THE ROLE OF MERGER STAGE ON GALAXY RADIO SPECTRA IN LOCAL INFRARED-BRIGHT STARBURST GALAXIES

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ABSTRACT

An investigation of the steep, high-frequency (i.e., \( \nu \sim 12 \, \text{GHz} \)) radio spectra among a sample of 31 local infrared-bright starburst galaxies is carried out in light of their HST-based merger classifications. Radio data covering as many as 10 individual bands allows for spectral indices to be measured over three frequency bins between 0.15 \(- 32.5 \, \text{GHz} \). Sources having the flattest spectral indices measured at \( \sim 2 \) and 4 GHz, arising from large free-free optical depths among the densest starbursts, appear to be in ongoing through post-stage mergers. The spectral indices measured at higher frequencies (i.e., \( \sim 12 \, \text{GHz} \)) are steepest for sources associated with ongoing mergers in which their nuclei are distinct, but either share a common stellar envelope and/or exhibit tidal tails. These results hold after excluding potential AGN based on their low 6.2 \( \mu \text{m} \) PAH EQWs. Consequently, the low-, mid-, and high-frequency spectral indices each appear to be sensitive to the exact merger stage. It is additionally shown that ongoing mergers, whose progenitors are still separated and share a common envelope and/or exhibit tidal tails, also exhibit excess radio emission relative to what is expected given the far-infrared/radio correlation, suggesting that there may be a significant amount of radio emission that is not associated with ongoing star formation. The combination of these observations, along with high-resolution radio morphologies, leads to a picture in which the steep high-frequency radio spectral indices and excess radio emission arises from radio continuum bridges and tidal tails that are not associated with star formation, similar to what is observed for so-called “taffy” galaxies. This scenario may also explain the seemingly low far-infrared/radio ratios measured for many high-z submillimeter galaxies, a number of which are merger-driven starbursts.

Subject headings: galaxies:active – galaxies:starbursts – infrared:galaxies – radio continuum:galaxies – submillimeter galaxies, a number of which are merger-driven starbursts.

1. INTRODUCTION

Encoded in the radio spectra of star-forming galaxies, which are typically well characterized by a power law (\( S_\nu \propto \nu^{-\alpha} \)), lies information on the thermal and non-thermal energetic processes powering them. Both thermal and non-thermal emission processes are typically associated with massive star formation, underlying the basis for the well known far-infrared/radio correlation (de Jong et al. 1985; Helou et al. 1985; Condon 1992). Far-infrared emission arises from re-radiated UV/optical photons that heat dust grains surrounding massive star-forming regions. The young, massive O/B stars in such regions, whose lifetimes are \( \lesssim 10 \, \text{Myr} \), produce ionizing radiation that is proportional to the amount of free-free emission. Stars more massive than \( \gtrsim 8 \, M_\odot \) end their lives as supernovae (SNe), whose remnants (SNRs) are thought to be the primary accelerators of cosmic-ray (CR) electrons, which emit synchrotron emission as they propagate through a galaxy’s magnetized interstellar medium (ISM).

The non-thermal emission typically dominates the free-free emission at frequencies \( \lesssim 30 \, \text{GHz} \) (Condon 1992), having a relatively steep spectrum (i.e., \( \alpha \approx 0.83 \); Niklas et al. 1997). Thermal bremsstrahlung (free-free) emission, on the other hand, has a much flatter spectrum (\( \alpha \approx 0.1 \)), making it difficult to separate this component from the non-thermal emission. Thus, at frequencies \( \gtrsim 30 \, \text{GHz} \), where the thermal fraction starts to become large, radio observations should become robust measures for the ongoing star formation rate in galaxies (Murphy et. al. 2011a, 2012). However, this has been shown to not necessarily be the case for a number of local luminous infrared galaxies (LIRGs), whose infrared (IR; \( 8 \sim 1000 \, \mu \text{m} \)) luminosities exceed \( L_{\text{IR}} \gtrsim 10^{11} \, L_\odot \).

In a number of these infrared-bright starbursts, their high-frequency (i.e., \( \gtrsim 10 \, \text{GHz} \)) radio spectra are much steeper than expected for an increased thermal fraction, and in some cases, even show possible evidence for spectral steepening (Clemens et al. 2008, 2010; Leroy et al. 2011). Understanding the physical underpinnings driving this behavior can greatly help with the interpretation of radio observations for higher redshift starbursts, which is important given that infrared-luminous galaxies appear to be much more common in the early universe and dominate the star formation rate density in the redshift range spanning \( 1 \lesssim z \lesssim 3 \), being an order of magnitude larger than today (e.g., Chary & Elbaz 2001; Le Floc’h et al. 2005; Caputi et al. 2007; Murphy et al. 2011a; Magnelli et al. 2013).

In the local universe, it is well-known that LIRGs and ultraluminous LIRGs (ULIRGs; \( L_{\text{IR}} \gtrsim 10^{12} \, L_\odot \)) appear to be undergoing an intense starburst phase. Within these systems are compact star-forming regions that have been triggered predominantly through major mergers (see e.g., Armus et al. 1987, 1988, 1989, 1990; Sanders et al. 1988a,b; Murphy et al. 1996).
Veilleux et al. (1993, 1997, 2002). Major mergers have the ability to significantly complicate the interpretation of observed radio properties when individual systems are not resolved, the classic case being the so-called “taffy” galaxies (Condon 1993, 2002). When unresolved, the systems appear to have nearly a factor of ~2 more radio continuum emission relative to what is expected giving the far-infrared/radio correlation, as well as unusually steep (i.e., \( \alpha \approx 1.0 \)) radio spectra. However, when resolved, it is clearly found that the integrated radio properties are driven by radio continuum emission that forms a bridge connecting the galaxy pairs: the radio continuum emission in the bridges are characterized by a steep spectrum and contain roughly an equal amount of emission as the individual galaxies, which have radio spectral indices and far-infrared/radio ratios typical of normal spiral galaxies (Condon et al. 1993, 2002).

