INFRARED DUST EMISSION IN THE OUTER DISK OF M51

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ABSTRACT

We examine faint infrared emission features detected in Spitzer Space Telescope images of M51, which are associated with atomic hydrogen in the outer disk and tidal tail at $R \approx R_{25}$ ($4.9 \times 14$ kpc at $d = 9.6$ Mpc). The infrared colors of these features are consistent with the colors of dust associated with star formation in the bright disk. However, the star formation efficiency (as a ratio of star formation rate to neutral gas mass) implied in the outer disk is lower than that in the bright disk of M51 by an order of magnitude, assuming a similar relationship between infrared emission and star formation rate in the inner and outer disks.

Subject headings: galaxies: individual (M51=NGC 5194) — galaxies: ISM — galaxies: spiral — galaxies: structure — infrared: galaxies

1. INTRODUCTION

Relatively little is known about the conditions in the interstellar medium (ISM) in the outer disks of spiral galaxies, yet an accounting of the ISM in these regions is integral to a full understanding of the galactic star formation process. Studies of the ISM at large radii can measure the available reservoir of neutral gas and dust in galaxies and assess the efficiency of ongoing star formation. Sensitive atomic hydrogen (H I) observations often reveal extended distributions of the ISM that may support the formation of additional stars or tidal dwarf galaxies (see classic reviews by van der Kruit & Allen 1978 and Haynes et al. 1984). However, measures of star formation associated with this extended neutral component are rare, thus hampering efforts to fully characterize the local star formation process.

Infrared imaging by the Spitzer Space Telescope (Werner et al. 2004) with IRAC (Fazio et al. 2004) and MIPS (Rieke et al. 2004) provides a new opportunity for mapping out dust in emission in nearby galaxies. Of particular interest is dust emission thought to arise from stochastically excited aromatic molecules, such as polycyclic aromatic hydrocarbons (PAHs; see, e.g., Leger & Puget 1984, Puget & Leger 1989, Boulanger et al. 1998, Helou et al. 2000, and Lu et al. 2003), at ~8 μm and thermal dust emission at ~24 μm. Studies with ISO and Spitzer suggest that 8 and 24 μm emission can be used to measure star formation rates on kiloparsec to global scales (e.g., Roussel et al. 2001; Dale et al. 2005; Calzetti et al. 2005). In this Letter, we examine infrared dust emission in the outer disk of M51 and compare the star-forming environment it represents with that of the bright disk of M51.

2. OBSERVATIONS AND DATA ANALYSIS

Figure 1 (Plate 1) shows M51 in H I, infrared (IR), and near-ultraviolet (NUV) emission. The Spitzer IR images (5.8, 8.0 μm: IRAC; 24, 70 μm: MIPS) were acquired from the Second Enhanced Data Release (2005 May 6) of the Spitzer Infrared Nearby Galaxies Survey (SINGS; Kennicutt et al. 2003). The data reduction pipeline is described in Regan et al. (2004). Calibration uncertainties are estimated to be 10% for the 5.8, 8.0, and 24 μm bands and 20% for the 70 μm band. No extended-source aperture corrections have been applied to the IRAC data. The inherent angular resolution is 2″ for the IRAC images, 6″ for the 24 μm MIPS image, and 18″ for the 70 μm MIPS image.

The GALEX NUV (1750–2750 Å) image was taken as part of the GALEX Nearby Galaxies Survey (NGS; see Bianchi et al. 2005) and acquired from the Multimission Archive at Space Telescope. The inherent angular resolution of the GALEX NUV image is 6″. As an additional check on the star formation rates in the outer disk, we conducted a parallel analysis using the Hα image of M51 published by Rand et al. (1992), which has an angular resolution of ~2″.

The H I data presented here were published by Rots et al. (1990). We are using their 21″ resolution data set. To highlight the strongest H I features in the outer disk, the integrated intensity map shown in Figure 1 was created using the AIPS task MOMNT, with 3 channel Hanning smoothing in velocity and 5 pixel (FWHM) Gaussian spatial smoothing. By comparing with the 34′ resolution images shown in Rots et al. (1990), it is clear that the H I image in Figure 1 shows the high column density ridges in the broader H I tail that extends away from the galaxy toward the southeast.

