An Initial Look at the Far Infrared-Radio Correlation within Nearby Star-Forming Galaxies Using the Spitzer Space Telescope

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ABSTRACT

We present an initial look at the far-infrared–radio correlation within the star-forming disks of four nearby, nearly face-on galaxies (NGC 2403, NGC 3031, NGC 5194, and NGC 6946). Using Spitzer MIPS imaging, observed as part of the Spitzer Infrared Nearby Galaxies Survey (SINGS), and Westerbork Synthesis Radio Telescope (WSRT) radio continuum data, taken for the WSRT SINGS radio continuum survey, we are able to probe variations in the logarithmic 24 μm/22 cm (q24) and 70 μm/22 cm (q70) surface brightness ratios across each disk at subkiloparsec scales. We find general trends of decreasing q24 and q70 with declining surface brightness and with increasing radius. The residual dispersion around the trend of q24 and q70 versus surface brightness is smaller than the residual dispersion around the trend of q70 versus radius, on average by ~0.1 dex, indicating that the distribution of star formation sites is more important in determining the infrared/radio disk appearance than the exponential profiles of disks. We have also performed preliminary phenomenological modeling of cosmic-ray electron (CR electron) diffusion using an image-smearing technique and find that smoothing the infrared maps improves their correlation with the radio maps. We find that exponential smoothing kernels work marginally better than Gaussian kernels, independent of projection for these nearly face-on galaxies. This result suggests that additional processes besides simple random walk diffusion in three dimensions must affect the evolution of CR electrons. The best-fit smoothing kernels for the two less active star-forming galaxies (NGC 2403 and NGC 3031) have much larger scale lengths than those of the more active star-forming galaxies (NGC 5194 and NGC 6946). This difference may be due to the relative deficit of recent CR electron injection into the interstellar medium for the galaxies that have largely quiescent disks.

Subject headings: cosmic rays — infrared: galaxies — radio continuum: galaxies
Online material: color figures

1. INTRODUCTION

A major result of the Infrared Astronomical Satellite (IRAS; Neugebauer et al. 1984) all-sky survey was the discovery of a correlation between the globally measured far-infrared (FIR; 42–122 μm) dust emission and the optically thin radio continuum emission of normal late-type star-forming galaxies without an active galactic nucleus (AGN; de Jong et al. 1985; Helou et al. 1985). The most remarkable feature of this correlation is that it displays such little scatter, ~0.2 dex, among galaxies spanning 5 orders of magnitude in luminosity. While the FIR emission is due to the thermal reradiation of interstellar starlight by dust grains, the radio emission is primarily nonthermal synchrotron emission from cosmic-ray electrons (CR electrons) that propagate in a galaxy’s magnetic field after initially being accelerated by supernova shocks or other processes. The physics that maintains a strong correlation between these two quantities over such a wide range of galaxies remains unclear.

The connection between radio and infrared emission from galaxies is that they are both powered by massive stars, as pointed out originally for starbursts by Harwit & Pacini (1975). Young massive stars, which heat up dust to provide the bulk of the FIR emission, are thought to be the same stars that end as supernovae (SNe) and bring about the synchrotron emission. Such a simplified picture, however, cannot fully explain the small dispersion measured among galaxies spanning ranges in magnetic field strength, metallicity, interstellar medium (ISM) mass, dust grain chemistry and distributions, and star formation rates (SFRs), which all contribute to the observed FIR/radio ratio of galaxies. In fact, some of these parameters individually have a larger dispersion among galaxies than what is measured for the FIR-radio correlation.

Various physical models for the global FIR-radio correlation have been introduced (e.g., Völk 1989; Helou & Bicay 1993;

If the general picture of the FIR-radio correlation is correct, and massive stars are largely responsible for both the infrared and radio emission from galaxies, the fact that the mean free path of UV photons (~100 pc) that heat the dust is much less than the diffusion length for a CR electron (~1–2 kpc) suggests that the radio image should resemble a smeared version of the infrared image. This idea was first introduced by Bicay & Helou (1990), who attempted to model the propagation of CR electrons by smearing IRAS scan data of galaxies using parameterized kernels containing the physics of the CR electron propagation and diffusion, to better match the morphology of the corresponding radio data. Later work by Marsh & Helou (1998) further tested this model using IRAS HIRES images and found that this prescription worked on large scales across galaxy disks.

In an attempt to better understand the FIR-radio correlation, we use infrared data from Spitzer observations obtained as part of the Spitzer Infrared Nearby Galaxies Survey (SINGS) legacy science project (Kennicutt et al. 2003). These data allow us to probe galaxies with dramatically increased angular resolution and sensitivity compared to past infrared missions, especially at 24 and 70 $\mu$m. Using high-resolution Spitzer imaging, we are also able to test the smearing model of Bicay & Helou (1990) with greater accuracy, at higher spatial resolution, and in more galaxies, with the aim of gaining better insight into CR electron diffusion and confinement within galaxy disks. In this paper we examine the FIR-radio correlation within four of the nearest face-on galaxies in the SINGS sample for which we have acquired both Spitzer MIPS and WSRT radio continuum data: NGC 2403, NGC 3031 (M81), NGC 5194 (M51a), and NGC 6946. These galaxies are quite diverse in their Hubble types and star formation activity, but their distances allow us to probe the correlation on the scale of a few hundred pc within each of their respective star-forming disks (see Table 1).

The paper is organized as follows: In § 2 we describe the observations and data analysis procedures. Then in § 3 we present the empirical results of our work. In § 4 we compare our results within disks to previous results on the global FIR-radio correlation and explore the role of cosmic ray propagation in the local FIR-radio correlation. Finally, in § 5 we provide a brief summary of the paper.

2. OBSERVATIONS AND DATA REDUCTION

2.1. Spitzer Images

Spitzer imaging was carried out for each galaxy using the Multiband Imaging Photometer for Spitzer (MIPS; Rieke et al. 2004) as part of the SINGS legacy science program. Accordingly, a detailed description of the basic observation strategy can be found in Kennicutt et al. (2003), although a few modifications have been made after receiving SINGS validation data on NGC 7331 (e.g., Regan et al. 2004). Note that each target is mapped (or visited) twice so that asteroids and other transient phenomena can be removed from the data if necessary. The MIPS data were processed using the MIPS Data Analysis Tools (DAT) versions 2.80–2.92 (Gordon et al. 2005). Due to residual artifacts such as latent images and background curvature in the 24 $\mu$m data, as well as short-term drifts in the 70 and 160 $\mu$m signals, additional processing beyond that of the standard MIPS DAT was necessary. These exceptions in the standard data processing are listed below.

For the 24 $\mu$m data, a few additional steps were performed on the data. First, the flat-fielding was performed in two steps. Flats dependent on the scan mirror position, created from off-target data in the scan map from all SINGS MIPS campaign data, were first applied to the data. Following this, flats independent of the scan mirror position, made from off-target frames in each visit’s scan map, were applied. Latent images from bright sources, erroneously high or low pixel values, and unusually noisy frames were also masked out before the data were mosaicked together. For the NGC 5194 and NGC 6946 data, mosaics of the data from each visit were made, and then linear backgrounds determined from sky regions outside of the optical disks were subtracted. The two mosaics were then averaged together to produce the final maps. For the NGC 2403 and NGC 3031 data, backgrounds were measured as a function of time in each scan leg and were subtracted before mosaicking. After this background subtraction, the data from both visits were mosaicked to form a single image. The final pixel scale and FWHM of the point-spread
function (PSF) are 0\textdegree 75 and 5\textdegree 77, respectively. The calibration factor applied to the final mosaic has an uncertainty of \(~\sim\)10\%, and the rms noise for the raw map is listed in Table 2 for each galaxy.

