions in their galaxies (Appendix B of their manuscript). As shown globally, a flatter spectral index is expected with star formation rate surface density in galaxies (Tabatabaei et al., 2017).

Additionally, Heesen et al. show a stronger correlation of observed spectral index with stellar and dynamical mass (or rotation velocity) than with SFR, indicating that the spectral index-SFR correlation is secondary with galaxy size driving the rest of the correlations. The synchrotron spectral index-SFR correlation is not stronger than spectral index- $M_\star$ (Figure 6.8 (c)) in our analysis, most likely due to the small sample size. Moreover, An et al. (2021) noted the steepening of the observed two-point spectral index ($\alpha_{1.3\text{ GHz}}^{3.0\text{ GHz}}$) with $M_\star$ while our analysis does not reveal such a trend (panel (c)). Galaxies

with higher $M_\star$ are expected to be larger (Gürkan et al., 2018), causing CREs to take longer time to escape from the galaxy; therefore, any steepening of α with $M_\star$ must be due to cooling losses.

An et al. (2021) noted the flattening of observed two-point spectral index ($\alpha_{1.3\text{GHz}}^{3.0\text{GHz}}$) with instantaneous sSFR_{IR} in the large SFR range $\gtrsim 10$. Similarly, Murphy et al. (2013) found an increase in the flattening of the observed radio spectral index ($\alpha_{1.4\text{GHz}}^{8.4\text{GHz}}$) with an increase in the sSFR. The sSFR is related to the compactness of the source (Elbaz et al., 2011). Murphy et al. (2013) interpreted it due to compact starbursts hosting deeply embedded star formation that becomes more optically thick in the radio and infrared. Our sample does not show such dependence because we use a modeled spectral index where the flattening due to FFE is considered (panel (d)). We find no correlation between α and M_{dust} for the sample (panel (e)), which is along the expectation that these galaxies retain the injection spectral index as the CRE escape lifetimes are long because of their large sizes. An essential difference between our analysis and the studies mentioned above is that they rely on the observed spectral index obtained between two frequencies to determine the CRE dependence on other galaxy properties, while we have used a clean spectral index (from radio SED modeling), which takes into account the low-frequency flattening due to FFA and high-frequency flattening due to FFE. Moreover, a direct comparison between our analysis and the An et al. analysis is not possible as they do not assess their trends with any proper correlation or rank analysis as done here. Although our nonthermal spectral index is a true estimator of the underlying CRE population, we do not find any trends because of the large spread caused by the small sample size used in our analysis (19 galaxies).

6.7 Summary and Conclusion

In this study, we have simultaneously modeled densely sampled SEDs of 14 ULIRGs in UV–IR–radio using the CIGALE SED modeling tool and radio-only wavebands ($\sim 54\text{ MHz}$ – 30 GHz) using the UltraNest Bayesian inference tool. Including results from our previous study based on 11 LIRGs (Dey et al., 2022), we discuss the global insight into the evolution of astrophysical properties of infrared bright galaxies. Our main conclusions are the following:

1. The sample consists primarily of Seyfert-type nuclei. Some galaxies show double or triple nuclei (e.g., IRAS 14394+5332), while none show large-scale radio jets. The radio emission is dominated by bright nuclei (e.g., Figure B.1) and can be combined with infrared to UV observations to model galaxy properties using CIGALE.
2. Our radio SED modeling using densely sampled SEDs of LIRGs and ULIRGs reveals that single power-law forms rarely characterize their spectra. Instead, we observe many bends and turnovers. Some ULIRGs turn out to be radio-loud AGNs due to the presence of GPS-type AGN in their centers; however, the bends in their radio

SEDs are a result of free-free absorption (also inferred in other studies, e.g., for IRAS F00183-7111 in [Norris et al., 2012](#)).

3. We note that 64% of ULIRGs and 63% of LIRGs show either one or two bends in their spectra. There is no indication that ULIRGs show more complicated radio spectra as compared to LIRGs despite their optical morphologies displaying more signs of interaction and mergers. However, we note that our sample sizes are small.
4. The values of q_{IR} and $q_{\text{IR}}(\text{CIGALE})$ for the ULIRGs sample are weakly correlated with $p=0.55$. The large spread in q_{IR} against the $q_{\text{IR}}(\text{CIGALE}) \approx 2.5$ is due to the different definitions used for the calculation. Merging and non-merging LIRGs have similar q_{IR} , but ULIRGs show larger spread and outliers. The q_{IR} values are influenced by AGN, as indicated by their large radio loudness.
5. The ULIRGs exhibit a range of TFs comparable with LIRGs. This could be due to the absorption of ionizing photons by dust, resulting in a decrease in the amount of ionizing gas present in ULIRGs. The emission measure for our LIRG and ULIRG samples are consistent with those found in the literature for galaxies of these classes.
6. Multiple studies have used the CIGALE to model star-forming galaxies, LIRGs, and ULIRGs, but only a few included radio measurements in the SED fitting. Including radio measurements in the CIGALE modeling mainly constrains the dust luminosity and SFR better. Our results indicate that the uncertainties in the L_{dust} and SFR estimates are improved by more than an order of magnitude compared to those derived using UV-IR SED modeling alone.
7. We show that total and nonthermal radio luminosity at 1.4 GHz can be used as good estimators of recent SFRs for all LIRGs and ULIRGs that do not show large radio loudness, meaning radio AGN influence. A weaker but still significant correlation of radio SFR at 1.4 GHz and old (100 Myr) SFR based on SED modeling is observed, which indicates multiple episodes of starburst activity during their lifetime.
8. We show that the total, nonthermal, and thermal radio luminosities at 4.8 GHz are also a good tracer of recent SFRs for our sources. As expected, the thermal luminosity at 4.8 GHz turns out to be a better tracer of recent SFR compared to the thermal luminosity at 1.4 GHz. Our new result suggests that the free-free emission is optically thick at 1.4 GHz while it becomes optically thin at 4.8 GHz.
9. Our results indicate that bolometric AGN fraction does not depend on the optical morphological class, consistent with those found in the literature.
10. We compared the modeled radio nonthermal spectral indices obtained from radio SED modeling with redshift, stellar mass, dust mass, SFR, and sSFR. The nonthermal spectral indices are not statistically significantly correlated with the above-mentioned properties.

7

Summary and future prospects

7.1 Summary and conclusions

This thesis presents the most detailed study of U/LIRGs in the multiwavelength domain. We have explored the synergy between UV-IR and radio SED modeling, which have traditionally been pursued independently. It's worth emphasizing that the findings presented in the thesis are unique in that no other study has conducted SED modeling across such an extensive frequency range encompassing the UV, IR, and radio domains.

U/LIRGs are the primary contributors to the co-moving star formation rate density (SFRD) of the Universe at $z > 1$, making them extremely interesting sources for studying galaxy formation and evolution. It has been shown that ULIRGs exhibit a notable evolution in their contribution to SFRD, approximately 10% at $z \sim 1$ and around 50% at $z \sim 2$; being relatively insignificant in the present-day Universe. Furthermore, slightly less luminous LIRGs peak in their contribution to the SFRD around $z \sim 1$, accounting for approximately 50% of most of the star formation at that epoch. The bulk infrared emission in these galaxies is due to warm dust heated by active galactic nuclei, starbursts due to major mergers, or both. This correlates well with the widely accepted evolutionary picture proposed by [Sanders et al. \(1988\)](#); [Hopkins et al. \(2008\)](#) placing U/LIRGs at a fixed stage in a larger evolutionary sequence between collation of gas-rich galaxies and red-dead elliptical ones. Hence, they provide excellent local laboratories for studying in detail the physical processes that could be associated with the hierarchical transformation of star-forming galaxies into elliptical galaxies. Detailed studies of local U/LIRGs are crucial for gaining a better understanding of processes and for developing and testing models

used to explain statistical studies of large populations of such galaxies at high redshifts, for which it is currently difficult to reach sufficient physical resolution. The key findings and conclusions of this thesis are described in the following sections.

7.1.1 Radio-only SED modeling

We intended to expand the current scope of radio SED modeling by incorporating low-frequency data into our analysis. Most existing models have primarily focused on frequencies above 1.4 GHz, neglecting the valuable information available at lower frequencies. To address this, we incorporate a physically motivated approach into our SED modeling, which takes into account the absorption processes at low-frequency along with the complex nature of the radio continuum considering scenarios where the emission originates from one or two distinct regions characterized by populations of cosmic ray electrons and varying optical depths. Using sophisticated Bayesian modeling techniques, we fit SED values with increasingly complex physical models, employing the Bayes factor to infer the most supported model, preventing overfitting. Following are the results specific to the nature of radio-only SED modeling of U/LIRGs:

7.1.2 Radio spectral curvature

Our analysis of densely sampled SEDs from LIRGs and ULIRGs reveals that single power-law forms rarely describe their spectra. Instead, we observe numerous bends and turnovers. Some ULIRGs turn out to be radio-loud AGNs due to the presence of GPS-type AGNs in their centers; however, the bends in the radio SEDs are attributed to free-free absorption and not to synchrotron self-absorption or Tsytovitch-Razin effects. Similarly, at higher frequencies, we often observe kinks or steepenings, indicating a secondary component of free-free absorption with high emission measures. This complexity has been observed in similar studies by [Clemens et al. \(2010\)](#) and [Galvin et al. \(2018\)](#). Physically, these turnovers suggest the integration of at least two distinct star formation regions within the large radio-synthesized beam. We note that 64% of ULIRGs and 63% of LIRGs show either one or two bends in their spectra. There is no indication that ULIRGs show more complicated radio spectra than LIRGs despite their optical morphologies displaying more signs of interaction and mergers. However, we note that our sample sizes are small.

Radio spectral indices

Contrary to frequent assumptions, the nonthermal spectral index in LIRGs varies between -0.45 and -1.75 , possibly influenced by star formation on cosmic ray electron energetics. In ULIRGs, spectral index values between ~ -0.6 and ~ -0.9 are consistent with the canonical synchrotron emission spectral index, while values between ~ -1.0 and ~ -1.5 align with the cooled synchrotron emission spectral index. For two galaxies (UGC 8696 and IRAS 14394+5332), the spectra are best fitted with a two-component model where the

derived spectral index of the second component is much steeper, ~ -1.9 . In these galaxies, when we compare the weights of the two CRE populations in the model C2, the steep spectrum component is only of the order of 1 to 1.5σ of the flatter spectrum component, thus the extremely steep spectral index can be easily attributed to uncertainties in the data or flux measurements. Moreover, given that high-frequency observations ($<7-8$ GHz) can often be underestimated due to their lower SNR leading to a steep spectrum, the most likely cause of extremely steep spectra is due to above mentioned affects.

Thermal fraction (TF), Emission Measure (EM), and electron densities (N_e)

The thermal fraction (TF) measures the contribution of thermal free-free emission to the observed total radio continuum. It is an excellent indicator of current star formation in galaxies as it probes the H_{II} region. The TF at 1.4 GHz was computed from the decomposed thermal and nonthermal flux estimated using the radio SED modeling. The ULIRGs exhibit a range of TFs comparable with those of LIRGs. This could be due to the absorption of ionizing photons by dust, resulting in a decrease in the amount of ionizing gas present in ULIRGs. We compute the EMs for our sources using the turnover frequencies obtained from our modeling and assuming a typical electron temperature of 10^4 K. The emission measures for our LIRG and ULIRG samples are consistent with those found in the literature for galaxies of these classes (Clemens et al., 2010; Galvin et al., 2018). Further, we obtained the electron densities (N_e) using the estimated EM and physical size of the source. The estimated N_e are in accord with those found in the literature (Clemens et al., 2010).

7.1.3 UV-IR-radio SED modeling

For UV-IR-radio SED modeling, we used publicly available data in 20-30 bands from different open-sourced space-based observing facilities. We employed the Code Investigating GALaxy Emission (CIGALE) SED fitting tool for the modeling. CIGALE is an open source panchromatic SED modeling code. It works on the principle of energy balance, i.e., the energy absorbed by dust in the UV-optical range is self-consistently emitted by dust in the mid- and far-IR range (Noll et al., 2009; Ciesla et al., 2015; Boquien et al., 2019). It further extends the spectrum to radio wavelength by modeling the thermal and nonthermal emission (Boquien et al., 2019; Yang et al., 2020, 2022). Following are the results specific to the nature of UV-IR-radio SED modeling of U/LIRGs:

Astrophysical properties

The CIGALE analysis yielded properties consistent with those expected for galaxies of these classes, including infrared luminosity, dust mass, stellar mass, dust temperature, star formation rates, and AGN fraction.

Attenuation

Analysis of V-band optical depth (τ_V) using CIGALE modeling showed a similar range between LIRGs and ULIRGs. Although ULIRGs exhibited higher SFRs compared to LIRGs, they showed a comparable range of τ_V . This similarity was partly due to a selection effect in ULIRGs, where saturation in the U -band led to clustering around $\tau_V \approx 2$.

Morphological classification

The sample included 11 LIRGs, comprising five merging galaxies and six isolated galaxies. In contrast, all ULIRGs were either interacting, pre-merging, or in a post-merging stage. The bolometric AGN fraction, LIRGs typically had a fraction of $<10\%$, while for most ULIRGs (11 out of 14), it ranged $\leq 30\%$ and reached as high as 99% . Statistical analysis using a two-sample KS test indicated that the bolometric AGN fraction did not significantly depend on the optical morphological class.

Radio data extension to UV-IR SED modeling

Notably, while CIGALE has been extensively used to model star-forming galaxies, LIRGs, and ULIRGs, only a limited number of studies have incorporated radio measurements in the SED fitting process. Including radio measurements in CIGALE modeling primarily enhances the constraints on dust luminosity and star formation rate (SFR). Our findings suggest that the uncertainties in dust luminosity (L_{dust}) and SFR estimates are reduced by more than an order of magnitude compared to those derived solely from UV-IR SED modeling. Our study highlights the importance of integrating radio data into the modeling process for a better characterization of the astrophysical properties of galaxies.

7.1.4 Comparison of parameters obtained from radio-only and UV-IR-radio modeling

SFR calibration

Our radio-only SED modeling enabled us to decompose the total radio emission into thermal and nonthermal radio components, respectively. Following the SFR calibration relation presented in [Murphy et al. \(2011\)](#), we calculated the total, nonthermal and thermal SFRs at 1.4 GHz and compared with SFR_{IR} obtained from SED modeling using CIGALE averaged at 10 and 100 Myrs. We show that the total and nonthermal radio luminosity at 1.4 GHz can be used as good estimators of recent SFRs for all LIRGs and ULIRGs that do not show large radio loudness, meaning radio AGN influence. A weaker but still significant correlation of radio SFR at 1.4 GHz and old (100 Myr) SFR based on SED modeling is observed, indicating multiple episodes of starburst activity during their lifetime. Further, we show that the total, nonthermal, and thermal radio luminosities at 4.8 GHz are also a good tracer of recent SFRs for our sources. As expected, the thermal

luminosity at 4.8 GHz turns out to be a better tracer of recent SFR compared to the thermal luminosity at 1.4 GHz. Our new result suggests that the free-free emission is optically thick at 1.4 GHz while it becomes optically thin at 4.8 GHz.

Variation of nonthermal spectral indices with galaxy properties

We compared the modeled radio nonthermal spectral indices obtained from radio SED modeling with redshift, stellar mass, dust mass, SFR, and sSFR estimated from UV-radio SED modeling using CIGALE for our truncated sample of 19 galaxies (nine LIRGs and 10 ULIRGs). We see that the nonthermal spectral indices are not statistically significantly correlated with the above-mentioned properties.

7.2 Future prospects

7.2.1 Radio continuum as a substitute for FIR continuum

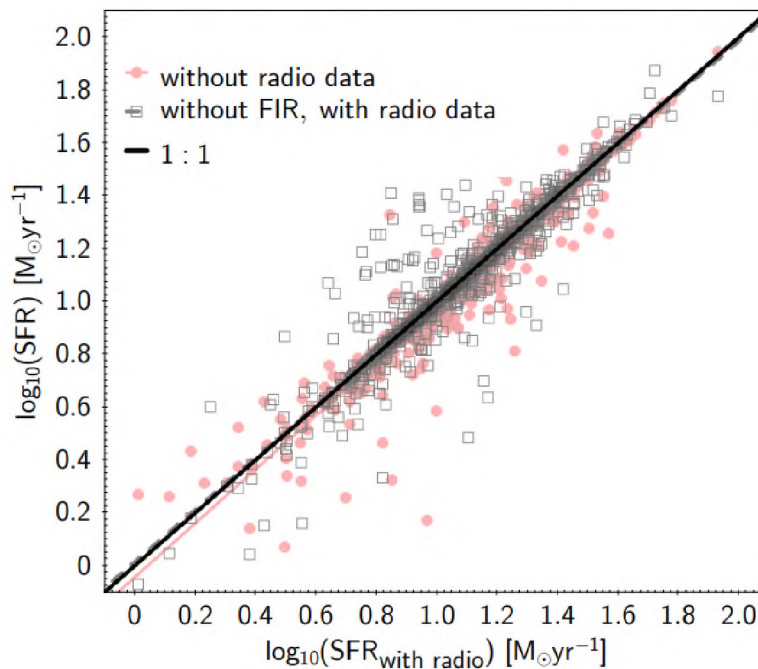


FIGURE 7.1: The comparison between $\log_{10}(\text{SFR})$ obtained from the SED modeling with and without radio data. Pink dots represent $\log_{10}(\text{SFR})$ from total UV-radio fitting, while gray open squares show $\log_{10}(\text{SFR})$ with radio data without FIR data. The solid black line indicates the 1:1 relation, with pink and olive lines representing linear fits to the data. These fits aid in understanding systematic differences between $\log_{10}(\text{SFR})$ values. Image from [Malek et al. \(2022\)](#).

Multiple studies have used the CIGALE to model star-forming galaxies, LIRGs, and ULIRGs, but only a few included radio measurements in the panchromatic SED fitting. Our results show that integrating radio continuum data in the SED modeling significantly

enhances the accuracy of derived dust luminosities and SFRs. Moreover, including radio continuum extension in UV-IR SED modeling presents a viable alternative to FIR photometry (Malek et al., 2022; Thorne et al., 2023). As demonstrated in Figure 7.1, a notable correspondence is observed between the SFRs obtained from the panchromatic SED modeling using UV-FIR continuum datasets and using UV-radio datasets, excluding the FIR measurements, respectively. This alignment is attributed to the robust IR-radio correlation. Theoretically, this correlation enables the utilization of radio continuum emission to constrain the re-emission of processed stellar light by dust, circumventing the need for FIR observations. This finding is valuable for estimating SED parameters due to the sparse availability of current and future planned FIR observatories and the upcoming plethora of radio data from the SKA and its precursors.

7.2.2 Radio-SFR tracer at high- z

The robust estimates of astrophysical properties of nearby galaxies obtained from modeling of densely sampled SEDs have significant implications for extending this research to high- z galaxies. Leveraging the insights gained from this study, we aim to apply these methodologies to high-redshift galaxies, which often have less densely sampled SEDs. This expansion holds the promise of providing new perspectives and a deeper understanding of distant galaxies and their evolutionary processes. Our comprehensive radio-only SED modeling, employing state-of-the-art Bayesian inference techniques, enables us to decompose the total radio continuum into its thermal and nonthermal components, allowing precise calculation of the corresponding SFRs. The radio emissions (nonthermal and thermal), unaffected by extinction, serve as excellent SFR tracers, and these are particularly suitable for high-redshift galaxies expected to be discovered through initiatives like the SKA and its Pathfinder projects. We aim to assess the efficacy of our radio-based SFR estimation methodology at high redshifts. Specifically, we will investigate its ability to produce reliable results with fewer data points and its ability to replicate the outcomes obtained from more extensively sampled SEDs. This research endeavor seeks to validate the viability of utilizing radio emission as a robust SFR tracer in the context of high-redshift galaxies, contributing to our understanding of their properties and evolution.

7.2.3 Dusty Starforming Galaxies as a signpost for protocluster

We intend to apply the methodologies and insight gained from our study to a sample of Dusty Star-Forming Galaxies (DSFGs) at redshift range $z \sim 3-4$. Cosmological simulations (Chiang et al., 2017) indicate that DSFGs are likely associated with galaxy overdensities within the most massive Dark Matter (DM) halos, serving as protoclusters (see Figure 7.2). They provide the earliest sites of star formation, where gas densities and galaxy-merger rates are highest.

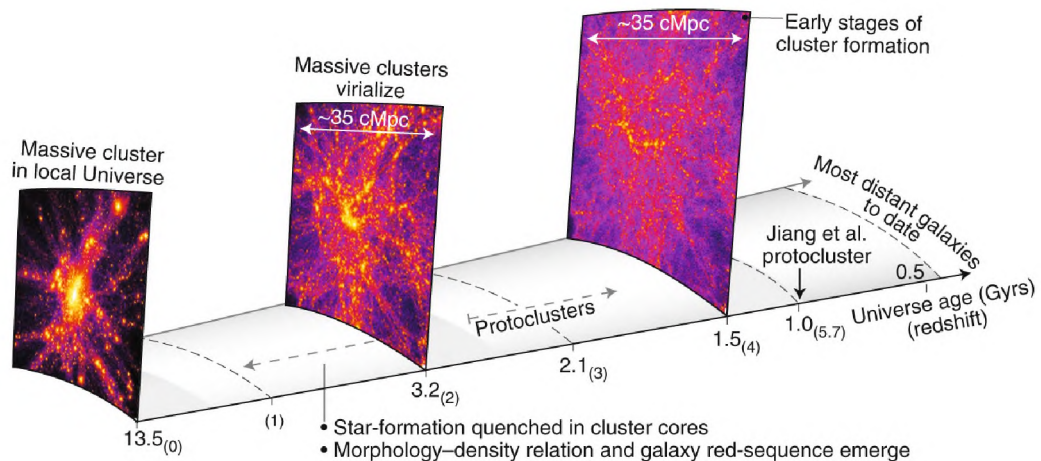


FIGURE 7.2: A schematic diagram of the cosmic evolution of a massive galaxy cluster (Rosati, 2018).

Wide-field surveys targeting red objects in Herschel SPIRE bands, known as “500 μ m-risers,” effectively identify DSFGs at $z \sim 3-4$ (Donevski et al., 2018). Utilizing the dust-to-stellar mass ratio ($M_{\text{dust}}/M_{\star}$) as a robust indicator of dust production and destruction rates in galaxies, Donevski et al. have identified a subset of 500 μ m-risers exhibiting elevated dust-to-stellar mass ratios, indicative of starburst DSFGs at $z \sim 3-4$. We plan to characterize the SED by employing a multiwavelength approach, leveraging data from multiple telescopes, such as Spitzer IRAC, HST, Herschel, and NOEMA in order to obtain various astrophysical properties of these galaxies. The project will aim to validate the following hypotheses:

Are 500 μ m-risers with enhanced dust-to-stellar mass ratios an effective signpost for the earliest galaxy overdensities, i.e., protocluster cores?

What produces enhanced M_{dust} relative to $M_{\star}$ in the central, dense region?

In addition, we plan to investigate the AGN feedback in the protocluster cores. Understanding the interplay between AGN activity and star formation is crucial for deciphering galaxy evolution, especially in dense environments such as protoclusters (Casey, 2016). We aim to detect radio AGN in DSFG candidates within protocluster cores. To identify the presence of radio AGN within DSFGs, we will leverage a key observational signature: their deviation from the established radio-FIR (q_{IR}) relation. Moreover, by utilizing available radio data, we aim to perform a detailed radio-only SED modeling based on the state-of-the-art Untranest Bayesian inference code (Dey et al., 2022, 2024).