By examination of the H I and IR images, 21 positions were chosen to represent the extended emission. These positions, listed in Table 1, correspond to local H I peaks that lie at intervals spaced by ~1′ along the extended IR features. Sixteen positions lie outside the $m_{25} = 25$ mag arcsec$^{-2}$ isophote, and the remaining five lie at radii $\geq 0.7R_{25}$ ($R_{25} = 4.9$; LEDA$^3$). H I spectra at each of the 21 positions were extracted from the original 21″ data cube. The typical velocity widths of the H I spectra are relatively small (no more than 3–4 channels for a typical spectrum, or $\Delta V_{chan} \sim 25$ km s$^{-1}$), suggesting the emission comes from relatively cool, dense atomic gas. We measured the H I integrated intensities directly from the spectra, integrating over the observed spectral line after subtracting off a linear baseline. The integrated intensities for all positions are within 17% of the integrated intensities that come from a fitted Gaussian function, and the majority are within 10%. The integrated intensities were then converted to H I column densities, assuming the standard optically thin conversion (van de Hulst et al. 1954), and reported in Table 1.

Some fraction of the 5.8 and 8 μm fluxes is due to starlight (see, e.g., Pahre et al. 2004a, 2004b and Helou et al. 2004). We used the starlight-subtraction technique of Pahre et al. (2004a) to create images of the dust emission in M51 at 5.8 and 8.0 μm;
thus, the 5.8 and 8.0 μm images in Figure 1 represent infrared dust emission at these wavelengths. Starlight contributes the majority of the observed 5.8 μm flux at some positions but is generally within the background uncertainty at 8 μm. For the 70 μm images, the fluxes at each position are dominated by systematic uncertainties due to residual striping in the image. Due to the significantly increased uncertainties in measured dust emission at 5.8 and 70 μm, we will use only 8 and 24 μm fluxes for calculating infrared star formation measures (§ 4).

The IR, NUV, and Hα images were smoothed by Gaussian functions to provide a 21″ effective resolution (~1 kpc for an assumed distance of 9.6 Mpc), and all fluxes are consequently reported in units of flux per 21″ FWHM Gaussian beam for consistency with the information available in the Hα image. To measure the flux at each position, the local background was measured in 20 positions outside the minimum Hα contour shown in Figure 1, but within 2.5 of the measured source position. The variance of the local background measurements is used to represent the uncertainty in the flux at each source position.

The background-subtracted fluxes for the smooth 8.0 μm, 24 μm, NUV, and Hα images are listed in Table 1. Fluxes smaller than 3 times the measured background variance are reported as upper limits. In addition, we report in Table 1 the value of the total IR luminosity, \( L_{\text{IR}} = L_{\text{IR}}(3–1100 \mu\text{m}) \), as inferred from the 8 and 24 μm fluxes and the empirical relation determined for M51 by Calzetti et al. (2005).\(^4\)

### 3. INFRARED EMISSION IN THE OUTER DISK

The lowest Hα column density shown in Figure 1 (\( N_{\text{H}_\alpha} = 1.6 \times 10^{20} \text{ cm}^{-2} \)) is overlaid as a single white contour on the IR and NUV images to show the spatial relationship of the outer IR, NUV, and Hα morphologies. Most of the IR and NUV images shown in Figure 1 have been slightly smoothed (5.8 and 8 μm to 5", 24 μm and NUV to 7") to improve the display of the faintest features.

\[^4\] \( \log L_{\text{IR}} = \log L_{24} + 0.908 + 0.793[\log (L_{\text{IR}}/L_{24})] \).
TABLE 2
MULTIWAVELENGTH STAR FORMATION RATES AND EFFICIENCIES