For the 70 and 160 \(\mu\)m data, the major addition to the processing beyond the standard MIPS DAT steps was the subtraction of short-term variations from a residual detector background drift. This step also removes the sky background emission. The region that includes the galaxy is excluded from the drift determination, so no extended emission is subtracted. The data from both visits were then used to make one mosaic, and a residual offset measured in regions around the target was subtracted from the maps. Some bright sources in the 70 \(\mu\)m data created negative latent images that appeared as dark streaks in the data. As an artifact of the background subtraction, bright and dark streaks appeared on opposite sides of these bright sources. These streaks, while visible in the images, are at a relatively low signal level and should not significantly affect the analysis. The final pixel scales are 3\textquoteleft 0 and 6\textquoteleft 0, and the FWHM of the PSFs are 17\textquoteleft 0 and 38\textquoteleft 0 at 70 and 160 \(\mu\)m, respectively. The calibration factors applied to the final mosaics have uncertainties of \(~\sim\)20\% for each band, and the rms noise for the raw 70 and 160 \(\mu\)m maps is listed in Table 2 for each galaxy.

While the calibration uncertainties do have a systematic effect on the measured flux ratios, they do not cause artificial trends as a function of signal strength. In contrast, the rms noise contributes to uncertainties in flux ratios as a function of surface brightness, possibly causing low-level artificial trends in the data. Accordingly, we only use pixels that have a signal at least 3 \(\sigma\) above the rms noise in our analysis to minimize these types of effects.

### 2.2. Radio Continuum Images

Radio continuum images at 22 and 18 cm were obtained using the Westerbork Synthesis Radio Telescope (WSRT). Each target was observed for a 12 hr integration in the “maxi-short” array configuration, which has particularly good sampling of short baselines (east-west baselines of 36, 54, 72 and 90 m are all measured simultaneously), as well as a longest baseline of about 2700 m. The target observations were bracketed by observations of the primary total intensity and polarization calibration sources 3C 147 and 3C 286, yielding an absolute flux density calibration accuracy of better than 5\%. The observing frequency was switched every 5 minutes between two settings (1366 and 1697 MHz). Each frequency setting was covered with eight subbands of 20 MHz nominal width spaced by 16 MHz to provide contiguous, non-attenuated coverage with a total bandwidth of 132 MHz. An effective integration time of 6 hr was realized at each frequency setting. All four polarization products and 64 spectral channels were obtained in each subband. After careful editing of incidental radio frequency interference, external total intensity and polarization calibration of the data was performed in the AIPS package. Subsequently, each field was self-calibrated using an imaging pipeline based on the MIRIAD package. Each of the eight subbands for a given frequency setting was first processed and imaged independently, and these were subsequently combined with an inverse variance weighting. Deconvolution of each subband image was performed iteratively within a threshold mask based on a spatial smoothing of the previous iteration. The individual frequency channels (of 312.5 kHz width) were gridded during imaging, so bandwidth smearing effects were negligible. In this way, a more smoothly good reconstruction of the brightness distribution was obtained for each target. The total detected flux density (scaled to a common reference frequency of 1365 MHz) was 460, 610, 1410, and 1690 mJy for NGC 2403, NGC 3031, NGC 5194, and NGC 6946, respectively. Although all of these values either agree with or slightly exceed current estimates in the literature (387, 624, 1310, and 1432 mJy; White & Becker 1992), they must still be regarded as lower limits, since the brightness distribution declines so smoothly into the noise floor. A more complete description of the processing steps will appear in R. Braun et al. (2006, in preparation).

Each final subband image was reprocessed to obtain a new output PSF, by first dividing the image fast Fourier transform (FFT) with the FFT of the Gaussian CLEAN restoring beam and then convolving the result with a model of the MIPS 70 \(\mu\)m beam to permit an accurate joint analysis with the MIPS data. The intrinsic FWHM of the radio beams is about 11\textquoteleft 0 east-west by 11\textquoteleft 0/sin \(\delta\) north-south at 1400 MHz and scales as the inverse of frequency, where \(\delta\) is the source declination. This was in all cases smaller than the MIPS 70 \(\mu\)m beam. Accordingly, the MIPS 70 \(\mu\)m beam sets the spatial resolution for the present study.

As the frequency difference between the 22 and 18 cm emission is rather small, with both wavelengths dominated by synchrotron emission, we consider only the 22 cm data for the infrared-radio analysis presented in this paper, since the signal-to-noise ratio at 22 cm was generally higher than that at 18 cm. The only exception is NGC 3031, for which a 20 cm map was created via a variance-weighted average of both the 22 and 18 cm data. This was done in order to obtain good image quality for this very challenging field, which has complications due to the low extended surface brightness disk of NGC 3031, as well as calibration and confusion problems due to the nearby starburst galaxy NGC 3034 (M82). To allow for proper comparison with the 22 cm data, we scaled the 20 cm flux density to what is expected at 22 cm when assuming a mean spectral index of \(~\sim\)0.7. The rms noise is given in Table 2 for each galaxy.

The expected number density of background radio sources detectable at the 5 \(\sigma\) level in our radio maps is \(~\sim\)0.17 arcminute\(^{-2}\) (Hopkins et al. 2003). This number translates into \(~\sim\)15 over the average area of a galaxy disk studied in this paper. These background radio sources fall into two categories: galaxies that are primarily star-forming, and those that are dominated by an AGN.

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>160 (\mu)m (MJy sr(^{-1}))</th>
<th>70 (\mu)m (MJy sr(^{-1}))</th>
<th>24 (\mu)m (MJy sr(^{-1}))</th>
<th>24 (\mu)m(^{a}) (MJy sr(^{-1}))</th>
<th>22 cm ((\mu)Jy beam(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 2403</td>
<td>0.61</td>
<td>0.35</td>
<td>0.044</td>
<td>0.0085</td>
<td>26</td>
</tr>
<tr>
<td>NGC 3031</td>
<td>0.96</td>
<td>0.37</td>
<td>0.042</td>
<td>0.011</td>
<td>24(^{a})</td>
</tr>
<tr>
<td>NGC 5194</td>
<td>0.94</td>
<td>0.43</td>
<td>0.044</td>
<td>0.019</td>
<td>29</td>
</tr>
<tr>
<td>NGC 6946</td>
<td>1.4</td>
<td>0.58</td>
<td>0.068</td>
<td>0.029</td>
<td>37</td>
</tr>
</tbody>
</table>

\(^{a}\) This 24 \(\mu\)m map was convolved to match the 70 \(\mu\)m PSF.

\(^{b}\) This rms measurement was based on a 20 cm radio map.

