CHANG-ES X: Spatially Resolved Separation of Thermal Contribution from Radio Continuum Emission in Edge-on Galaxies

Carlos J. Vargas1, Silvia Carolina Mora-Partiarroyo2, Philip Schmidt2, Richard J. Rand3, Yelena Stein4, René A. M. Walterbos1, Q. Daniel Wang5, Aritra Basu5, Maria Patterson6, Amanda Kepley7, Rainer Beck2, Judith Irwin8, George Heald9, Jiangtao Li10, and Theresa Wiegert10

1 Department of Astronomy, New Mexico State University, Las Cruces, NM 88001, USA
2 Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany
3 Department of Physics and Astronomy, University of New Mexico, 1919 Lomas Boulevard NE, Albuquerque, NM 87131, USA
4 Astronomisches Institut, Ruhr-Universität Bochum, Universitätsstr. 150, D-44780 Bochum, Germany
5 Department of Astronomy, University of Massachusetts, 710 North Pleasant Street, Amherst, MA 01003, USA
6 Department of Astronomy, University of Washington, Box 351580, Seattle, WA 98195, USA
7 NRAO Charlottesville, 520 Edgemont Road, Charlottesville, VA, 22903-2475, USA
8 Queen’s University, Kingston, ON, Canada
9 CSIRO Astronomy and Space Science, 26 Dick Perry Avenue, Kensington WA 6151, Australia
10 Dept. of Astronomy, University of Michigan, 311 West Hall, 1085 S. University Avenue, Ann Arbor, MI 48109, USA

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Abstract

We analyze the application of star formation rate calibrations using Hα and 22 μm infrared (IR) imaging data in predicting the thermal radio component for a test sample of three edge-on galaxies (NGC 891, NGC 3044, and NGC 4631) in the Continuum Halos in Nearby Galaxies—an EVLA Survey (CHANG-ES). We use a mixture of Hα and 24 μm calibration from Calzetti et al. and a linear 22 μm only calibration from Jarrett et al. on the test sample. We apply these relations on a pixel-to-pixel basis to create thermal prediction maps in the two CHANG-ES bands: L and C band (1.5 GHz and 6.0 GHz, respectively). We analyze the resulting nonthermal spectral index maps, and find a characteristic steepening of the nonthermal spectral index with vertical distance from the disk after application of all methods. We find possible evidence of extinction in the 22 μm data as compared to 70 μm Spitzer Multiband Imaging Photometer imaging in NGC 891. We analyze a larger sample of edge-on and face-on galaxy 25–100 μm flux ratios, and find that the ratios for edge-ons are systematically lower by a factor of 1.36, a result we attribute to excess extinction in the mid-IR in edge-ons. We introduce a new calibration for correcting the Hα luminosity for dust when galaxies are edge-on or very dusty.

Key words: galaxies: halos – galaxies: star formation – infrared: galaxies – radio continuum: galaxies

1. Introduction

Radio continuum emission from active star-forming galaxies contains both free–free (thermal) and synchrotron (nonthermal) emission. Separating the emission from each component allows for each to be studied individually. Under the assumption of equipartition, analyses of the nonthermal component allow for a characterization of the magnetic fields and the cosmic rays (CRs) that illuminate those fields.

In cases where data from two discrete radio continuum frequencies are available, separation of the thermal and nonthermal components has been carried out by assuming a constant nonthermal spectral index, e.g., Klein et al. (1982). One of the first papers with an advanced separation of thermal and nonthermal radio emission other than assuming a constant nonthermal spectral index is that by Beck & Graeve (1982), where the thermal emission from M31 was estimated from a catalog of Hα regions, corrected for extinction. The bulk of CR particles are believed to be accelerated in supernova shocks in star-forming regions. As CRs propagate outward, they suffer energy losses that result in a steepening of the synchrotron spectral index (Condon 1992). Since assuming a constant nonthermal spectral index makes it impossible to study variations due to CR production and energy losses in the spectral index distribution, an alternate separation approach must be employed.

Free–free emission and recombination line emission both originate from ionized regions, making recombination lines a good tracer for thermal emission. Hα, in particular, is the most preferred recombination line to observe, since it is the strongest Balmer line. However, Hα emission is strongly obscured by dust along the line of sight and needs to be corrected for extinction, especially in edge-on galaxies. It is also worth noting that radio recombination lines are not subject to extinction along the line of sight and would thus be ideal for tracing thermal emission. However, these lines are too faint to map on a resolved basis with current technology from the diffuse ionized regions in nearby galaxies. Tabatabaei et al. (2007) used Effelsberg 6.2 cm observations in an attempt to map radio recombination line emission in M33, but were unsuccessful. We note that extragalactic carbon radio recombination lines have been detected in M82 with LOFAR (Morabito et al. 2014). The authors of that study infer that the detected carbon lines are likely associated with cold atomic gas near the nucleus of M82.

Dust grains emitting at IR wavelengths can be heated by ionizing and non-ionizing photons from both young and evolved stars, as well as AGN. Empirical relations have been established relating mid-IR emission to star formation, and thus thermal emission from HII regions. These empirical relations rely on the assumption that the distribution of dust-heating mechanisms other than young stars (i.e., evolved stars, AGN, etc.) are negligible, or similar to the distribution of young stars. Also, mid-IR emission originates from substantially heated grains, thus the correlation with young, massive stars is likely
robust. Additionally, Hα emission and 24 μm emission show spatial correlation in face-on galaxies, thus suggesting that dust shells around evolved stars do not contribute significantly to mid-IR emission. AGN contribution likely skews these empirical relations in the central regions of galaxies that host AGN. However, separate observations tailored to search for AGN are needed to determine whether a galaxy is a host.

The emission from heated dust grains can be empirically related to the extinction of Hα emission, allowing extinction-corrected Hα emission to be used as a tracer of the star formation rate (SFR). Star formation in both obscured and unobscured regions can be traced by a combination of Hα and 24 μm measurements (Kennicutt et al. 2007). Calzetti et al. (2007) found that Hα emission corrected using 24 μm data adequately traces extinction-corrected Paα (a star formation tracer less affected by extinction than Hα) emission in the H II regions of 33 galaxies in the Spitzer Infrared Nearby Galaxies Survey (SINGS). Furthermore, Kennicutt et al. (2009) found good agreement between integrated Hα emission corrected for extinction with mixed Hα and 24 μm luminosities. They also find good agreement using Hα/β ratios in optical spectra, where deviations from a theoretical constant ratio in the interstellar medium (ISM) allow for an Hα extinction correction.