| $\Delta\alpha$ (arcsec) | $\Delta\delta$ (arcsec) | $M^*_{\text{H} \alpha}$ ($10^4 M_\odot$ yr$^{-1}$) | SFR(H$\alpha$, corr)$^a$ | SFR(H$\alpha$, corr) | SFR(NUV) | SFR(L(IR)) | SFR(L(IR)) |
|-----------------------|------------------------|---------------------------------|----------------------|----------------------|------------|------------|------------|
| Outer Disk             |                        |                                 |                      |                      |            |            |            |
| -40.5                 | 225.8                  | 11                              | (0.56)               | (0.80)               | 3.1        | 11         | (0.007)    | 0.097      |
| -63.8                 | 209.3                  | 5.5                             | (1.1)                | (1.3)                | 2.5        | 13         | (0.024)    | 0.23       |
| -90.8                 | 162.0                  | 8.0                             | 1.0                  | 1.3                  | 2.5        | 18         | 0.016      | 0.22       |
| -207.8                | 113.3                  | 4.2                             | 2.0                  | 2.3                  | 1.2        | 3.0        | 0.053      | 0.070      |
| -189.8                | 65.3                   | 3.4                             | 1.7                  | 2.0                  | 2.0        | 6.5        | 0.056      | 0.19       |
| -258.0                | -52.5                  | 5.1                             | 0.95                 | 1.1                  | 1.2        | 5.2        | 0.022      | 0.10       |
| -224.3                | -198.8                 | 4.7                             | 1.7                  | 2.0                  | 1.0        | 7.6        | 0.043      | 0.16       |
| -150.8                | -254.3                 | 6.0                             | (0.79)               | (0.95)               | 6.5        | 6.3        | (0.016)    | 0.10       |
| -191.3                | -270.8                 | 5.9                             | 1.4                  | 1.7                  | 0.75       | (2.6)      | 0.029      | 0.044      |
| -153.0                | -310.5                 | 6.7                             | (0.35)               | (0.43)               | (0.73)     | 3.2        | (0.006)    | (0.047)    |
| -114.8                | -342.8                 | 7.2                             | 1.1                  | 1.4                  | (0.21)     | (2.1)      | 0.019      | (0.028)    |
| 71.3                  | -333.8                 | 7.3                             | (0.36)               | (0.45)               | (1.2)      | (2.6)      | (0.006)    | (0.035)    |
| 96.8                  | -306.8                 | 5.9                             | 1.9                  | 2.3                  | (0)        | (2.4)      | 0.039      | (0.040)    |
| 102.0                 | -273.8                 | 12                              | 4.2                  | 6.0                  | 6.7        | 7.6        | 0.051      | 0.064      |
| 141.0                 | -267.8                 | 5.8                             | 1.6                  | 1.9                  | (0.60)     | 2.2        | 0.033      | 0.038      |
| 221.3                 | -234.0                 | 6.8                             | 3.0                  | 3.7                  | 4.6        | (1.5)      | 0.054      | (0.022)    |
| 177.8                 | -225.8                 | 5.9                             | 1.3                  | 1.5                  | 2.8        | 1.8        | 0.026      | 0.031      |
| 192.0                 | -150.8                 | 4.4                             | 1.2                  | 1.4                  | 0.95       | (1.6)      | 0.031      | (0.038)    |
| 201.0                 | -122.3                 | 7.0                             | 1.3                  | 1.7                  | 2.1        | 3.0        | 0.024      | 0.043      |
| 208.5                 | -63.8                  | 5.3                             | 1.4                  | 1.7                  | 3.8        | 4.8        | 0.032      | 0.091      |
| 204.8                 | 90.0                   | 6.6                             | (0.95)               | (1.2)                | 6.7        | 15         | (0.018)    | 0.23       |

| Inner Disk            |                        |                                 |                      |                      |            |            |            |
| -8.3                  | 52.5                   | 23.8                            | 288                  | 603                  | 144        | 772        | 2.5        | 3.2        |
| -63.8                 | 37.5                   | 24.5                            | 126                  | 269                  | 138        | 499        | 1.1        | 2.0        |
| -66.0                 | 33.0                   | 17.3                            | 183                  | 313                  | 225        | 366        | 1.8        | 2.1        |
| -102.0                | -51.8                  | 11.6                            | 90.1                 | 129                  | 227        | 321        | 1.1        | 2.8        |
| -90.8                 | -90.8                  | 19.8                            | 354                  | 655                  | 222        | 756        | 3.3        | 3.8        |
| 38.3                  | -64.5                  | 17.8                            | 132                  | 229                  | 161        | 672        | 1.3        | 3.8        |
| 69.8                  | -38.3                  | 18.4                            | 122                  | 215                  | 252        | 609        | 1.2        | 3.3        |
| -159.8                | -128.3                 | 19.3                            | 68.5                 | 125                  | 58.5       | 163        | 0.64       | 0.84       |
| 99.0                  | -120.8                 | 16.2                            | 284                  | 470                  | 152        | 451        | 2.9        | 2.8        |
| 142.5                 | -14.3                  | 18.4                            | 107                  | 189                  | 139        | 222        | 1.0        | 1.2        |

Note: — Values enclosed in parentheses were derived from flux upper limits (see Table 1).