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**TABLE 2**  
**rms Noise of Spitzer Infrared and WSRT Radio Maps**

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>160 (\mu)m (MJy sr(^{-1}))</th>
<th>70 (\mu)m (MJy sr(^{-1}))</th>
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At flux densities $\gtrsim 3$ mJy, AGNs dominate the radio source counts at 20 cm and are expected to be found at a frequency of $\sim 1$ per the average area of the sample galaxies (Becker et al. 1995). Such sources can often be distinguished by their characteristic (double or triple) morphologies and much higher surface brightnesses compared to a galaxy’s diffuse radio disk. At lower flux densities, star-forming galaxies dominate the counts. As such, they may introduce some additional scatter into our flux ratios, but are unlikely to lead to a systematic bias since they affect $\sim 4\%$ of the total area analyzed within each galaxy. Accordingly, we do not expect significant contamination of our analysis by background sources, but in general, very deep, high-resolution radio or FIR imaging would be required to determine if any particular deviation from a constant FIR/radio ratio were due to a confusing background source.

2.3. Image Registration and Resolution Matching

In the following analysis, we focus on the 24 and 70 $\mu$m Spitzer MIPS data, since they have angular resolutions better than or similar to our WSRT radio data. The calibrated MIPS and radio continuum images for each galaxy underwent a preanalysis procedure to ensure that the different PSFs and sampling at each wavelength did not introduce artifacts into our results. Each image was first sky-subtracted using a variance-weighted mean calculated from regions surrounding the galaxy. The images at different wavelengths were then cropped to a common field of view and regridded to a pixel scale of 3$''$.

The MIPS 24 $\mu$m images were then convolved to match the 70 $\mu$m beam using custom smoothing kernels. The convolution kernels convert an input PSF into a lower resolution output PSF using the ratio of Fourier transforms of the output to input PSFs. As part of the creation of these kernels, the high-frequency noise in the input PSF is suppressed (for details, see K. D. Gordon et al. 2006, in preparation). The resulting 70 and 24 $\mu$m maps are displayed in the second and third columns of Figure 1, respectively, and the rms noise of the convolved 24 $\mu$m maps is listed in Table 2. The final radio maps, which have beams matched to the MIPS 70 $\mu$m PSF (see § 2.2.), are displayed in the first column of Figure 1. Finally, we cross-correlated the radio and MIPS images to measure and remove any existing MIPS position offsets.

After the above image registration and PSF matching was carried out, we constructed logarithmic infrared/radio ratio ($q$) maps, where

$$q_{\lambda} (\mu m) \equiv \log \left[ \frac{f_{\lambda}(\lambda) \text{ (Jy)}}{f_{\lambda}(22 \text{ cm}) \text{ (Jy)}} \right], \quad (1)$$

for $\lambda = 24$ and 70 $\mu$m. The only exception, as mentioned in § 2.2, is the case of NGC 3031, where a 20 cm radio continuum map was used. The $q_{70}$ and $q_{24}$ maps for each galaxy are displayed in the fourth and fifth columns, respectively, of Figure 1, for pixels that have $>3\sigma$ detections in each of the infrared and radio images.

We tested to ensure that using the monochromatic 70 $\mu$m emission does not significantly affect conclusions drawn about the FIR-radio correlation by comparing $q_{\text{FIR}}$ and $q_{\lambda}$ maps at matching resolutions. In order to do this we performed the same preanalysis procedure described above to properly match the radio continuum and the 24 and 70 $\mu$m images to the resolution and pixel scale at 160 $\mu$m. We then constructed a total infrared (3–1100 $\mu$m) map using equation (4) from Dale & Helou (2002) and estimated the FIR fraction using the same Dale & Helou (2002) spectral energy distribution (SED) models for pixels with $>3\sigma$ detections in each MIPS band. Finally, we constructed the logarithmic FIR/radio ratio map following the convention of Helou et al. (1985), such that

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

for pixels that are also detected above the 3 $\sigma$ level in the radio continuum image. The 160 $\mu$m, FIR, and $q_{\text{FIR}}$ maps for each galaxy are presented in the left, middle, and right columns, respectively, of Figure 2. Results comparing the behavior of the monochromatic $q_\lambda$ ratios with the $q_{\text{FIR}}$ ratios at matching resolutions are presented in § 3.1.

2.4. Aperture Photometry

To probe the variations that exist within each galaxy, we compare the $q_\lambda$ values that differentiate, to the extent possible, the nuclear, arm, interarm, disk, inner disk, and outer disk environments. This procedure is carried out over “critical” apertures, defined by diameters equal to the FWHM of the PSF. Critical apertures of a given angular extent naturally correspond to different projected physical scales for galaxies at different distances. If we assume distances to each galaxy as given in Table 1, the FWHM of the 70 $\mu$m beam corresponds to critical apertures of $\sim 0.3$, $0.3$, $0.5$, and $0.75$ kpc for NGC 2403, NGC 3031, NGC 6946, and NGC 5194, respectively.

Aperture masks were created using the 24 $\mu$m images in their native resolution. The different regions are defined as follows. Nuclear regions are the bright central point in the galaxy, co-spatial in both the infrared and radio maps (except for NGC 2403, where the nucleus was not identifiable). Arm regions trace the spiral arms and are centered on individual giant H II regions where possible, but also contain the observed emission between discrete star-forming regions within each arm. Interarm regions probe the more quiescent areas between spiral arms. Inner disk regions are circumnuclear regions ($r \lesssim 5$ kpc) that are both bright and not clearly associated with any large coherent structures, such as an inner ring of spiral arms. We define the star-forming disk to contain all obvious star formation sites visible in the 24 $\mu$m images. Disk regions are areas within the star-forming disk that are both diffuse and not clearly associated with any type of coherent structures. Outer disk regions are identified as areas of diffuse emission surrounding the star-forming disk. Our aperture masks for each galaxy are illustrated in Figure 3. Results of the aperture photometry are discussed in § 3, and a summary of statistical results, including the mean ($\langle q_\lambda \rangle$) and dispersion ($\sigma_\lambda$) of the measured logarithmic infrared/radio ratios for each galaxy, is presented in Table 3.

3. RESULTS

3.1. Infrared/Radio Maps

An inspection of the $q_\lambda$ maps, presented in the fourth and fifth columns of Figure 1, reveals structure in the ratio images corresponding to the patterns of star formation in each galaxy disk. We also find that all galaxies have dynamic ranges in $q_{70}$ and $q_{24}$, each spanning $\gtrsim 1$ dex. For comparison, previous studies of the FIR/radio ratios within NGC 3031 (M81) showed variations by a factor of 6, excluding its AGN (Gordon et al. 2004), and by an order of magnitude within M31 (Hoernes et al. 1998).