To date, several studies have estimated thermal emission in spiral galaxies at various inclinations, i.e., Tabatabaei et al. (2007), Basu et al. (2012), Leroy et al. (2012), and Basu et al. (2017). However, galaxies viewed edge-on add another complication. Line-of-sight Hα extinction is certainly higher in the midplanes of edge-on galaxies, since photons are more likely to encounter dust particles on their long paths. Thus, the observed Hα may be only from sources residing on the near side of the galaxy. Additionally, structures such as spiral arms, bars, and distortions make spiral galaxies non-homogeneous. Hence, the observed Hα emission may not be representative of the full-disk emission. Dust extinction effects decrease with increasing wavelength, and so IR emission should be largely unaffected.

The Continuum Halos in Nearby Galaxies—an EVLA Survey (CHANG-ES; Irwin et al. 2012a, 2012b, 2013, 2015, 2016; Wiegert et al. 2015; Damas-Segovia et al. 2016; Li et al. 2016) aims to establish the connection between star formation in galaxy disks and nonthermal processes, such as halo magnetic fields, CR injection and propagation, and AGNs. To accomplish this goal, CHANG-ES has observed 35 highly inclined galaxies in the nearby universe with the Karl G. Jansky Very Large Array (VLA) in B, C, and D configurations. The variety of the VLA antenna configurations allow studies on various spatial scales. The observations were performed in L band (centered at 1.5 GHz) and C band (centered at 6 GHz) in all polarization products. CHANG-ES improves on past radio continuum surveys by the large sample size, by the diversity of the physical sizes within the sample, and by the large bandwidths obtained with the Wideband Interferometric Digital ARchitecture (WIDAR) correlator at the VLA. The latter is perhaps the most drastic improvement: WIDAR allows the CHANG-ES observations to be, in some cases, an order of magnitude more sensitive to continuum emission than previous studies, and also allows for an improved study of the regular magnetic field morphology by applying the rotation measure synthesis algorithm (Burn 1966; Brentjens & de Bruyn 2005).

Li et al. (2016) found that the radio-IR correlation is shifted for CHANG-ES galaxies from those found for face-on galaxies. The shift implied that the mid-IR emission could itself be subject to extinction. Furthermore, the mid-IR SFR estimates used by that study and calculated in Wiegert et al. (2015) for the CHANG-ES sample were a factor of ∼2.3 lower than those from IRAS total infrared (TIR) estimates in Irwin et al. (2012a). While differing SFR calibrations for TIR and mid-IR emission may explain some of this discrepancy, it may also indicate that 22 μm emission may suffer from measurable extinction in edge-on galaxies, and may need correction before SFR estimation and thermal prediction.

Owing to the added complexity of an edge-on perspective, there is no standard method for estimating the thermal component of edge-on galaxies, especially at small spatial scales. Hence, this study examines the validity of predicting the thermal emission in edge-on galaxies using both ancillary Hα and mid-IR imaging as a proxy for thermal emission in a subsample of three galaxies from the CHANG-ES survey: NGC 891, NGC 3044, and NGC 4631, and aims to identify a consistent method of thermal prediction for edge-on galaxies. The calibrated radio continuum images and method from the doctoral theses of Schmidt (2016) and Mora Partiarroyo (2016) are used in this study for NGC 891 and NGC 4631, respectively.

### 2. Data

We identified three galaxies within the CHANG-ES survey with preexisting and readily available Hα imaging of their entire disks in order to test methods of independently estimating the thermal radio component using both Hα and Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010) 22 μm mid-IR imaging. The three galaxies chosen for this test sample were NGC 891, NGC 3044, and NGC 4631. In addition to the current availability of Hα imaging for these galaxies, NGC 891 and NGC 4631 are both well studied. NGC 3044 has a relatively high surface SFR and is smaller in size than the other two, making a short-spacings correction less of a concern. The properties of each galaxy are listed in Table 1.

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| Galaxy   | Type  | D(Mpc) | d25 (') | d25 (kpc) | SFR (M☉ yr⁻¹) | Surface SFR (×10⁻³ M☉ yr⁻¹ kpc⁻²) |
|----------|-------|--------|---------|-----------|---------------|-----------------------------------|
| NGC 891  | Sb    | 9.1    | 12.2    | 33.6      | 1.55          | 3.13                               |
| NGC 3044 | SbC   | 20.3   | 4.4     | 26.0      | 0.95          | 3.70                               |
| NGC 4631 | SBCd  | 7.4    | 14.7    | 32.3      | 1.33          | 3.10                               |
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Note. The total SFR and surface SFR are calculated from the WISE 22 μm imaging and are quoted for the entire CHANG-ES sample in Wiegert et al. (2015).
2.1. CHANG-ES Data

CHANG-ES observations in C band were centered at 6 GHz and have a bandwidth of 2 GHz in 16 spectral windows, each divided into 64 channels. In L band, observations were centered at 1.5 GHz and have a bandwidth of 512 MHz in 32 spectral windows, each divided into 2048 channels.

CHANG-ES data taken in VLA C and D configurations at both frequency bands were used. See Table 2 in Irwin et al. (2012a) for the theoretical noise limits and resolutions of the various observations, and we refer to Tables 4 and 5 in Wiegert et al. (2015) for the resulting rms and beam size of the D-array observations. All radio maps used for this analysis are primary-beam corrected.

The radio data used for NGC 891 and NGC 4631 are corrected for short spacings using single-dish Effelsberg 100 m telescope observations, taken with the purpose of supplementing the CHANG-ES data. The optical diameter of NGC 3044 is ~4.4. The largest detectable sizes of the CHANG-ES observations are 16′ at L band, and 4′ at C band (see Irwin et al. 2012a). Therefore, missing flux at L band for NGC 3044 will be negligible, and missing flux at C band will be low. For details on the Effelsberg observations and the combination of single-dish and interferometer data see Schmidt (2016) and Mora Partiarroyo (2016).