In this paper, an explanation is presented for occurrences of steep radio spectra observed in local ULIRGs within the context of the merger stage. The paper is organized as follows. In §2 the sample and data used in the analysis are presented. In §3 the major results are described, and then discussed in §4 to piece together a self-consistent picture describing the radio properties for this sample of local starbursts. Finally, the main conclusions are summarized in §5.

## 2. DATA AND ANALYSIS

The galaxy sample being analyzed here is drawn from sources in the IRAS revised Bright Galaxies Sample (Soifer et al. 1989; Sanders et al. 2003) having 60 \( \mu \)m flux densities larger than 5.24 Jy and far-infrared (FIR; 42.5 – 122.5 \( \mu \)m) luminosities \( \geq 10^{11.25} \) L\(_{\odot}\). The 40 systems that meet these criteria were originally imaged by Condon et al. (1991) at 8.4 GHz with 0\(^{\prime}\).25 resolution.

For 31 of these sources, Clemens et al. (2008) presented

![Table 1](image-url)
additional new very large array (VLA) 22.5 GHz data (obtained in D-configuration), along with new 8.4 GHz data for 7 objects (obtained in C-configuration) and archival observations to increase the radio spectral coverage of each system. Additional lower frequency data at 244 and 610 MHz were obtained and presented in Clemens et al. (2010), and for 14 and 13 sources existing 6.0 and 32.5 GHz measurements, respectively from Leroy et al. (2011) are used. The present analysis focuses on these 31 galaxies (see Table 1) having well sampled radio spectra between 0.15 and 32.5 GHz (typically 6 bands with as many as 10 including some of combination of data observed at 0.151, 0.244, 0.365, 0.610, 1.4, 4.8, 6.0, 8.4, 15.0, 22.5, and 32.5 GHz). While these radio data span over an order of magnitude in frequency and have varying spatial resolutions, missing short-spacing data will not significantly affect the results given that the highest frequency radio data should be sensitive to $\gtrsim 1'$ angular scales, much larger than the typical emitting regions for this sample of infrared-bright galaxies.

For NGC 3690, UGC 08387, UGC 08696, and IRAS F15163+4255, the 22.5 GHz flux densities of Clemens et al. (2008) are significantly lower than the 32.5 GHz flux densities presented in Leroy et al. (2011). These discrepancies may be associated with the difficulties of measuring flux densities through the pressure-broadened 22.3 GHz line of atmospheric water vapor, and therefore the 22.5 GHz flux densities for these 4 sources are not included in the present analysis. Additionally, the 15 GHz flux density UGC 08387, which was reduced from archival VLA data by Clemens et al. (2008), is found to be discrepant with the combination of lower frequency radio data and the 32.5 GHz flux density of Leroy et al. (2011), and is therefore not used. For IRAS F15163+4255, the 4.8 GHz flux density measured by Gregory & Condon (1991) using the 91 m telescope in Green Bank is found to be significantly discrepant with the 6.0 GHz flux density of Leroy et al. (2011), and is dropped from the analysis as well.

IRAS-based far-infrared fluxes and logarithmic far-infrared-to-radio ratios at 1.4 and 8.4 GHz, each of which were reported in Clemens et al. (2008), are also used in the analysis. The far-infrared flux, $F_{\text{FIR}}$, is estimated using IRAS 60 and 100 $\mu$m flux densities and the relation given by Helou et al. (1985) such that, 

$$ F_{\text{FIR}} = 1.26 \times 10^{-14} \left[ 2.58 f_{\nu}(60 \mu m) + f_{\nu}(100 \mu m) \right] \text{Jy} $$

Logarithmic $F_{\text{FIR}}$/radio ratios at frequency $\nu$ are also defined using the relation given by Helou et al. (1985)
such that

\[ q_\nu = \log \left( \frac{F_{\text{FIR}}}{3.75 \times 10^{12} \text{ W m}^{-2}} \right) - \log \left( \frac{S_\nu}{\text{W m}^{-2} \text{Hz}^{-1}} \right) \]  

(2)

Each of these values is given in Table 1 for each source.

The mid-infrared spectral properties were collected by the Spitzer Infrared Spectrograph (IRS; [Houck et al. 2004]) as part of the Great Observatories All-Sky LIRG Survey (GOALS [Armus et al. 2009]), and are taken from Stierwalt et al. (2013). For 2 sources, IRS observations missed the nucleus of the galaxy (IRAS F01417+1651, IRAS F03359+1523). In the analysis 6.2 \( \mu \text{m} \) polycyclic aromatic hydrocarbon (PAH) equivalent widths (EQWs) and 9.7 \( \mu \text{m} \) silicate strengths (see Stierwalt et al. [2013]) are used. Similar to Murphy et al. (2013), the measured 6.2 \( \mu \text{m} \) PAH EQWs is used as an active galactic nuclei (AGN) discriminant. Sources hosting AGN typically have very small PAH EQWs (e.g., [Genzel et al. 1998; Armus et al. 2005]). Specifically, starburst dominated systems appear to have 6.2 \( \mu \text{m} \) PAH EQWs that are \( \gtrsim 0.54 \mu \text{m} \) (Brandl et al. 2006), while AGN have 6.2 \( \mu \text{m} \) PAH EQWs that are \( \lesssim 0.27 \mu \text{m} \). In this paper it is assumed that all sources having PAH EQWs \( \gtrsim 0.27 \mu \text{m} \) are primarily powered by star formation. Given that the PAH EQW is used as an AGN discriminant, we exclude both sources missing IRS data in the present analysis when focusing on star formation dominated systems. The silicate strength at 9.7 \( \mu \text{m} \) is defined as \( s_{9.7} = \log \left( \frac{f_{9.7}}{C_{9.7} \mu \text{m}} \right) \), where \( f_{9.7} \mu \text{m} \) is the measured flux density at the central wavelength of the absorption feature and \( C_{9.7} \mu \text{m} \) is the expected continuum level in the absence of the absorption feature. For two sources (UGC 04881 and NGC 3690), IR luminosity-weighted averages of individual IRS measurements from each nuclear are used.