7.2.4 Panchromatic SED modeling of spatially resolved NGC 253: a high-resolution approach

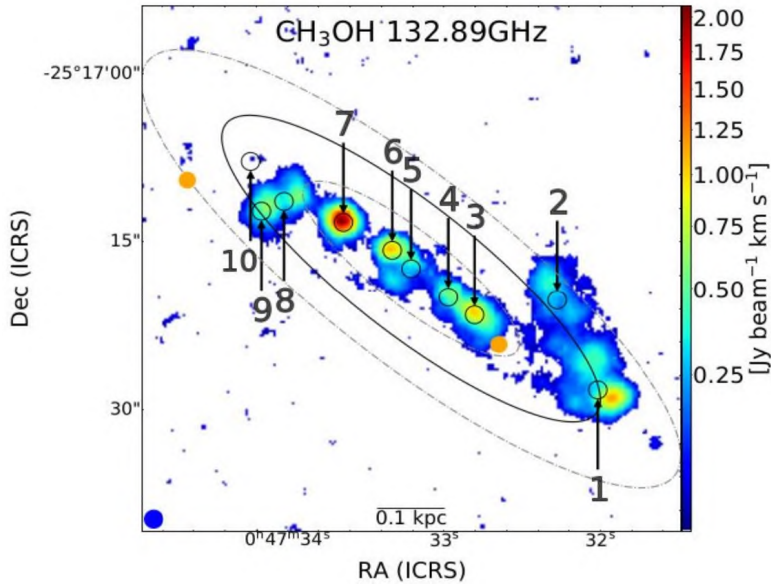


FIGURE 7.3: Integrated intensity map for the methanol line emission at 132.9 GHz (ALMA). Numbers indicates the identified GMCs from (Humire et al., 2022).

Until now, we have used galaxy-averaged flux densities for SED modeling and estimated galaxy-averaged physical parameters valid on kpc scales. However, the physical conditions can vary significantly on ten pc-scales (corresponding to the typical sizes of H_{II} regions) within a galaxy. With this aim, we want to apply methods used and developed in this thesis to a few spatially resolved nearby sources. We will perform SED modeling of galaxies such as NGC 253 and M 82. Studying the physical characteristics of spatially resolved regions is essential for gaining insight into multiphase interstellar medium (ISM) conditions and understanding their formation and evolution. Advancements in ground- and space-based instruments in recent decades have provided unprecedented multiwavelength information. The main scope of this work will be to produce the first high-resolution (3 arcsec) multiwavelength SED, covering optical to sub-mm/cm regimes of an extragalactic source. We have chosen the well-studied central molecular zone (CMZ) of the nuclear starburst NGC 253 and focused on its nuclear giant molecular clouds (GMCs) (~ 30 pc) that account for half of its star formation (Figure 7.3).

In conclusion, the prospects of the work carried out in this thesis extend beyond the study of U/LIRGs. This encompasses investigating fundamental physical mechanisms within Giant Molecular Clouds (GMCs) in nearby galaxies to exploring distant high-redshift galactic systems, particularly given the imminent availability of high-quality deep-photometric data in the near future.

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A

Appendix

A.1 Summary of observations gathered for radio-only and UV–radio SED modeling for the sample of LIRGs, including short notes on the targets

Tables [A1](#) and [A2](#) provide the basic information on the GMRT and VLA continuum datasets analysed by us while the Table [A3](#) provides the integrated flux densities used in radio-only SED modeling. Figure [A.1](#) provides the overlay of the radio contours of DSS images for our galaxies. At the same time, the corner plots for the check on degeneracy on the model parameters are given in Figure [A.2](#).

TABLE A1: Primary and phase calibrators used in our GMRT observations.

Name	Primary (325 MHz)	Phase (325 MHz)	Primary (610 MHz)	Phase (610 MHz)
ESO 500–G034	3C 286, 3C 468.1	1130–148	3C 147, 3C 286	1130–148
NGC 3508	3C 286, 3C 468.1	1130–148	3C 147, 3C 286	1130–148
ESO 440–IG058	3C 286, 3C 468.1	1248–199	3C 147, 3C 286	1248–199
ESO 507–G070	3C 286, 3C 468.1	1248–199	3C 147, 3C 286	1248–199
NGC 5135	3C 286, 3C 468.1	1248–199	3C 147, 3C 286	1248–199
IC 4280	3C 286, 3C 468.1	1248–199	3C 147, 3C 286	1248–199
NGC 6000	3C 286, 3C 468.1	1626–298	3C 147, 3C 286	1626–298
IR 16164–0746	3C 286, 3C 468.1	1626–298	3C 147, 3C 286	1626–298
ESO 453–G005	3C 286, 3C 468.1	1626–298	3C 147, 3C 286	1626–298
IR 18293–3413	3C 286, 3C 468.1	1830–360	3C 147, 3C 286	1830–360
ESO 593–IG008	3C 286, 3C 468.1	1830–360	3C 147, 3C 286	1830–360

TABLE A2: Summary of new GMRT and the archival VLA datasets analysed by us.

ID	Date of obs.	Tel.	Arr.	Frequency	BW (MHz)	IF	Int. (min)	rms ($\frac{\text{mJy}}{\text{beam}}$)	Synth. Beam ($''\times''$)	PA ($^\circ$)	S/N	Area (arcsec^2)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
ESO 500-G034												
23_051	2013 Jun 11	GMRT		325 MHz	32	1	32	0.78	12.49 $\times$ 7.72	33.92	142	518.9
23_051	2012 Oct 20	GMRT		610 MHz	32	1	32	0.18	6.04 $\times$ 4.27	−21.00	394	330.4
AC345	1993 May 24	VLA	CnB	1.4 GHz	50	2	2.5	0.50	25.13 $\times$ 14.66	−21.90	22	1686.8
AD229	1989 Feb 20	VLA	BnA	4.8 GHz	50	2	7.5	0.14	1.67 $\times$ 0.91	−61.11	79	11.1
AV186	1991 Mar 26	VLA	D	14.9 GHz	50	2	10.5	0.47	9.49 $\times$ 4.85	−10.96	19	113.5
NGC 3508												
23_051	2013 Jun 11	GMRT		325 MHz	32	1	32	0.84	10.94 $\times$ 7.89	38.16	41	1703.1
23_051	2012 Oct 20	GMRT		610 MHz	32	1	32	0.31	5.63 $\times$ 4.32	−34.77	42	997.5
AC205	1988 Mar 23	VLA	C	1.4 GHz	50	3.9	2	0.90	24.98 $\times$ 16.46	−9.73	26	1729.7
ESO 440-IG058												
23_051	2013 Jun 11	GMRT		325 MHz	32	1	32	0.60	10.94 $\times$ 7.89	38.16	41	705.9
23_051	2012 Oct 20	GMRT		610 MHz	32	1	32	0.17	7.79 $\times$ 4.20	−32.17	275	421.4
AS412	1990 Oct 6	VLA	CnB	1.4 GHz	50	2	7.9	0.28	21.50 $\times$ 11.44	−48.59	30	1147.1
AS412	1990 Oct 6	VLA	CnB	4.8 GHz	50	2	7.5	0.11	6.59 $\times$ 4.09	−44.93	92	187.1
ESO 507-G070												
23_051	2013 Jun 11	GMRT		325 MHz	32	1	32	1.4	10.73 $\times$ 8.11	4.80	81	466.2
23_051	2012 Oct 20	GMRT		610 MHz	32	1	32	0.67	7.35 $\times$ 4.11	−43.75	190	174.5
AR531	2003 Nov 1	VLA	B	1.4 GHz	50	2	10.5	0.45	8.18 $\times$ 5.47	12.12	165	177.2
AD215	1988 Jun 9	VLA	DnC	4.8 GHz	50	2	9.3	0.15	13.69 $\times$ 12.64	−60.82	190	794.9
AV186	1991 Mar 26	VLA	D	14.9 GHz	50	2	10	0.52	10.10 $\times$ 4.67	−16.23	39	142.5
NGC 5135												
23_051	2013 Jun 11	GMRT		325 MHz	32	1	32	1.8	11.96 $\times$ 7.97	4.75	558	775.0
23_051	2012 Oct 20	GMRT		610 MHz	32	1	32	0.35	7.84 $\times$ 4.13	−38.36	747	730.2
AW126	1985 Apr 1	VLA	BnA	1.4 GHz	50	2	14.6	0.23	5.22 $\times$ 3.28	49.38	10	156.1
AC351	1993 Feb 4	VLA	BnA	4.8 GHz	50	2	18.3	0.1	1.53 $\times$ 1.16	−63.68	316	34.4
IC 4280												
23_051	2013 Jun 11	GMRT		325 MHz	32	1	32	0.59	11.95 $\times$ 8.08	9.45	99	1226.3

23_051	2012 Oct 20	GMRT		610 MHz	32	1	32	0.23	7.21×4.22	−39.93	99	995.6
AC345	1993 May 24	VLA	CnB	1.4 GHz	50	2	3.9	0.55	18.83×14.30	−48.84	56	1114.6
AD215	1988 Jun 14	VLA	DnC	4.8 GHz	50	2	8.5	0.17	13.15×10.61	−54.87	44	1251.0
NGC 6000												
23_051	2012 Oct 20	GMRT		610 MHz	32	1	32	0.28	6.75×4.36	−17.18	600	1333.1
AC345	1993 May 24	VLA	CnB	1.4 GHz	50	2	2	0.52	27.01×12.43	−44.71	207	2970.5
AC326	1992 Jul 13	VLA	D	4.8 GHz	50	2	2	0.37	34.85×16.08	18.22	156	2828.2
IR 16164−0746												
23_051	2012 Oct 20	GMRT		610 MHz	32	1	32	1.3	5.54×4.66	−17.18	152	127.8
AT149	1993 Apr 26	VLA	B	1.4 GHz	50	2	2.2	0.43	6.60×5.54	−0.78	137	139.7
ESO 453-G005												
23_051	2012 Oct 20	GMRT		610 MHz	32	1	32	0.35	8.10×4.14	−32.73	100	227.4
AC345	1993 May 24	VLA	CnB	1.4 GHz	50	2	1.9	1.6	37.58×11.48	−46.21	15	798.3
IR 18293−3413												
23_051	2013 Jun 11	GMRT		325 MHz	32	1	32	1.7	14.20×9.26	−5.84	423	836.7
23_051	2012 Oct 20	GMRT		610 MHz	32	1	32	1.2	13.34×3.98	−47.24	200	687.9
AT0	1983 Nov 30	VLA	BnA	4.8 GHz	50	2	8.5	0.21	1.03×0.43	8.44	23	11.1
AP534	2007 Jun 11	VLA	A	8.4 GHz	50	2	80.3	0.038	0.60×0.24	6.59	53	10.1
ESO 593-IG008												
23_051	2013 Jun 11	GMRT		325 MHz	32	1	32	0.62	11.15×9.56	−19.53	226	667.8
23_051	2012 Oct 20	GMRT		610 MHz	32	1	32	0.34	10.19×4.16	−53.63	134	404.3
AT149	1993 May 23	VLA	CnB	1.4 GHz	50	2	5.2	0.68	26.66×12.93	33.36	75	1329.3
AF446	2007 Mar 29	VLA	D	4.8 GHz	50	2	3.6	1.1	31.22×22.34	−25.85	226	1452.5

Column: (1) proposal identifier of the observation, (2) date of observations, (3) telescope used, (4) configuration array used for VLA observations, (5) central frequency of observation, (6) bandwidth used, (7) number of sub bands used during the observation, (8) integration time used to image the target, (9) typical rms noise on image near to the target measured using TVSTAT, (10) synthesized beam achieved, (11) position angle of the restoring beam, measured counter-clockwise from the standard north direction, (12) signal to noise (S/N) ratio of the source detection (ratio of peak flux density of the source and the rms noise on the map), (12) integration area used in TVSTAT.

TABLE A3: Integrated radio flux densities used for the SED fitting.

Name	Obs. Freq. (GHz)	S (mJy)	error (mJy)	Ref.
(1)	(2)	(3)	(4)	(5)
ESO 500-G034	0.091	174.25	33.06	(1)
	0.122	153.25	21.27	(1)
	0.150	155.9	24.19	(2)
	0.158	144.25	17.01	(1)
	0.189	137.5	15.39	(1)
	0.219	122.5	13.48	(1)
	0.325	139.74	7.28	(3)
	0.610	108.21	5.46	(3)
	1.4	62.61	2.23	(4)
	3.0	26.184	2.67	(5)
	4.8	19.32	0.72	(4)
	10.0	15.7	0.15	(8)
	14.9	9.67	0.88	(4)
NGC 3508	.074	560	70	(6)
	0.091	459.75	34.52	(1)
	0.122	339.75	17.53	(1)
	0.150	230.0	32.8	(2)
	0.158	288.25	10.30	(1)
	0.189	274.25	7.41	(1)
	0.219	245.25	7.13	(1)
	0.325	195.80	10.66	(3)
	0.610	135.92	7.15	(3)
	1.4	55.57	2.93	(4)
	3.0	3.13	0.41	(5)
ESO440-IG058	0.091	260.75	40.56	(1)
	0.122	205.5	28.18	(1)
	0.150	156	23.07	(2)
	0.158	195.5	21.70	(1)
	0.189	190.25	20.78	(1)
	0.219	172.75	18.21	(1)
	0.325	160.01	8.23	(3)
	0.610	97.36	4.92	(3)
	0.843	72.1	5.7	(7)
	1.4	49.795	1.64	(4)
	3.0	32.32	3.22	(5)
	4.8	19.71	0.68	(4)
	10.0	9.7	0.9	(8)
ESO 507-G070	0.091	389.25	54.62	(1)
	0.122	344	40.52	(1)
	0.150	160.0	23.56	(2)
	0.158	276.5	30.61	(1)
	0.189	238.75	29.15	(1)
	0.219	224.25	24.04	(1)

A.1 SUMMARY OF OBSERVATIONS GATHERED FOR RADIO-ONLY AND UV-RADIO SED
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NGC 5135	0.325	117.14	6.90	(3)
	0.610	87.79	4.75	(3)
	1.4	55.12	1.93	(4)
	3.0	32.44	3.26	(5)
	4.8	36.3	1.15	(4)
	14.9	19.37	1.17	(4)
	0.091	1011.25	173.16	(1)
	0.122	890.25	91.63	(1)
	0.150	826.8	83.7	(2)
	0.158	777.50	78.90	(1)
	0.189	649.75	67.38	(1)
	0.219	663.25	66.80	(1)
	0.325	533.40	27.29	(3)
	0.610	370.32	18.61	(3)
	1.40	165.69	5.03	(4)
IC 4280	2.31	100.00	17.20	(10)
	3.0	95.766	9.794	(5)
	4.80	58.51	1.82	(4)
	6.70	48.00	7.20	(9)
	0.091	271.50	49.90	(1)
	0.122	283.75	35.56	(1)
	0.150	186.1	27.54	(2)
	0.158	222.75	25.13	(1)
	0.189	189.15	22.93	(1)
	0.219	162.00	17.45	(1)
	0.325	162.4	8.46	(3)
	0.610	109.63	5.68	(3)
	1.4	48.04	1.92	(4)
	3.0	28.183	4.87	(5)
NGC 6000	0.092	913	105.53	(1)
	0.122	727.75	77.61	(1)
	0.150	418.2	59.55	(2)
	0.158	586.25	61.00	(1)
	0.189	569.75	58.18	(1)
	0.220	494	50.05	(1)
	0.61	287.03	14.51	(3)
	1.4	153.32	7.86	(4)
	4.8	62.70	2.10	(4)
IR 16164-0746	0.091	191.25	58.92	(1)
	0.122	176.50	37.05	(1)
	0.150	151.5	21.88	(2)
	0.158	183.75	26.98	(1)
	0.189	154.75	22.18	(1)
	0.219	200.25	30.21	(1)
	0.61	88.17	5.49	(3)
	1.4	62.36	3.26	(4)
	3.0	44.12	4.45	(5)
ESO 453-G005	0.15	81.6	12.67	(2)

	0.61	38.21	2.17	(3)
	0.84	29.40	2.9	(7)
	1.40	23.39	2.55	(4)
	3.00	14.28	1.45	(5)
IR 18293-3413	0.091	1390	152.79	(1)
	0.122	1006.75	107.71	(1)
	0.150	780.4	111.26	(2)
	0.158	907	92.79	(1)
	0.189	832.25	84.61	(1)
	0.219	710.25	72.27	(1)
	0.325	458.96	23.45	(3)
	0.610	405.18	20.84	(3)
	1.4	226.8	10.56	(11)
	3	106.53	10.81	(5)
	4.8	36.58	2.18	(4)
	8.4	22.09	1.16	(4)
ESO 593-IG008	0.092	261.45	71.30	(1)
	0.122	379.5	53.73	(1)
	0.150	250.0	36.07	(2)
	0.158	289.5	34.07	(1)
	0.189	277.5	30.62	(1)
	0.220	240	25.86	(1)
	0.325	174.46	8.90	(3)
	0.61	116.29	5.93	(3)
	1.4	60.35	2.36	(4)
	3.0	20.867	2.23	(5)
	4.8	21.86	1.91	(4)

Columns: (1) source name; (2) observing frequency; (3) integrated flux density of the source (4) the error in the flux density including the absolute calibration uncertainty (Sect 2.1), (5) references - (1) GLEAM, (2) TGSS ADR1 (Intema et al., 2017), (3) current observations, (4) re-analysed VLA, (5) VLASS (Gordon et al., 2021), (6) VLSSr (Lane et al., 2014), (7) SUMSS (8) ATCA, (9) Effelsberg (Impellizzeri et al., 2008), (10) SPASS (Meyers et al., 2017), (11) NVSS.

A.1 SUMMARY OF OBSERVATIONS GATHERED FOR RADIO-ONLY AND UV-RADIO SED MODELING FOR THE SAMPLE OF LIRGs, INCLUDING SHORT NOTES ON THE TARGETS vii

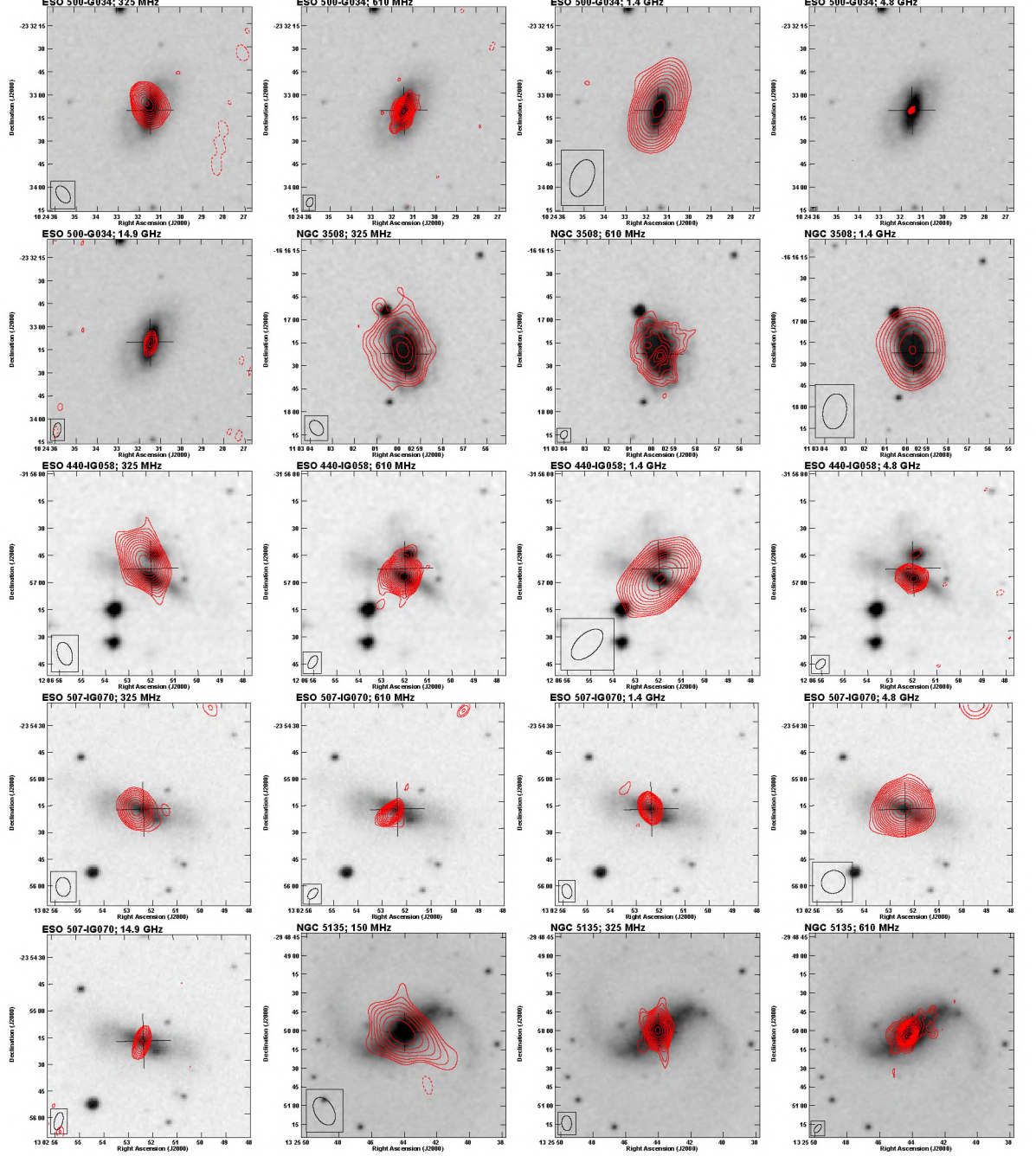


FIGURE A.1: 150 MHz-15 GHz radio contour images (red) overlaid on the optical DSS2 R-band images (grey scale) for the samples of 11 LIRGs analysed by us. The radio contours begin at 3σ of the rms noise on the radio map (Column 8 of Tab. A2) and increase by $(\sqrt{2})^n$ where n ranges from 0,1,2,...20. The -3σ radio intensity is shown by dashed contours and the synthesized beam achieved is given at the bottom left corner of the image.