By comparing our $q_{\text{FIR}}$ maps in Figure 2 with the $q_{70}$ and $q_{24}$ maps in Figure 1, we find that the morphologies and associated trends are generally similar. Quantitatively, we compare the dispersions in $q_{\text{FIR}}$ ($\sigma_{\text{FIR}}$), $q_{70}$ ($\sigma_{70}$), and $q_{24}$ ($\sigma_{24}$) across each disk using projected 1.5 kpc diameter apertures. If we look at the
Fig. 1.—From left to right for each galaxy: a 22 cm radio map (except in the case of NGC 3031, for which a 20 cm radio map is plotted), a 70 $\mu$m map, a 24 $\mu$m map (matched to the 70 $\mu$m resolution), a map of $q_{70}$ for pixels with 3 $\sigma$ detections in both the input radio and 70 $\mu$m maps, and a map of $q_{24}$ for pixels with 3 $\sigma$ detections in both the input radio and 24 $\mu$m maps. The units of the radio maps are in units of log (Jy beam$^{-1}$), and the infrared maps are in units of log (MJy sr$^{-1}$). All maps are displayed with a stretch ranging from the rms background level to the maximum surface brightness in the galaxy disk. In the radio map of NGC 3031, estimation of the maximum surface brightness excluded its AGN and SN 1993J, located in the arm south of the nucleus. Note that H II regions and spiral arms are visible in the $q_{24}$ maps, indicating that they have an excess of infrared emission relative to radio continuum emission. [See the electronic edition of the Journal for a color version of this figure.]
computed dispersion for each disk in Table 4, we find that the scatter generally decreases when using 70 $\mu$m data as opposed to the 24 $\mu$m data and is lowest in all cases when using the estimated FIR emission. This suggests that the correlation between the radio and FIR emission within each galaxy is tighter than the correlation between the radio and either of the monochromatic 70 or 24 $\mu$m emission bands. However, since the dispersion in $q_{70}$ is only $\sim$0.03 dex larger than the dispersion in $q_{\text{FIR}}$, we perform our analysis at our best common resolution between the infrared and radio data (i.e., at the 70 $\mu$m resolution), since the

![Images of galaxy maps](https://example.com/galaxy_maps.png)
area of the beam is a factor of \( \sim 4 \) smaller than at the resolution of the 160 \( \mu m \) data.

We find elevated infrared/radio ratios at 70 and 24 \( \mu m \) associated with bright structures appearing in the input infrared and radio images of each galaxy. The most obvious case is seen for the bright spiral arms of NGC 3031, NGC 5194, and NGC 6946. The spiral structure in all three of these galaxies is visible in their infrared/radio ratio maps, which show enhanced values along the arms with local peaks centered on H\( \pi \) regions and depressed ratios located in the quiescent interarm and outer disk regions of each galaxy. For NGC 2403, which does not have a grand-design spiral morphology, we still see peaks in \( q_{70} \) and \( q_{24} \) that are associated with H\( \pi \) regions.

While the peaks in the \( q_{24} \) and \( q_{70} \) maps appear spatially coincident, there is a slight difference in their morphologies. Even after degrading the resolution of the 24 \( \mu m \) maps to match the PSF at 70 \( \mu m \), the corresponding \( q_{24} \) maps display a more compact morphology around star-forming regions within each galaxy. This observation is expected, since 24 \( \mu m \) emission traces hotter dust than emission at 70 \( \mu m \) and is therefore more localized around active star-forming regions. In comparing the \( q_{24} \) and \( q_{70} \) maps for NGC 3031, NGC 5194, and NGC 6946, we find that the spiral arms in each galaxy appear less broad and have more strongly peaked H\( \pi \) regions in the \( q_{24} \) maps compared to those in the \( q_{70} \) maps. We find a similar result for the bright H\( \pi \) regions in NGC 2403. These observations are consistent with recent Spitzer results by Helou et al. (2004), who report the 24 \( \mu m \) emission to be strongly peaked in star-forming regions within NGC 300 and consequently suggest that emission at 24 \( \mu m \) is an intimate tracer of ongoing star formation.

Fig. 3.—Aperture masks plotted on 24 \( \mu m \) images of each galaxy, using critical apertures defined with diameters equal to the FWHM of the 70 \( \mu m \) PSF (\( \sim 17'' \)). (The color scheme used in the electronic edition is as follows: nucleus, cyan; inner disk, red; disk, magenta; outer disk, yellow; arm, blue; and interarm, green.) See § 2.4 for more details about the aperture definitions. [See the electronic edition of the Journal for a color version of this figure.]
3.2. Infrared/Radio Ratios versus Infrared Surface Brightness

In order to see how the $q_4$ ratios vary with the strength of infrared surface brightness within each galaxy, we produced scatter plots using the infrared and radio flux densities extracted from our aperture photometry scheme described in § 2.4. Since the measuring apertures are equal in diameter for each galaxy, the measured flux densities are directly proportional to the surface brightnesses. These results are illustrated for both $q_{70}$ and $q_{24}$ in Figures 4 and 5, respectively. As these plots have naturally correlated axes, we overplotted the relation expected if the radio disk were completely flat in brightness across the entire galaxy.

In Figures 4 and 5, we see a general trend of increasing infrared/radio ratios with increasing infrared surface brightness. The slopes of the regression lines within the scatter plots are significantly lower (by a factor of $\approx 2$) than what would be expected for a radio disk characterized by a constant surface brightness. This nonlinearity of increasing infrared/radio ratio with increasing infrared surface brightness within galaxies has been observed by other authors (Marsh & Helou 1995; Hoernes et al. 1998; Hippelein et al. 2003) and is opposite to the nonlinearity observed in the global FIR-radio correlation, in which the radio power of galaxies increases faster than the infrared luminosity (Fitt et al. 1988; Cox et al. 1988; Condon et al. 1991). The concern that this nonlinearity may be a color effect is unwarranted, since the gradient in the color correction $\text{FIR}/f_v(10\mu m)$ would have to be $\approx 5$ times steeper than what is observed to eliminate this trend. The measured dispersion in $q_{70}$ and $q_{24}$ is $\approx 0.25$ dex for each galaxy (see Table 3), which is only slightly larger than the nominal dispersion of 0.2 dex measured in the global FIR-radio correlation for late-type star-forming galaxies that do not host powerful AGNs (Helou et al. 1985). Our measured dispersion, however, is in agreement with what was found by Yun et al. (2001), who used a much larger sample of galaxies spanning a wider range of parameters than prior IRAS-based efforts.

In comparing Figures 4 and 5 for each galaxy, we find that the dispersion in $q_{24}$ is a bit larger than what is found for $q_{70}$, except in the case of NGC 3031. However, if we look at the dispersion about each regression line, we find the dispersion in $q_{24}$ to be generally smaller than what is found for $q_{70}$.

3.3. Environmental Trends

In all galaxies, there are clear differences in the $q_4$ values among the different galaxy disk environments. The different environments are well separated in Figures 4 and 5 and tend to clump along the regression lines in these figures due to their relative surface brightnesses. The measured dispersion for each environment appears to scale with the range of star formation activity within it. We also find that in the galaxies with a well-defined infrared nucleus, the infrared/radio ratios of the nuclei do not fall along the regression line, as seen in Figures 4 and 5. In NGC 3031 we find that the nuclear $q_{70}$ and $q_{24}$ ratios lie $\approx 1.7$ and $\approx 1.2$ dex, respectively, below what is expected from the fitted regression line. We also find that the circumnuclear regions of NGC 3031 display a trend of decreasing infrared/radio ratios with increasing infrared

### Table 3

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Nucleus</th>
<th>Inner Disk</th>
<th>Disk</th>
<th>Outer Disk</th>
<th>Arm</th>
<th>Interarm</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q_{70}$</td>
<td></td>
<td>0.21</td>
<td>0.17</td>
<td>0.15</td>
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<table>
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<th>$\sigma_{70}$</th>
<th>$\sigma_{\text{FIR}}$</th>
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<tr>
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<tr>
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<td>0.16</td>
</tr>
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</tr>
<tr>
<td>NGC 6946</td>
<td>0.18</td>
<td>0.14</td>
<td>0.12</td>
</tr>
</tbody>
</table>

Note.—Dispersions ($\sigma$) were calculated for $q_{24}$, $q_{70}$, and $q_{\text{FIR}}$ within each galaxy disk, using apertures with projected diameters of 1.5 kpc.