$^a$ Offsets measured from the center position $\alpha, \delta = 13^\mathrm{h}29^\mathrm{m}52^\mathrm{s}.6, +47^\circ11'43''(J2000)$.

$^b$ Gas mass includes H i for the outer disk and H i + H$_2$ for the inner disk (see § 4 for details).

$^c$ SFR derived from extinction-corrected H$\alpha$ fluxes (see § 4 for details).

distributed in a foreground screen. The conversion factor from Kennicutt (1998) was then used to obtain an H$\alpha$ SFR.

The IR and H$\alpha$ SFRs are listed in Table 2 and plotted as a function of H i column density in Figure 2. There is no discernable trend in SFR with H i column density, but the range of H i column density (and radius) is small. It is clear that we are detecting real infrared flux, as seen by the correlation between 8 and 24 $\mu$m fluxes shown in the inset of Figure 2. In addition, the 8 $\mu$m/24 $\mu$m flux ratios are consistent with values measured within the optical disks of M51 and other nearby spiral galaxies (Regan et al. 2004; Helou et al. 2004; Calzetti et al. 2005), and are high enough to suggest that depletion of metals will not contribute to a dearth of PAH-band emitters at 8 $\mu$m (Engelbracht et al. 2005). This is particularly true for M51, where there is little or no radial metallicity gradient (Bresolin et al. 2004). The H$\alpha$ SFRs are characteristically lower, but except for position 3, they are within a factor of 5 of the IR SFRs at the positions where both IR and H$\alpha$ SFRs are measured.

The L(IR) SFRs per 21$''$ beam in the outer disk positions are calculated to be (2–20) $\times 10^{-4} M_\odot$ yr$^{-1}$, and the H$\alpha$ SFRs lie in the range (1–6) $\times 10^{-4} M_\odot$ yr$^{-1}$. The corresponding gas masses per beam inferred from the H i column density (including a factor of 1.36 for helium) are $\sim$(3–12) $\times 10^6 M_\odot$, with a median value of 6 $\times 10^5 M_\odot$.

Ten positions in the bright inner disk were chosen to represent typical inner disk SFRs. The SFRs determined from H$\alpha$ and

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**FIG. 2** — Star formation rates, from H$\alpha$ (triangles) and L(IR) (squares), for the 21 positions from Table 1, plotted as a function of H i column density. Upper limits are indicated by open symbols. *Inset:* 8 $\mu$m vs. 24 $\mu$m flux for the 21 outer disk positions.
L(IR) from these positions are also listed in Table 2. The L(IR)
SFRs for the inner disk positions are typically within a factor of
3 of the Hα SFRs, consistent with the measured scatter in
the empirical relationship between L(IR) and the 8 μm/24 μm
color ratio in the bright inner disk (Calzetti et al. 2005). Again, the
inferred Hα SFRs are generally lower than SFRs determined
from L(IR), but both are 2 orders of magnitude higher than in
the outer disk: we measure (160–770) × 10^4 M⊙ yr^{-1} using
L(IR) and (130–660) × 10^4 M⊙ yr^{-1} using Hα. The inner
disk gas masses per beam were ~12–25 × 10^6 M⊙, as determined
from a combination of the H i column density and the H2 column
density. N(H2) was measured from the published CO-integrated
intensity maps published by Helfer et al. (2003), assuming
N(H2) = (3 × 10^{20} cm^{-2} (K km s^{-1})^{-1})/l_{CO}.