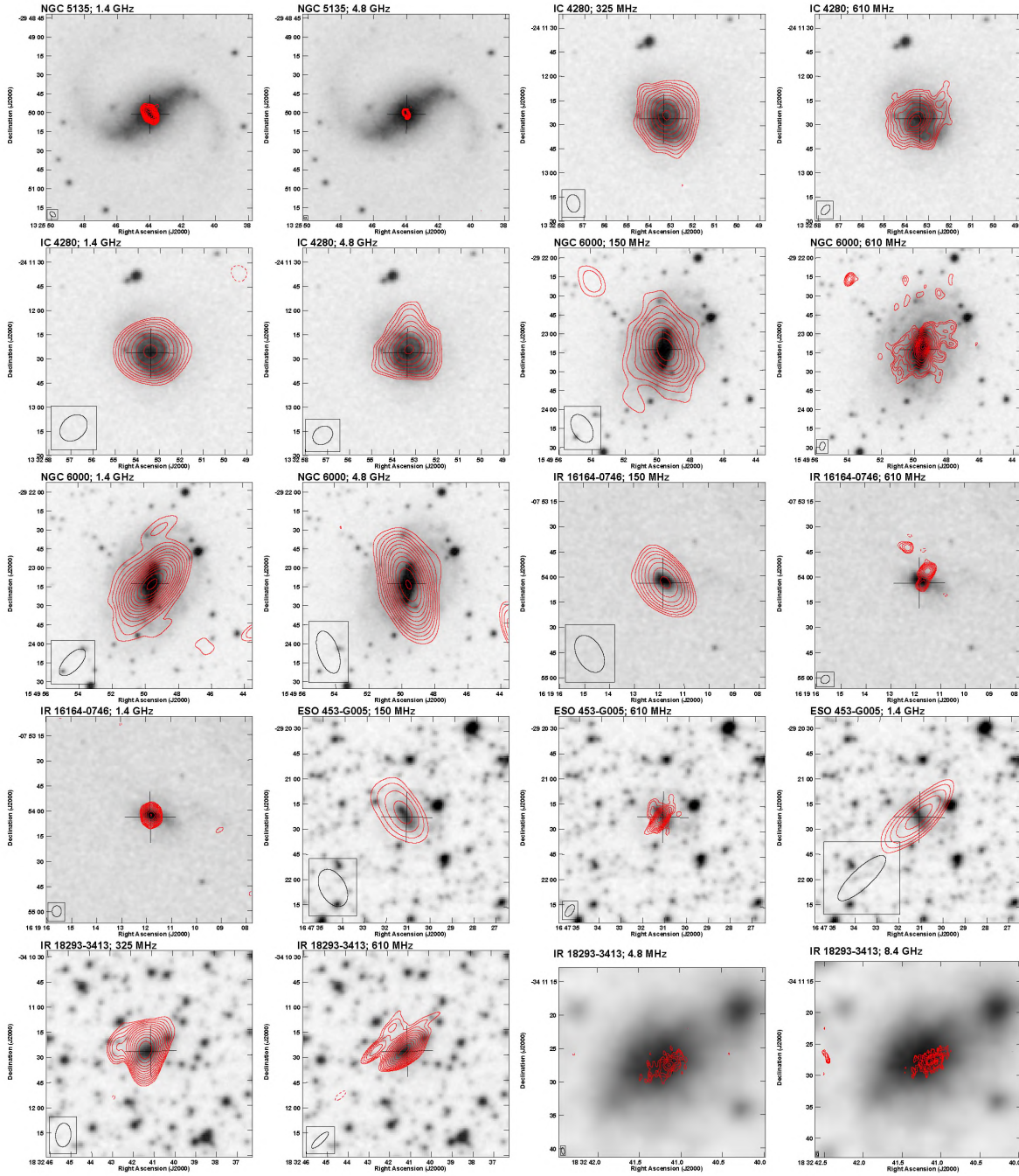


FIGURE A.1: continued

A.1 SUMMARY OF OBSERVATIONS GATHERED FOR RADIO-ONLY AND UV–RADIO SED
MODELING FOR THE SAMPLE OF LIRGS, INCLUDING SHORT NOTES ON THE TARGETS ix

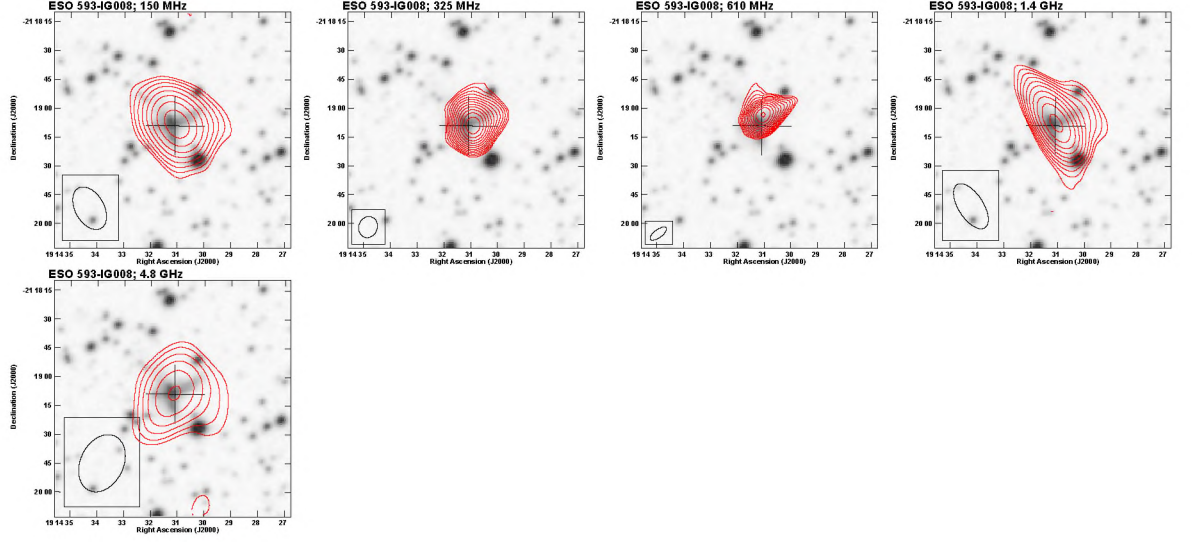


FIGURE A.1: continued

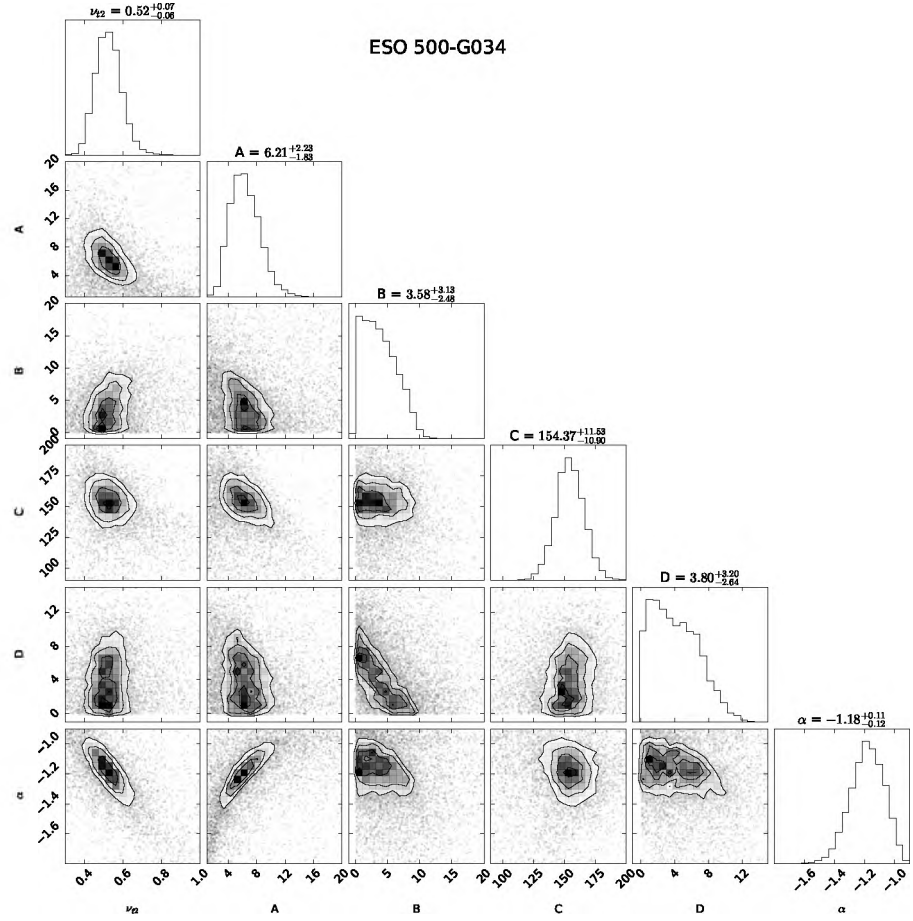


FIGURE A.2: Corner plots showing the one and two-dimensional posterior probability distribution of the estimated parameters in the radio SED modeling for each galaxy.

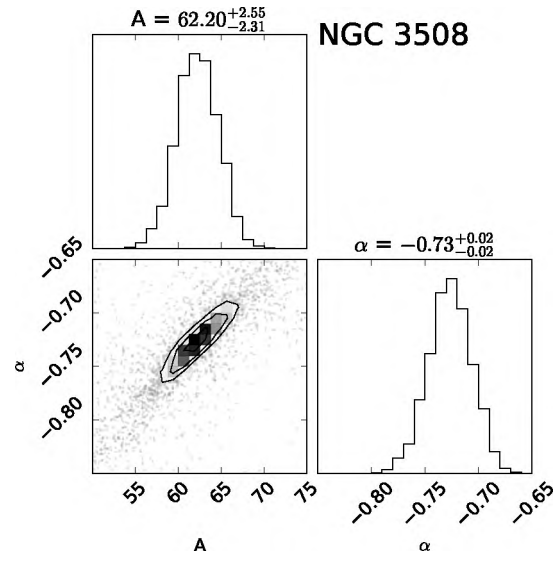


FIGURE A.2: Continued.

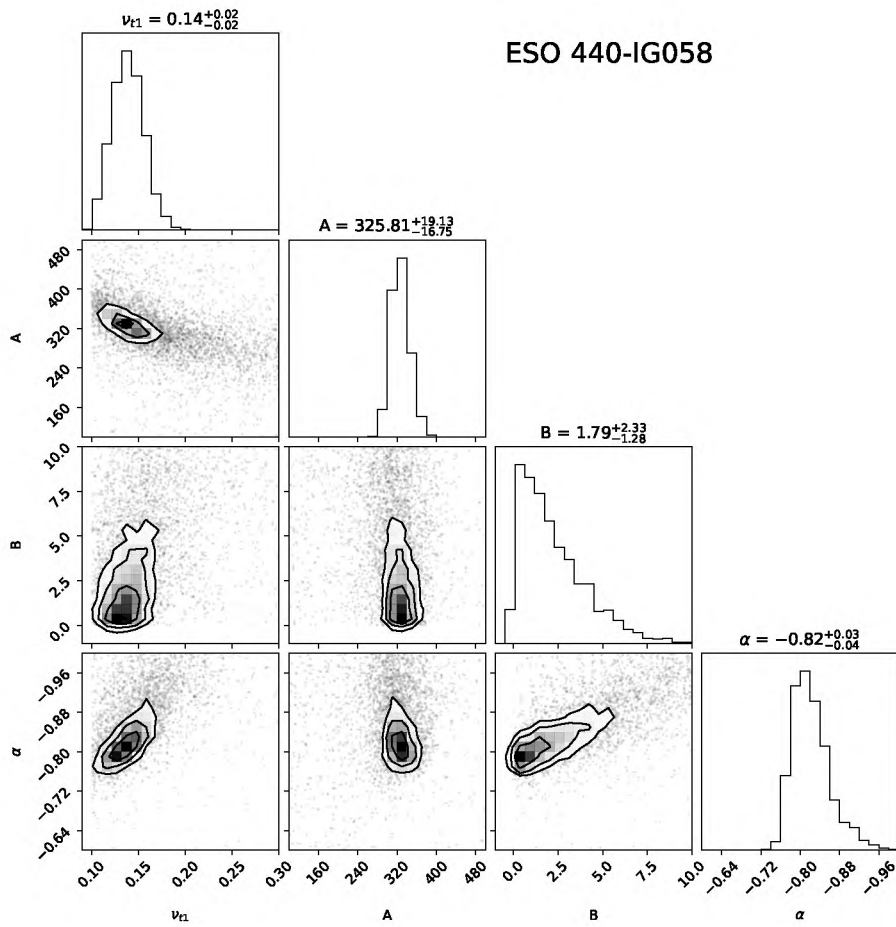


FIGURE A.2: continued

A.1 SUMMARY OF OBSERVATIONS GATHERED FOR RADIO-ONLY AND UV–RADIO SED
MODELING FOR THE SAMPLE OF LIRGs, INCLUDING SHORT NOTES ON THE TARGETS xi

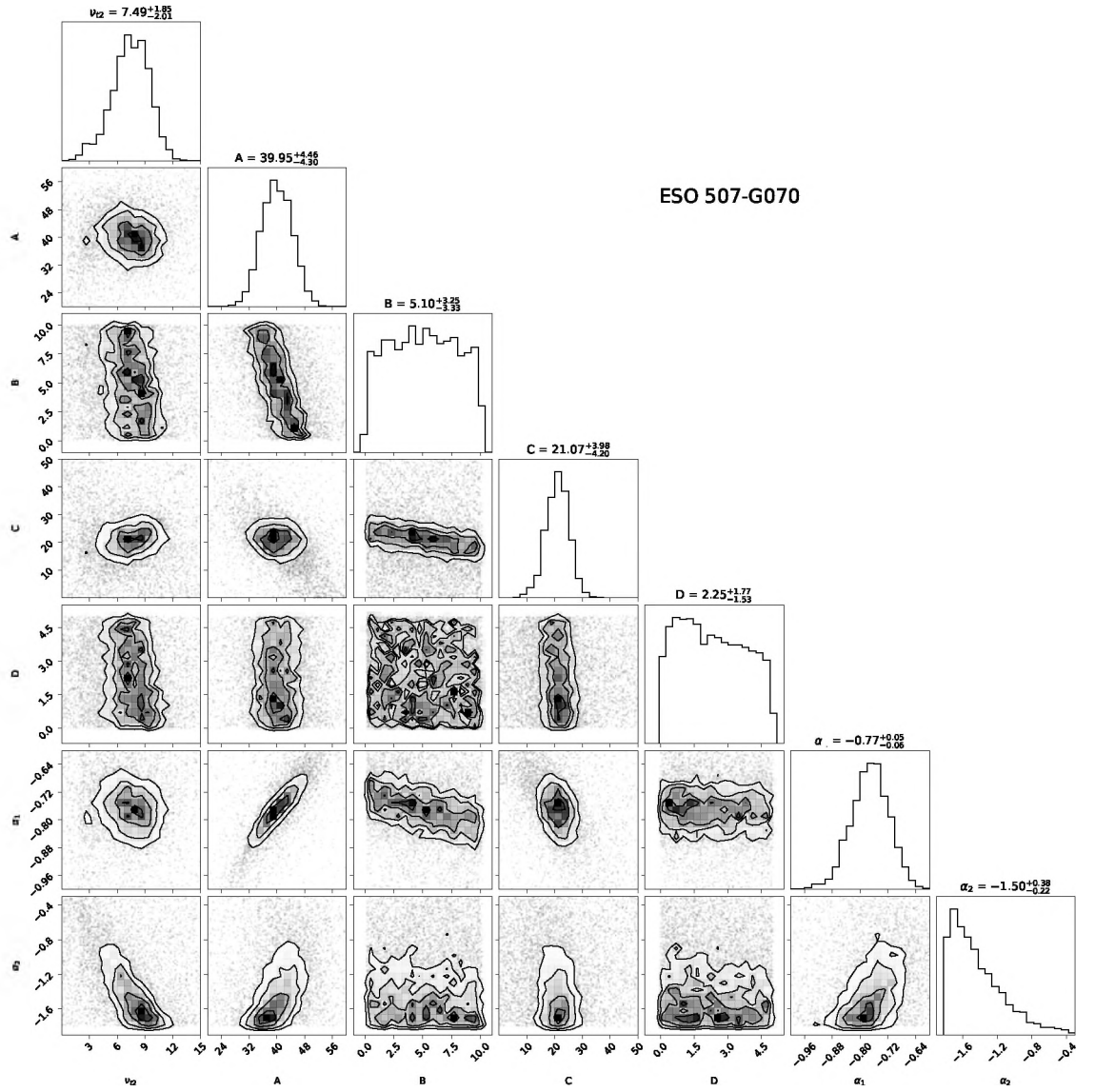


FIGURE A.2: Continued.

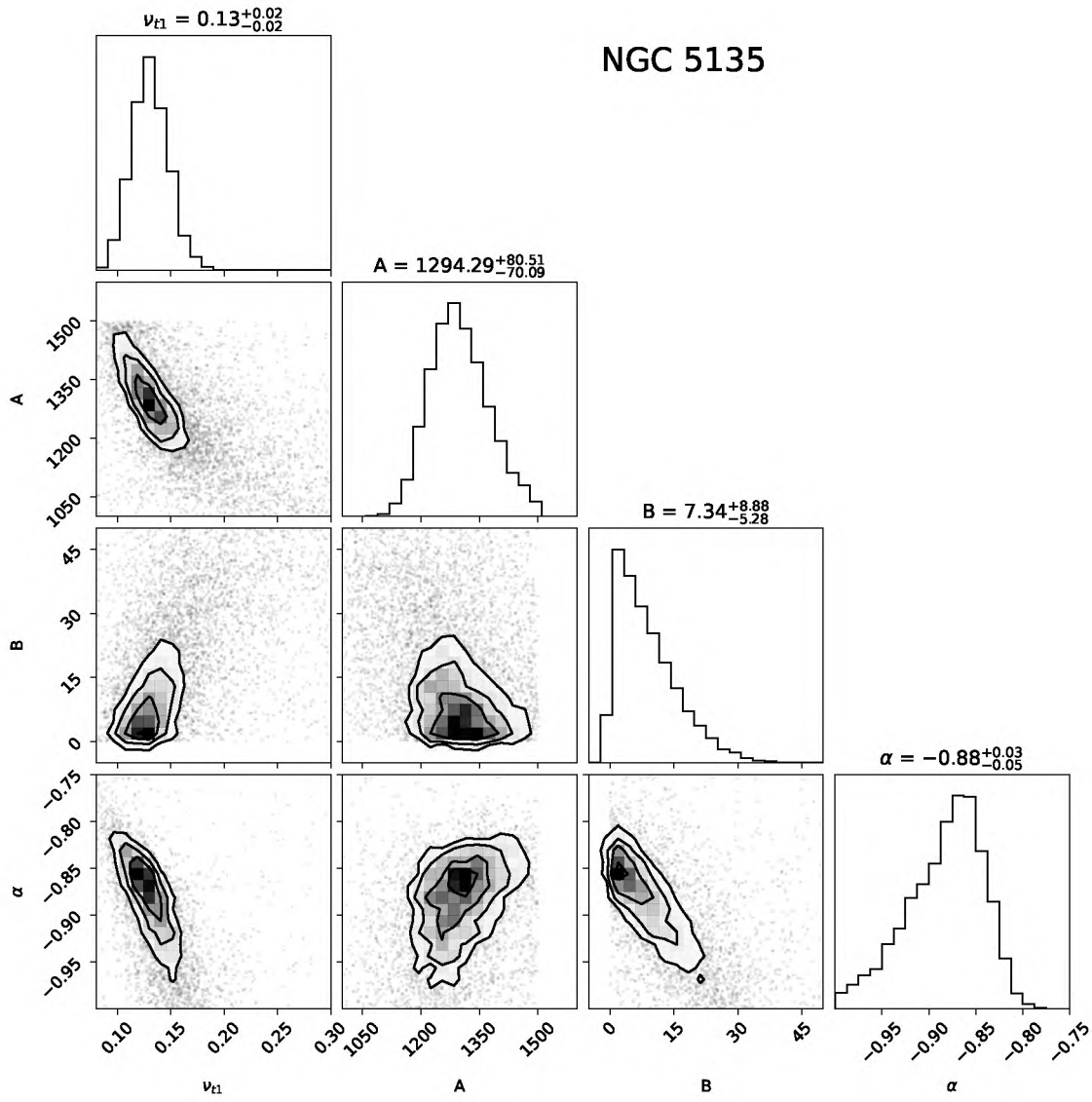


FIGURE A.2: Continued.

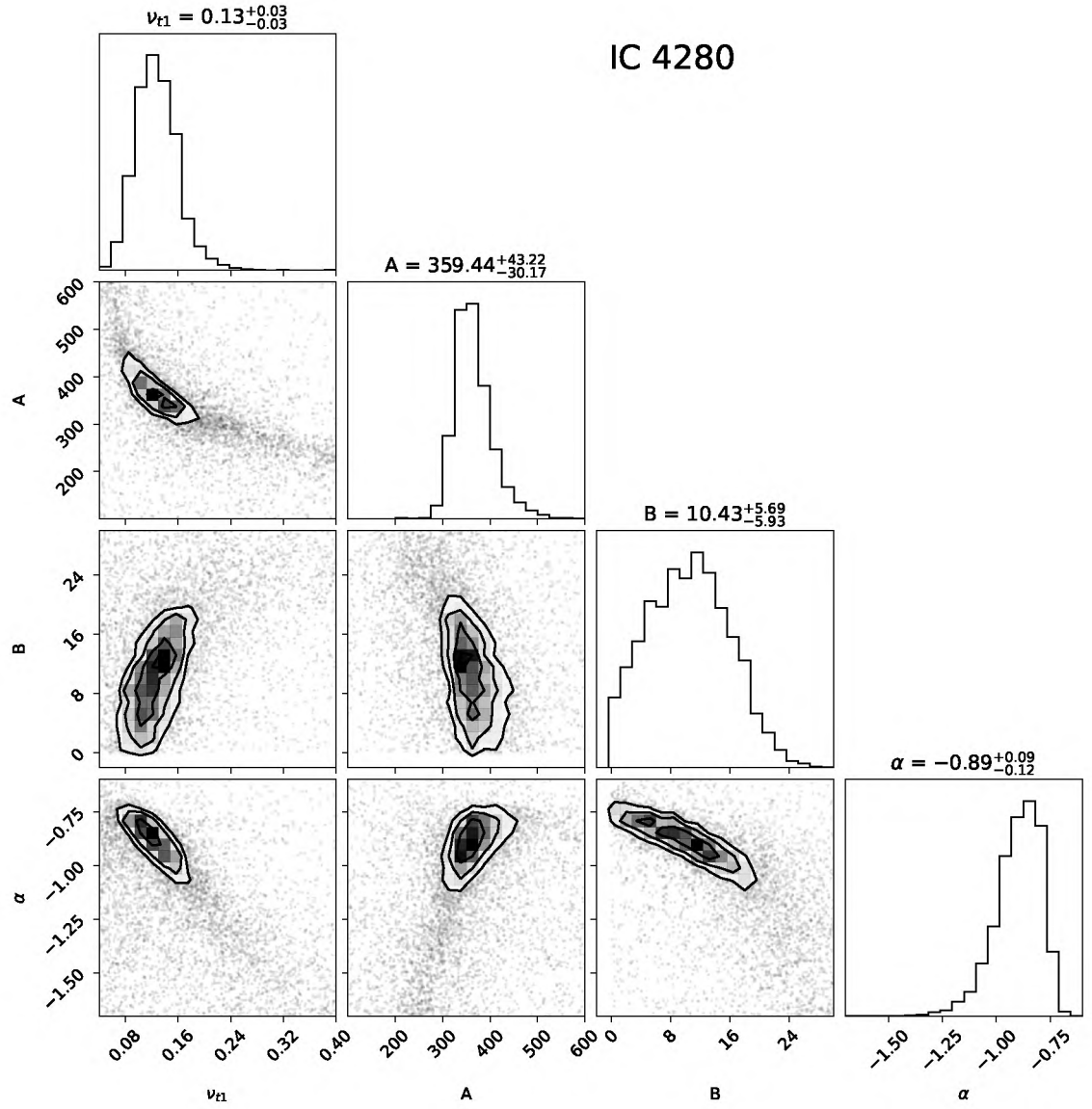
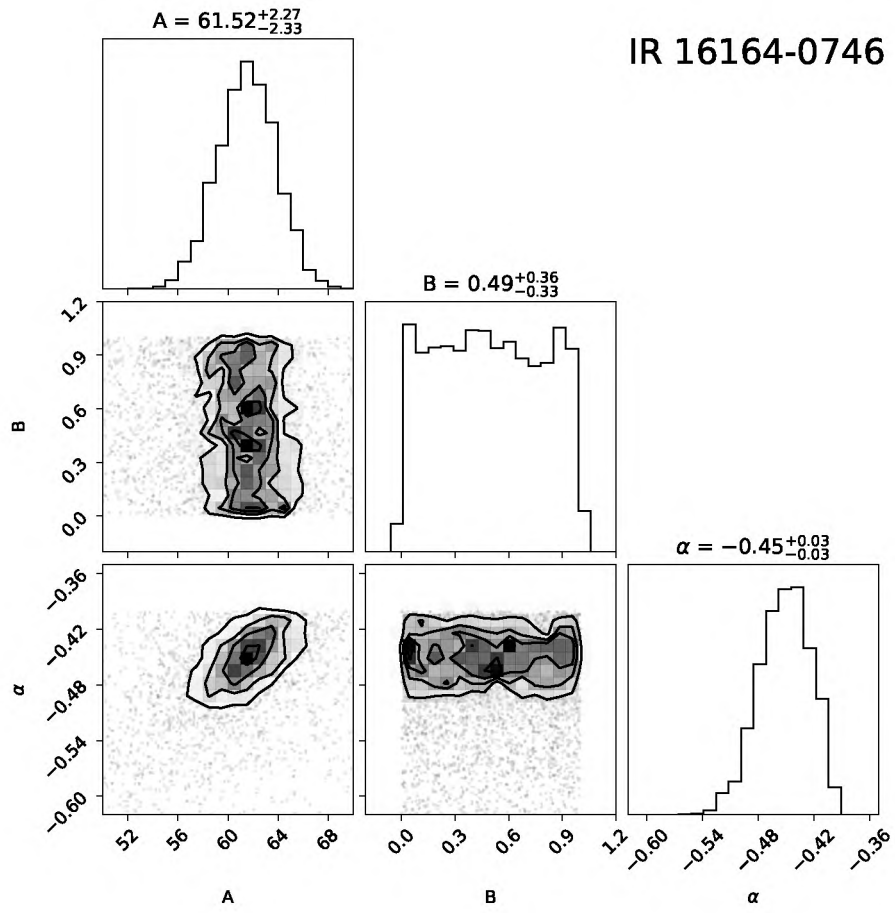


FIGURE A.2: Continued.