This analysis additionally makes use of merger classifications based on available Hubble Space Telescope (HST) imaging for 29 galaxies taken as part of an HST/ACS survey of the GOALS sample (Kim et al. 2013; A.S. Evans et al. 2013, in preparation). The merger classifications were assigned using both HST optical [i.e., Advance Camera for Surveys (ACS) B- (F435W) and I-band (F814W)] and near-infrared [i.e., Near Infrared Camera and Multi-Object Spectrometer (NICMOS) H-band (F160W)] imaging. The individual mergers stages are classified by an integer value ranging from 0 to 6, and are described in detail by Haan et al. (2011). Briefly, the numerical classifications are defined in the following way: 0 = non-merger, 1 = pre-merger, 2 = ongoing merger with separable progenitor galaxies, 3 = ongoing merger with progenitors sharing a common envelope, 4 = ongoing merger with double nuclei plus tidal tail, 5 = post-merger with single nucleus plus prominent tail, and 6 = post-merger with single nucleus and a disturbed morphology. For two sources, merger classifications are not available. HST data were not taken for NGC 6286, and the HST/ACS data saturated for the observations of UGC 08658 (Mrk 231). Each of these properties is given in Table 1.

3. RESULTS

A number of the infrared-bright galaxies being investigated here are known to have high-frequency (i.e., \( > 10 \text{GHz} \)) radio spectra that are much steeper than expected given that the thermal fraction should increase with frequency and work to flatten the spectra (e.g., Clemens et al. 2008, 2010; Leroy et al. 2011). In the following section, correlations between various galaxy properties that may help to explain such steep, high-frequency radio spectral indices are investigated after removing potential AGN from the sample using the mid-infrared spectroscopic data. A number of physical considerations have already been put forth and discussed by Clemens et al. (2008), including those used to explain the high frequency turnover in the starburst galaxy NGC 1569 by Lisenfeld et al. (2004), and we refer the reader to these papers. To summarize, these physical

![Figure 1. The median radio spectral indices calculated at three different frequency bins listed in Table 2. The horizontal error bar illustrate the standard deviation among the median frequencies per bin, while the vertical error bars illustrate the error on the median spectral index. In the top panel, sources are binned based on their 6.2 \( \mu \text{m} \) PAH EQWs, where starbursts (i.e., 6.2 \( \mu \text{m} \) PAH EQW \( > 0.54 \mu \text{m} \)) and AGN (i.e., 6.2 \( \mu \text{m} \) PAH EQW \( < 0.27 \mu \text{m} \)) show statistically different average radio spectral indices in the low- and mid-frequency bins. As pointed out in Clemens et al. (2008), there is a clear trend of spectral flattening/steepening towards lower/higher frequencies among this sample of local infrared-bright galaxies. In the bottom panel, only sources primarily powered by star formation (i.e., 6.2 \( \mu \text{m} \) PAH EQW \( \gtrsim 0.27 \mu \text{m} \)) are considered. Overplotted are expected spectral indices for star forming galaxies having a non-thermal spectral index of \( \alpha \approx 0.83 \) and 1.4 GHz thermal fractions of \( f_\nu \approx 5 \) (dashed line), 10 (dotted line), and 15% (dot-dashed line) at 1.4 GHz (see Figure 2). The solid line uses the expectation for the model with a 1.4 GHz thermal fraction of 5%, except sets the free-free optical depth to unity at 1 GHz. This model seems to do a reasonable job fitting through the data points among the sample of star formation dominated sources.](image-url)
processes include synchrotron aging, stochastic events such as radio hypernovae, rapid temporal variations in the star formation rate, and the escape of low energy CRs through convective transport. Each scenario has been found to be unsatisfactory for this sample of local starburst galaxies in a large part due to the extremely short (i.e., $\sim 10^4$ yr; Condon et al. 1991) radiative lifetimes estimated for CR electrons in such systems, which requires a near continuous injection of particles.

3.1. Radio Spectral Curvature

The radio spectra of each source are broken up into low-, mid-, and high-frequency bins, so the spectral curvature of each source can be crudely measured. The low frequency bin is defined as $\nu < 5$ GHz, the mid-frequency bin spans $1$ GHz $< \nu < 10$ GHz, and the high-frequency bin is defined as $\nu > 4$ GHz. This allows the radio spectral index to be calculated using typically 3 or more data points in each frequency bin (see exact numbers in Table 2). The spectral index is estimated by an ordinary least squares fit over each frequency bin range, weighted by the photometric errors. Each spectral index is given in Table 2 along with uncertainties from the fitting. Additionally given in Table 2 is the average frequency, weighted by the signal-to-noise of each photometric data point, over which the radio spectral index was calculated.

In the top panel of Figure 1 the median spectral indices of each bin are plotted as a function of the median frequency over which the spectral indices were calculated. The median frequencies of the low-, mid-, and high-frequency bins are $\approx 2$, $4$, and $12$ GHz, respectively. The horizontal error bar indicates the standard deviation in the average frequencies, while the vertical error bar is the error on the average spectral index. Average spectral indices are shown for the entire sample, as well as for starbursting and AGN-dominated systems, as defined by their $6.2$ $\mu$m PAH EQWs (see Figure 2).