Taking the ratio of the SFR and the available gas mass in the
same beam, we find the star formation efficiency (SFE) for each
position (Table 2). For the outer disk positions of M51, the L(IR)
SFEs are 0.04–0.2 Gyr^{-1}, and the Hα SFEs are 0.02–0.06 Gyr^{-1}.
The median SFE for the 10 outer disk positions where significant
emission was detected in Hα, 8 μm, and 24 μm is 0.04 and 0.07 Gyr^{-1}
from Hα (corrected) and L(IR), respectively. For the inner disk
positions of M51, the L(IR) SFEs are 0.8–4 Gyr^{-1}, and the Hα SFEs are 0.6–3 Gyr^{-1}. The median SFE for the inner
disk positions is 1.3 and 2.8 Gyr^{-1} from extinction-corrected Hα
and L(IR), respectively.

A comparison of the median SFEs for inner and outer disk
positions suggests that star formation is ~30–40 times less
efficient in the outer disk than in the bright disk, demonstrating
that 8 and 24 μm emission traces star formation similarly in
the inner and outer disks. While the uncertainties in these measures
are large when considering both measures of low flux
values and significant assumptions in the local star formation
calibration, these calculations suggest that star formation is
roughly an order of magnitude less efficient in the outer disk
than in the bright inner disk.

5. ROBUSTNESS OF INFRARED STAR FORMATION EFFICIENCIES

To assess the robustness of our conclusion of low SFE in the
outer disk of M51, we also compared the Hα star formation rates
calculated here with the rates determined from NUV emission,
using the NUV-SFR calibration of Kennicutt (1998). The calculated
SFRs from NUV measures are also listed in Table 2. For
the positions where both NUV and Hα fluxes are significantly
detected, the derived SFRs (without extinction correction) are
within a factor of ~2.5 of one another. Given the relatively small
extinction corrections at these positions, these measures are ex-
pected to be reasonably representative of the outer disk star for-
mation rate. This comparison, combined with the Hα-IR compa-
tion above, suggests that the IR measurements presented here
do not artificially underestimate the SFR (e.g., due to potentially
lower dust temperatures and metallicities in the outer disk).

In considering the robustness of our relative SFE measures,
we must also assess the accuracy of our neutral gas measures.
Molecular gas is likely present in the outer disk, but with a
significantly lower average column density (see, e.g., Braine
& Herpin 2004) over ~1 kpc scales, such that the contribution
of molecular mass to the total neutral gas mass should be small.
In any case, a contribution from molecular gas in the outer
disk only creates a larger discrepancy between the SFE in the
inner and outer disks of M51. Similarly, if the CO-to-H2 conver-
sion factor used for the inner disk is too high, the discrep-
ancy between inner and outer disk SFEs would also increase.

6. DISCUSSION AND CONCLUSIONS

Measures of IR, UV, and Hα emission associated with the
extended neutral gas component of M51 suggest that star for-
mation in the outer disk of M51 is roughly an order of magnitude
less efficient than at smaller radii. This may be due to a slower
H 1 to H2 conversion, possibly because of the lower pressures
in the outer disk ISM. Recent CO and UV observations (Braine
& Herpin 2004; Neff et al. 2005) have shown that both molecular
gas and star formation are present in the outer disks of spiral
galaxies, and they appear linked to the H 1. Deeper infrared
studies of the outer regions of spiral galaxies will provide a
valuable opportunity to test the local effects of the interstellar
radiation field, metallicity, and gas phase on infrared dust emis-
sion, and thus help to better define the relationship of star for-
mation and gas content.

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Fig. 1.—Emission from M51 at the wavelengths listed in the lower left corner of each panel. Red circles with a diameter equal to the 21" resolution are overlaid on the H\textsc{i} image, for each of the positions listed in Table 1. The lowest flux level shown in the H\textsc{i} map (corresponding to 1.6 × 10²⁰ cm⁻²) is indicated by a single white contour in the other five panels. The bright inner disk in the IR and NUV images has been saturated here in order to show faint, outer features more clearly; red contours show the general structure in the inner disk at each wavelength. The range of fluxes displayed logarithmically by the color table in each image is as follows: for 5.8 μm, 0.003–0.2 MJy sr⁻¹; for 8.0 μm, 0.3–2.5 MJy sr⁻¹; for 24 μm, 0.04–1.0 MJy sr⁻¹; for 70 μm, 0.3–10 MJy sr⁻¹; for NUV, 1.2 × 10²²–1.9 × 10²³ ergs s⁻¹ Hz⁻¹.