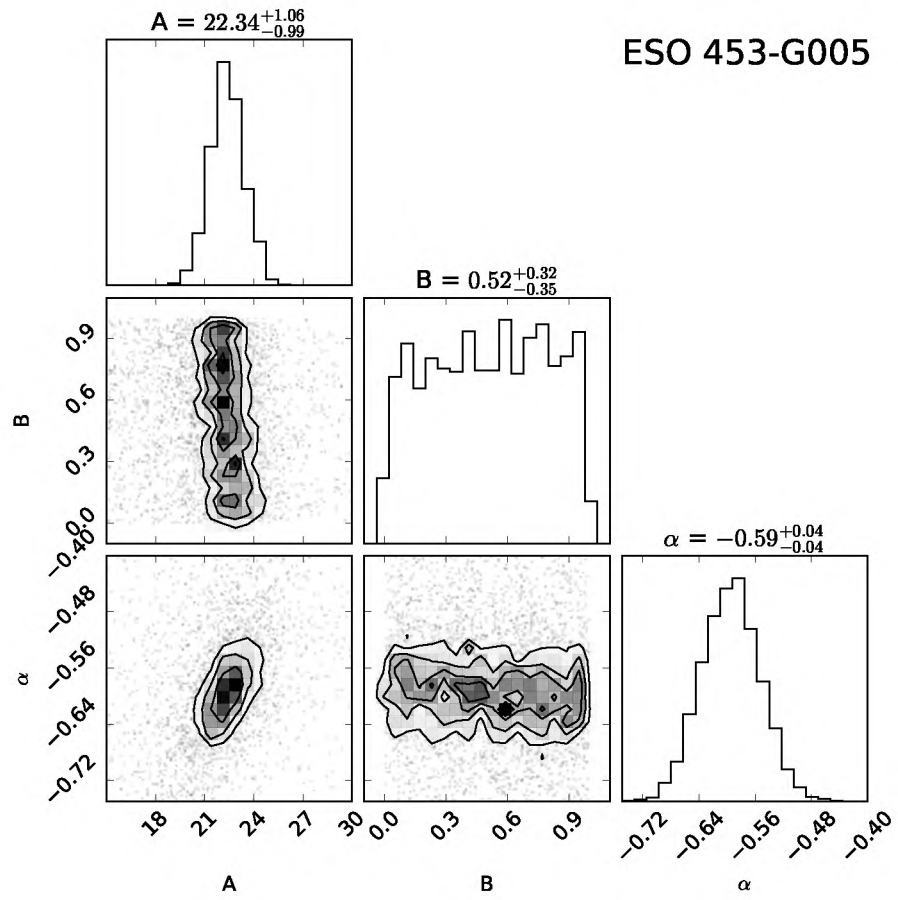


FIGURE A.2: Continued.

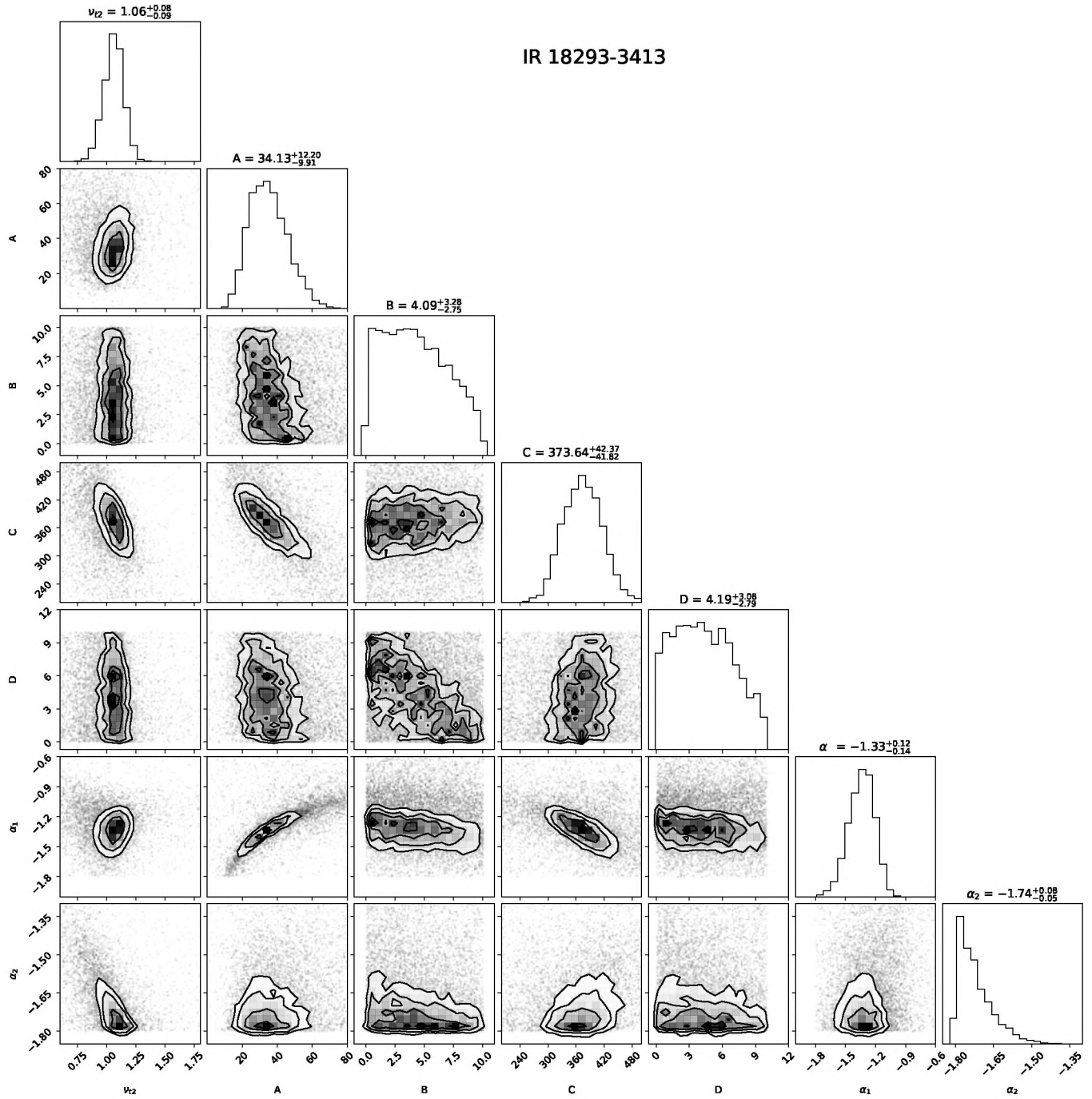


FIGURE A.2: Continued.

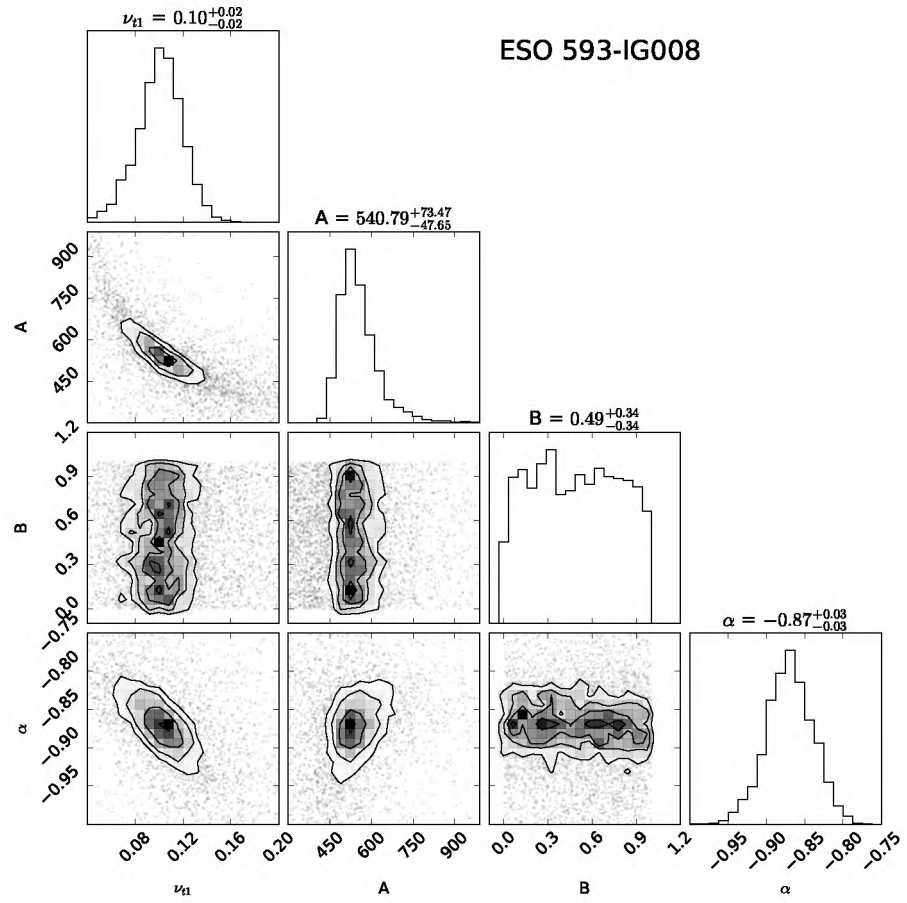


FIGURE A.2: Continued.

A.2 Summary of UV-IR observations gathered for SED modeling via CIGALE

Table A4 lists the flux densities used in CIGALE modeling.

TABLE A4: Integrated UV-IR flux densities used for the SED fitting.

Name	Instrument	Passband	S (mJy)	error (mJy)	Integration Area (a×b)	Ref.
(1)	(2)	(3)	(4)	(5)	(6)	(7)
ESO 500-G034	SMSS	g'	10.9	3.2	$3.3'' \times 3.3''$	(1)
		r'	16	0.9	$3.3'' \times 3.3''$	(1)
		i'	18.2	2.1	$3.3'' \times 3.3''$	(1)
		z'	21.3	1	$3.3'' \times 3.3''$	(1)
	2MASS	J	52.6	0.88	$55.6'' \times 26.7''$	(2)
		H	72.4	1.69	$55.6'' \times 26.7''$	(2)
		Ks	66.3	1.86	$55.6'' \times 26.7''$	(2)
	WISE	W1	40.0	0.22	$22'' \times 22''$	(3)
		W2	33.7	0.18	$22'' \times 22''$	(3)
		W3	223	1.23	$22'' \times 22''$	(3)
		W4	756	4.18	$22'' \times 22''$	(3)
	AKARI	N60	9430	350	$40'' \times 50''^\dagger$	(5)
		WIDE-S	13100	400	$40'' \times 50''^\dagger$	(5)
		WIDE-L	13700	500	$70'' \times 90''^\dagger$	(5)
		N160	11400	600	$70'' \times 90''^\dagger$	(5)
NGC3508	GALEX	FUV	1.44	0.04	$3.5'' \times 3.5''$	(6)
		NUV	2.8	0.02	$3.5'' \times 3.5''$	(6)
	SDSS	g'	13.7	1.08	$22.9'' \times 22.9''$	(7)
		r'	28	0.1	$22.9'' \times 22.9''$	(7)
		i'	36.4	0.1	$22.9'' \times 22.9''$	(7)
		z'	51.7	0.1	$22.9'' \times 22.9''$	(7)
	2MASS	J	69.2	1.29	$60.4'' \times 33.8''$	(2)
		H	81.2	2.06	$60.4'' \times 33.8''$	(2)
		Ks	72.8	2.52	$60.4'' \times 33.8''$	(2)
	WISE	W1	45.5	0.21	$22'' \times 22''$	(3)
		W2	31.8	0.175	$22'' \times 22''$	(3)
		W3	254	1.41	$22'' \times 22''$	(3)
		W4	495	3.19	$22'' \times 22''$	(3)
	AKARI	N60	6347	493	$42'' \times 42''^\dagger$	(5)
		WIDE-S	10690	486	$42'' \times 42''^\dagger$	(5)
		WIDE-L	14229	1450	$60'' \times 60''^\dagger$	(5)
		N160	14740	1620	$60'' \times 60''^\dagger$	(5)
ESO 440-IG058	GALEX	FUV	0.18	0.02	$4.63'' \times 4.63''$	(6)
		NUV	0.45	0.01	$3.5'' \times 3.5''$	(6)
	SMSS	g	1.88	0.43	$7.5'' \times 7.5''$	(1)
		r	2.00	0.11	$7.5'' \times 7.5''$	(1)
		i	2.74	0.09	$7.5'' \times 7.5''$	(1)
		z	2.83	0.08	$7.5'' \times 7.5''$	(1)

ESO 507-G070	IRAC	IRAC1	18.75	1.8		(8)
		IRAC2	14.62	1.4		(8)
		IRAC3	56.63	5.6		(8)
		IRAC4	182.56	18		(8)
	IRAS	IRAS1	200	38	$0.8' \times >0.8'^{\dagger}$	(4)
		IRAS2	760	35	$0.8' \times >0.8'^{\dagger}$	(4)
	<i>Herschel</i> -PACS	Blue	7972	363	$35'' \times 35''$	(9)
		Green	10620	480	$35'' \times 35''$	(9)
		Red	8597	380	$35'' \times 35''$	(9)
	<i>Herschel</i> -SPIRE	PSW	3371	203	$50'' \times 50''$	(9)
		PMW	1278	79	$50'' \times 50''$	(9)
		PLW	489	30	$50'' \times 50''$	(9)
	GALEX	FUV	0.09	0.01	$3.5'' \times 3.5''$	(6)
		NUV	0.21	0.01	$3.5'' \times 3.5''$	(6)
	SMSS	g'	2.72	0.14	$3.55'' \times 3.55''$	(1)
		r'	3.98	0.05	$3.55'' \times 3.55''$	(1)
		i'	6.42	0.09	$3.55'' \times 3.55''$	(1)
	2MASS	J	16.7	0.18	$14'' \times 14''$	(2)
		H	23.6	0.31	$14'' \times 14''$	(2)
		Ks	23.4	0.30	$14'' \times 14''$	(2)
	WISE	W1	24.7	0.14	$22'' \times 22''$	(3)
		W3	104	0.58	$22'' \times 22''$	(3)
	<i>Herschel</i> -PACS	Blue	16320	750	$43'' \times 43''$	(9)
		Green	16900	770	$43'' \times 43''$	(9)
		Red	10660	470	$43'' \times 43''$	(9)
	<i>Herschel</i> -SPIRE	PSW	3747	228	$55'' \times 55''$	(9)
		PMW	1405	87	$55'' \times 55''$	(9)
		PLW	451	29	$55'' \times 55''$	(9)
NGC 5135	GALEX	FUV	0.97	0.01	$3.5'' \times 3.5''$	(6)
		NUV	3.16	0.01	$3.5'' \times 3.5''$	(6)
	SMSS	g'	27.9	1.7	$3.83'' \times 3.83''$	(1)
		r'	40.6	3.9	$3.83'' \times 3.83''$	(1)
		i'	48.7	3.6	$3.83'' \times 3.83''$	(1)
		z'	54.5	1.5	$3.83'' \times 3.83''$	(1)
	2MASS	J	59.8	0.832	$14'' \times 14''$	(2)
		H	79.9	1.11	$14'' \times 14''$	(2)
		Ks	76.7	1.14	$14'' \times 14''$	(2)
	IRAC	IRAC1	131.9	1.3		(8)
		IRAC2	103.9	1.3		(8)
		IRAC3	219.9	2.1		(8)
		IRAC4	521.9	5.2		(8)
	IRAS	IRAS1	630	35	$0.8' \times >0.8'^{\dagger}$	(4)
	<i>Herschel</i> -PACS	Blue	21440	1070	$70'' \times 70''$	(9)
		Green	31120	1560	$70'' \times 70''$	(9)
		Red	26860	1340	$70'' \times 70''$	(9)
	<i>Herschel</i> -SPIRE	PSW	12370	810	$100'' \times 100''$	(9)
		PMW	5058	333	$100'' \times 100''$	(9)
		PLW	1577	106	$100'' \times 100''$	(9)

IC 4280	GALEX	FUV	0.71	0.02	$3.5'' \times 3.5''$	(6)
		NUV	1.62	0.02	$3.5'' \times 3.5''$	(6)
	SMSS	g'	18.9	3.1	$3.36'' \times 3.36''$	(1)
		r'	25.3	0.4	$3.36'' \times 3.36''$	(1)
		i'	32.4	0.7	$3.36'' \times 3.36''$	(1)
		z'	37.5	0.8	$3.36'' \times 3.36''$	(1)
	2MASS	J	33.8	0.19	$14'' \times 14''$	(2)
		H	44.1	0.244	$14'' \times 14''$	(2)
		Ks	39.7	0.33	$14'' \times 14''$	(2)
	WISE	W1	58.9	0.27	$22'' \times 22''$	(3)
		W2	39.3	0.22	$22'' \times 22''$	(3)
		W3	281	1.55	$22'' \times 22''$	(3)
		W4	365	2.35	$22'' \times 22''$	(3)
	<i>Herschel</i> -PACS	Blue	7647	383	$45'' \times 45''$	(9)
		Green	12970	650	$45'' \times 45''$	(9)
		Red	12520	630	$45'' \times 45''$	(9)
	<i>Herschel</i> -SPIRE	PSW	5631	369	$65'' \times 65''$	(9)
		PMW	2431	150	$65'' \times 65''$	(9)
		PLW	771	48	$65'' \times 65''$	(9)
NGC 6000	SWIFT-UVOT	W2	0.432	0.02	$4.85'' \times 4.85''$	(10)
		M2	0.578	0.02	$5.00'' \times 5.00''$	(10)
		W1	0.959	0.04	$6.25'' \times 6.25''$	(10)
		U	3.13	0.12	$4.35'' \times 4.35''$	(10)
		B	6.41	0.26	$5.40'' \times 5.40''$	(10)
		V	11.3	0.45	$5.85'' \times 5.85''$	(10)
	SMSS	g'	24.3	0.9	$3.58'' \times 3.58''$	(1)
		r'	44.6	1.6	$3.58'' \times 3.58''$	(1)
		i'	65.8	1.1	$3.58'' \times 3.58''$	(1)
		z'	82.5	10.2	$3.58'' \times 3.58''$	(1)
	WISE	W1	145	0.80	$22'' \times 22''$	(3)
		W2	106	0.58	$22'' \times 22''$	(3)
		W3	827	4.57	$22'' \times 22''$	(3)
		W4	3010	16.6	$22'' \times 22''$	(3)
	AKARI	N60	41889	2010	$42'' \times 42''^\dagger$	(5)
		WIDE-S	43500	963	$42'' \times 42''^\dagger$	(5)
		WIDE-L	36169	4030	$60'' \times 60''^\dagger$	(5)
		N160	47470	4950	$60'' \times 60''^\dagger$	(5)
IR 16164-0746	GALEX	FUV	0.024	0.002	$3.5'' \times 3.5''$	(6)
		NUV	0.07	0.01	$4.8'' \times 3.5''$	(6)
	SMSS	g'	1.91	0.33	$3.2'' \times 3.2''$	(1)
		r'	3.27	0.39	$3.2'' \times 3.2''$	(1)
		i'	4.44	0.28	$3.2'' \times 3.2''$	(1)
		z'	85.35	0.09	$3.2'' \times 3.2''$	(1)
	2MASS	J	10.30	0.19	$14'' \times 14''$	(2)
		H	14.90	0.276	$14'' \times 14''$	(2)
		Ks	15.1	0.34	$14'' \times 14''$	(2)
	WISE	W1	58.9	0.27	$22'' \times 22''$	(3)
		W2	39.3	0.22	$22'' \times 22''$	(3)

ESO 453-G005	<i>Herschel</i> -PACS	W3	281	1.55	$22'' \times 22''$	(3)
		W4	365	2.35	$22'' \times 22''$	(3)
		Blue	13290	610	$40'' \times 40''$	(9)
		Green	15030	680	$40'' \times 40''$	(9)
		Red	10210	450	$40'' \times 40''$	(9)
	<i>Herschel</i> -SPIRE	PSW	3581	220	$60'' \times 60''$	(9)
		PMW	1266	80	$60'' \times 60''$	(9)
		PLW	407	28	$60'' \times 60''$	(9)
		NUV	0.131	0.01	$3.7'' \times 3.7''$	(6)
	GALEX	SMSS	r	4.06	$3.8'' \times 3.8''$	(1)
			z	4.68	$3.8'' \times 3.8''$	(1)
	2MASS	J	11.1	0.29	$14'' \times 14''$	(2)
		H	14.7	0.45	$14'' \times 14''$	(2)
		Ks	12.9	0.40	$14'' \times 14''$	(2)
	WISE	W1	27.6	0.25	$22 \times 22''$	(3)
		W2	16.3	0.19	$22 \times 22''$	(3)
		W3	63.3	0.7	$22 \times 22''$	(3)
		W4	209	1.7	$22 \times 22''$	(3)
IR 18293-3413	<i>Herschel</i> -PACS	Blue	12190	550	$35'' \times 35''$	(9)
		Green	13950	630	$35'' \times 35''$	(9)
		Red	10040	440	$35'' \times 35''$	(9)
	<i>Herschel</i> -SPIRE	PSW	4150	252	$55'' \times 55''$	(9)
		PMW	1635	101	$55'' \times 55''$	(9)
		PLW	575	35	$55'' \times 55''$	(9)
	XMM-OM	UVW1	0.02	0.003	$5.7'' \times 5.7''$	(11)
		SMSS	g	4.06	$3.9'' \times 3.9''$	(1)
	2MASS		r	9.19	$3.9'' \times 3.9''$	(1)
			z	19.9	$3.9'' \times 3.9''$	(1)
		Ks	12.9	0.40	$14'' \times 14''$	(2)
		J	49.8	0.28	$14'' \times 14''$	(2)
		H	80.70	0.37	$14'' \times 14''$	(2)
		Ks	88.4	0.33	$14'' \times 14''$	(2)
	WISE	W1	88.3	0.50	$22'' \times 22''$	(3)
		W2	78.2	0.43	$22'' \times 22''$	(3)
		W3	761	3.51	$22'' \times 22''$	(3)
		W4	2270	126	$22'' \times 22''$	(3)
ESO 593-IG008	<i>Herschel</i> -PACS	Blue	45710	2110	$50'' \times 50''$	(9)
		Green	59130	2710	$35'' \times 35''$	(9)
		Red	45840	2070	$35'' \times 35''$	(9)
	<i>Herschel</i> -SPIRE	PSW	17220	1070	$70'' \times 70''$	(9)
		PMW	6454	400	$70'' \times 70''$	(9)
		PLW	1987	122	$70'' \times 70''$	(9)
	GALEX	FUV	0.166	0.01	$3.5'' \times 3.5''$	(6)
		NUV	0.30	0.01	$3.5'' \times 3.5''$	(6)
	SMSS	g	1.69	0.12	$2.8'' \times 2.8''$	(1)
		r	4.07	0.1	$2.8'' \times 2.8''$	(1)
		i	6.23	0.15	$2.8'' \times 2.8''$	(1)
		z	6.15	0.07	$2.8'' \times 2.8''$	(1)

2MASS	J	14	0.5	$24.5'' \times 24.5''$	(2)
	H	25.2	1.0	$24.5'' \times 24.5''$	(2)
	Ks	27.1	1.2	$24.5'' \times 24.5''$	(2)
IRAS	IRAS1	180	25	$0.8' \times >0.8'^{\dagger}$	(4)
	IRAS2	510	38	$0.8' \times >0.8'^{\dagger}$	(4)
<i>Herschel</i> -PACS	Blue	7972	363	$40'' \times 40''$	(9)
	Green	10620	480	$40'' \times 40''$	(9)
	Red	8597	380	$40'' \times 40''$	(9)
<i>Herschel</i> -SPIRE	PSW	3371	203	$50'' \times 50''$	(9)
	PMW	1278	79	$50'' \times 50''$	(9)
	PLW	489	30	$50'' \times 50''$	(9)

Columns: (1) source name; (2) Instrument; (3) Passband; (4) total flux densities of the source (5) the error in the flux densities; (6) integration area used in aperture photometry in terms of length of semi-major axis $a \times$ length of semi-minor axis b (for circular apertures, semi-major axis = semi-minor axis),

† source is flagged as resolved or marginally resolved in (Sanders et al., 2003),

‡ full-width at half maximum of the 2-D Gaussian used in profile fitting photometry;

(7) references - (1) Wolf et al. (2018), (2) 2MASS Extended Mission Data Release (Skrutskie et al., 2006) (3) Wright et al. (2010); Mainzer et al. (2011), (4) (Sanders et al., 2003), (5) Kawada et al. (2007) (6) <https://galex.stsci.edu/GR6/?page=mastform>, (7) The 16th Data Release of the Sloan Digital Sky Surveys (Ahumada et al., 2020), (8) For discussion on IRAC flux estimation, see Section 5.3.2, (9) Chu et al. (2017), (10) Yershov (2014), (11) Page et al. (2012)

A.3 Specific results on individual galaxies

1. **ESO 500-G034**: classified as an intermediate between the Seyfert type AGN nucleus and a starburst galaxy (Hill et al., 1999), the densely sampled radio spectrum covering ~ 2.3 decades in frequency (70 MHz-14.9 GHz) is fitted with a two-component model representing two distinct star-forming regions where the first component is without turnover. The turnover frequency is ~ 0.52 GHz. The synchrotron spectral index, $\alpha = -1.15$. The TF at 1.4 GHz is $\sim 11.4\%$. The CIGALE modeling estimates a $SFR_{IR} = 5.72 M_{\odot} \text{ yr}^{-1}$, high $L_{\text{dust}} = 10^{11.86} L_{\odot}$, and low AGN fraction = 1.11%, respectively. The low AGN fraction obtained by our analysis contradicts the previous results by Hill et al. (1999) who classified this source as an intermediate between an AGN and a starburst galaxy (its low is AGN fraction is also confirmed by Díaz-Santos et al., 2017).
2. **NGC 3508**: classified as a spiral galaxy (Veilleux et al., 1995), its densely sampled radio spectrum covering 2.9 decades in frequency (70 MHz-3 GHz) is fitted with a single component model characterized by synchrotron emission only. The synchrotron spectral index, $\alpha = -0.73$. The TF is 0 as this emission is characterized by synchrotron emission (i.e. no free-free component). The CIGALE modeling gives $SFR_{IR} = 3.90 M_{\odot} \text{ yr}^{-1}$, $L_{\text{dust}} = 10^{11.25} L_{\odot}$, and AGN fraction = 6.00%, respectively, for this galaxy.
3. **ESO 440-IG058**: classified as a galaxy merger with a LINER-type AGN northern

neighbor (Corbett et al., 2003), this galaxy is known to show shock-dominated emission for the southern system (Rodríguez-Zaurín et al., 2011). Its radio SED covering 2.1 decades (70 MHz-10.0 GHz) is fitted with single-component star-forming region properties (including absorption) with a turnover at ~ 140 MHz. Synchrotron spectral index, $\alpha = -0.82$. The computed TF is 3.17%. The CIGALE-estimated SFR_{IR} , L_{dust} , AGN fraction are $42.66 M_{\odot} \text{ yr}^{-1}$, $10^{10.99} L_{\odot}$, $\sim 4.53\%$, respectively. Our SFR_{IR} value is comparable within uncertainty to that obtained in literature ($\sim 36 M_{\odot} \text{ yr}^{-1}$; Miluzio et al., 2013) and ($\sim 48 M_{\odot} \text{ yr}^{-1}$; Herrero-Illana et al., 2017).