While a rather clear distinction between the average radio spectral indices measured between 1.49 and 8.44 GHz (essentially the $\alpha_{\text{mid}}$ presented here) was pointed out by Murphy et al. (2013), whereby AGN-dominated sources typically have a much flatter radio spectral index compared to starburst-dominated sources, the high-frequency radio spectral indices are statistically indistinguishable between both AGN- and starburst-dominated systems. Using the $6.2$ $\mu$m PAH EQW to split the sources up into starburst and AGN-dominated systems, the median high-frequency radio spectral index for starburst dominated systems is 0.78, with a standard deviation of 0.16. For the AGN-dominated systems, the median spectral index is 0.71, albeit with a slightly larger scatter of 0.20. Thus, the steep spectral indices at $\sim 12$ GHz do not seem to be the result of radio emission associated with an AGN.

In the bottom panel of Figure 1 the average spectral indices in each frequency bin are plotted for only those sources whose energetics are thought to be dominated by star formation based on having a $6.2$ $\mu$m PAH EQW $\geq 0.27$ $\mu$m. The over plotted lines correspond to expectations based on 4 different radio spectra that are shown in Figure 2 to illustrate the change in radio spectral index as a function of frequency based on the increased thermal fraction towards higher frequencies for a normal star-forming galaxy. The radio-to-infrared models are based on the physical description given in Murphy (2009), where the total infrared $(8-10000 \mu m)$ flux is set to $F_{\text{IR}} = 10^{-9}$ W m$^{-2}$ and the source is assumed to follow the far-infrared/radio correlation. The radio spectra are constructed following the prescription given in Murphy (2009), resulting in a non-thermal spectral index of $\approx 0.83$ with 1.4 GHz thermal radio fractions of $f_{1.4\text{GHz}} \approx 5$ (dashed line), $10$ (dotted line), and $15$% (dot-dashed line). These 1.4 GHz thermal fractions correspond to $30$ GHz thermal fractions of $f_{30\text{GHz}} \approx 33$, 51, and 63%, respectively.

As pointed out by Clemens et al. (2008), and also seen by Leroy et al. (2011) using new $33$ GHz VLA data, there is a clear trend of spectral flattening/steepening towards lower/higher frequencies among this sample of local, merger-driven starburst galaxies, which is clearly discrepant from the expectations of typical radio spectra for star-forming galaxies. However, by taking the model having a $1.4$ GHz thermal fraction of $5\%$, modified by free-free absorption where the free-free optical depth is $\tau_{\text{ff}} = (\nu/\nu_{\text{b}})^{-2.1}$ and becomes unity at $\nu_{\text{b}} = 1$ GHz, the model largely fits the observed trend (solid line).

3.2. The High-Frequency Indices Compared to the Compactness of the Sources

Recently, it has been shown that the flattening of the radio spectrum measured between 1.4 and 8.4 GHz (i.e., essentially the spectral index in the mid-frequency bin presented here) among this sample of local infrared-bright starbursts increases with increasing $9.7 \mu$m silicate optical depth, 8.44GHz brightness temperature, and decreasing size of the radio source even after removing potential AGN (Murphy et al. 2013), supporting the idea that compact starbursts show spectral flattening as the result of increased free-free absorption (Condon et al. 1991). In Figure 3 the strength of the 9.7 $\mu$m silicate feature is plotted against the high-frequency radio spectral index indicating the absence of any such trend. Even
after removing sources identified as harboring AGN due to their small 6.2 µm PAH EQW, a trend is still not found. This indicates that the compactness of the starburst likely does not affect the steepness of the high-frequency radio spectrum.

3.3. The Radio Spectral Indices as a Function of Merger Stage

As already shown by Condon et al. (1991), there is a general trend among this sample of local starbursts in which more compact (i.e., higher surface brightness) sources tend to have flatter radio spectral indices, consistent with compact sources becoming optically thick at low (i.e., \( \nu \lesssim 5 \) GHz) radio frequencies. Another way one can illustrate this is by plotting the radio spectral index as a function of merger stage, which is done for the low-, mid-, and high-frequency radio spectral indices in Figure 4. The top, middle, and bottom panels plot radio spectral indices at frequencies of \( \sim 2, 4, \) and 12 GHz, respectively, against merger stage. The horizontal lines in each panel corresponds to the expected spectral index at that frequency given the model radio spectra shown in Figure 2. Only two models are shown: a normal star-forming galaxy having a 1.4 GHz thermal fraction of 10%, and a star-forming galaxy with an original 1.4 GHz thermal fraction of 5% except that the free-free optical depth becomes unity at 1 GHz.

In the top and middle panels, it seems that the flattest spectrum sources falling below what is expected for a normal star-forming galaxy, as indicated by the dotted line, are only found in ongoing and post-mergers with strongly disturbed morphologies. The only outlier appears to be the non-merger IRASF10173+0828, which has a flat spectrum at all frequency bins and hosts an OH megamaser (Mirabel & Sanders 1984) along with a highly compact radio core (Lonsdale et al. 1993). This finding is robust even after removal of potential AGN as indicated by low 6.2 µm PAH EQWs. However, this trend does not persist when the high-frequency spectral indices, measured at \( \sim 12 \) GHz, are plotted against
merger sequence in the bottom panel. After removing potential AGN, the steepest spectrum sources, falling well above what is expected for a normal star-forming galaxy as indicated by the dotted line, are only found among those sources categorized as ongoing mergers in which galaxy nuclei are distinct, but share a common envelope and/or exhibit tidal tails as observed in their stellar light. In contrast, pre- and post-stage mergers do not seem to exhibit such steep spectral indices. Thus, the low-, mid-, and high-frequency spectral indices each appear to be sensitive to the exact stage of the merger.