---

**TABLE 3**

**Aperture Photometry Statistics for Galaxy Regions**

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<thead>
<tr>
<th>Parameter</th>
<th>Nucleus</th>
<th>Inner Disk</th>
<th>Disk</th>
<th>Outer Disk</th>
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<table>
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<tr>
<th>Galaxy</th>
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<tr>
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<td>0.15</td>
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<td>NGC 3031</td>
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<td>0.16</td>
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<tr>
<td>NGC 5194</td>
<td>0.16</td>
<td>0.12</td>
<td>0.11</td>
</tr>
<tr>
<td>NGC 6946</td>
<td>0.18</td>
<td>0.14</td>
<td>0.12</td>
</tr>
</tbody>
</table>
surface brightness. As the nucleus of NGC 3031 is known to host an AGN, this result is expected. The nucleus of NGC 5194 is categorized as an H ii/Seyfert 2, and accordingly we find that the associated $q_{70}$ and $q_{24}$ ratios lie below the expectation of the regression line by 0.3 dex. The nuclear $q_{70}$ and $q_{24}$ ratios in NGC 6946 lie below the regression line expectation by 0.4 dex, even though NGC 6946 is not known to host an AGN, which would provide extra radio emission.

3.4. Radial Trends

We identify any radial trends that might exist for $q_{70}$ and $q_{24}$ in Figures 6 and 7, respectively. For each galaxy in our sample, there is an obvious trend of decreasing $q_{70}$ and $q_{24}$ ratios with increasing galactocentric radius. A similar trend was also found by Bica & Helou (1990), who, using IRAS scan data, observed a decrease in 60 $\mu$m/20 cm ratios with increasing radius. This result can be characterized by smaller scale lengths for the infrared disks than the radio disks.

What we find in Figures 6 and 7 is a slight trend of increasing dispersion in the infrared/radio ratios with radius. The only exceptions are for NGC 2403 at 24 $\mu$m and NGC 3031, in which the dispersion is large in the circumnuclear region due to a combination of the central AGN and the non-Gaussian MIPS PSF. We also note that NGC 3031 displays anomalously low infrared/radio ratios for a few apertures at a radius of ~4 kpc because of SN 1993J. This trend of increasing dispersion in $q_{70}$ and $q_{24}$ with radius does not seem to be an artifact of lower signal-to-noise ratios at larger radii, as the general appearance of Figures 6 and 7 persists even when we increase the detection threshold from 3 $\sigma$ to 6 $\sigma$. We also find that the dispersion in $q_{70}$ and $q_{24}$ at constant radius is much larger than that at constant surface brightness. To quantify this, we computed the dispersion in 1 kpc and 1.5 Jy bins about the median radius and flux density, respectively, and find that the dispersion in $q_{70}$ and $q_{24}$ at constant radius is much larger than that at constant surface brightness. By moving farther out radially into the disks of galaxies, two effects occur. There is a general drop in the disk surface brightness coupled with a drop in the H ii region density. These two effects likely drive the increase in scatter for the $q_{70}$ and $q_{24}$ ratios with radius and is the reason that there is a more firm correlation between the infrared/radio ratio and surface brightness than with radius. This suggests that the distribution of star formation sites within the disk is more important in determining the overall appearance of the infrared/radio disk maps than the underlying
4. DISCUSSION

4.1. Infrared/Radio Relations inside and among Galaxies

The goal of this study is to improve our understanding of the physical processes governing the FIR-radio correlation. Accordingly, we compare the results of global FIR-radio studies with local (/C24 kiloparsec scale) FIR-radio studies. Identifying similarities and differences in the observed trends between local and global studies can help to constrain the physical scales and the associated processes responsible for the FIR-radio correlation.

4.1.1. Relating IRAS q60 to Spitzer q70

Since most of the previous work on the FIR-radio correlation has been done using IRAS data, we had to convert the IRAS 60 μm flux densities to the nearby Spitzer 70 μm flux densities for comparison. In order to convert IRAS 60 μm to Spitzer 70 μm flux densities, we used the IRAS 60 μm/100 μm flux density ratios along with the SED models of Dale & Helou (2002). The models allow for IRAS 60 μm/100 μm flux density ratios in the range from 0.2847 to 1.635, which correspond to a range in Spitzer 70 μm/IRAS 60 μm flux density ratios between 0.9585 and 1.568. This relation between Spitzer f(70 μm) and IRAS f(60 μm) and f(100 μm) flux densities is approximated by

\[
\frac{f(70 \ \mu m)}{f(100 \ \mu m)} = \left\{ \begin{array}{c}
\frac{\sum_{i=0}^{3} \xi_i}{f(100 \ \mu m)} \left[ \frac{f(60 \ \mu m)}{f(100 \ \mu m)} \right]^i, 
\text{if } 0.3044 \leq \frac{f(60 \ \mu m)}{f(100 \ \mu m)} \leq 1.635, \\
1.532 f(60 \ \mu m), 
\text{if } 0.2847 \leq \frac{f(60 \ \mu m)}{f(100 \ \mu m)} < 0.3044,
\end{array} \right.
\]

where (ξ0, ξ1, ξ2, ξ3) = (1.976, -1.582, 0.9632, -0.2308). We derived these coefficients using a singular value decomposition solution to an overdetermined set of linear equations, as described in § 15.4 of Press et al. (2002).

4.1.2. Comparison with Global Infrared/Radio Ratios

For a comparison of our results to previous global FIR-radio correlation data, we made use of IRAS and NRAO VLA Sky Survey (NVSS; Condon et al. 1998) data collected for a sample of 1809 galaxies by Yun et al. (2001). Of these 1809 galaxies, 1752 had IRAS 60 μm/100 μm flux density ratios that were compatible with the range of Dale & Helou (2002) SED models, and for this subsample we converted the observed IRAS 60 μm flux densities into estimated Spitzer 70 μm flux densities (see § 4.1.1). Using

![Fig. 5.—Same as Fig. 4, but for q24 as a function of the 24 μm flux density. [See the electronic edition of the Journal for a color version of this figure.]](image-url)
the 1.4 GHz NVSS data and estimated distances to the sources (Yun et al. 2001), we plot global infrared/radio ratios along with our local infrared/radio ratios for 1.5 kpc diameter apertures versus luminosity in Figure 8 (top). Although the NVSS is a snapshot survey and is therefore prone to miss extended emission from galaxies that have large angular extents, Yun et al. (2001) pay proper attention to these effects and derive unbiased 1.4 GHz fluxes. It should be noted that this sample, however, has been found to contain both confused IRAS measurements and AGNs missed by automated procedures, which are not expected to obey the FIR-radio correlation. We also compare our $q_{24}$ results within galaxies to global $q_{24}$ ratios from data obtained as part of the Spitzer First Look Survey (FLS) in Figure 8 (bottom). A total of 179 sources are plotted using 24 μm and Very Large Array (VLA) 1.4 GHz measurements that have k-corrected using an SED-fitting method as described in Appleton et al. (2004). Objects that have a $q_{24}$ value well below 0 are likely to be galaxies hosting an AGN and are not expected to follow any correlation found in our aperture work within galaxies.