2.2. \textit{Hα} Imaging

The \textit{Hα} imaging data for NGC 891 were taken at Kitt Peak National Observatory (KPNO) using the 4 m telescope by MP. The narrowband \textit{Hα} filter we used has a central wavelength of 6574.74 Å and a FWHM of 80.62 Å, and it was chosen to

![Figure 1. Input data for NGC 891. Left: \textit{Hα} with L-band contours overlaid; right: \textit{WISE} 22 µm with C-band contours overlaid. All images are shown at their highest resolution (\textit{Hα}–1″, 22 µm–12″). Contours on the L- and C-band images begin at 3σ and increase in multiples of 2. The 3σ lowest contour for the L-band image is at 75 µJy beam$^{-1}$, and that of the C-band image is 24 µJy beam$^{-1}$. The beam size for the C-band contours is 9.70 × 8.8, and that of the L-band contours is 10.5 × 9.7. The beams of the overlaid radio images are shown in the lower left corner of each respective panel. The \textit{Hα} and 22 µm images are shown in a logarithmic stretch.](image)

![Figure 2. Input data for NGC 3044. Left: \textit{Hα} with L-band contours overlaid; right: \textit{WISE} 22 µm with C-band contours overlaid. Contours on the L- and C-band images begin at 3σ and increase in multiples of 2. The 3σ lowest contour for the L-band image is at 63 µJy beam$^{-1}$, and that of the C-band image is 14 µJy beam$^{-1}$. The beam size for the C-band contours is 10.7 × 9.6, and that of the L-band contours is 11.4 × 10.6. The beams of the overlaid radio images are shown in the lower left corner of each respective panel. The \textit{Hα} and 22 µm image resolutions are the same as in Figure 1, and are shown in a logarithmic stretch.](image)
The beam size for the C-band contours is 8.9 × 8.6, and that of the L-band contours is 10.1 × 9.9. The beams of the overlaid radio images are shown in the lower left corner of each respective panel. The Hα and 22 μm image resolutions are the same as in Figure 1, and are shown in a logarithmic stretch.

To remove foreground stars, and a constant background was subtracted. An aperture correction for extended sources, a color correction, and calibration correction for spiral galaxies were applied as in Jarrett et al. (2013). No corrections were made for extinction. In what follows, when 24 μm fluxes are needed, we obtain them from 22 μm fluxes by multiplying by a factor of 1.03, as found from the tight linear relation of the two fluxes by Wiegert et al. (2015) for CHANG-ES galaxies (see also Jarrett et al. 2013). The maps were convolved to a Gaussian beam with an FWHM of 15′′ using the kernels provided by Aniano et al. (2011), as those kernels are the closest to the WISE WERGA data resolution, without exceeding its native resolution (note that this is not necessary for the Hα imaging, which has Gaussian PSFs throughout). After convolution, the images were regridded to the geometry of the radio maps.

### 3. Method

The main goal of this paper is to create and analyze maps of the predicted thermal radio continuum emission (thermal prediction maps, hereafter) for three edge-on galaxies using conventional SFR tracers and calibrations, and to then identify a general method of thermal prediction for edge-on galaxies. To that end, we analyze the relations between Hα and 24 μm emission and the extinction-corrected Hα emission.

We begin with a mid-IR monochromatic relation to SFR from Jarrett et al. (2013):

$$SFR_{22 \mu m} = (0.04) (M_\odot \text{ yr}^{-1})$$

$$= 7.50 (\pm 0.07) \times 10^{-10} \nu_{22} (L_\odot).$$

This is a direct relation between 22 μm (rather than 24 μm) intensity and SFR, which is directly related to thermal flux, and also has the added benefit of being linear. We also use this method for consistency with CHANG-ES Paper IV (Wiegert et al. 2015), in which this SFR calibration was used. We refer to this method as the “22 μm only method,” hereafter. We note the existence of other mid-IR monochromatic relations to SFR or extinction-corrected Hα emission, such as Relaño et al. (2007). These calibrations using the 24 μm band are nonlinear, and thus need to be linearized for use on a pixel-to-pixel basis, else the sums of the pixels in the resulting image will be a factor of ~3 larger than the predicted sum from integrated...
values. We effectively linearized the calibration from Relaño et al. (2007) by forcing the sum of each thermal prediction map derived using this method to be the same as the sum using integrated values. The average relative difference between the predicted thermal flux results using the linearized Relaño et al. (2007) relation and the relation from Jarrett et al. (2013) was ∼5%. In light of their similarity, we elected to move forward using the linear 22 μm calibration from Jarrett et al. (2013).

We also use a combination of Hα and 24 μm emission from Calzetti et al. (2007), which we refer to as the “mixture method,” hereafter:

\[
L(H\alpha_{\text{corr}}) = L(H\alpha_{\text{obs}}) + a \cdot \nu L_{\nu}(24 \mu m).
\]

The coefficient \(a\) is effectively a weighting factor for the 24 μm contribution to the mixture. We adopt a value of \(a = 0.031\), which was empirically measured by Calzetti et al. (2007) with a stated uncertainty of 0.006 (∼20%). We elect to use \(a = 0.031\) instead of \(a = 0.02\) from Kennicutt et al. (2009) since the former was estimated in H II regions, rather than integrated galaxies. The individual pixels for which we calculate the SFR are closer to the size scale of HII regions than to that of entire galaxies. More specifically, the pixel size in the final versions of each map is 2.5′, which corresponds to physical sizes of 110, 246, and 90 pc at the assumed distances of NGC 891, NGC 3044, and NGC 4631, respectively. The relations we analyze assume H II region sizes of 100–200 pc.

We note that all empirical relations to SFR used in this work assume the same initial mass function (IMF).

We then relate the extinction-corrected Hα emission to SFR using the following relation from Murphy et al. (2011):

\[
\frac{\text{SFR}_{\text{mix}}}{M_\odot \text{ yr}^{-1}} = 5.37 \times 10^{-42} \left( \frac{L(H\alpha_{\text{corr}}) + a \cdot \nu L_{\nu}(24 \mu m)}{\text{erg} \cdot \text{s}^{-1}} \right).
\]

Finally, for both methods, assuming case B recombination, we calculate the thermal radio component in L and C bands directly from the SFR found from Equations (1) or (3), by combining with Equation (11) from Murphy et al. (2011):

\[
\frac{L_{\nu}^T}{\text{erg s}^{-1} \text{Hz}^{-1}} = 2.2 \times 10^{27} \left( \frac{T_e}{10^4 \text{ K}} \right)^{0.45} \times \left( \frac{\nu}{\text{GHz}} \right)^{-0.1} \left( \frac{\text{SFR}_{\nu}}{M_\odot \text{ yr}^{-1}} \right)
\]

We assume an electron temperature of \(T_e = 10,000\) K, and consider uncertainties in this key parameter in the following subsection. The estimates of SFR from the thermal indicators, SFR_{22 μm} and SFR_{mix}, are used in Equation (4) as SFR_{\nu}.

We note the existence of another possible method of estimating thermal emission in galaxies, used in Tabatabaei et al. (2013), where dust optical depth maps are generated by fitting the far-IR SED. However, this method must assume the shape of the radiation field, which would likely change dramatically along various lines of sight in the edge-on case. This method also must assume a geometry such that the dust surface density maps may be applied to the Hα data at each pixel to correct for extinction. In the edge-on case, there are likely some regions where Hα emission suffers from so much extinction that it would not be detected. In such regions, the application of this method is unclear. Last, we lack the data needed to reproduce this analysis for the CHANG-ES sample.