3.4. Far-Infrared-to-Radio Ratios as a Function of Merger Stage

In Figure 4 it has been shown that sources having the steepest spectra appear to be associated with systems classified as ongoing mergers in which the progenitors are separable and share a common envelope or display strong tidal features. To determine whether merger stage affects the total radio continuum emission, rather than just the spectral index, the difference between the nominal and observed logarithmic $F_{\text{FIR}}$/radio ratios at 1.4 and 8.4 GHz are plotted in the top and bottom panels of Figure 5, respectively, against merger stage. The difference between the nominal and observed $F_{\text{FIR}}$/radio ratios are defined as,

$$\delta q_{\nu} = q_{0,\nu} - q_{\nu},$$

such that a positive value indicates excess radio emission per unit far-infrared emission, and $q_{0,\nu}$ is the nominal $F_{\text{FIR}}$/radio ratio for local star-forming systems. Under the assumption that the far-infrared emission is a good measure for the total star formation rate in each system, a large value of $\delta q_{\nu}$ indicates excess radio emission per unit star formation rate. At 1.4 GHz, $q_{0,1.4\text{GHz}} \approx 2.34$ dex with a scatter of 0.26 dex among $\sim 1800$ galaxies spanning nearly 5 orders of magnitude in luminosity (e.g. Yun et al. 2001), among other properties (e.g. Hubble type, far-infrared color, and $F_{\text{FIR}}$/optical ratio). Assuming a typical radio spectrum, with a spectral index of $\alpha \approx 0.8$ (Condon 1992), this translates into a nominal $F_{\text{FIR}}$ to 8.4 GHz flux density ratio of $q_{0,8.4\text{GHz}} \approx 2.94$ dex.

In the top panel of Figure 5 it can be shown that galaxies having the largest 1.4 GHz excesses appear to be ongoing mergers that share a common envelope before and after removal of potential AGN. However, there is a good deal of scatter in this figure, and there are a number of sources for which significant excesses of far-infrared emission are observed relative to the measured 1.4 GHz flux densities. Since the $q_{1.4\text{GHz}}$ ratios are clearly affected by free-free absorption at low frequencies in the most compact starbursts (Condon et al. 1991), it may be better to see if such trend persists using emission at a higher frequency, where free-free absorption is considered to be largely negligible, such as 8.4 GHz. This is shown in the bottom panel of Figure 5 where $\delta q_{8.4\text{GHz}}$ is plotted against merger stage and the exact same behavior is found, albeit with a much smaller dispersion per merger sequence bin. Excluding potential AGN, there appears to be a trend in which sources classified as ongoing mergers that share a common envelope have excess radio emission per unit star formation rate relative to both early and post-stage mergers, which exhibit nominal $F_{\text{FIR}}$/radio ratios. Thus, similar to radio spectral indices, the far-infrared-to-radio ratios appear to be sensitive to merger stage.

4. DISCUSSION

As previously stated, a number of physical scenarios to explain the steep radio spectral indices among this sample of local starburst galaxies have been proposed in the literature, particularly by the original study of Clemens et al. (2008). While simple arguments to produce steep spectra via increased synchrotron and inverse Compton losses appear to fall short, given that the most compact starbursts are not the sources that exhibit the steepest spectra, an alternative explanation is proposed. It has been known for some time that, when caught in the act, merging systems can create bridges of synchrotron emission that stretch between the progenitor galaxies, whose brightness contours resemble stretching strands of
Figure 6. Radio continuum maps and contours for 6 non-AGN systems, chosen to span the range of merger stages classified through HST imaging, are displayed (merger stage classifications are given in the lower left corner of each panel). For Mrk 331, UGC 04881, IC 1623, and IRAS F15163+4255, 1.4 GHz maps from Condon et al. (1990) are shown, all having resolutions of 1′′5 except for IC 1623 (2′′1). However, for the more compact sources UGC 08387 and IRAS F01364-1042, the higher resolution (0′′25) 8.4 GHz maps from Condon et al. (1991) are shown. The contour levels start at 3 times the RMS noise of each map and are shown using a square-root scaling. For the pre-merger, Mrk 331, its companion galaxy is not shown in the panel, as it is ≈2′ away.

“taffy” (Condon et al. 1993). The two most well-known cases of “taffy” galaxies are the face-on colliding systems UGC 12914/5 (Condon et al. 1993) and UGC 813/6 (Condon et al. 2002).

The space between the spiral galaxy pairs UGC 12915/5 and UGC 813/6 are filled with synchrotron emission, implying that they must contain both relativistic electrons and magnetic fields. The magnetic field of the bridge is presumably stripped from the merging spiral galaxy disks as they interpenetrated during a recent collision, however there is some debate as to whether the relativistic electrons in the bridge have escaped the merging spirals, as originally suggested by Condon et al. (1993), or are rather a new population of relativistic electrons that have been diffusively accelerated in a shock associated with a gas dynamical interaction during the merger (Lisenfeld & Volk 2010). As discussed below, if such a scenario is also responsible for the properties of the starbursting mergers investigated here, the latter explanation appears more appealing.

Other prominent features of the “taffy” systems include: (1) An exceptionally steep spectrum located at the center of the radio bridges (i.e., \( \alpha \approx 1.3 \), which is roughly \( \Delta \alpha = 0.5 \) steeper than the spectral indices of the galaxy disks). (2) A ratio of \( F_{\text{FIR}}/\text{radio} \) for the entire system that is significantly lower than that of normal star-forming galaxies, but typical for the individual spiral galaxy disks. (3) A significant fraction of HI stripped by the collisions that resides between the spiral disks. (4) A significant amount of molecular gas in the bridge (Braine et al. 2003) whose physical conditions are comparable to those in the diffuse clouds of the Galaxy (Zhu et al. 2007). (5) A small amount of warm (i.e., 5 – 17 \( \mu m \); Jarrett et al. 1999) and cold (i.e., 450 and 850 \( \mu m \); Zhu et al. 2007) dust located in the bridge, indicating a low amount on ongoing star formation. (6) Rotational lines of H\(_2\) emission that dominate the mid-infrared spectrum and appear strongest near the center of the bridge (Peterson et al. 2012).