4. **ESO 507-G070**: classified as a Seyfert-type AGN nucleus (Condon et al., 1996) in a post-merger system (Stierwalt et al., 2013; Paspaliaris et al., 2021), its radio SED covering ~ 2.3 decades in frequency (70 MHz-14.9 GHz) is best-fitted with a two-component model representing two distinct star-forming regions with different ultra-relativistic electron populations and high frequency turnover. The synchrotron spectral indices for the two populations, α_1 and α_2 , are -0.77 and -1.50 , respectively. The TF is $\sim 9\%$. The SFR_{IR} , L_{dust} , AGN fraction are $22.40 M_{\odot} \text{ yr}^{-1}$, $10^{10.93} L_{\odot}$, $\sim 2.0\%$, respectively. Its UV-IR SED has previously been modeled with CIAGLE by Paspaliaris et al. (2021) who reported comparable L_{dust} ($=10^{11.1} L_{\odot}$), and SFR_{IR} ($45.1 M_{\odot} \text{ yr}^{-1}$), and lower AGN fraction (0%) as compared to our results.
5. **NGC 5135**: classified as having a Seyfert-type AGN nucleus (Condon et al., 1996) with strong starburst along the spiral arms (Muñoz Marín et al., 2007), its radio SED covering ~ 2.0 decades in frequency (70 MHz-6.7 GHz) is fitted with single-component star-forming region properties (including absorption) with a turnover at ~ 0.130 GHz. The synchrotron spectral index, $\alpha = -0.88$. The TF is $\sim 3.6\%$. The CIGALE-estimated SFR_{IR} , L_{dust} , AGN fraction are $11.22 M_{\odot} \text{ yr}^{-1}$, $10^{11.21} L_{\odot}$, $\sim 6\%$, respectively.
6. **IC 4280**: classified as a spiral galaxy (Fairall et al., 1989; Jin et al., 2019), its radio SED covering ~ 1.6 decades (70 MHz-3.0 GHz) is best-fitted with a single-component star-forming region properties (including absorption) with a turnover at ~ 140 MHz. The synchrotron spectral index, $\alpha = -0.9$. The TF is 11.9%. The CIGALE-estimated SFR, L_{dust} , AGN fraction are $11.75 M_{\odot} \text{ yr}^{-1}$, $10^{11.36} L_{\odot}$, $\sim 6\%$, respectively.
7. **NGC 6000**: classified as a starburst galaxy (Carollo et al., 2002), its radio SED covering ~ 1.6 decades in frequency (70 MHz-3.0 GHz) is best-fitted with emission from a single star-forming region without a low frequency turnover. The synchrotron spectral index is -0.66 . The TF is 0.3%. The CIGALE-estimated SFR, L_{dust} , and AGN fraction are $2.04 M_{\odot} \text{ yr}^{-1}$, $10^{10.79} L_{\odot}$, $\sim 1.06\%$, respectively.
8. **IR 16164-0746**: classified as a late stage merger (Stierwalt et al., 2013) with a single LINER-type nucleus and a tidal-tail (Dixon and Joseph, 2011; Hung et al., 2015), its radio SED covering ~ 1.6 decades in frequency (70 MHz-3.0 GHz) is best-fitted with emission from a single star-forming region without low frequency turnover. The synchrotron spectral index is ~ -0.5 . The TF is 0.8%. The CIGALE-estimated SFR, L_{dust} , AGN fraction are $33.11 M_{\odot} \text{ yr}^{-1}$, $10^{10.77} L_{\odot}$, $\sim 2.2\%$, respectively.
9. **ESO 453-G005**: a galaxy pair that appears to be dominated by star-forming activity, although it does not show signs of interaction (Rich et al., 2015), its poorly sampled radio SED covering ~ 1.3 decades in frequency (150 MHz-3.0 GHz) is best-fitted

with emission from a single star-forming region without a low-frequency turnover. The synchrotron spectral index is ~ -0.6 . The TF is 2%. The CIGALE-estimated SFR, L_{dust} , AGN fraction are $3.31 M_{\odot} \text{ yr}^{-1}$, $10^{10.97} L_{\odot}$, $\sim 4.7\%$, respectively.

10. **IR 18293-3413**: a complex system, classified both as early-merger (Haan et al., 2011) and mid-merger (Ricci et al., 2017) galaxy system with no evidence of AGN activity (X-ray spectrum; Risaliti et al., 2000), its radio SED covering ~ 2.1 decades in frequency (70 MHz-8.4 GHz) is best-fitted with two-component model representing two distinct star-forming regions with different ultrarelativistic CRe and one region without any turnover. The synchrotron spectral indices for the two populations are, -1.35 and -1.74 , respectively. The turnover frequency is 1.06 GHz. The TF is $\sim 3.7\%$. The CIGALE-estimated SFR, L_{dust} , AGN fraction are $15.48 M_{\odot} \text{ yr}^{-1}$, $10^{11.7} L_{\odot}$, $\sim 2.5\%$, respectively.
11. **ESO 593-IG008**: known as the ‘Bird’ (Väisänen et al., 2017), this system is a well-known galaxy merger (Stierwalt et al., 2013; Hung et al., 2015). Its radio SED covering 1.8 decades (70 MHz-4.8 GHz) is fitted with single-component star-forming region synchrotron (including absorption) with a turnover at ~ 100 MHz. Synchrotron spectral index, $\alpha = -0.87$. The computed TF is 0.6%. The CIGALE-estimated SFR, L_{dust} , AGN fraction are $51.3 M_{\odot} \text{ yr}^{-1}$, $10^{11.18} L_{\odot}$, $\sim 3.9\%$, respectively.

B

Appendix

B.1 Summary of observations gathered for radio-only and UV–radio SED modeling for the sample of ULIRGs, including short notes on the targets

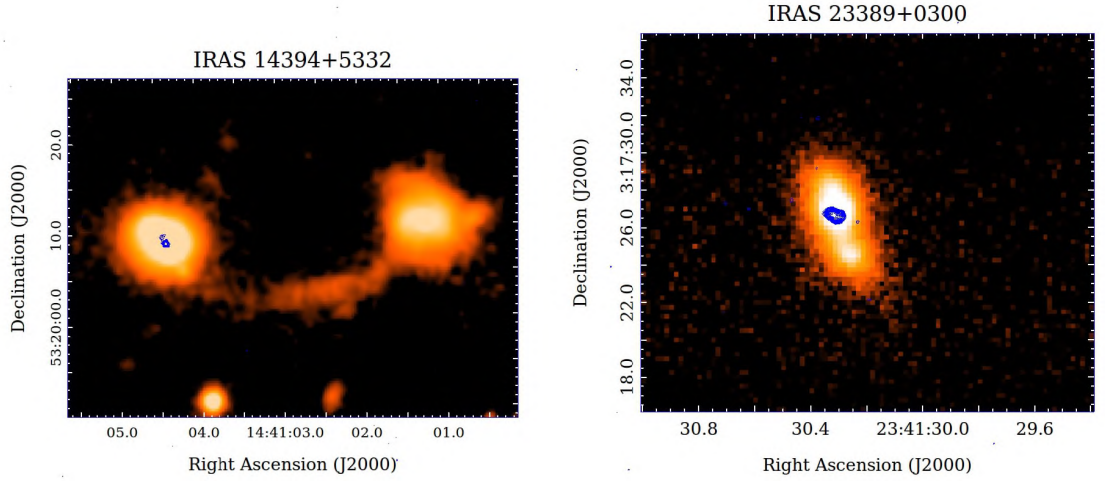


FIGURE B.1: 8.4 GHz intensity contours (blue color) overlayed on PanStars I-band image for the galaxies IRAS 14394+5332 (left panel) and IRAS 23389+0300 (right panel). Radio contours begin at 3σ where σ is the background noise level and increase by factors of $(\sqrt{2})^n$ with $n=0,1,2,3,\dots$. For the galaxies, IRAS 14394+5332 and IRAS 23389+0300, the σ s are $65.96 \mu\text{Jy beam}^{-1}$ and $66.33 \mu\text{Jy beam}^{-1}$, respectively, and the synthesized beam sizes are $0.26'' \times 0.24''$ (position angle= 50.80°) and $0.26'' \times 0.25''$ (position angle= -62.68°), respectively.

TABLE B.1: Integrated radio flux densities used for the SED fitting.

Name	Obs. Freq.	S	error	Ref.
(1)	(2)	(3)	(4)	(5)
IRAS F00183-7111	0.091	227.25	48.07	(a)
	0.122	340.00	39.27	(a)
	0.158	372.50	39.34	(a)
	0.189	397.00	41.51	(a)
	0.219	403.00	41.74	(a)
	0.843	424.00	24.76	(b)
	0.887	430.90	43.09	(c)
	1.4*	317.00*	1.57*	(d)
	2.08	239.55	14.34	(e)
	4.8*	100.00*	8.60*	(f)
	5.52	86.24	5.03	(e)
	8.60	48	10.28	(f)
	9.02	46.87	3.35	(e)
IRAS F03538-6432	0.091	458.25	58.11	(a)
	0.122	356.75	38.60	(a)
	0.158	321.50	33.29	(a)
	0.189	274.75	28.99	(a)
	0.219	242.75	26.25	(a)
	0.843	79.7	4.75	(b)
	0.887	78.28	9.15	(c)
	2.1	32.20	3.17	(e)
	5.5*	12.17*	0.91*	(e)
	9.0	6.56	0.96	(e)
IRAS 08572+3915	0.150	8.6	0.99	(g)
	0.610	11	6	(h)
	1.4*	4.7*	0.42*	(i)
	3	5.0	0.56	(j)
	4.8*	4.4*	0.24*	(k)
	8.4	4.1	0.23	(k)
	22.5	3.18	0.314	(k)
	32.5	2.1	0.404	(k)
UGC 5101	0.074	590	101.5	(m)
	0.150	231.33	33.3	(g)
	0.244	310	30	(g)
	0.330	308	77	(n)
	0.610	212	4	(g)
	1.4*	170.1*	7.72*	(i)
	3.0	82.39	8.24	(j)
	4.8*	65.4*	1.96*	(k)
	5.95	61.5	1.84	(o)
	8.4	51.05	1.53	(p)
	15	30	10.04	(k)
	22.5	18	1.14	(k)

B.1 SUMMARY OF OBSERVATIONS GATHERED FOR RADIO-ONLY AND UV-RADIO SED
MODELING FOR THE SAMPLE OF ULIRGs, INCLUDING SHORT NOTES ON THE TARGETS

IRAS 10565+2448	32.5	16.8	1.21	(k)
	0.150	99.3	14.74	(g)
	0.244	80	20	(g)
	0.610	102	7	(g)
	0.887	71.77	7.23	(c)
	1.4*	57*	2.71*	(i)
	3.0	33.76	3.88	(j)
	4.8*	22.21*	0.68*	(k)
IRAS 12112+0305	8.4	12.70	0.38	(k)
	0.150	33.8	6.97	(g)
	0.244	35	20	(g)
	0.610	32	6.0	(g)
	0.8875	33.306	4.409	(c)
	1.4*	24	1.39	(i)
	3.0	17	1.73	(j)
	4.8*	12.44*	0.7*	(q)
UGC 8058	8.4	8.6	0.26	(p)
	14.9	5.75	0.32	(q)
	22.5	5.7	0.33	(k)
	0.054	1336.78	11.08	(r)
	0.074	1000	123.69	(m)
	0.150	730	103.45	(g)
	0.244	590	20	(g)
	0.365	551	39.013	(k)
	0.610	403	20	(g)
	1.4*	308	12.1	(i)
	3	293.66	29.37	(j)
	4.8*	265*	8.01*	(k)
	5.95	313	9.39	(o)
	8.4	189	5.75	(k)
	10.63	190	11.16	(s)
	15	146	4.49	(k)
IRAS 13305-1739	22.5	137	4.57	(k)
	30	129	9.003	(t)
	32.5	88	4.38	(o)
	0.091	377	51.28	(a)
	0.122	320.5	37.62	(a)
	0.158	258.00	27.68	(a)
	0.189	230.50	26.2	(a)
	0.219	209.75	22.43	(a)
	0.352	139	18.87	(u)
	0.887	68.07	8.61	(c)
UGC 8696	1.298	48.37	4.16	(q)
	1.4*	48*	3.6*	(i)
	3.0	20.7	2.1	(j)
	8.44	6.3	0.34	(q)
	0.054	488.55	19.64	(r)
	0.074	380	70	(m)

	0.150	454.4	64.55	(g)
	0.244	394	20	(g)
	0.365	335	37	(k)
	0.610	222	8	(g)
	1.4*	144.7*	6.69*	(i)
	2.7	96	6.65	(k)
	3.0	88.4	8.86	(j)
	4.8*	71*	15.15*	(k)
	8.4	43.75	2.17	(k)
	15	29.5	1.33	(k)
	22.5	14.3	0.52	(k)
	32.5	19.9	2.47	(l)
IRAS 14348-1447	0.091	183.25	45.79	(a)
	0.122	105.15	21.91	(a)
	0.150	79.5	13.73	(g)
	0.158	90.2	15.12	(a)
	0.189	85.7	13.63	(a)
	0.219	92	12.22	(a)
	0.352	53	6.89	(u)
	0.610	30	6	(g)
	0.887	47.17	6.08	(c)
	1.4*	35.9*	1.61*	(i)
	3.0	22.5	2.42	(j)
	8.4	10.8	1.05	(k)
	22.5	4.5	0.51	(k)
IRAS 14394+5332	0.054	271.41	6.56	(r)
	0.150	230	23.0	(q)
	0.150	224	33.0	(g)
	0.327	142	35.11	(q)
	1.4*	42*	2.45*	(i)
	3	23.72	2.38	(j)
	8.5	13.7	0.411	(v)
	15	5.6	0.034	(q)
IRAS17179+5444	0.150	177.3	25.4	(g)
	0.365	510	20.5	(q)
	1.4*	332*	14.11*	(i)
	3	179	17.91	(j)
	4.85*	117.88*	6.96*	(q)
	8.4	65.6	6.0	(w)
	14.9	27	1.77	(q)
IRAS F23529-2119	0.091	236	33.29	(a)
	0.122	115.25	14.77	(a)
	0.158	61.67	7.88	(a)
	0.189	47.95	5.78	(a)
	0.219	42.42	4.99	(a)
	0.887	22.78	3.16	(c)
	1.4*	16.2*	0.85*	(i)
	2.1	9.66	2.41	(d)

B.1 SUMMARY OF OBSERVATIONS GATHERED FOR RADIO-ONLY AND UV–RADIO SED
MODELING FOR THE SAMPLE OF ULIRGs, INCLUDING SHORT NOTES ON THE TARGETS

	5.5*	4.77*	0.47*	(d)
	9	3.01	0.685	(d)
IRAS 23389+0300	0.074	1751	222.17	(m)
	0.150	2608.2	368.91	(g)
	0.178	3400	892.46	(q)
	0.365	2650	67.79	(q)
	0.408	2225.48	356.3	(q)
	0.653	1900	152	(x)
	0.887	1330.24	162.68	(c)
	1.298	845	72.68	(q)
	1.4*	863*	36.69*	(i)
	3.0	390	39.05	(j)
	4.85*	199*	16.15*	(y)
	6.0	194	1.94	(v)
	8.4	95	3.5	(v)
	15.0	41	4.28	(q)

Columns: (1) source name; (2) observing frequency; (3) integrated flux density of the source (4) the error in the flux density including the absolute calibration uncertainty,(5) references - (a) GLEAM, (b) SUMSS, (c)ASKAPHale et al. (2021), (d) ATCA Galvin et al. (2016), (e) McConnell et al. (2012), (g) TGSS ADR1 (Intema et al., 2017), (g) Clemens et al. (2010), (i) NVSS, (j) VLASS (Gordon et al., 2021), (k) Clemens et al. (2008), (l) Barcos-Muñoz et al. (2017), (m) VLSSr Lane et al. (2014), (n) Rengelink et al. (1997), (o) Leroy et al. (2011), (p) Vardoulaki et al. (2015),(q) Nandi et al. (2021), (r) LoLLS (de Gasperin et al., 2023), (s) Bica et al. (1995), (t) Lowe et al. (2007), (u) De Breuck et al. (2002), (v) reanalyzed VLA, (w) Myers et al. (2003), (x) Wright and Otrupcek (1990), (y) Griffith et al. (1995) , * used in UV-radio SED modeling using CIGALE.

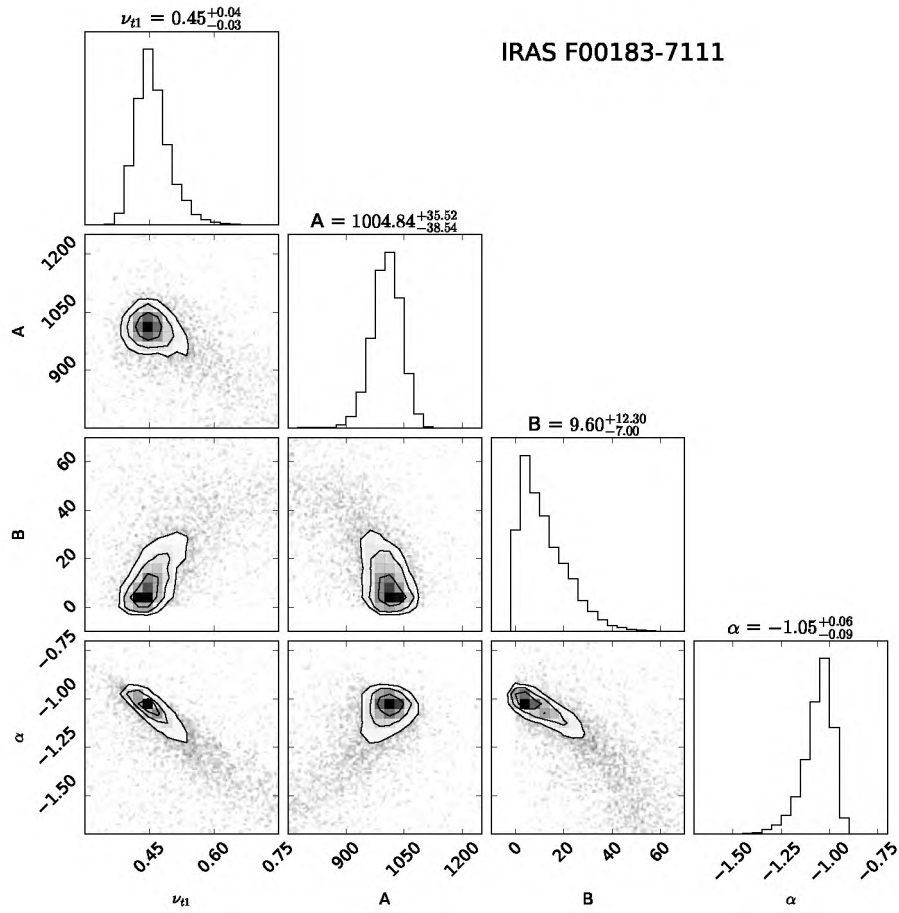


FIGURE B.2: Corner plots showing the one and two-dimensional posterior probability distribution of the estimated parameters in the radio SED modeling for each galaxy.

IRAS F03538-6432

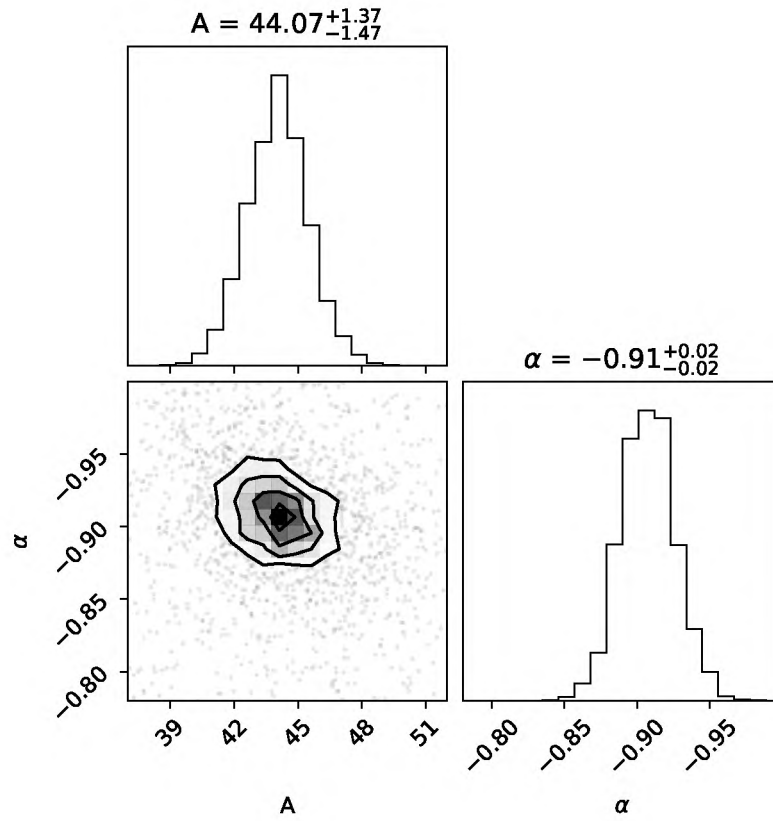


FIGURE B.2: Continued.