In Table 5 we list the means and standard deviations of $q_{70}$ and $q_{24}$ found within and among galaxies, as well as the number of measurements used to calculate each. In this comparison we present all data points, including the few outliers in each sample. For our four sample galaxies, the local dispersions in $q_{24}$ and $q_{70}$ are nearly identical. The dispersion in the ~kiloparsec-scale $q_{70}$ ratios is comparable to what is measured globally, but the dispersion in the global $q_{24}$ ratios is 0.13 dex higher than what is measured within galaxies. This increase in dispersion may be due to sample selection, as the FLS contains galaxies at $z \approx 1$, while the Yun et al. (2001) sample contains objects only up to $z \approx 0.15$. Samples at higher redshifts likely include a larger number of AGNs and perhaps less evolved galaxy disks compared to samples limited to lower redshifts, and both effects may increase the dispersion.

In both panels of Figure 8, the global infrared/radio ratios of our sample galaxies appear to be slightly higher than the median of the corresponding local kiloparsec-scale values. This offset is not statistically significant, as the global value is never greater than the median by more than 1 σ, and is likely due to the bluest regions in galaxies contributing a large fraction of the global flux. What clearly appears as a significant difference between the local and global infrared/radio ratios is the behavior of $q_{k}$ versus increasing luminosity. In both the FLS and Yun et al. (2001) samples the infrared/radio ratios are roughly constant with increasing galaxy luminosity, while within each disk, the infrared/radio ratios clearly increase with luminosity. We will see in § 4.2.2 that the difference in $q_{k}$ versus luminosity within and among galaxies is likely due to the diffusion of CR electrons within the galaxy disks. Although we do not see a strong nonlinearity in either sample of global infrared/radio ratios, we note that a nonlinearity...
in the global FIR-radio correlation is known to exist. However, this trend in global FIR/radio ratios is the opposite of what we find on kiloparsec scales within galaxies, which is that galaxies with low FIR luminosities have radio luminosities lower than those expected from a linear fit to the correlation (Fitt et al. 1988; Cox et al. 1988; Condon et al. 1991).

4.2. Cosmic Ray Diffusion

4.2.1. Image-Smearing Model Technique

The phenomenological image-smearing model of Bicay & Helou (1990) predicts that the radio morphology of a galaxy can be reproduced by convolving the FIR image with a specific smearing kernel, $\kappa(r)$, containing the diffusion information of the galaxy’s cosmic-ray electrons. As previous work relied on IRAS maps made using the maximum correlation method (MCM), described by Aumann et al. (1990), to achieve the “super-resolution” of $\lesssim 1''$ (i.e., Marsh & Helou 1998), it is worth repeating this analysis using the current Spitzer maps obtained at the natural resolution of the instruments. We performed a simple image-smearing analysis for both the Spitzer 24 and 70 $\mu$m data and look for a preference among Gaussian and exponential smearing kernels projected either in the plane of the sky or in the plane of the galactic disk. The choice of Gaussian and exponential kernels are due to their differences in describing the diffusion and confinement characteristics of CR electrons. Gaussian kernels suggest a simple random walk diffusion scenario for CR electrons in each disk. Exponential kernels, which have broader tails than Gaussian kernels of the same scale length, are suggestive of CR electron escape on timescales less than or comparable to the diffusion timescales and correspond to empirical “leaky box” models (Bicay & Helou 1990).

The kernel, $\kappa(r)$, is a function of a two-dimensional angular position vector $r$ with magnitude $r = (x^2 + y^2)^{1/2}$, where $x$ and $y$ are the right ascension and declination offsets on the sky. Let $R(r)$ and $I(r)$ denote the observed radio and infrared images, respectively. Let us denote the type of function and projection of the parameterized kernel by the subscripts $t$ and $p$, such that Gaussian ($G$) and exponential ($e$) kernels projected in the plane of the galaxy ($g$), $\kappa(r)_{t,g}$, take the form of $\kappa(r)_{G,g} = e^{-r^2/r_0^2}$ and $\kappa(r)_{e,g} = e^{-r/r_0}$, respectively, where

$$r_0 = \frac{l \cos i}{\sqrt{1 - (x \sin \theta + y \cos \theta)^2 \sin^2 i/r^2}^{1/2}}. \tag{4}$$

The quantity $i$ is the inclination, where $i = 0$ defines a face-on projection, $\theta$ is the position angle of the tilt axis of the galactic disk measured east of north, and $l$ is the $e$-folding length of the smearing kernel. When the kernels are oriented in the plane of

![Fig. 7.—Same as Fig. 6, but for $q_{24}$. [See the electronic edition of the Journal for a color version of this figure.]](image-url)
Fig. 8.—Top: 1.5 kpc aperture $q_{70}$ ratios for each sample galaxy, plotted with global $q_{70}$ ratios estimated for the Yun et al. (2001) sample (see § 4.1.1). Bottom: 1.5 kpc aperture $q_{24}$ ratios for each sample galaxy, plotted with global $q_{24}$ ratios for the Spitzer FLS sample (Appleton et al. 2004). In both panels the nuclear and global $q_i$ values for each of the four sample galaxies are identified by large diamonds and triangles, respectively. Note that a nuclear aperture was not defined for NGC 2403. [See the electronic edition of the Journal for a color version of this figure.]
the sky \((s)\), denoted as \(k(r)_{i,s}\), both \(i\) and \(s\) are equal to 0, which sets \(r_0 = l\). We define the quantity

\[
\phi(Q, t, p, l) = \log \left( \frac{\left( \sum Q^{-1} I_j(t, p, l) - \sum R_j \right)^2}{\sum R^2_j} \right),
\]

where \(Q = \sum \tilde{I}_j(r) / \sum R_j(r)\) is used as a normalization factor [i.e., \(\log Q = \log_2(\text{global})\)]. \(\tilde{I}_j(t, p, l)\) represents the infrared image after smearing with a kernel of type \((t, p)\) and with scale length \(l\), and the subscript \(j\) indexes each pixel. This quantity \(\phi\) was minimized to determine the best-fit smearing kernel for each galaxy in our sample. We normalize by the squared sum of radio flux density to allow for proper comparison of our galaxies, which vary in intrinsic surface brightness. Estimation of the residuals was carried out after first removing pixels not detected at the 3 \(\sigma\) level and then editing out identifiable contaminating background radio sources and SNe. Because the AGN nucleus of NGC 3031 is also identifiable in the infrared images, it was removed before smearing the infrared images and in the calculation of the residuals. In the case of NGC 5194, its companion galaxy (NGC 5195) was removed before calculating the residuals. We find the best-fit kernel by determining the minimum in \(\log \phi\) as a function of smearing scale length \(l\), as shown in Figures 9 and 10. The quantity

\[
\Phi = \log \left( \frac{\phi(Q, t, p, 0)}{\min(\phi(Q, t, p, l))} \right),
\]

which is the maximum depth of each residual trough, is a measure of how much the correlation is improved by smoothing the infrared image.

Because \(\phi\) and \(\Phi\) characterize the residual behavior for the entire galaxy as single quantities, we also constructed residual maps for the best-fit smearing kernels to inspect the spatial variations of the residuals. The residual image is defined as

\[
\text{residual image} = \log \left( Q^{-1} \tilde{I}(r) - \log(R(r)) \right).
\]

In Figures 11 and 12 we plot residual maps for the best-fit exponential kernels oriented in the plane of the sky for the 70 and 24 \(\mu\text{m}\) data, respectively.