4.1. “Taffy”-Like Starbursts

Among the merging starbursts investigated here, those having the steepest high-frequency (\( \nu \sim 12 \) GHz) radio spectra, and significant excesses of radio emission relative to their observed far-infrared emission, appear to be galaxies in an ongoing merger and either share a common stellar envelope or have significant tails. Both of these radio characteristics are also found in “taffy” systems, whose steep spectra and excess radio emission per unit star formation rate arises from the radio continuum emission in the bridge connecting the merging galaxies. Given that simple physical arguments based on the escape and radiative cooling times of CR electrons to explain these properties among local compact starburst fail, a taffy-like merger scenario appears to be an appealing way to explain the low \( F_{\text{FIR}}/\text{radio} \) ratios and steep high-frequency spectra.

In Figure 6 radio continuum maps are shown for 6 galaxies that largely span the full merging sequence and...
do not appear to harbor buried AGN based on their measured 6.2 μm PAH EQWs. Each system has been highlighted as a star in Figures 4 and 5. Mrk 331 is a pre-merger, exhibiting a symmetric 1.4 GHz radio continuum morphology, as well as a typical radio spectrum and \( F_{\text{FIR}}/\text{radio} \) ratio. UGC 04881 is characterized as an ongoing merger with separable progenitor galaxies. IC 1623 is optically classified as an ongoing merger whose progenitors share a common envelope, which is consistent with its 1.4 and 8.4 GHz radio morphologies. It has a high-frequency radio spectral index of \( \approx 0.95 \), and a factor of 1.6 excess radio emission relative to what is expected given the far-infrared/radio correlation. The excess radio emission appears easily explained by summing the diffuse synchrotron emission that is not associated with the colliding star-forming galaxy disks. IRAS F15163+4255 is classified (by the \( HST \)/data) as an ongoing merger with two nuclei and a prominent tidal tail. This source has very weak 1.4 and 8.4 GHz radio continuum emission that appears to form a bridge between the two progenitor galaxies, keeping it right on the far-infrared/radio correlation. This source also exhibits a somewhat steep high frequency radio spectral index of \( \approx 0.84 \). Like IRAS F15163+4255, UGC 08387 is also classified as an ongoing merger harboring two nuclei and a prominent tidal tail. Given that the progenitor galaxies are not separated by a large angular extent, the high (0′′.25) 8.4 GHz radio continuum map of Condon et al. [1991] is necessary to resolve both components. Similar to IC 1623, the 8.4 GHz morphology is consistent with its optical merger classification, as there are tidal tails of synchrotron emission. UGC 08387 has a high-frequency radio spectral index of \( \approx 0.70 \) and 40% excess radio emission at 8.4 GHz than expected giving its far-infrared flux. Finally, the post-stage, ultra-compact, merger IRAS F01364+1042 is shown, also requiring the use of the high-resolution 8.4 GHz radio map in which their appears to be a single source having seemingly undisturbed radio continuum contours. This system has an extremely flat low- and mid-frequency radio spectral index, presumably due to free-free absorption occurring in the compact starbursts, but a rather normal high-frequency spectral index. Consequently, its \( q_{8.4\text{GHz}} \) value is significantly larger than average, unlike its rather typical \( q_{8.4\text{GHz}} \) value.

Focusing in on IC 1623, 1.4 to 8.4 GHz (4″ resolution) spectral index contours are overlaid on an I-band (F814W) \( HST/ACS \) image in Figure 7. The radio spectral indices are found to be rather typical relative to normal star-forming galaxies for both merging galaxy disks (i.e., \( q_{8.4\text{GHz}} \approx 0.7 \)). The eastern galaxy disk hosts the most deeply embedded star formation, and the radio spectral index clearly flattens right on the peak of the starburst. Similar to the “taffy” systems, the radio spectral index is found to steepen significantly along the radio continuum bridge connecting the galaxy pair, peaking at the midpoint between the two galaxy disks with \( q_{8.4\text{GHz}} \approx 0.92 \). Furthermore, like the “taffy” systems, high-resolution \(^{12}\text{CO} \) observations show a significant amount of molecular gas located in the overlap regions connecting the two galaxy nuclei (Yun et al. [1994]; Iono et al., 2004), thus providing material for the galactic magnetic fields to be anchored as they stretch during the merger process. A similar situation is observed by plotting the 1.4 to 8.4 GHz (3′ resolution) spectral index contours on the I-band (F814W) \( HST/ACS \) image of IRAS F15163+4255 in Figure 8. While the northern and southern galaxy nuclei appear to have significantly different spectral indices, peaking around \( q_{8.4\text{GHz}} \approx 0.6 \) and \( q_{8.4\text{GHz}} \approx 0.8 \), respectively, there is a strong steepening of the indices towards the emission connecting the two galaxy nuclei peaking at \( q_{8.4\text{GHz}} \approx 1.1 \) at the midpoint between the interacting disks.

Explaining the steep radio spectral indices and lower than average \( F_{\text{FIR}}/\text{radio} \) ratios as the result of ongoing mergers seems to be fairly well supported by the data. To date, it has been hard to explain the steep high-frequency spectra in this sample of starbursts given that the rapid (\( \sim 10^4 \) yr) synchrotron and inverse Compton cooling times render diffusion and escape losses to be negligible, and thus cannot work to steepen the spectra. In fact, escape as an explanation is in disagreement with the data, given that the loss of CR electrons would effectively lower the total synchrotron power, whereas galaxies with steep high-frequency spectral indices can have low \( F_{\text{FIR}}/\text{radio} \) ratios. By creating a magnetized medium through the dynamical interaction of the merging galaxy pairs, similar to that of the taffy systems, provides a location where the CR electrons can radiatively cool without the continuous injection and acceleration of new particles.