### 3.1. Uncertainties

For both the input Hα and 22 μm imaging, we estimate background variations that contribute to uncertainties. We estimate the background uncertainty by finding the rms value in 100 × 100 pixel boxes in regions with no galaxy emission. We quantify the uncertainty per pixel as the mean of these ten rms background values.

We estimate the uncertainties in [NII] emission line subtraction within the Hα imaging by estimating the line throughput in the narrowband Hα filters. According to Collins et al. (2000), the throughput of the two [NII] lines in NGC 3044 is very low. Thus, we conservatively add an uncertainty of 10% to the Hα imaging of that galaxy to account for potential [NII] contamination. The Hα images for NGC 891 and NGC 4631 both contain emission from the [NII] line within their narrowband filter, and the line contribution is accounted for (see Section 2). We add an uncertainty to the treatment of the [NII] line flux of 10% to Hα measured fluxes.

The electron temperature \(T_e\) is also an uncertain quantity. We assume the electron temperature to range between 7000 and 13,000 K (i.e., \(T_e = 10,000 \pm 3000\) K). This uncertainty has the largest effect on the output thermal flux—adding an uncertainty of ∼14% to the final predicted thermal fluxes. All mentioned sources of uncertainty and uncertainties in the empirical SFR relations are combined and accounted for using standard error-propagation techniques.

We would also like to note that the method of applying SFR relations to estimate thermal radio contribution does not rely on an IMF assumption, even though that is the case for the individual SFR relations. Since Equation (11) from Murphy et al. (2011) and our Equation (3) were derived using the same ionizing photon rate from the same assumed IMF, variations in the ionizing photon rate (from variations in the assumed IMF) balance each other out when inverting Equation (11) from Murphy et al. (2011) to arrive at our Equation (4).

We can assess the effects of the various systematic uncertainties by noting the differences we see in the derived nonthermal spectral index maps between our methods. From difference maps in the nonthermal spectral index, we see a difference that is typically ∼5% in the central disk and ∼10% in the outer disk. Thus we conclude that the resulting nonthermal science is largely unaffected by the systematic uncertainties in our methods.

### 4. Thermal Prediction Results

#### 4.1. NGC 891

The thermal prediction results for NGC 891 using the 22 μm only method and mixture method are shown in Figures 4 and 5, respectively. Both methods show similar results. Within the disk, C-band thermal fractions range between 8% and 30% in both methods. Outside of the disk, thermal fractions sit at ∼5% in both methods, but the mixture method produces slightly more uniformly distributed extraplanar thermal emission. In both methods, we also see evidence that the nonthermal spectral index steepens with vertical distance from the disk.

Small differences between the two methods in each galaxy of the test sample can be seen by comparing the regions along the plane of the galaxy within ∼3–5 kpc of the center and outside...
Figure 4. Thermal prediction results for NGC 891 using the 22 μm only method. The top row of the panels shows the predicted thermal flux in colorscale and contours. Contours correspond to $0.45 \mu$Jy pix$^{-1}$ · (1, 3, 9, 27 ...). The colorscale and contours are at the same levels in the two top panels. The central row of panels shows the thermal fraction maps in C and L band using this method. The bottom row contains the nonthermal spectral index obtained from subtracting the predicted thermal component in C and L band, and the total spectral index distribution. All spectral indices shown are taken between C and L band. The total spectral index is obtained from observed radio maps before subtracting the thermal emission. All panels are at 15arcsec resolution, and the beam is shown in the lower left region of the lower left panel.
of $\sim$3–5 kpc, which we refer to as the inner and outer disks, respectively. In the case of NGC 891, both methods show a lower thermal fraction in the central disk ($\sim$11% on average at C band) than in the outer disk ($\sim$22% on average at C band). For the mixture method, it is likely that \textsc{H}$\alpha$ encounters so much extinction that the calibrations used are no longer valid in the central disk. In fact, we see that the 22 $\mu$m emission dominates the mixture in the central disk as a result of the \textsc{H}$\alpha$ extinction. The central deficiency of thermal emission in the 22 $\mu$m only method could perhaps be due to extinction in the 22 $\mu$m band itself. NGC 891 is an almost perfectly edge-on disk and is a very dusty, late-type spiral, making it the most likely place for
extinction at 22 μm to occur. In principle, it is also possible that the central deficiency in thermal emission is truly due to decreased star formation in the central disk, and that CR diffusion produces nonthermal emission there. However, this scenario is likely unrealistic.

We note that the ratio [N II]/Hα was found to increase to ~1.5 at large heights above the disk (z ~ 3 kpc) of NGC 891 by Rand (1998). We explored the effects of this change in assumed [N II]/Hα by multiplying the input Hα image for NGC 891 in the mixture method by a factor of 0.5. We find that while the thermal fractions above the disk increase by a factor of ~1.2, the nonthermal spectral index above the disk is almost completely unaffected, changing by a factor of only 1.005 at most. Since the nonthermal results are almost completely unaffected and the true [N II] throughput in the Hα filter would have to be assumed, we do not add a correction for [N II]/Hα variations with height above the disk.

4.2. NGC 3044

The thermal prediction results for NGC 3044 using the 22 μm only method and mixture method are shown in Figures 6 and 7, respectively. Unlike in NGC 891, the thermal morphology is different between the two methods. The 22 μm only results show roughly constant thermal fraction values throughout the disk that range between ~10%–18% at C band. The mixture method shows larger thermal fractions in the outer disk than in the central disk, reaching as high as 80% at C band. These large thermal fraction regions trace bright HII regions in the Hα image. The Hα emission is the most direct tracer of thermal emission, so the method that we adopt must reproduce at least the thermal emission implied by the Hα emission. For this reason, the mixture method is more valid here than the 22 μm only method, which under-predicts the thermal contribution in the outer disk regions of this galaxy.

Vertically, we see that the mixture method shows more extraplanar thermal emission. As in NGC 891, we also see
evidence for a steepening of the nonthermal spectral index with vertical distance from the disk.

NGC 3044 is not as dusty or edge-on as NGC 891. Thus, the fact that we do not see a deficiency of the thermal fraction in the central disk region of NGC 3044 using the 22 μm only method implies that the 22 μm emission in NGC 891 may be suffering from extinction.

4.3. NGC 4631

The thermal prediction results for NGC 4631 using the 22 μm only method and mixture method are shown in Figures 8 and 9, respectively. The case of NGC 4631 is similar to NGC 3044; we find a roughly uniform thermal fraction distribution throughout the disk using the 22 μm only method, while the outer disk shows considerably more thermal emission using the mixture method. From the 22 μm only method, disk thermal fraction values range from 5% to 13% (minimum in L band, maximum in C band). For the mixture method, disk thermal fraction values range from 7% to 60%. The mixture method also produces more extraplanar thermal emission than the 22 μm only method.