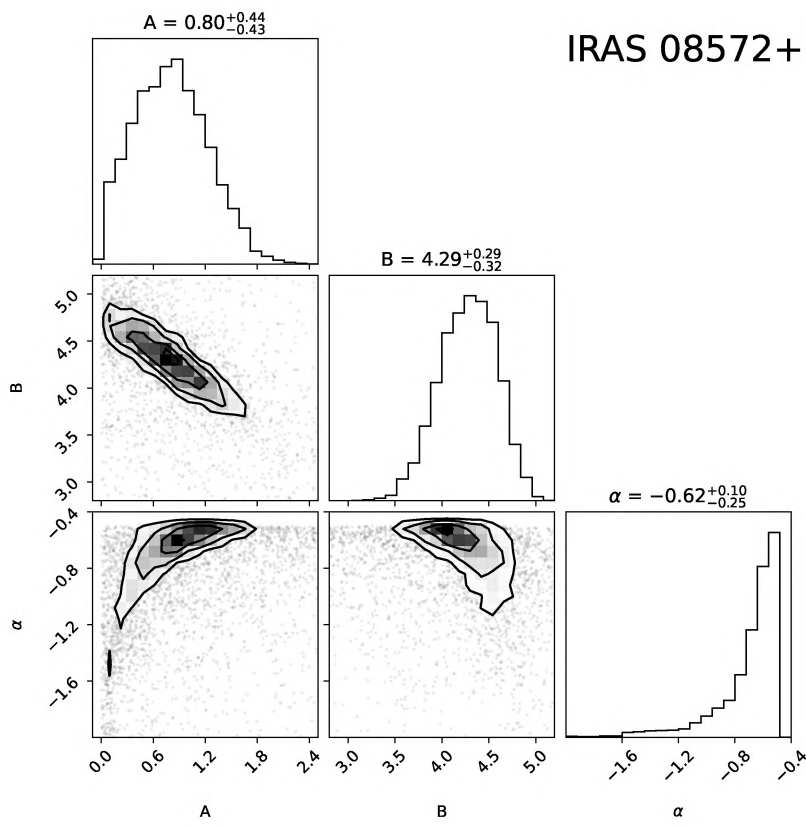


FIGURE B.2: Continued.

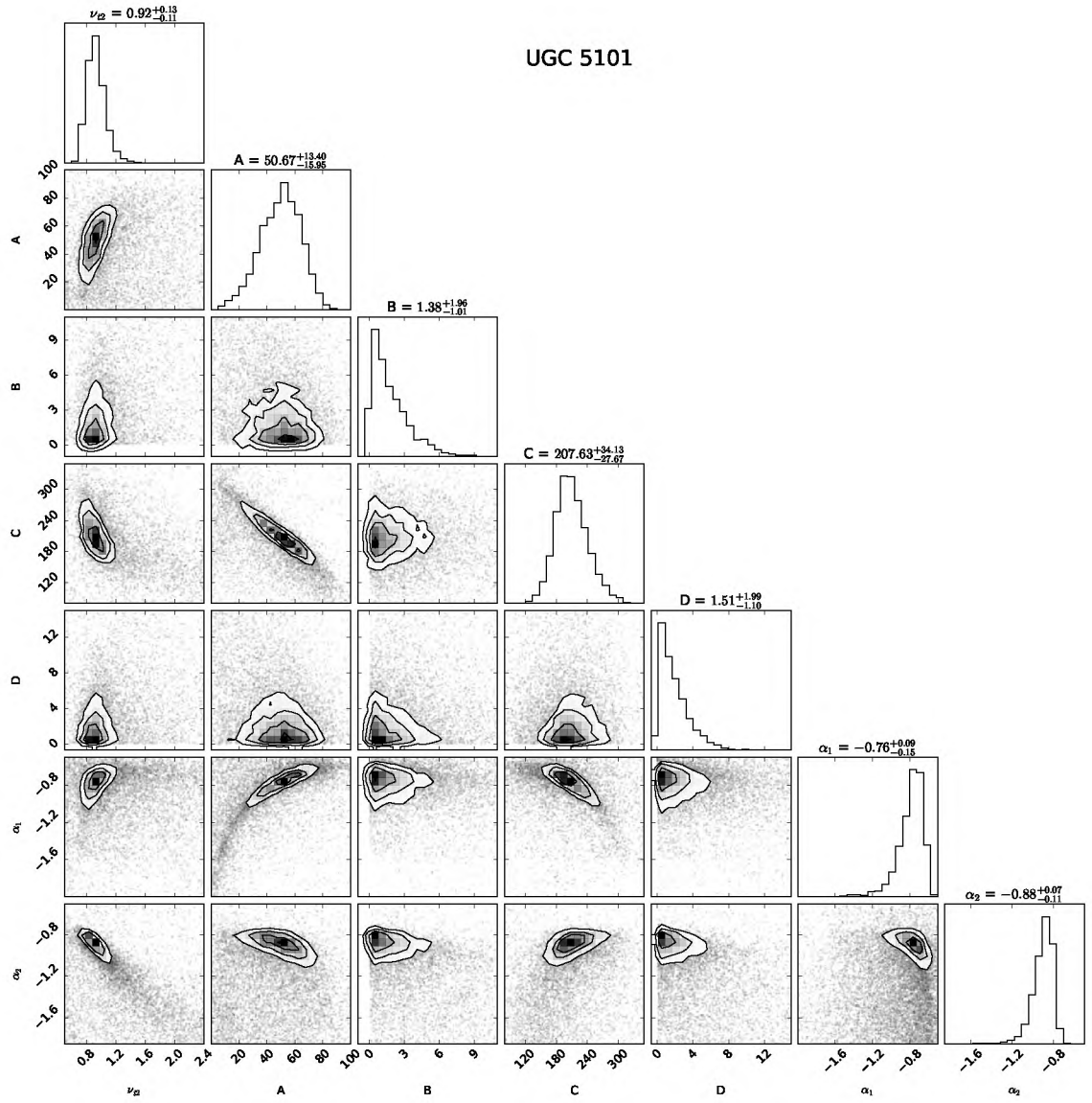


FIGURE B.2: Continued.

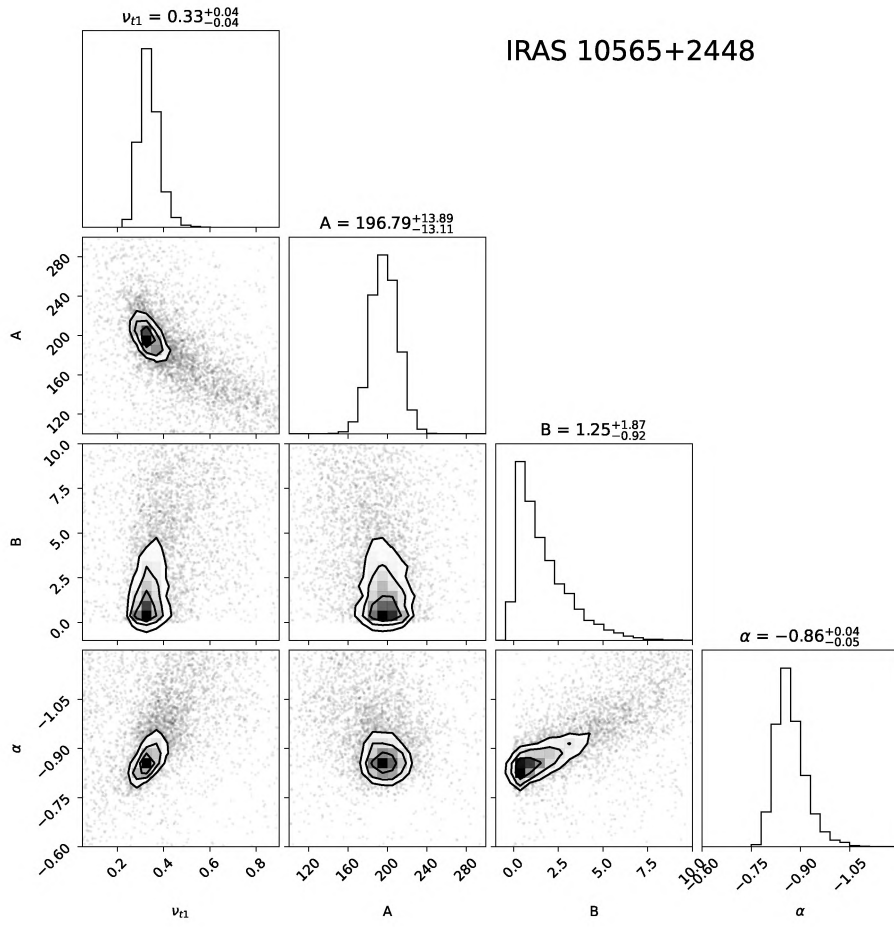


FIGURE B.2: Continued.

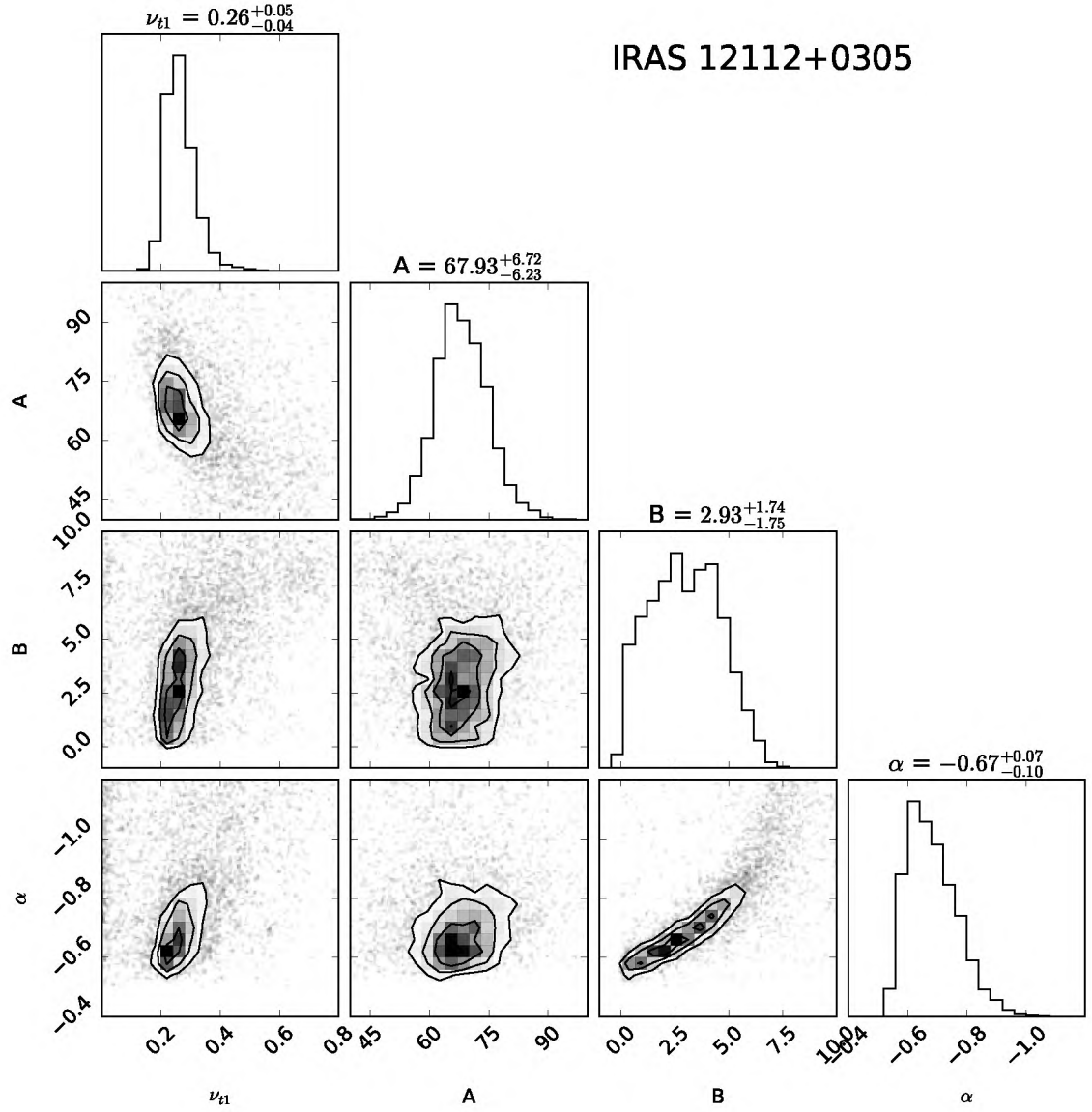


FIGURE B.2: Continued.

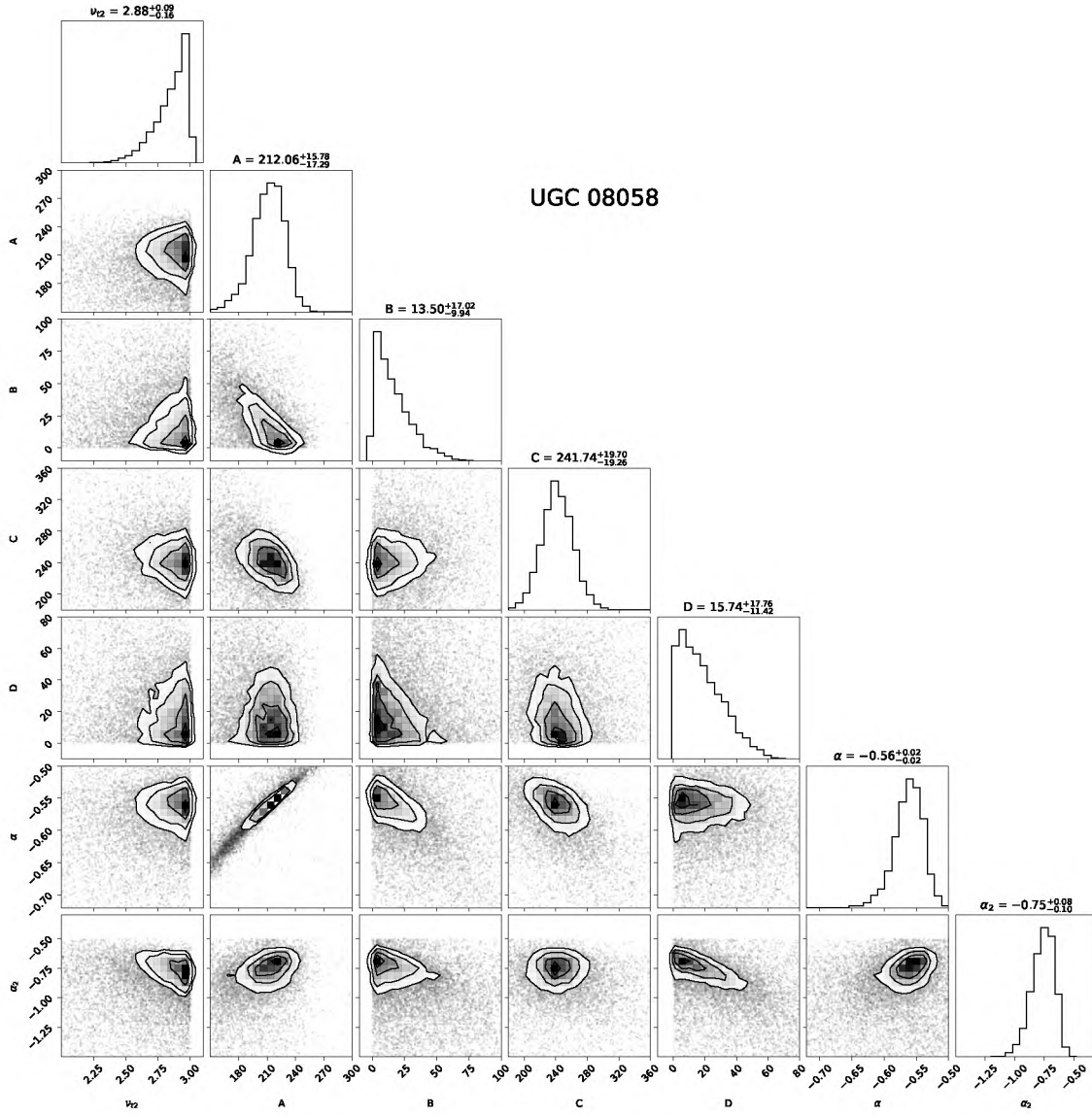


FIGURE B.2: Continued.

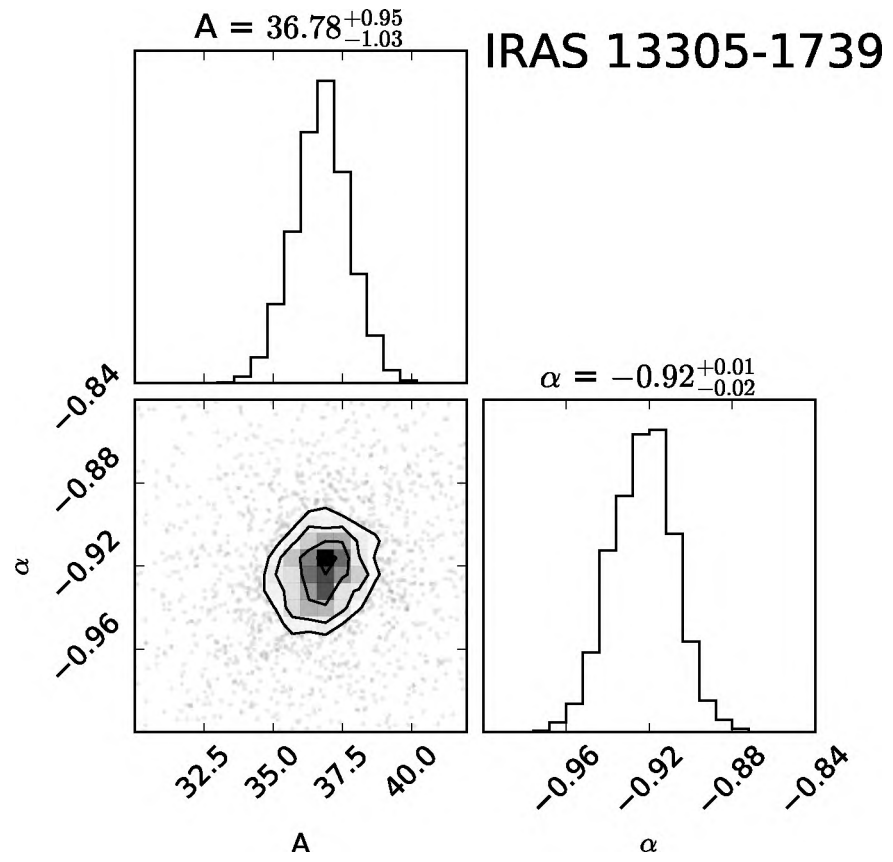


FIGURE B.2: Continued.

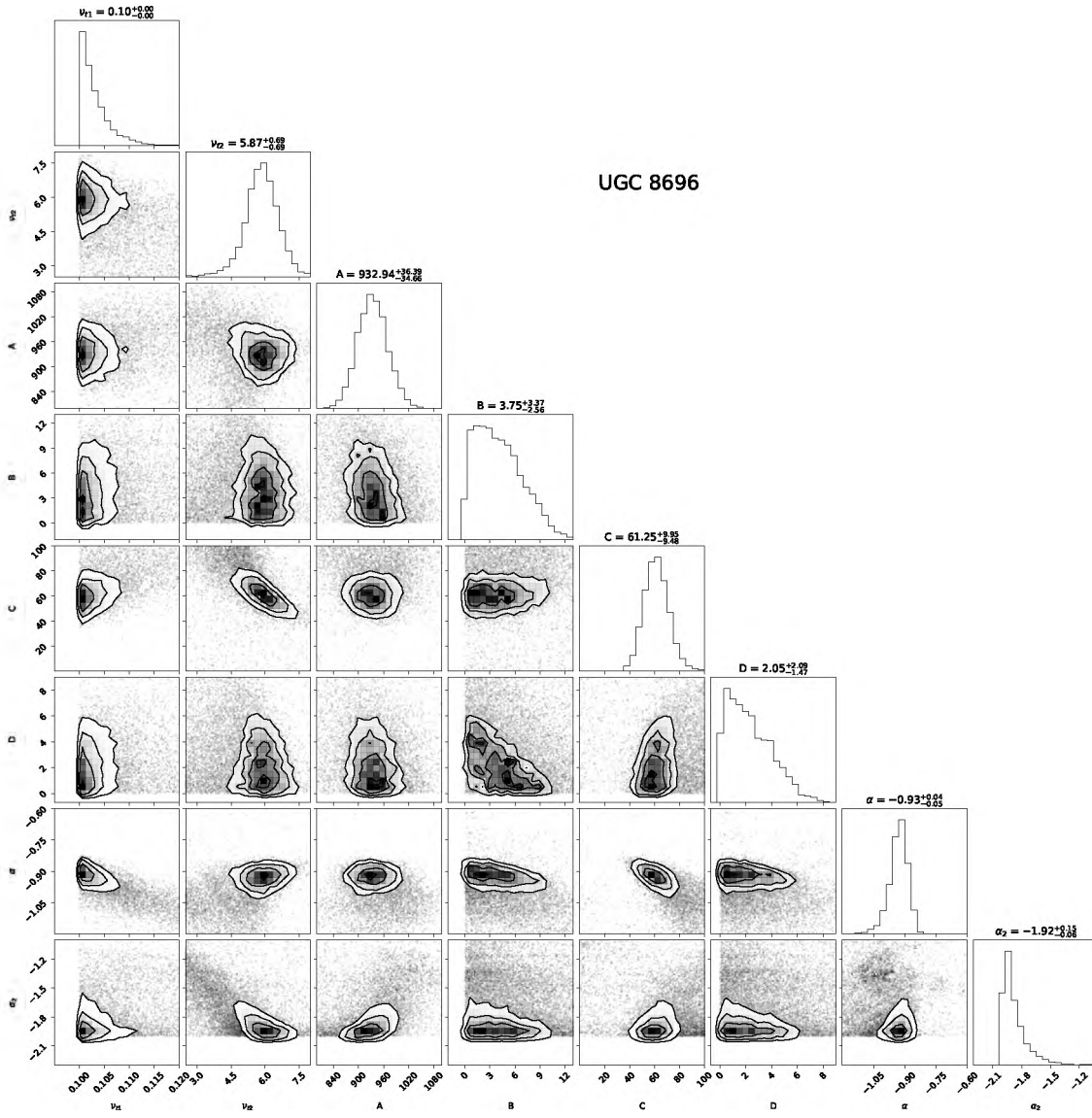


FIGURE B.2: Continued.

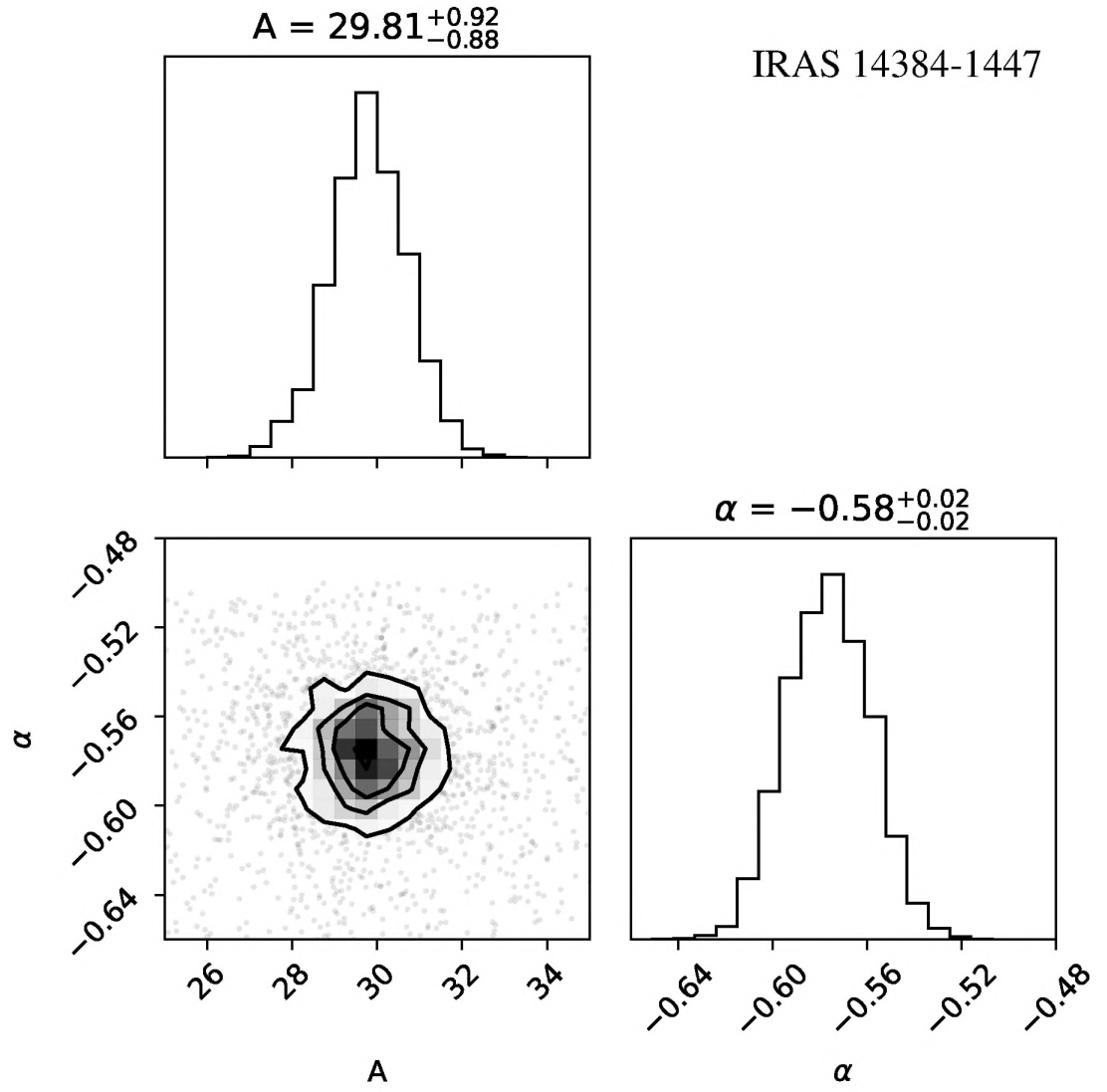


FIGURE B.2: Continued.