Given the rapid cooling times due to radiative losses in the compact starbursts embedded in the merging disks,
it seems unlikely that the relativistic electrons associated with synchrotron bridges and/or tidal tails were injected and accelerated in the starburst itself, and have propagated to such distances. As an example, the distance to the midpoint between the two 1.4 GHz “hot spots” in the merging disks of IC 1623 is ≈5″, which projects to a linear distance of ≈2 kpc at a distance of 85.5 kpc. This distance is actually smaller than the ≈15″ (6 kpc) separation between the two galaxy nuclei. Following the description for propagation and physical processes responsible for CR electron energy losses given in Murphy (2009), it can be shown that the time for 1.4 GHz emitting electrons to reach this midpoint is significantly longer than their radiative lifetime. Assuming random walk diffusion, characterized by an energy-dependent diffusion coefficient, the propagation time is ≈2.6 × 10⁷ yr. The radiative lifetime for CR electrons emitted within a 2′/5 radius of the western galaxy, which likely includes the bulk 1.4 GHz emission associated with star formation in that disk, is ≈2.9 × 10⁷ yr, nearly two orders of magnitude shorter.

Additionally, the time that the merger is expected to spend in either of these classifications is no more than a few times ≈10⁷ yr (Haan et al. 2011), which is roughly an order of magnitude longer than the synchrotron cooling times of CR electrons that may populate a bridge, assuming the magnetic field stays in equipartition with the disk it is being pulled out of, and that the radiation field and ISM density leads to negligible inverse Compton and bremsstrahlung cooling, respectively. Thus, it appears more likely that charged particles in such regions have been diffusively accelerated via shocks associated with the available mechanical energy of the merger (e.g., Lisenfeld & Volk 2010). The speed of the galaxy collisions are a few ≈100 km s⁻¹ (e.g., G. Privon et al. 2013, in preparation), and therefore super-Alfvénic for typical ISM Alfvén speeds a few ≈10 km s⁻¹. The Alfvénic Mach number is much larger than unity, at the order \( M_A^2 \sim O(100) \gg 1 \), allowing for shocks that can diffusively accelerate CR particles. This is similar to the Alfvénic Mach numbers within the Sedov-Taylor expansion phase of a SNRs.

This explanation for diffusive acceleration via shocks associated with the merger is additionally supported by integral field spectroscopic observations of infrared-bright mergers. For the case of IC 1623, Rich et al. (2011) have shown that optical emission line diagnostic ratios indicate the presence of widespread shock excitation induced by ongoing merger activity. The energy associated with the shocks in the interacting regions between the two galaxy disks is estimated to be \( \sim 4 \times 10^{47} \) erg s⁻¹ based on the amount of Hα line emission having widths \( \geq 100 \) km s⁻¹ in the interacting region (i.e., \( 80 \times L_{\text{Hα}} \) where \( L_{\text{Hα}} \sim 5 \times 10^{40} \) erg s⁻¹; Rich et al. 2011, 2010). This value is nearly a factor of \( \sim 1.5 \times 10^3 \) times larger than the total 8.4 GHz luminosity of the source (\( \nu L_{\nu, 8.4 \text{ GHz}} \sim 3 \times 10^{39} \) erg s⁻¹), suggesting that, for a proton-to-electron ratio of \( \sim 100 \) in this GeV energy range, \( \sim 4\% \) of the total mechanical luminosity from the shock needs to go into accelerating CRs to explain a factor of \( \sim 2 \) extra radio emission. This is much less than the typical \( 10–30\% \) efficiency of particle acceleration in SNRs (e.g., Berezhko & Volk 1997; Kang & Jones 2003; Caprioli et al. 2010).

4.2. The Case for a Steeper Injection Spectrum in Dense Starbursts

While it is argued here that the most likely explanation for the steep high-frequency radio spectra and “excess” radio emission in this sample of local starbursts arises from synchrotron bridges and tails associated with the stage of the merger, another explanation that has not been currently explored is a systematic change (steepening) in the injection spectrum in this sample of starbursts. Naively, such an scenario does not seem that implausible given the ISM conditions in dense starbursts.

The efficiency in which CRs are accelerated in SNRs plays a significant role in determining the synchrotron emissivity from galaxies. One could imagine a scenario in which the adiabatic phase of supernovae is halted as it expands into the ambient medium, thus reducing the amount of energy lost to adiabatic expansion leaving “extra” energy that could be used in the acceleration of CRs, thereby increasing the total synchrotron emission per unit star formation rate relative to normal galaxies. For example, the modeling of Dorfi (1991) shows that the total acceleration efficiency for CRs increases from \( \sim 0.15 E_{SN} \) to \( \sim 0.25 E_{SN} \), where \( E_{SN} = 10^{51} \) erg is
the total explosion energy of the SNe, when the external
ISM density is increased from \(\sim 1 \text{ cm}^{-3}\) to \(\sim 10 \text{ cm}^{-3}\).
Additionally, an increase in the injection efficiency can
work to steepen the CR injection spectrum (Caprioli 2012).
The ISM densities of starbursts are typically much larger
(e.g., \(n_{\text{ISM}} \sim 10^4 \text{ cm}^{-3}\)), thus the evolution of
SNRs will likely be different and may work to increase
the synchrotron emissivity in such galaxies through an
increased efficiency in particle acceleration, as well as
result in steeper radio spectra due to a steeper initial
injection spectra.

However, given that the densest starbursts, which ex-
hibit the flattest low- and mid-frequency spectral in-
dices are associated with late/post-stage mergers, and
also have typical high-frequency radio spectral indices as
well as normal \(F_{\text{FIR}}/\text{radio}\) flux density ratios, this ex-
planation seems less likely. This additionally suggests
that the excess radio emission in starbursts as a result
of increased secondary electrons may not be a likely ex-
planation (e.g., Murphy 2009; Lacki et al. 2010), since
the densest starbursts (i.e., post mergers) provide the
environment for which secondary production should be
the most efficient. For example, in a dense starburst,
having a much larger ISM density, the cross-section for
collisions between CR nuclei and the interstellar gas is
increased, thus increasing the number of \(\gamma\)’s for a fixed
primary nuclei/electron ratio, which may actually domi-
nate the diffuse synchrotron emission. Yet, the densest,
post-merger starbursts do not show evidence for excess
radio emission per unit star formation rate like those sys-
tems in which the progenitors are still clearly separated
and exhibit a non-negligible amount of diffuse radio emis-
sion in features such bridges and tails.