As is the case for NGC 3044, bright H II regions in the outer disk drive the predicted thermal emission up in the outer disk. The 22 μm only method does not reproduce the intensity of thermal emission in the regions that are implied by the Hα component in the mixture, and thus leads to an underprediction. We also note that the central-disk-predicted thermal emission values agree within 5% for the two methods in NGC 4631.

We list the integrated thermal prediction results for all three galaxies in Table 2.

4.4. Hα and 22 μm Contribution to the Mixture Method

It is useful to analyze the contribution of each component to the mixture method to better understand the morphological behavior of this method’s thermal prediction results. We create maps of the 22 μm image contribution to the mixture. Specifically, we show maps of \( \frac{L(H\alpha) + aL_{\text{22 μm}}}{\text{Total Flux}} \). Thus, the magnitudes in the maps are the fractional contribution of the 22 μm image contribution to the total mixture method. These maps are shown in Figure 10.

The results differ from galaxy to galaxy. In NGC 891, we see that the 22 μm emission is almost completely dominant in the entirety of the disk, while the Hα becomes slightly more present above and below the disk. This effect could be related to the dust lanes at high vertical distance found in Howk & Savage (1997). In NGC 3044, we find that Hα seems to be more dominant throughout the disk, with a larger contribution from the 22 μm imaging in bands above the central disk. Since
NGC 3044 is a disturbed disk seen slightly less than edge-on, it is possible that this effect is due to emission from the front side and back side of the disk masquerading as vertical emission. We also see clear H\textalpha dominance in HII region clumps in the disk. For NGC 4631, we see that the H\textalpha is largely dominant throughout, except in the central disk. Extreme values that arise at the outermost edges of the emission are not considered reliable, and are likely due to wings in the WISE PSF (see Cutri et al. 2012).

5. Infrared Extinction

In NGC 891, we have identified possible signs of extinction in the WISE 22 \textmu m data. These signs are observed as a central depression in thermal fraction using the mixture and 22 \textmu m only methods. To explore the existence of this extinction and its implications for the nonthermal emission, we employ ancillary Spitzer MIPS 70 and 160 \textmu m imaging, and analyze the far-IR total flux properties of a larger sample from the Infrared Astronomical Satellite (IRAS) Revised Bright Galaxy Sample (RBGS; Sanders et al. 2003).

5.1. Spitzer MIPS Imaging

We analyze existing Spitzer MIPS 70 and 160 \textmu m imaging for NGC 891 (Bendo et al. 2012) and NGC 4631 (Dale et al. 2009). No MIPS data exist for NGC 3044. We plot the ratios of MIPS band maps and WISE 22 \textmu m imaging, all convolved to Gaussian beams using the kernels from Aniano et al. (2011), and smoothed to match the resolution of the 160 \textmu m image in Figure 11. In the plot of the 22/70 \textmu m ratio (lower right panel), the ratio appears to be lowest in the central region, and increases radially. This might indicate extinction in the central disk, which is also hinted at by the previous thermal prediction results. The same map ratios are plotted for NGC 4631 in Figure 12. The 22/70 \textmu m ratio does not appear to vary radially, as in NGC 891.

We note that the 70 and 100 \textmu m emission likely originates from larger dust grains than the grains responsible for the 22 \textmu m emission. These larger grains do not necessarily trace the population of the smaller grains, which could explain the differing morphologies. We also note the possible contribution of cirrus to the 70 \textmu m imaging, which would arise from dust.
heating by sources other than star formation. The existence of cirrus in the 70 $\mu$m imaging could lead to an overestimate of the thermal contribution in some regions.

We use the MIPS 70 $\mu$m image to independently predict the thermal radio component via the SFR calibration from Calzetti et al. (2010):

$$\text{SFR}_{70 \mu m} = \left( \frac{L_{\text{H}\alpha}}{M_\odot \text{yr}^{-1}} \right) = \frac{L_{\nu}(70 \mu m)}{1.7 \times 10^{43} \text{ erg s}^{-1}}.$$ (4)

From this step, we use Equation (4) to predict the corresponding thermal radio component in L and C bands throughout the entire disk of NGC 891, as seen in the 70 $\mu$m only prediction shown in Figure 13, does seem to be consistent with our speculation that the 22 $\mu$m emission suffers from extinction in the central disk.

### 5.2. Electron Temperature

We next consider the possibility that variations in the electron temperature could account for the lower thermal fraction in the central disk regions of galaxies. Through varying the assumed electron temperature between 7000 and 13,000 K (the expected range of $T_e$ in galaxy disks), we find that the thermal fraction would vary from 11% to 21% in the central disk region of NGC 891 for the same input data. Thus, variations in $T_e$ of $\sim$3000 K could explain the variations in thermal fraction along the disk that we see in the two methods. In fact, $T_e$ is likely to decrease in regions of high metallicity, such as the central disk region of NGC 891, which would lower the thermal fraction of the radio emission. For example, Zurita & Bresolin (2012) measured electron temperatures as low as $\sim$7100 K in regions at low galactocentric distance and high

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**Table 2** Integrated Results of Various Calibrations and Methods

| Galaxy    | $L_{\text{H}\alpha}$ ($10^{44}$ erg s$^{-1}$) | $F_{22 \mu m}$ (Jy) | $F_{\text{C-band}}$ (mJy) | $F_{\text{L-band}}$ Mixture (mJy) | $F_{\text{L-band}}$ 22 $\mu$m Only (mJy) |
|-----------|-----------------------------------------------|---------------------|----------------------------|----------------------------------|---------------------------------|
| NGC 891   | 0.16 ± 0.027                                  | 5.84 ± 0.18         | 205.86 ± 6.9               | 24.6 ± 5.4                       | 26.3 ± 4.2                     |
| NGC 3044  | 1.04 ± 0.25                                   | 0.7 ± 0.03          | 37.5 ± 0.9                 | 6.2 ± 1.2                        | 3.7 ± 0.5                      |
| NGC 4631  | 2.02 ± 0.33                                   | 7.88 ± 0.24         | 284.4 ± 7.4                | 59.3 ± 12.8                      | 34.1 ± 5.5                     |

Note. Column values from left to right: galaxy name, integrated H$\alpha$ luminosity, integrated 22 $\mu$m flux density, integrated total C-band flux density, integrated predicted thermal C-Band flux density via the mixture method, integrated predicted thermal C-band flux density via the 22 $\mu$m only method. Thermal prediction results are provided for C-band only, as L-band results are all scaled versions of the C-band results.