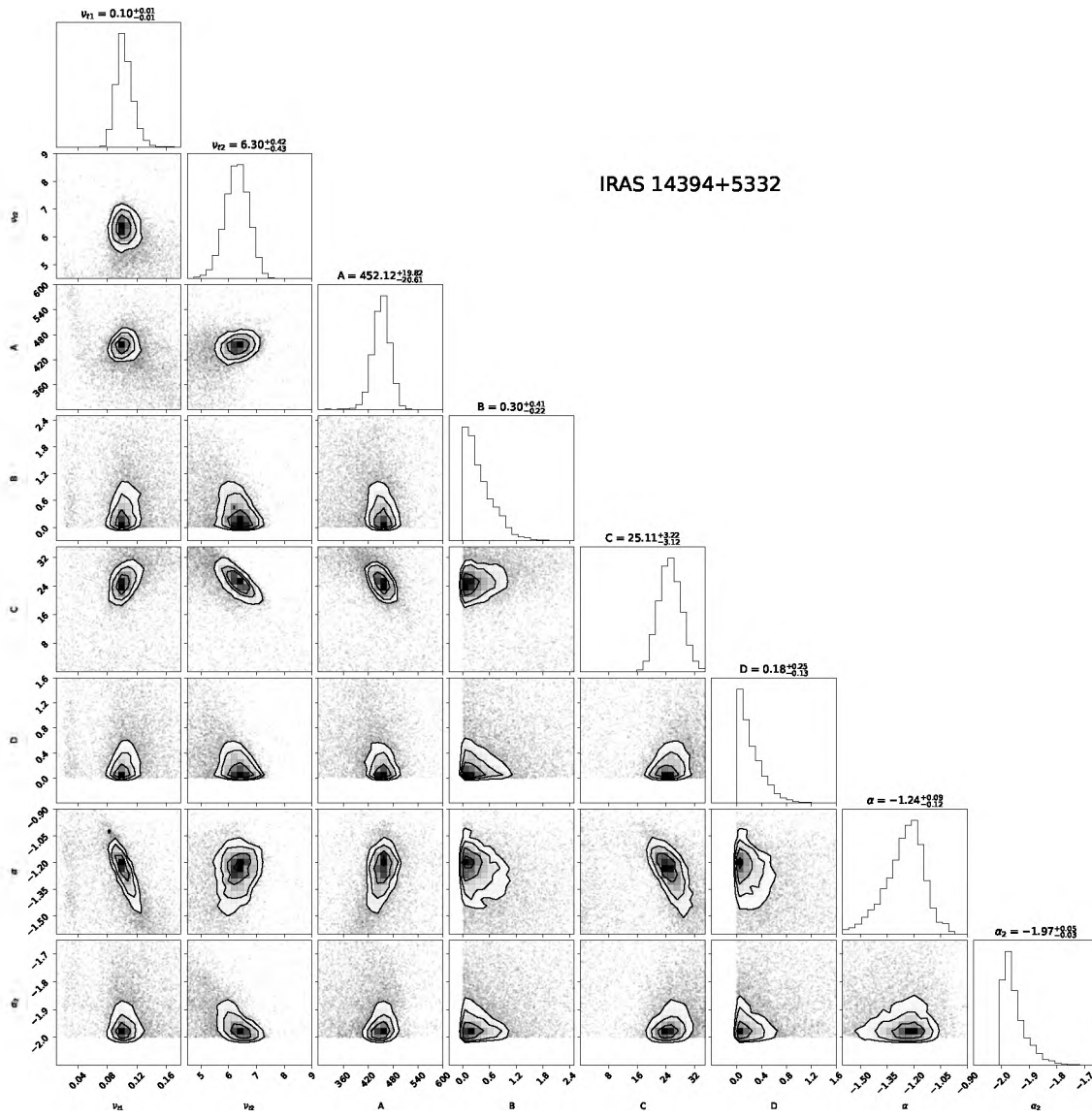


FIGURE B.2: Continued.

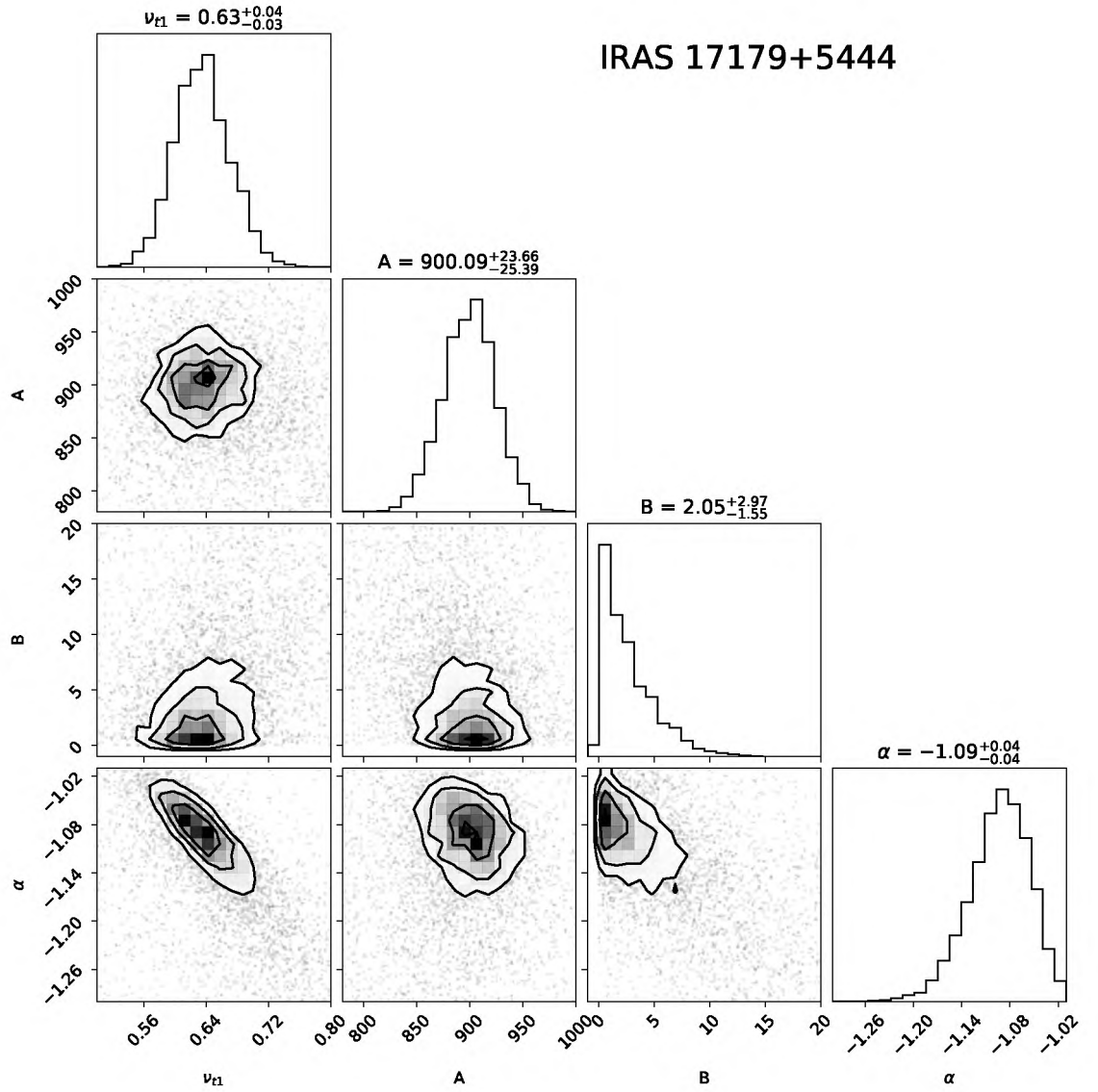


FIGURE B.2: Continued.

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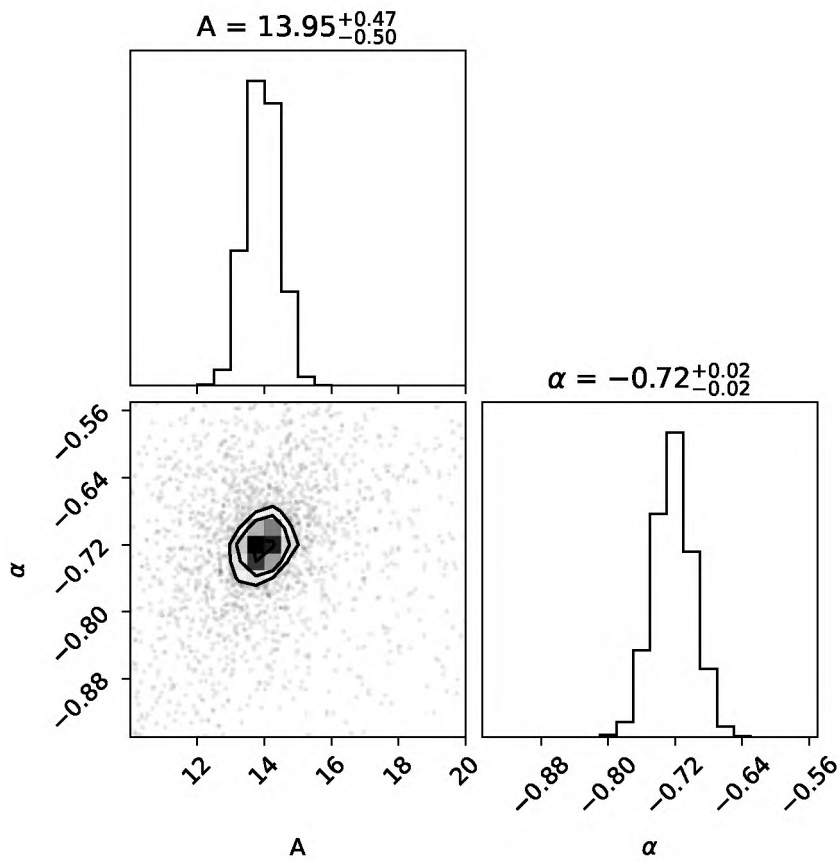


FIGURE B.2: Continued.

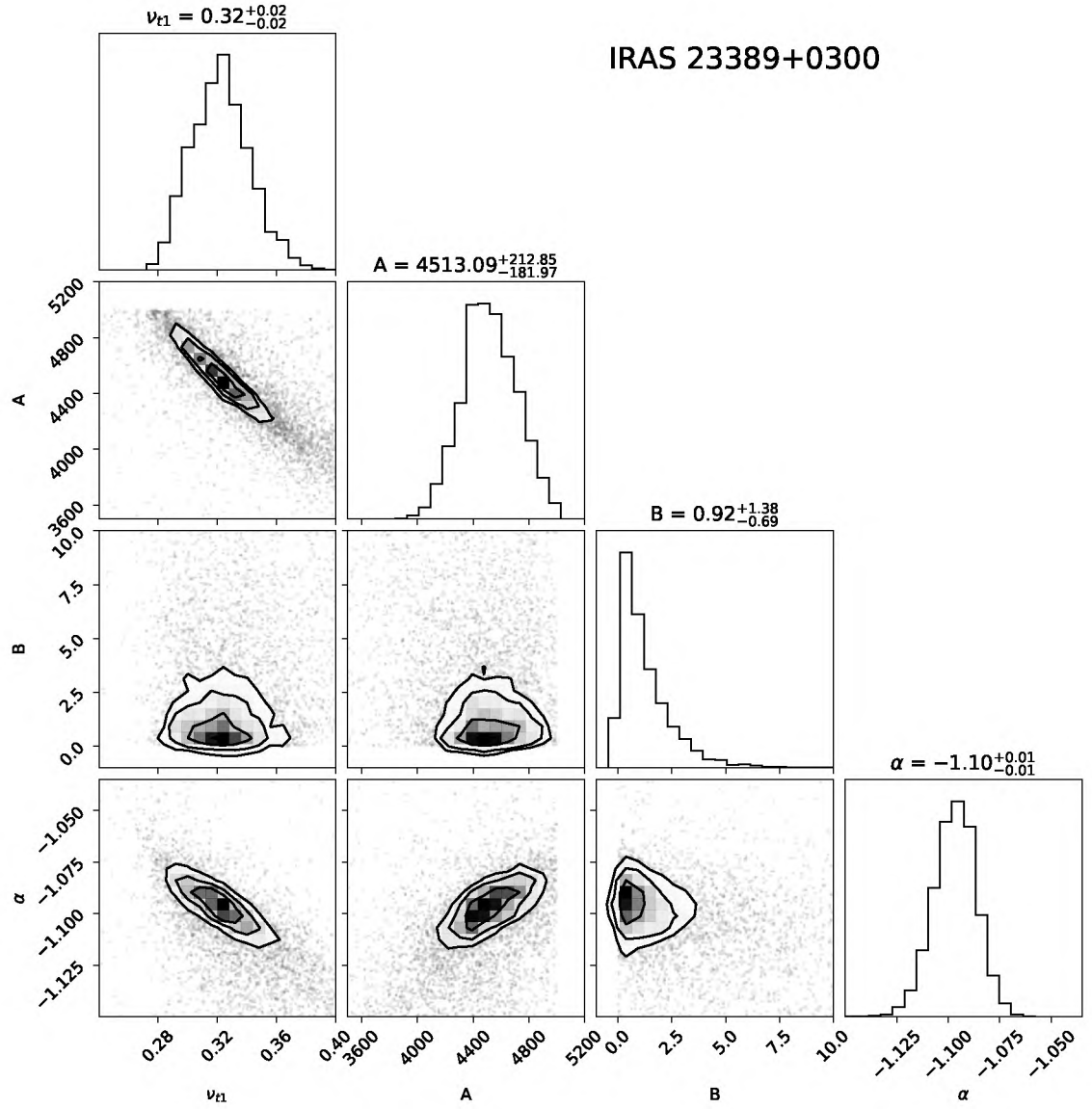


FIGURE B.2: Continued.

B.2 Summary of UV-IR observations gathered for SED modeling via CIGALE

TABLE B.2: Integrated UV-IR flux densities used for the SED fitting.

Name	Instrument	Passband	S (mJy)	error (mJy)	Integration Area (a×b)	Ref.
(1)	(2)	(3)	(4)	(5)	(6)	(7)
IRAS F00183-7111	GALEX	FUV	0.012	0.004	$7.3'' \times 7.3''$	(a)
		NUV	0.012	0.001	$3.5'' \times 3.5''$	(a)
	2MASS	J	0.35	0.09	$4'' \times 4''$	(b)
		H	0.41	0.13	$4'' \times 4''$	(b)
		Ks	0.81	0.19	$4'' \times 4''$	(b)
	Spitzer	IRAC1	2.9	0.3	$12'' \times 12''$	(c)
		IRAC3	22	2.0	$12'' \times 12''$	(c)
	WISE	W1	1.91	00.01	$8.25'' \times 8.25''$	(d)
		W2	7.51	0.04	$8.25'' \times 8.25''$	(d)
		W3	29	0.21	$8.25'' \times 8.25''$	(d)
		W4	97.1	1.25	$16.5'' \times 16.5''$	(d)
	IRAS	IRAS2	133	10.2	$>0.8' \times >0.8'^{\dagger}$	(e)
		IRAS3	1200	83.7	$>0.8' \times >0.8'^{\dagger}$	(e)
		IRAS4	1190	119	$>0.8' \times >0.8'^{\dagger}$	(e)
	MIPS	MIPS2	1500	225	$8'' \times 8''$	(c)
		MIPS3	540	80	$8'' \times 8''$	(c)
IRAS 03538-6432	GALEX	FUV	0.027	0.004	$3.6'' \times 3.6''$	(a)
		NUV	0.0052	0.004	$3.5'' \times 3.5''$	(a)
	SMSS	g	0.19	0.02	$2.75'' \times 2.75''$	(f)
		r	0.28	0.04	$2.75'' \times 2.75''$	(f)
		i	0.20	0.04	$2.75'' \times 2.75''$	(f)
		z	0.36	0.04	$2.75'' \times 2.75''$	(f)
	2MASS	J	0.55	0.05	$4'' \times 4''$	(b)
		H	1.01	0.21	$4'' \times 4''$	(b)
		Ks	1.27	0.05	$4'' \times 4''$	(b)
	WISE	W3	15.3	0.127	$8.25'' \times 8.25''$	(d)
		W4	57.6	0.903	$16.5'' \times 16.5''$	(d)
	Spitzer	IRAC1	1.8	0.02	$5.8'' \times 5.8''$	(g)
		IRAC2	2.72	0.02	$5.8'' \times 5.8''$	(g)
		IRAC3	4.8	0.07	$5.8'' \times 5.8''$	(g)
		IRAC4	12	0.1	$5.8'' \times 5.8''$	(g)
	AKARI	N60	1020	350	$40'' \times 50''^{\ddagger}$	(h)
		WIDE-S	986	61	$40'' \times 50''^{\ddagger}$	(h)
		WIDE-L	1540	150	$70'' \times 90''^{\ddagger}$	(h)
		N160	1050	420	$70'' \times 90''^{\ddagger}$	(h)
IR08572+3915	GALEX	FUV	0.085	0.01	$3.5'' \times 3.5''$	(a)
		NUV	0.128	0.008	$3.5'' \times 3.5''$	(a)
	SDSS	u'	0.20	0.02	$5.87'' \times 5.87''$	(i)
		g'	0.87	0.03	$8.21'' \times 8.21''$	(i)

UGC 5101	2MASS	r'	1.33	0.05	$7.71'' \times 7.71''$	(i)
		i'	1.70	0.07	$7.11'' \times 7.11''$	(i)
		z'	1.85	0.10	$5.46'' \times 5.46''$	(i)
	WISE	J	3.10	0.47	$14'' \times 14''$	(b)
		H	3.74	0.52	$14'' \times 14''$	(b)
		Ks	4.42	0.53	$14'' \times 14''$	(b)
	Herschel-PACS	W1	23.9	2.21	$8.25'' \times 8.25''$	(d)
		W2	111	10	$8.25'' \times 8.25''$	(d)
		W3	325	29.9	$8.25'' \times 8.25''$	(d)
		W4	1290	119	$16.5'' \times 16.5''$	(d)
	Herschel-SPIRE	Blue	6398	282	$35'' \times 35''$	(i)
		Green	4452	194	$35'' \times 35''$	(i)
		Red	1997	84	$35'' \times 35''$	(i)
	GALEX	PSW	521	31	$45'' \times 45''$	(i)
		PMW	188	14	$45'' \times 45''$	(i)
		PLW	42	7	$45'' \times 45''$	(i)
		FUV	0.056	0.002	$3.5'' \times 3.5''$	(a)
	SDSS	NUV	0.19	0.007	$3.5'' \times 3.5''$	(a)
		u'	0.087	0.01	$13.37'' \times 13.37''$	(i)
		g'	4.02	0.01	$13.37'' \times 13.37''$	(i)
		r'	8.40	0.002	$13.37'' \times 13.37''$	(i)
	2MASS	i'	13.20	0.026	$13.37'' \times 13.37''$	(i)
		z'	19.41	0.066	$13.37'' \times 13.37''$	(i)
		J	15.7	0.31	$23.4'' \times 14.5''$	(b)
		H	23.6	0.46	$23.4'' \times 14.5''$	(b)
	WISE	Ks	31.6	0.59	$23.4'' \times 14.5''$	(b)
		W1	31.7	0.17	$22'' \times 22''$	(d)
		W2	77.8	0.43	$22'' \times 22''$	(d)
		W3	156	0.86	$22'' \times 22''$	(d)
	IRAS	W4	566	3.13	$22'' \times 22''$	(d)
		IRAS2	1030	15	$>0.8' \times >0.8'$	(e)
		IRAS3	11500	808	$>0.8' \times >0.8'$	(e)
		IRAS4	20200	1010	$>0.8' \times >0.8'$	(e)
IR 10565+2448	AKARI	N60	11200	700	$40'' \times 50''^{\dagger}$	(h)
		WIDE-S	14600	1000	$40'' \times 50''^{\dagger}$	(h)
		WIDE-L	15600	1000	$70'' \times 90''^{\dagger}$	(h)
		N160	11600	2700	$70'' \times 90''^{\dagger}$	(h)
	GALEX	FUV	0.032	0.002	$3.5'' \times 3.5''$	(a)
		NUV	0.129	0.003	$3.5'' \times 3.5''$	(a)
	SDSS	u'	0.393	0.014	$5.87'' \times 5.87''$	(i)
		g'	1.72	0.032	$8.21'' \times 8.21''$	(i)
		r'	3.525	0.054	$7.71'' \times 7.71''$	(i)
		i'	5.63	0.076	$7.11'' \times 7.11''$	(i)
	2MASS	z'	7.49	0.088	$5.46'' \times 5.46''$	(i)
		J	11.9	0.321	$17.8'' \times 16.7''$	(b)
		H	16.7	0.53	$17.8'' \times 16.7''$	(b)
		Ks	17.9	0.638	$17.8'' \times 16.7''$	(b)
	WISE	W1	14.6	0.081	$22'' \times 22''$	(c)