<table>
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<th>Type</th>
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<th>(\sigma_{70})</th>
<th>(N_{70})</th>
<th>(q_{24})</th>
<th>(\sigma_{24})</th>
<th>(N_{24})</th>
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<td>179</td>
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<tr>
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<td>0.95</td>
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<td>282</td>
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</table>

Notes.—Statistics within galaxies, using apertures of 1.5 kpc in diameter. The global 70 \(\mu\text{m}\) data were taken from the Yun et al. (2001) sample, and the global 24 \(\mu\text{m}\) data were taken from the Spitzer FLS sample (Appleton et al. 2004). All data points, including outliers, were used in calculating these statistics for each set of data.
If we make the assumption that propagation of CR electrons is symmetric in the plane of the sky, we can crudely attempt to measure the CR electron diffusion length within each galaxy disk. The infrared images, $I(r)$, might be considered a “smeared” version of the distribution of the original sources of infrared luminosity. They are “smeared” due to both the heating of dust by UV photons, which have a scale length $l_{	ext{UV}}$ some hundreds of pc away from their originating sources, and the angular resolution of the telescope, which has a beam width $l_{\text{beam}}$. Accordingly, the infrared image, $\tilde{I}(r)$, artificially smeared by a kernel with a scale length $l$, has an effective scale length of $l_{\tilde{I}}$, such that

$$l_{\tilde{I}}^2 = l_{\text{beam}}^2 + l_{	ext{UV}}^2 + l^2.$$  \hfill (8)

The radio images are initially “smeared” by both the angular resolution of the telescope and the propagation of CR electrons, which has a scale length of $l_{\text{CRE}}$, such that the total scale length of the radio continuum image, $l_R$ is approximated by

$$l_R^2 = l_{\text{beam}}^2 + l_{\text{CRE}}^2.$$  \hfill (9)

Assuming that the smearing model holds, we set $l_R^2 = l_I^2$ and find a general relation between the scale length of the smearing kernel and the scale lengths of the UV-heating photons and CR electrons such that

$$l^2 = l_{\text{CRE}}^2 - l_{\text{UV}}^2.$$  \hfill (10)

The scale length of the best-fit smearing kernel is a combination of the CR electron and UV photon scale lengths, and we cannot separate their effects with the current data. However, the scale length of the CR electrons is probably significantly larger than that for the UV photons (e.g., Helou & Bicay 1993), and therefore it is the dominant term in the scale length of the best-fit smearing kernel. Once we have determined the best-fit smearing kernels, we use the corresponding smeared infrared maps to perform the same aperture photometry as described in § 2.4 to calculate the mean and dispersion in $q_{\phi}$, and the dispersion in $q_{\phi}$ are given in Table 6 for each galaxy and kernel type.

4.2.2. Image-Smeearing Model Results

We look to see whether the image-smearing model works to significantly improve the correlation between the infrared and radio morphologies of galaxies. Determining the functional form and scale length of the best-fit smearing kernel provides insight into the propagation and diffusion characteristics of cosmic rays within galaxy disks.

An examination of Figures 9 and 10 shows that the image-smearing technique improves the overall correlation between the radio maps and the 70 and 24 $\mu$m images by an average of 0.2 and 0.6 dex, respectively, in $\log \phi$. Even though the infrared wavelengths studied trace two different temperature regimes and grain species, we find similar preferences in kernels for both the smeared 70 and 24 $\mu$m images. We find that exponential kernels

![Fig. 10.—Same as Fig. 9, but using smeared 24 $\mu$m images matched to the resolution of the 70 $\mu$m beam.](image-url)
are preferred independent of projection, since they have $\Phi$-values at least 0.04 dex larger than those from Gaussian kernels. This result differs from Marsh & Helou (1998), who found Gaussian and exponential kernels to work equally well, but is consistent with Bicay & Helou (1990). Since Gaussian kernels describe a simple random walk diffusion for CR electrons, additional processes such as escape and decay appear to be necessary to describe the evolution of CR electrons through the galaxy disks, as was suggested by Bicay & Helou (1990). Each galaxy displays a marginal difference between exponential kernels oriented in the plane of the sky and those oriented in the plane of the galaxy. This poor discrimination for kernel projections is not surprising due to the low inclination of these face-on targets.

We choose to only present residual maps for exponential kernels oriented in the plane of the sky (Figs. 11 and 12), since this kernel typically had the largest value of $\Phi$ for each galaxy. Residual images for the other kernels look very similar. It is obvious from the residual maps that a simple symmetric function cannot properly fit each part of the galaxy, as the arm, interarm, and individual giant H II regions strongly deviate from having zero residuals. However, the residuals in Figures 11 and 12 show two distinct and opposite trends. In the more active star-forming galaxies (NGC 2403 and NGC 3031; SFR $> 1 M_\odot$ yr$^{-1}$), star-forming regions in the disk display radio excesses, while the interarm and outer disk regions generally have infrared excesses. Because the less active star-forming galaxies have larger smearing scale lengths, the bright star-forming regions that appear in the infrared images of these galaxies are oversmoothed. This oversmoothing of the star-forming regions redistributes a larger amount of flux into the more quiescent parts of the galaxy disks than is needed to match what is observed in the radio image. The larger scale lengths and oversmoothing of discrete star-forming sites in these less active star-forming galaxies may be due to the diffuse emission dominating the appearance of the disk. We propose that the relative paucity of H II regions translates into a deficit of recent CR electron injection into the ISM and a longer effective timescale for CR electron diffusion. While this picture is self-consistent and accounts for the data on the four sample galaxies, further tests are required to ascertain its applicability outside of this small sample of galaxies.

The CR electron scale lengths for the exponential kernels oriented in the plane of the sky range from a few hundred pc to a couple of kpc. Three out of the four galaxies have smearing scale lengths for the 70 $\mu$m maps that are smaller than what is found for the 24 $\mu$m maps by a couple hundred pc. This result is not surprising, since the 24 $\mu$m emission is associated with hotter dust and is more centrally peaked around bright star-forming regions than the 70 $\mu$m emission. The exception is NGC 3031,

![NGC 2403](image1.png)

![NGC 3031](image2.png)

![NGC 5194](image3.png)

![NGC 6946](image4.png)

Fig. 11.—Residual images after subtracting the observed radio maps from the smeared 70 $\mu$m images (as defined in § 4.2.1) for each galaxy, using the best-fit exponential kernel oriented in the plane of the sky. [See the electronic edition of the Journal for a color version of this figure.]
Fig. 12.—Residual images after subtracting the observed radio maps from the smeared 24 μm images (as defined in § 4.2.1) for each galaxy, using the best-fit exponential kernel oriented in the plane of the sky. The 24 μm maps were first convolved to match the 70 μm PSF. [See the electronic edition of the Journal for a color version of this figure.]

### TABLE 6

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>NGC 2403</th>
<th>NGC 3031</th>
<th>NGC 5194</th>
<th>NGC 6946</th>
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<td>l (pc)</td>
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<td>σ_σ_l (pc)</td>
<td>0.16</td>
<td>0.23</td>
<td>0.17</td>
<td>0.18</td>
</tr>
</tbody>
</table>

Notes.—The scale length l is given in units of pc. The newly measured dispersion in q_l (σ_σ_l) is calculated over the same apertures as for σ_l and σ_σ in Table 3, including the regions that were removed before calculating residuals.
which does not have well-determined scale lengths, perhaps because the galaxy is mainly quiescent and lacks a large number of luminous star-forming regions for the size of its disk, so the majority of the 24 µm emission is as diffuse as the 70 µm emission. While the smearing scale lengths at 70 and 24 µm for NGC 3031 are not well determined, those for NGC 2403 do seem relatively well determined, even though both galaxies have similar star formation rate surface densities. A comparison of H II region luminosity functions shows that NGC 3031 has fewer higher-luminosity H II regions than NGC 2403 (Petit et al. 1988; Sivan et al. 1990), which may account for this difference.