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Figure 9. Thermal prediction results for NGC 4631 using the mixture method. The panel layout, resolution, and contours are the same as in Figure 8.
**Figure 10.** Maps of the fractional contribution of 22 μm emission to the total mixture method results in each of the three test sample galaxies. High values represent regions where the 22 μm emission is the dominant component in the mixture method results.

**Figure 11.** Infrared ratio maps for NGC 891. Values near the edges of emission are likely unreliable because of background uncertainties and low signal-to-noise ratios.
metallicity in M31. With this in mind, and because the 70 and 160 μm emissions are likely to stem from other dust populations than the 22 μm emission, we deem the presence of extinction in the central disk regions of our galaxies’ 22 μm data inconclusive at this point.

5.3. Independent Evidence for Mid-IR Extinction

Here we further explore the issue of extinction at 22 μm in edge-on galaxies (and arrive at a global estimate of the effect) via a different direction. First, we note two lines of evidence that highlight the concern. The first comes from studies of the mid-IR extinction law in the disk of the Milky Way. Measurements of the extinction at wavelength \( \lambda \) relative to that in the \( K_s \) filter, \( A_{\lambda}/A_{K_s} \), for wavelengths of 22 and 24 μm have been made by Flaherty et al. (2007), Chapman et al. (2009), and Xue et al. (2016). The measured values span a wide range, with some authors finding evidence for higher values found on sightlines with lower \( A_{K_s} \). As an illustration of how significant extinction at these wavelengths might be in an edge-on disk, we consider the following illustrative example. We assume \( K_s \equiv A_V/(A_B - A_V) = 3.1 \), and \( N_H/A_V = 1.9 \times 10^{21} \text{ cm}^{-2} \text{ mag}^{-1} \), where \( N_H \) is the H column density (Bohlin et al. 1978), a representative gas density of 1 cm\(^{-3}\), a path length of 10 kpc, and \( A_{24}/A_{K_s} = 0.4 \). For these assumptions, \( A_{24} \) is significant at 0.7 mag. Second, Li et al. (2016) reported that the average total IR (dominated by far-IR emission) to mid-IR luminosity ratio of the CHANG-ES sample is significantly higher than that in the samples of Rieke et al. (2009) and Calzetti et al. (2010), which contain star-forming galaxies with a range of inclinations. Assuming negligible extinction at far-IR wavelengths, a dependence of this ratio on inclination is an indication of excess mid-IR extinction in edge-on galaxies. However, the properties of the CHANG-ES sample do not match those of the other two, so that biases may be present.

To optimally address the issue via such a ratio, a large sample of galaxies with a range of inclinations (including a significant number of edge-on galaxies) observed at mid- and far-IR wavelengths in a uniform way is desirable. Unfortunately, no such samples exist for galaxies observed with any combination of Spitzer MIPS, Herschel, and WISE photometers. We therefore turn to the IRAS RBGS (Sanders et al. 2003), where fluxes are available for 629 galaxies. The RBGS is a flux-limited sample of all extragalactic objects observed by IRAS with 60 μm fluxes >5.4 Jy. Our main focus is the variation of the 25–100 μm flux ratio, \( f_{25}/f_{100} \). Ideally, one would wish to examine this ratio as a function of inclination, but we restrict ourselves to comparing only two samples of galaxies, edge-on and non-edge-on, given the size of the survey.

We limited our study to disk galaxies (S0 to Sm) with no confusion flags on their fluxes. While 23 CHANG-ES galaxies are in the RBGS, we increased the edge-on sample to 52 by examining optical images of all the RBGS galaxies to find those that appeared to be very edge-on in that they showed no sign of face-on disk structures (such as spiral structure) viewed at a high inclination. We then need a non-edge-on comparison sample that matched the properties of the edge-on sample as closely as possible. For this sample, we restricted the axial ratios (from Lyon–Meudon Extragalactic Database, LEDA) to be \( \leq 2 \) to exclude highly inclined galaxies. The non-edge-on sample has 227 galaxies. For disk galaxies in the full RBGS sample, we found that \( f_{25}/f_{100} \) varies systematically with type and with \( L_{\text{TIR}} \) (the 8–1000 IR luminosity (Perault 1987), in units of \( L_\odot \), with earlier type and higher \( L_{\text{TIR}} \) disk galaxies showing higher \( f_{25}/f_{100} \) (Figures 14 and 15). We therefore restricted the non-edge-on sample to span the same range of
Figure 13. Thermal prediction results using 70 μm MIPS data for NGC 891. The resolution is 20" in each panel. The panel layout and contours are the same as in Figure 4.
type (−1 to 9, or SO to Sm) and $L_{\text{TIR}}$ (log $L_{\text{TIR}} = 9.22$ to 11.32) as the edge-on sample. However, the distribution of galaxy types in each sample is somewhat different, with earlier type disks being somewhat more common in the edge-on sample (Figure 16).

Therefore, to control for the variation of $f_{25}/f_{100}$ with type, we calculated median values of $f_{25}/f_{100}$ for the non-edge-ons and the edge-ons for four bins of type, namely −1 to 2, 3 to 5, 6 to 7, and 8 to 9. Within these ranges, the variation of $f_{25}/f_{100}$ in the full RBGS sample is relatively small. Although outliers only have a small effect on the medians, two outliers in the edge-on sample, M82 (a starburst) and NGC 4388, with $f_{25}/f_{100}$ ratios $>10$ from the median of the other galaxies in their bin, were removed. Two galaxies, NGC 1068 and NGC 4151 (both Seyferts), were removed from the non-edge-on sample via the same criterion. We then formed the ratio of these two medians for each of the four type bins, and then averaged these ratios for the bins, weighted by the total number of galaxies in both samples in each bin. The distribution of $L_{\text{TIR}}$ values for the two samples is very similar, hence we do not need to correct for any $L_{\text{TIR}}$ bias. The non-edge-on sample extends to somewhat larger distances than the edge-on sample, but we found no correlation of $f_{25}/f_{100}$ with distance in the full RBGS that would suggest distance bias is a concern.

Histograms of $f_{25}/f_{100}$ for the two samples are shown in Figure 17. They appear to be different, with a high $f_{25}/f_{100}$ tail in the non-edge-on sample that is absent from the edge-on sample. Controlling for type as above, the resulting value for the $f_{25}/f_{100}$ contrast between non-edge-ons and edge-ons is $1.35 \pm 0.11$. This differs insignificantly from the value found without controlling for type, which is $1.36 \pm 0.09$. A Kolmogorov–Smirnov test was performed to determine whether the values of $f_{25}/f_{100}$ for the two samples could be drawn from the same parent population. The probability of this being the case is rejected with >99.9% confidence.