4.3. An Explanation for Low FIR/Radio Ratios in
High-z SMGs?

A significant fraction of submillimeter galaxies (SMGs)
detected at redshifts between \(2 \lesssim z \lesssim 4\) similarly show
excess (i.e., a factor of \(\geq 3\)) radio emission relative to their
total far-infrared emission and a nominal \(F_{\text{FIR}}/\text{radio}\)
ratios (e.g., Kovács et al. 2006; Valiante et al. 2007;
Capak et al. 2008; Murphy et al. 2009; Daddi et al.
2009; Coppin et al. 2009a; Knudsen et al. 2010; Smolčić et al.
2011). Although, it is worth pointing out that this is not
true for all samples of SMGs at these redshifts (e.g., Chapman et al. 2010). AGN provide
a likely explanation for the excess radio emission in
such sources given that a number are detected in hard
\(2.0 - 8.0 \text{ keV}\) X-rays (Alexander et al. 2005), however, it
is possible that those sources without evidence for
AGN may exhibit excess radio emission associated with
being involved in an ongoing merger.

At such cosmological distances, it is currently un-
clear what fraction of SMGs are major mergers rather
than isolated disks, but the morphologies for a num-
ber of resolved sources seem to suggest major mergers
that are driving intense bursts of star formation (e.g.,
Chapman et al. 2008; Hodge et al. 2013). With the At-
cama Large Millimeter/submillimeter Array (ALMA)
now online, resolving these dusty starbursts into individ-
ual components is becoming easier (e.g., Hezaveh et al.
2013; Hodge et al. 2013). For instance, the lensed star-
forming galaxy SPT-S053816-5030.8, at a redshift of
\(z = 2.783\), has a radio spectrum that appears to flat-
ten (\(\alpha \approx 0.18\)) towards low frequencies, while having
a rather steep (\(\alpha \approx 0.76\)) spectrum at high frequencies
(Aravena et al. 2013), similar to what is seen among the
local compact starbursts investigated here. While the
estimated (rest-frame) \(q_{6.2 \text{GHz}}\) value for this source is
slightly larger than the local average value, consistent
with expectations given the spectral flattening at lower
frequencies assuming optically-thick free-free emission,
the \(q_{6.2 \text{GHz}}\) value is \(\sim 0.36\) dex smaller than the local av-
erage value, implying excess radio emissions per unit star
formation rate.

New imaging at 350 GHz using ALMA along with lens
modeling (Hezaveh et al. 2013) suggests that this SMG
is in fact composed of two galaxies, one of which is a
compact source that dominates the far-infrared emission.
Both the radio continuum properties and 350 GHz mor-
phology suggests that the source is consistent with being
powered by merger-driven star formation as observed in
local (U)LIRGs. Thus, at least for this SMG, excess non-
thermal radio emission associated with the merger may
provide a natural explanation for its steep radio spec-
tral index at high frequencies and presumably excess ra-
dio emission per unit star formation rate relative to nor-
mal star-forming galaxies rather than requiring the need
to invoke cosmic conspiracies (e.g., Lacki & Thompson
2010). Having better multifrequency radio data for a
large number of these high-redshift SMGs, to see if their
spectra is also steep at high frequencies, may help to ex-
plain exactly why this population of starbursting galaxies
appear to have significantly more radio emission per unit
star formation rate than expected.

5. Conclusions

An examination of the radio continuum properties for
a sample of local infrared-bright starbursts has been in-
vestigated against their merger classification. This was
done to shed light on the curious nature of the radio
spectra among such sources, specifically those having
steeper than expected radio spectra observed at frequen-
cies \(\sim 12 \text{ GHz}\) as pointed out by Clemens et al. (2008).
The main conclusions from this investigation can be sum-
marized as follows:

1. Sources categorized as starbursts and AGN via their
\(6.2 \mu \text{m}\) PAH EQWs have similar high-
frequency (\(\nu \sim 12 \text{ GHz}\)) radio spectral indices, sug-
gesting that the steep spectra among some sources
at these frequencies are not the result of radio emis-
sion associated with an AGN.

2. Sources having the steepest radio spectral indices
at \(\sim 12 \text{ GHz}\), while also appearing to be powered
primarily by star formation as indicated by their
\(6.2 \mu \text{m}\) PAH EQWs, appear to be classified as ongo-
ing mergers in which the progenitors are still sepa-
rated and either share a common envelope or show
significant tidal tails in their stellar light. Simi-
larly, these same galaxies also exhibit excess radio
emission relative to what is expected given their
observed far-infrared emission and the tight far-
infrared/radio correlation, suggesting that there is
excess radio emission not associated with ongo-
ing star formation activity. The combination of
these observations leads to a picture in which the
steep high-frequency radio spectral indices and excess radio emission arises from radio continuum bridges and tidal tails in which a new population of relativistic electrons have been accelerated and can radiatively cool producing a steep spectrum. Such a scenario is consistent with high-resolution radio morphologies of the sources as a function of merger stage, as well as the radio spectral index map for the merging galaxy pairs IC 1623 and IRAS F15163+4255.

3. Among all sources whose energetics are thought to be dominated by star formation given their 6.2 μm PAH EQWs, their average radio spectral indices at ~2, 4, and 12 GHz appear to be fairly well fit by a model radio spectrum having a non-thermal radio spectral index of ≈0.83, a 1.4 GHz thermal fraction of ≈5% (corresponding to ≈33% at 30GHz) modified by free-free absorption where the free-free optical depth becomes unity at ≈1GHz.

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