The dispersion across each disk is found to be lower by at least ~0.04 dex when we use the smeared infrared images to construct the infrared/radio ratio maps, except for NGC 3031, which is probably due to the inclusion of its AGN in calculating the dispersion. We also find that the slopes in the $q_{70}$ and $q_{24}$ versus infrared surface brightness relations are, on average, factors of ~2 and ~1.5 times smaller, respectively, when using the smeared infrared images. Accordingly, this reduction in slope improves the linearity of $q_1$. Since this nonlinearity within disks is suppressed by smearing the infrared images, it may well be a result of the diffusion of CR electrons away from star-forming sites. In this case, such a nonlinearity should not be found in the global correlation when integrating the flux over entire galaxies, which is indeed what is observed in Figure 8.

Assuming that the differences between the radio and infrared distributions are due to the diffusion to CR electrons, we can relate the best-fit smearing scale lengths to the mean ages of the CR electron populations of each galaxy. Comparing the shapes of the residual curves in Figures 9 and 10 for each galaxy, we find quite distinct behaviors between our two more active star-forming galaxies (NGC 5194 and NGC 6946) and our two less active star-forming galaxies (NGC 2403 and NGC 3031). The curves for NGC 5194 and NGC 6946 have clearly defined minima for each kernel type. In contrast, the curves in NGC 2403 and NGC 3031 are less well behaved, with the initial decrease in residuals being less smooth and, in the case of NGC 2403 at 70 µm, displaying clearly defined first and second minima that have scale lengths greater and less than 1 kpc. We speculate that the double-minimum behavior, especially present for NGC 2403 in Figure 9, results from a superposition of two populations of CR electrons: those from an older episode of star formation, now associated with the diffuse radio disk, and those from a more recent episode of star formation, associated with the prominent H II regions. We also speculate that NGC 2403 has gone through a period of relative quiescence between the two episodes of star formation. The relatively small scale lengths (~1 kpc) found in the first minimum of NGC 2403 are consistent with the scale lengths observed in NGC 6946 and NGC 5194. They correspond to the spreading scale length values expected in galaxies with typical ISM density $\gtrsim 5$ cm$^{-3}$ and CR electron ages $\lesssim 5 \times 10^7$ yr (Helou & Bicay 1993). These relatively young CR electrons are thought to have been recently accelerated in star-forming regions. Scale lengths $\sim 1$ kpc, however, are expected for older CR electrons that have been diffusing through the ISM for $\gtrsim 5 \times 10^7$ yr. The double-minimum behavior is more apparent in NGC 2403, presumably because of the relative luminosities of the diffuse disk emission compared to the H II regions and because of the geometry of the star formation sites with respect to the disk.

5. SUMMARY

We present an initial look at the FIR-radio correlation within galaxies using infrared and radio data taken as part of the Spitzer Infrared Nearby Galaxies Survey (SINGS) and the parallel WSRT SINGS project. We report on four of the most nearby objects in our sample, which allow us to probe physical scales down to 0.3 kpc, for a 17″ beam, and analyze the variations in the logarithmic ratios of 70 and 24 µm dust emission to 22 cm radio continuum emission.

We have also performed preliminary modeling of CR electron diffusion using the image-smearing technique of Bicay & Helou (1990). We find that this phenomenological model of smoothing the infrared maps to match the morphology of the radio maps does indeed improve the correlation. This model relies on the fact that CR electrons emit synchrotron radiation as they diffuse away from the same star-forming regions that heat dust, effectively creating a smoother version of the infrared image at radio wavelengths. Characterizing the optimal smoothing kernel for the infrared map provides insight into the evolution of the CR electrons, including an estimate of their diffusion scale lengths. In our image-smearing analysis we have tested the differences between Gaussian and exponential smoothing kernels oriented in the planes of the galaxy and sky on the 70 and 24 µm maps of each galaxy.

As emission from 70 and 24 µm probes different grain populations, the variations in the logarithmic 70 µm/22 cm ($q_{70}$) and 24 µm/22 cm ($q_{24}$) surface brightness ratios across each galaxy disk are not identical. From comparisons of the $q_{70}$ and $q_{24}$ behavior within our sample, along with our image-smearing analysis, we find the following:

1. The ratios $q_{70}$ and $q_{24}$ generally decrease with declining surface brightness and increasing radius. However, the dispersion measured in $q_{70}$ and $q_{24}$ at constant surface brightness is found to be smaller than that at constant radius by ~0.1 dex, which suggests that the distribution of star formation sites is more important in determining the infrared/radio disk appearance than the underlying exponential disk elements, such as the ISM mass distribution and the older stellar population.

2. The $q_{24}$ ratio maps are more strongly peaked on star-forming regions than the $q_{70}$ ratio maps at matching resolution, and consequently the dispersion in $q_{70}$ for each disk is generally smaller (~0.03 dex) than what is found for $q_{24}$, except in the case of NGC 3031. This is consistent with the 24 µm emission being more closely correlated spatially with sites of active star formation than the cooler 70 µm dust emission, as was found by Calzetti et al. (2005) and Helou et al. (2004).

3. The ratio of FIR (42–122 µm) emission to radio emission within galaxies displays less scatter than the monochromatic $q_{70}$ and $q_{24}$ ratios at matching resolution. However, the dispersion in $q_{70}$ is never more than ~0.03 dex larger than the dispersion in $q_{24}$ for each galaxy.

4. The dispersion in the global FIR-radio correlation is comparable to the dispersion measured in $q_{70}$ and $q_{24}$ within the galaxy disks on 1.5 kpc scales. Also, the trend of increasing infrared/radio ratio with increased luminosity within each galaxy is not observed in the global correlation probably due to the diffusion of cosmic-ray electrons.

5. The phenomenological modeling of cosmic-ray electron (CR electron) diffusion using an image-smearing technique is successful, as it both decreases the measured dispersion in $q_{70}$ and $q_{24}$ by an average of ~0.05 dex and reduces the slopes in the $q_{70}$ and $q_{24}$ versus infrared surface brightness relations, on average, by a factor of ~1.75. This reduction in slope suggests that the nonlinearity in $q_1$ within galaxies may be due to the diffusion of CR electrons from star-forming regions.

6. The image-smearing models with exponential kernels work marginally better to tighten the correlation between the radio and
infrared maps than Gaussian kernels, independent of projection. This result suggests that CR electron evolution is not well described by random walk diffusion in three dimensions alone and requires additional processes, such as escape and decay.

Using a simple symmetric smearing kernel to smooth the infrared image does not provide a perfect fit to the radio continuum image, and it leaves organized structures such as arms and H ii regions still visible. Our two less active star-forming galaxies display radio excesses around star-forming regions in their residual maps, while our two more active galaxies have infrared excesses around star-forming arms. This difference in the appearance of the residual maps may be due to timescale effects in which there has been a deficit of recent CR electron injection into the ISM in the two less active star-forming galaxies, thus leaving the underlying diffuse disk as the dominant structure in the morphology.

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