We therefore conclude, assuming negligible extinction at 100 μm, that edge-on galaxies have an extra attenuation of 1.36 in their IRAS 25 μm emission relative to galaxies with axial ratios $\leq 2$. We assume that the same value applies in the WISE 22 μm band, although a more thorough analysis would account for the relative spectral response of the 22 and 25 μm bands and the (uncertain) shape of the measured extinction law between 22 and 25 μm (see below), but this is beyond the scope of the current paper.

Although our main interest is $f_{25}/f_{100}$, we repeated the analysis for the other IRAS bands. For $f_{12}/f_{100}$ and $f_{60}/f_{100}$, much weaker trends with type were found in the full RBGS. We therefore calculated median values for each sample and found that $f_{12}/f_{100}$ and $f_{60}/f_{100}$ are higher for non-edge-on galaxies by $1.12 \pm 0.12$ and $1.13 \pm 0.13$, respectively—this is not a significant difference. The approximate wavelength range of the 12 μm IRAS response was about 8–15 μm (Beichman et al. 1988; IRAS Explanatory Supplement), which, as dust models (e.g., Weingartner & Draine 2001) indicate, includes
the silicate absorption feature centered at 9.7 \( \mu m \) as well as a low-extinction trough (although this is less pronounced in the ice mantle model of Wang et al. 2015) at around 14 \( \mu m \). These models would suggest that the lower 12 \( \mu m \) relative to 25 \( \mu m \) extinction implied by our results is surprising. However, there may be marginal support for this result from the Milky Way observations. With the aforementioned caveat, we note that values of \( A_{24}/A_{KS} \) from Chapman et al. (2009) toward low \( A_{KS} \) sightlines are somewhat higher than values of \( A_{12}/A_{KS} \) (Lutz 1999 and Xue et al. 2016), although \( A_{24}/A_{KS} \) and \( A_{24}/A_{KS} \) found by Xue et al. (2016) indicate the opposite trend.

6. Recommended Thermal Prediction Method

The RBGS results suggest that the WISE 22 \( \mu m \) emission is not entirely optically thin for all edge-on galaxies. The RBGS analysis brought to light a factor of 1.36 of extinction, which represents the average extinction across entire galaxies. A single consistent method of thermal prediction is needed for edge-on galaxies. In all galaxy cases, the mixture method captures thermal flux that must necessarily be present as implied by the \( H_0 \) contribution, in the vertical direction. In NGC 3044 and NGC 4631, we see evidence of this in the outer disk as well. With this in mind, we elect to use the mixture method over the 22 \( \mu m \) only method for edge-on galaxies.

Additionally, we add a correction for extinction to the 22 \( \mu m \) data. This correction will be applied via an adjustment to the a factor in the mixture method corresponding to the average extinction value determined by the RBGS analysis above. Accounting for the factor of 1.36 average extinction within the original a value of 0.031 causes the new a value to increase to 0.042. While correct on average, this correction does not account for potential variations in extinction on a galaxy-to-galaxy basis; additional gas and dust information is required to verify this. The mixture method relation that is valid for edge-on and extremely dusty galaxies is included in Equation (6):

\[
L(\text{Ho}_{\text{corr}}) = L(\text{Ho}_{\text{obs}}) + 0.042 \cdot \nu L_{\nu}(24 \mu m). \tag{6}
\]

We show the integrated thermal prediction results with the recommended method in Table 3, and a comparison of the thermal fraction results in C band between \( a = 0.031 \) and \( a = 0.042 \) in Figure 18. The results of the mixture method with \( a = 0.042 \) show a slight increase in the overall thermal fraction as compared to those of \( a = 0.031 \), as expected.

One could envision a method of thermal prediction where the 22 \( \mu m \) data are corrected for extinction by varying the a factor in the mixture method to represent changes in the path length along different lines of sight. We currently do not have the gas and dust properties that would be mapped by further ancillary data on hand for each galaxy in our sample. Thus, a path-length-dependent method would not be trivial, and would require further assumptions.

Additionally, a more complex treatment of this “a” factor could take into account its variation with dust column density and height above the plane, e.g., by introducing a dependence of “a” on \( \nu L_{\nu}(24 \mu m) \), hence replacing \( a \cdot \nu L_{\nu}(24 \mu m) \) by a nonlinear term \( a \cdot \nu L_{\nu}(24 \mu m)^x \) on the right-hand side of Equation (2). Constraining this “x” exponent would require further a priori information on the expected thermal contribution. The best extinction-free observational tool for obtaining the expected thermal contribution in edge-on galaxies would likely be radio mapping at frequencies where the thermal component dominates (\( \sim 30 \) GHz).

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**Table 3**

Integrated Results of the Mixture Method with Correction for 22 \( \mu m \) Extinction

| Galaxy   | \( F_{\text{C-band}} \) (mJy) | \( F_{\text{L-band}} \) (mJy) | \( F^\prime_{\text{C-band}} \) (mJy) | \( F^\prime_{\text{L-band}} \) (mJy) | \( \%F_{\text{C-band}} \) | \( \%F_{\text{L-band}} \) | \( \Delta \%F_{\text{C-band}} \) |
|----------|-------------------------------|-------------------------------|---------------------------------|---------------------------------|---------------------------|---------------------------|---------------------------|
| NGC 891  | 205.86 ± 6.9                  | 743.9 ± 14.9                  | 32.0 ± 7.0                      | 36.8 ± 8.1                      | 15.5 ± 4.1                | 4.9 ± 1.3                 | ∼12                       |
| NGC 3044 | 37.5 ± 0.9                    | 104.2 ± 2.1                   | 7.3 ± 1.4                       | 8.4 ± 1.6                       | 19.5 ± 4.3                | 8.1 ± 1.7                 | ∼23                       |
| NGC 4631 | 284.4 ± 7.4                   | 1083.0 ± 37.0                 | 69.8 ± 15.1                     | 80.2 ± 17.3                     | 24.5 ± 6.1                | 7.4 ± 1.9                 | ∼14                       |

Note. \( F_{\text{C-band}} \) and \( F_{\text{L-band}} \) are the total integrated C-band and L-band flux densities from the CHANG-ES data. \( F^\prime_{\text{C-band}} \) and \( F^\prime_{\text{L-band}} \) are the integrated predicted thermal flux densities at C band and L band, respectively. The percentage thermal fraction values at C band and L band are included, under \( \%F_{\text{C-band}} \) and \( \%F_{\text{L-band}} \). In the rightmost column, we include \( \Delta \%F_{\text{C-band}} \), the estimated mean change in C-band thermal fraction from the inner disk to the outer disk in the 22 \( \mu m \) extinction-corrected method.
7. Nonthermal Spectral Index Behavior

Maps of the nonthermal spectral index for the three test sample galaxies using the final recommended method is included in Figure 19. Vertical variations nonthermal spectral index distribution can be seen in all galaxies, independent of the method used to obtain the thermal prediction. We analyze the change in nonthermal spectral index with vertical distance from the major axis by defining five rectangular boxes oriented along the minor axis for each galaxy. The boxes have a height of 1 kpc, and are contiguously oriented to span ±2 kpc from the major axis, with the central box encompassing the inner ±0.5 kpc. The lengths of the boxes were chosen so that each box contains as much emission as possible. We calculate the mean nonthermal spectral index value in each box. The results of this analysis are included in Table 4.