IRAS 12112+0305	IRAS	W2	15.6	0.10	$22'' \times 22''$	(c)
		W3	155	0.854	$22'' \times 22''$	(c)
		W4	655	3.62	$22'' \times 22''$	(c)
		IRAS1	217	32.6	$>0.8' \times >0.8'^{\dagger}$	(e)
	<i>Herschel</i> -PACS	IRAS2	1140	13	$>0.8' \times >0.8'^{\dagger}$	(e)
		IRAS3	12100	606	$>0.8' \times >0.8'^{\dagger}$	(e)
		IRAS4	15100	757	$>0.8'_n \times >0.8'^{\dagger}$	(e)
		Blue	14300	640	$35'' \times 35''$	(i)
	<i>Herschel</i> -SPIRE	Green	15800	710	$35'' \times 35''$	(i)
		Red	10500	460	$35'' \times 35''$	(i)
		PSW	3640	215	$45'' \times 45''$	(i)
		PMW	1340	78	$45'' \times 45''$	(i)
	GALEX	PLW	381	22	$45'' \times 45''$	(i)
		FUV	0.09	0.002	$3.5'' \times 3.5''$	(a)
		NUV	0.17	0.002	$3.5'' \times 3.5''$	(a)
	SDSS	u'	0.21	0.02	$8.09'' \times 8.09''$	(i)
		g'	0.62	0.02	$8.09'' \times 8.09''$	(i)
		r'	1.03	0.02	$8.09'' \times 8.09''$	(i)
		i'	1.64	0.03	$8.09'' \times 8.09''$	(i)
	2MASS	z'	1.77	0.08	$8.09'' \times 8.09''$	(i)
		J	3.94	0.36	$18'' \times 18''$	(b)
		H	5.11	0.52	$18'' \times 18''$	(b)
		Ks	5.15	0.71	$18'' \times 18''$	(b)
	WISE	W1	3.96	0.08	Profile fit	(d)
		W2	4.66	0.09	Profile fit	(d)
		W3	54.2	0.8	Profile fit	(d)
		W4	303	5.86	Profile fit	(d)
	IRAS	IRAS2	509	14.3	$>0.8' \times >0.8'^{\dagger}$	(e)
		IRAS3	8500	510	$>0.8' \times >0.8'^{\dagger}$	(e)
		IRAS4	9980	798	$>0.8' \times >0.8'^{\dagger}$	(e)
	<i>Herschel</i> -PACS	Blue	9283	419	$35'' \times 35''$	(i)
		Green	9241	415	$35'' \times 35''$	(i)
		Red	5831	254	$35'' \times 35''$	(i)
	<i>Herschel</i> -SPIRE	PSW	1974	119	$45'' \times 45''$	(i)
		PMW	796	49	$45'' \times 45''$	(i)
		PLW	226	16	$45'' \times 45''$	(i)
UGC 8058	XMM-OM	UVW1	1.38	0.01	$4.12'' \times 3.02''$	(k)
		UVW2	0.42	0.01	$2.93'' \times 2.26''$	(k)
	SDSS	u'	3.66	0.01	$2.37'' \times 2.37''$	(i)
		g'	11.16	0.01	$2.37'' \times 2.37''$	(i)
		r'	15.70	0.02	$2.37'' \times 2.37''$	(i)
		i'	9.03	0.03	$2.37'' \times 2.37''$	(i)
		z'	29.11	0.05	$2.37'' \times 2.37''$	(i)
	2MASS	J	58.9	0.01	$36.4'' \times 30.2''$	(b)
		H	111	1.64	$36.4'' \times 30.2''$	(b)
		Ks	191	2.83	$36.4'' \times 30.2''$	(b)
	WISE	W1	240	1.11	$22'' \times 22''$	(c)
		W2	409	1.89	$22'' \times 22''$	(c)

IRAS13305-1739	IRAC	W3	1310	6.01	$22'' \times 22''$	(c)
		W4	5290	29.2	$22'' \times 22''$	(c)
		IRAC3	605	0.10	$5.8'' \times 5.8''$	(g)
		IRAC4	800	0.008	$5.8'' \times 5.8''$	(g)
	IRAS	IRAS1	1870	93.6	$>0.8' \times >0.8'^{\dagger}$	(e)
		IRAS2	8662	93.6	$>0.8' \times >0.8'^{\dagger}$	(e)
		IRAS3	20200	1010	$>0.8' \times >0.8'^{\dagger}$	(e)
		IRAS4	32000	1600	$>0.8' \times >0.8'^{\dagger}$	(e)
	<i>Herschel</i> -PACS	Blue	34900	1590	$35'' \times 35''$	(i)
		Green	30410	1370	$35'' \times 35''$	(i)
		Red	16930	740	$35'' \times 35''$	(i)
	<i>Herschel</i> -SPIRE	PSW	5685	343	$50'' \times 50''$	(i)
		PMW	2007	123	$50'' \times 50''$	(i)
		PLW	597	36	$50'' \times 50''$	(i)
	GALEX	FUV	0.048	0.008	$4.3'' \times 4.3''$	(a)
		NUV	0.071	0.006	$3.5'' \times 3.5''$	(a)
	SMSS	g	1.02	0.05	$5.28'' \times 5.28''$	(f)
		r	1.1	0.06	$5.28'' \times 5.28''$	(f)
		i	1.38	0.04	$5.28'' \times 5.28''$	(f)
		z	1.1	0.06	$5.28'' \times 5.28''$	(f)
	2MASS	J	3.06	0.17	$14'' \times 14''$	(b)
		H	3.44	0.023	$14'' \times 14''$	(b)
		Ks	3.64	0.02	$14'' \times 14''$	(b)
	WISE	W1	3.06	0.03	$22'' \times 22''$	(d)
		W2	6.37	0.08	$22'' \times 22''$	(d)
		W3	45.9	0.38	$22'' \times 22''$	(d)
		W4	227	1.67	$22'' \times 22''$	(d)
	IRAS	IRAS2	392	17.2	$>0.8' \times >0.8'^{\dagger}$	(e)
		IRAS3	1160	93.1	$>0.8' \times >0.8'^{\dagger}$	(e)
		IRAS4	1040	251	$>0.8' \times >0.8'^{\dagger}$	(e)
	AKARI	WIDE-S	1095	168	$40'' \times 50''^{\ddagger}$	(h)
		WIDE-L	795.3	79	$70'' \times 90''^{\ddagger}$	(h)
UGC 8696	GALEX	FUV	0.132	0.013	$3.5'' \times 3.5''$	(a)
		NUV	0.364	0.013	$3.5'' \times 3.5''$	(a)
	SDSS	u'	0.871	0.007	$2.37'' \times 2.37''$	(i)
		g'	3.70	0.007	$9.30'' \times 9.30''$	(i)
		r'	6.92	0.01	$9.30'' \times 9.30''$	(i)
		i'	10.57	0.02	$9.30'' \times 9.30''$	(i)
		z'	11.70	0.03	$9.30'' \times 9.30''$	(i)
	2MASS	J	19.5	0.40	$29'' \times 16.8''$	(b)
		H	25.3	0.68	$29'' \times 16.8''$	(b)
		Ks	28	0.84	$29'' \times 16.8''$	(b)
	WISE	W1	23.6	2.17	$15'' \times 85''$	(c)
		W2	36.6	3.37	$15'' \times 85''$	(c)
		W3	232	21.4	$15'' \times 85''$	(c)
		W4	1690	155	$15'' \times 85''$	(c)
	IRAC	IRAC1	27	2.48	$15'' \times 85''$	(g)
		IRAC2	37.9	3.49	$15'' \times 85''$	(g)

IR 14348-1447	IRAS	IRAC3	79.4	7.31	$15'' \times 85''$	(g)
		IRAC4	183	16.9	$15'' \times 85''$	(g)
		IRAS1	240	17	$>0.8' \times >0.8'^{\dagger}$	(e)
		IRAS2	2280	9.41	$>0.8' \times >0.8'^{\dagger}$	(e)
	<i>Herschel</i> -PACS	IRAS3	22500	42	$>0.8' \times >0.8'^{\dagger}$	(e)
		IRAS4	22500	70	$>0.8' \times >0.8'^{\dagger}$	(e)
		Blue	24460	1110	$35'' \times 35''$	(i)
	<i>Herschel</i> -SPIRE	Green	22320	1000	$35'' \times 35''$	(i)
		Red	12740	560	$35'' \times 35''$	(i)
		PSW	4177	252	$55'' \times 55''$	(i)
	GALEX	PMW	1531	94	$55'' \times 55''$	(i)
		PLW	427	26	$55'' \times 55''$	(i)
		FUV	0.065	0.002	$3.5'' \times 3.5''$	(a)
	SMSS	NUV	0.138	0.002	$3.5'' \times 3.5''$	(a)
		g	.486	0.87	$3.5'' \times 3.5''$	(a)
		r	1.35	0.23	$3.5'' \times 3.5''$	(a)
	2MASS	i	2.31	0.32	$3.5'' \times 3.5''$	(a)
		z	1.92	0.10	$3.5'' \times 3.5''$	(a)
		H	6.47	0.66	$26.86'' \times 26.86''$	(b)
	WISE	Ks	9.67	0.92	$26.86'' \times 26.86''$	(b)
		W1	4.00	.029	$8.25'' \times 8.25''$	(c)
		W2	4.86	0.031	$8.25'' \times 8.25''$	(c)
	IRAS	W3	44.4	0.28	$8.25'' \times 8.25''$	(c)
		W4	337	2.17	$16.5'' \times 16.5''$	(c)
		IRAS2	560	84	$>0.8' \times >0.8'^{\dagger}$	(e)
	<i>Herschel</i> -PACS	IRAS3	6870	412	$>0.8' \times >0.8'^{\dagger}$	(e)
		IRAS4	7490	674	$>0.8' \times >0.8'^{\dagger}$	(e)
		Blue	8260	373	$35'' \times 35''$	(i)
	<i>Herschel</i> -SPIRE	Green	8385	376	$35'' \times 35''$	(i)
		Red	5475	239	$35'' \times 35''$	(i)
		PSW	1967	117	$45'' \times 45''$	(i)
IRAS14394+5332	SDSS	PMW	728	44	$45'' \times 45''$	(i)
		PLW	217	14	$45'' \times 45''$	(i)
		u'	0.187	0.003	$3.34'' \times 3.34''$	(i)
	2MASS	g'	0.547	0.002	$3.34'' \times 3.34''$	(i)
		r'	0.945	0.003	$3.34'' \times 3.34''$	(i)
		i'	1.840	0.006	$3.34'' \times 3.34''$	(i)
	IRAS	z'	1.870	0.012	$3.34'' \times 3.34''$	(i)
		J	2.66	0.18	$14'' \times 14''$	(b)
		H	3.77	0.22	$14'' \times 14''$	(b)
	AKARI	Ks	3.64	0.31	$14'' \times 14''$	(b)
		IRAS2	346	3.6	$>0.8' \times >0.8'^{\dagger}$	(e)
		IRAS3	1950	78	$>0.8' \times >0.8'^{\dagger}$	(e)
	GALEX	IRAS4	2400	120	$>0.8' \times >0.8'^{\dagger}$	(e)
		WIDE-S	1780	130	$40'' \times 50''^{\ddagger}$	(h)
		WIDE-L	1770	410	$70'' \times 90''^{\ddagger}$	(h)
IRAS 17179+5444	GALEX	N160	910	213	$70'' \times 90''^{\ddagger}$	(h)
		NUV	0.018	0.001	$3.5'' \times 3.5''$	(a)

IRAS F23529-2119	SDSS	u'	0.08	0.003	$3.84'' \times 3.84''$	(i)
		g'	0.36	0.002	$3.84'' \times 3.84''$	(i)
		r'	0.87	0.003	$3.84'' \times 3.84''$	(i)
		i'	1.47	0.004	$3.84'' \times 3.84''$	(i)
		z'	1.83	0.01	$3.84'' \times 3.84''$	(i)
	2MASS	J	2.04	0.17	$14'' \times 14''$	(b)
		H	2.09	0.28	$14'' \times 14''$	(b)
		Ks	2.77	0.28	$14'' \times 14''$	(b)
	Spitzer	IRAC1	2.39	0.02	$5.8'' \times 5.8''$	(g)
		IRAC2	3.86	0.02	$5.8'' \times 5.8''$	(g)
		IRAC3	7.11	0.08	$5.8'' \times 5.8''$	(g)
		IRAC4	18.3	0.1	$5.8'' \times 5.8''$	(g)
	IRAS	IRAS2	202	7.62	$>0.8' \times >0.8'^{\dagger}$	(e)
		IRAS3	1360	68.1	$>0.8' \times >0.8'^{\dagger}$	(e)
		IRAS4	1920	153	$>0.8' \times >0.8'^{\dagger}$	(e)
	AKARI	WIDE-S	1340	40	$40'' \times 50''^{\dagger}$	(h)
		WIDE-L	1380	89	$70'' \times 90''^{\dagger}$	(h)
		N160	1650	68	$70'' \times 90''^{\dagger}$	(h)
	GALEX	FUV	0.008	0.001	$3.5'' \times 3.5''$	(a)
		NUV	0.013	0.001	$3.5'' \times 3.5''$	(a)
	SDSS	u'	0.032	0.002	$2.73'' \times 2.73''$	(i)
		g'	0.052	0.001	$2.60'' \times 2.60''$	(i)
		r'	0.105	0.002	$5.10'' \times 5.10''$	(i)
		i'	0.176	0.003	$4.98'' \times 4.98''$	(i)
		z'	0.232	0.011	$5.74'' \times 5.74''$	(i)
	2MASS	J	0.42	0.03	$4'' \times 4''$	(b)
		Ks	0.78	0.02	$4'' \times 4''$	(b)
	WISE	W1	2	0.05	$0.5'' \times 0.5''$	(d)
		W2	3.11	0.07	$0.5'' \times 0.5''$	(d)
		W3	15.3	0.127	$0.5'' \times 0.5''$	(d)
		W4	57.6	0.903	$0.5'' \times 0.5''$	(d)
	Spitzer	IRAC1	1.9	0.02	$3.8'' \times 3.8''$	(g)
		IRAC2	2.7	0.02	$3.8'' \times 3.8''$	(g)
		IRAC3	4.4	0.07	$3.8'' \times 3.8''$	(g)
		IRAC4	8.9	0.06	$3.8'' \times 3.8''$	(g)
	IRAS	IRAS3	327	55.5	$>0.8' \times >0.8'^{\dagger}$	(j)
		IRAS4	627	132	$>0.8' \times >0.8'^{\dagger}$	(j)
IRAS 23389+0300	GALEX	FUV	0.004	0.002	$5.3'' \times 5.3''$	(a)
		NUV	0.009	0.002	$3.5'' \times 3.5''$	(a)
	SDSS	u'	0.019	0.002	$2.42'' \times 2.42''$	(i)
		g'	0.053	0.002	$2.42'' \times 2.42''$	(i)
		r'	0.937	0.003	$2.42'' \times 2.42''$	(i)
		i'	1.82	0.006	$2.42'' \times 2.42''$	(i)
		z'	1.84	0.01	$2.42'' \times 2.42''$	(i)
	2MASS	J	0.77	0.17	$4'' \times 4''$	(b)
		H	0.76	0.17	$4'' \times 4''$	(b)
		Ks	1.22	0.15	$4'' \times 4''$	(b)
	WISE	W1	1.04	0.02	$8.25'' \times 8.25''$	(d)

AKARI	W2	1.44	0.04	$8.25'' \times 8.25''$	(d)
	W3	15.70	0.22	$8.25'' \times 8.25''$	(d)
	W4	123	2.82	$8.25'' \times 8.25''$	(d)
	N60	1400	490	$40'' \times 50''^\dagger$	(j)
	WIDE-S	1320	396	$40'' \times 50''^\dagger$	(j)
	WIDE-L	1100	660	$70'' \times 90''^\dagger$	(j)
	N160	2000	320	$70'' \times 90''^\dagger$	(j)

Columns: (1) source name; (2) Instrument; (3) Passband; (4) total flux densities of the source (5) the error in the flux densities; (6) integration area used in aperture photometry in terms of length of semi-major axis $a \times$ length of semi-minor axis b (for circular apertures, semi-major axis = semi-minor axis), † source is flagged as resolved or marginally resolved in (Sanders et al., 2003), ‡ full-width at half maximum of the 2-D Gaussian used in profile fitting photometry; (7) references - (a) <https://galex.stsci.edu/GR6/?page=mastform>, (b) 2MASS Extended Mission Data Release (Skrutskie et al., 2006) (c) Spoon et al. (2009), (d) Wright et al. (2010); Mainzer et al. (2011), (e) (Sanders et al., 2003), (f) Wolf et al. (2018), (g) Spitzer Science Center and Infrared Science Archive (2021), (h) AKARI, (i) The 16th Data Release of the Sloan Digital Sky Surveys (Ahumada et al., 2020), (j) Pollo et al. (2010)

B.3 Notes on individual galaxies

1. **IRAS F00183-7111:** classified as a Seyfert 2 type nucleus (Armus et al., 1989), the VLBI imaging of this galaxy reveals a GPS source at its center with linear size equal to ≈ 1 kpc (Norris et al., 2012). In addition, the near-IR imaging indicates a disturbed morphology and a single nucleus with large extinction values (Rigopoulou et al., 1999) while the optical morphology appears as an unremarkable smudge on $20''$ scale (Heckman et al., 1990). This galaxy is known for its high SFR, high AGN fraction, and radio AGN-like nature. Our CIGALE modeling estimates $\text{SFR}_{\text{IR}} = 891.25 \text{ M}_\odot \text{ yr}^{-1}$, AGN fraction = $\sim 50\%$, and $R_{\text{AGN}}=30$ which corroborates above conclusions.
2. **IRAS F03538-6432:** classified as a Seyfert 2 type nucleus (Cui et al., 2001), this galaxy is believed to be in advanced merger state because the optical morphology from HST imaging shows three distinct nuclei and a few tidal tails (Cui et al., 2001). This galaxy is a border-line radio loud galaxy with $R_{\text{AGN}}=\sim 10$.
3. **IRAS 08572+3915:** classified as dynamically young system formed by two disks' galaxies which are in the process of merging (Arribas et al., 2000), this system shows a presence of a buried AGN in the north-west galaxy (Rupke and Veilleux, 2013). This source presents the highest AGN fraction and the lowest SFR in our sample (see also Efstathiou et al., 2014). Moreover, this source hosts a very obscured nucleus, which is thick even in the mid-IR at the $9.7\mu\text{m}$ spectral feature, and shows large water and ice opacities (Stierwalt et al., 2014). We further note that its CIAGLE estimated dust luminosity from starformation is low ($=10^{10.19} \text{ L}_\odot$). This is because of the obscured AGN (Efstathiou et al., 2014) with a high AGN fraction $=99\%$, responsible for most of the observed dust luminosity ($=10^{12.09} \text{ L}_\odot$; torus

luminosity from CIGALE). Moreover, our radio modeling shows a very high thermal fraction=86% for this source which must be due to absorption of ionizing photons by dust (see Section 6.6.4).

4. **UGC 05101:** classified as an intermediate Seyfert 1.5 type galaxy (Sanders et al., 1988) with a disturbed morphology containing a single red nucleus. It is a late-stage merger (Veilleux et al., 2002) undergoing strong circumnuclear starburst suggested by the detection of characteristic polycyclic aromatic hydrocarbon (PAH) features in MIR spectra (Martínez-Paredes et al., 2015). Although our radio SED modeling utilizes a larger dataset and frequency coverage, particularly at the lowest (74 MHz) and the highest (32.5 GHz) ends, our best-fit SED model is similar to that obtained by Clemens et al. (2010) but with two electron populations. Moreover, our derived values of α_2 and the turnover frequency are consistent within uncertainties with Clemens et al. (2010).

5. **IRAS 10565+2448:** classified as HII galaxy by spectral type (Veilleux et al., 1995) undergoing minor merger (Wu et al., 1998) with a second nucleus at the northeast of the bright nucleus and a third galaxy at the tidal tail (Murphy et al., 1996). Yuan et al. (2010) classified it as a starburst-AGN composite galaxy while Vega et al. (2008) and Vardoulaki et al. (2015) assert it to be a starburst galaxy based on spectral-index map.

The best-fit radio SED model turns out to be the same as that of Clemens et al. (2010), though with a steeper $\alpha=1.1$ and a higher turnover frequency, $\nu_t=0.5$ GHz as compared to our analysis. The low AGN fraction= $\sim 5\%$ and $R_{\text{AGN}}=1$ obtained from our analysis confirms that this galaxy is indeed starburst dominated, supporting the claim by Vardoulaki et al. (2015).

6. **IRAS 12112+0305:** classified as a LINER-type (Kim and Sanders, 1998) or a Seyfert 2 galaxy (Yuan et al., 2010), this system in a post-merger state with two merging nuclei (Kim et al., 2002). This system shows an Infrared spectrum from the nuclear emission dominated by PAH emission features (Veilleux et al., 2009), hence showing no AGN signature from the infrared energy diagnostics. Its radio SED is best-modeled by a single-component model (C) with a turnover at 0.26 GHz. Although our turnover frequency matches within uncertainty with that from the SYNAGE modeling (~ 290 MHz Nandi et al., 2021); the radio emission is due to starforming processes with the turnover due to FFA.
7. **UGC 08058:** classified as a Seyfert 2 galaxy (Veilleux et al., 1995) in a post-merger stage (Paspaliaris et al., 2021), this is a well-known AGN having a double-lobed radio structure at parsec scales, revealed from VLBI imaging (Ulvestad et al., 1999). Both our SED modeling and Clemens et al. (2010) SED modeling fits this galaxy with a two-component model where Clemens et al. fits find turnovers at 210 MHz and 3.9 GHz. Our best-fit radio SED covers more data at low frequency (54 MHz from LoLLS) end and the first component of our best-fit model is without a turnover. In contrast, the turnover frequency for the second component is smaller than given in Clemens et al. (2010).

8. **IRAS 13305-1739:** classified as a Seyfert 2 nucleus with a slight isophotal distortion in optical image (Veilleux et al., 2002), this galaxy does not show a double-lobed radio morphology (Nandi et al., 2021). The SYNAGE modeling of this galaxy indicates a turnover frequency at ~ 1.7 GHz (Nandi et al., 2021) which is not corroborated with our analysis where it is best fit with a single PL model. This is most likely due to the inclusion of low frequency (down to ~ 70 MHz from GLEAM) data in the SED modeling by us.
9. **UGC 8696:** classified as a Seyfert 2 galaxy (Koski, 1978; Sanders et al., 1988) with highly disturbed morphology with a 40 Kpc tidal tail, indicating a post-merger system. The presence of radio AGN from LOFAR imaging was proposed by Kukreti et al. (2022). Its radio SED is best modeled with a two-component model characterized by different nonthermal electron populations and turnovers (C2). The turnover frequencies are 0.16 GHz and 7.51 GHz, respectively. Our radio SED fit model recovers a turnover at low frequency (160 MHz) because of the use of low-frequency data (54 MHz from LOLLS) by us. Clemens et al. (2010) fits a two-component model with a single turnover at 1 GHz, which is not seen in our analysis. Vega et al. (2008) notes an 11% AGN fraction from radio-FUV modeling, slightly higher than our estimates.
10. **IRAS 14348-1447:** classified as a pair of colliding galaxies (Sanders et al., 1988) with a Seyfert 1 optical nucleus (Vega et al., 2008), the system shows radio emission resulting from both radio AGN and starburst (Vardoulaki et al., 2015). Clemens et al. (2010) fits this galaxy with a turnover at 1 GHz where our best-fit radio model turns out to be a single PL, because of having more data at a lower frequency range (< 500 MHz). Vega et al. (2008) notes an 8% AGN fraction from radio-FUV modeling, slightly higher than our estimates(=1.3%).
11. **IRAS 14394+5332:** classified as a triplet with an east component having a Seyfert 2 nucleus and two close nuclei at a separation 2.6 kpc and connected to a west component with the long tidal tail of ~ 35 kpc (Veilleux et al., 2002). The VLA observations conducted by Crawford et al. (1996) indicate the presence of an obscured AGN contributing the most to the radio continuum in the east component. Its radio SED is best modeled with a two-component model characterized by different nonthermal electron populations and turnovers (C2). The SYNAGE modeling of its radio SED from Nandi et al. (2021) fits a power-law. This is due to the inclusion of more data particularly at low-frequency (54 MHz from LOLLS), intermediate-frequency VLASS (3 GHz) and high-frequency VLA observations (8.4 MHz), analyzed by us (Table B.1).
12. **IRAS 17179+5444:** classified as a Seyfert 2 merger system with a single nucleus surrounded by a tidal material which seems to be extending to the south-west (Veilleux et al., 2002). This galaxy is known to host a GPS radio source, revealed from the VLBI imaging (de Vries et al., 2009). The SYNAGE modeling by Nandi et al. (2021) reveals a spectral turnover at 590 MHz, similar to that obtained by us.
13. **IRAS F23529-2119:** classified as a Seyfert 2 galaxy (Clements et al., 1996b) and a disturbed optical morphology with an off-center nucleus leaving a broad plume to the east resulting from post-merger (Clements et al., 1996a; Rigopoulou et al., 1999). This galaxy is classified as a radio-excess source ($q_{\text{IR}} \leq 1.4$), indicative of an AGN activity (Yun et al., 2001).

14. **IRAS 23389+0300:** classified as a Seyfert 2 nucleus and a pre-merger system (Rodríguez Zaurín et al., 2009), the northern galaxy hosts a double-lobed radio AGN of GPS type with a linear size of ~ 830 pc (Nagar et al., 2003). Its radio SED is best-modeled by the single-component model (C) with a turnover at 0.32 GHz. The SYNAGE modeling by Nandi et al. (2021) reveals a spectral turnover at 177 MHz, while our analysis recovers it at 320 MHz. This could be due to a better sampled SED used in our analysis. CIGALE estimated radio-loudness is ~ 800 , which supports the view that this could be a young radio AGN of GPS type (Nandi et al., 2021).