The results in Table 4 show clear evidence for a steepening of the nonthermal spectral index with increased distance from the major axis, on average. We note that this analysis does not account for radial variations in the nonthermal spectral index. However, radial variations in the nonthermal spectral index can be clearly seen in the morphology included in Figure 19. They tend to be closely associated with regions of high SFR. We note one interesting exception: the farthest southwestern extension of the disk in NGC 891 shows a knot with a very flat nonthermal spectral index. Normally, this is indicative of star formation processes. However, in this case, there is very little thermal flux in that region.

A previous study of the total spectral index of NGC 891 by Hummel et al. (1991) shows a relatively flat disk spectral index.
Nonthermal Spectral Index, $a = 0.042$

Figure 19. Nonthermal spectral index results using the recommended method of thermal prediction. All panels are shown at $15''$ resolution, and the beam is shown in the lower left region of each panel.

$(\alpha \sim -0.4)$ that steepens with vertical distance to $\alpha \sim -0.9$ in the halo. A similar behavior is seen in NGC 4631 as reported by Hummel & Dettmar (1990) with data at 327 MHz and 1.49 GHz, where $\alpha \sim -0.45$ in the disk, and approaches $\alpha \sim -1.0$ in the halo. Klein et al. (1984) estimated the global nonthermal spectral index in NGC 891 to be $\alpha \sim -0.9$, which is similar to our results for this galaxy. Our new sensitive data, coupled with secure thermal subtraction method, now lead to a high-quality determination of the vertical variation of the nonthermal spectral index and therefore opens the possibility for careful CR propagation modeling.

Studies of the nonthermal radio continuum component that do not take the morphology of thermal emission into account (e.g., Heesen et al. 2009; Mulcahy et al. 2014) may suffer from some inaccuracies. In general, if the magnetic field strengths are calculated with the assumption of energy equipartition between the magnetic field and CRs, the field strength will increase with steepening of the nonthermal spectral index. In this study, we find that typical nonthermal spectral indices are flattest in the disk. Thus, previous studies that assume a singular and steep nonthermal spectral index throughout the galaxy may be underestimating the magnetic field strength. Since synchrotron losses scale with magnetic field strength, underestimating the magnetic field strength will lead to an underestimation of synchrotron losses. The opposite is true in halo regions, where the nonthermal spectral index may be steeper than assumed.

8. Summary and Conclusions

We have analyzed various methods of SFR estimation, and thus thermal radio continuum prediction, in a test sample of three edge-on galaxies (NGC 891, NGC 3044, and NGC 4631) included in the CHANG-ES sample. The goal of the analysis was to determine a method for producing consistent and accurate estimates of the thermal radio component in edge-on galaxies.

We have used H$\alpha$ imaging from various sources, and WISE 22 $\mu$m maps from Jarrett et al. (2012) with enhanced resolution to create SFR maps for the test sample using two methods: a mixture of H$\alpha$ and 22 $\mu$m, and 22 $\mu$m only. We found that the 22 $\mu$m only method misses thermal flux that the H$\alpha$ data is sensitive to, both in the outer disk and in extraplaneous regions of the test sample galaxies. We also found possible evidence for extinction in the 22 $\mu$m band itself for NGC 891.

We have further explored the possibility of 22 $\mu$m extinction in NGC 891 by using Spitzer MIPS 70 and 160 $\mu$m imaging of both NGC 891 and NGC 4631. We found that flux ratio maps of 22/70 $\mu$m show slight evidence for extinction at 22 $\mu$m in the central disk of NGC 891 only. A thermal prediction map created from 70 $\mu$m data only also corroborates this.

We have explored the possibility that the potential extinction features in the thermal prediction results can be explained through variations in electron temperature. We found that the difference in observed thermal fraction from the central disk to outer disk can be explained by varying the electron temperature within its uncertainty. This would be consistent with a lowering of the electron temperature in the central disk with increased metallicity. Currently, this possibility cannot be ruled out, but a more detailed study of the physical conditions in edge-on galaxies is needed to more plausibly explain the behavior of our results.

We have compiled an expanded sample of edge-on and face-on galaxies within the RBGS, which contains fluxes in all IRAS bands. Flux ratios of 25–100 $\mu$m show that the edge-on sample is characteristically lower in flux than the face-on sample, which points to extinction. This extinction acts as a lowering of the 25 $\mu$m flux by a factor of 1.36 on average for the edge-on sample.

Using this independent measurement of extinction, we applied a correction factor of 1.36 to the 22 $\mu$m data in the mixture method (Equation (2)), which corresponds to raising the IR weighting factor in the mixture method to $a = 0.042$.

We recommend that the thermal radio component of edge-on galaxies is best estimated using the mixture method. For edge-ons, we additionally recommend a correction of the 22 $\mu$m data for extinction by increasing the $a$ factor in the mixture method to 0.042.

We outlined evidence that the nonthermal spectral index steepens with vertical distance for the galaxies of the test sample in Section 7. This vertical steepening is likely due to CR aging; CR injection sites, such as supernova remnants and young O–B stars, tend to be located within galaxy disks. As CRs propagate upward out of the disk, the higher energy CRs lose energy. This energy loss is observed as a steepening of the spectral index in regions with an older population of CRs. We also see evidence for radial variations in the nonthermal spectral index, which are closely associated with star formation.
regions within the galaxy disk, indicating that CR injection occurs in complexes of high star formation. An exception is the southwestern extension of the disk in NGC 891. This region shows a complex with an extremely flat nonthermal spectral index, with very minimal thermal flux associated with the region. However, more information is needed on the region to fully understand what drives the peculiar behavior.

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ORCID iDs

Richard J. Rand @ https://orcid.org/0000-0003-2048-4228
René A. M. Walterbos @ https://orcid.org/0000-0002-0782-3064
Q. Daniel Wang @ https://orcid.org/0000-0002-9279-4041
Aritra Basu @ https://orcid.org/0000-0001-5558-2560
Amanda Kepley @ https://orcid.org/0000-0002-3227-4917
Jiangtao Li @ https://orcid.org/0000-0001-6239-3821
Theresa Wiegert @ https://orcid.org/0000-0002-3502-4833

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