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Probing the cold and warm molecular gas in the Whirlpool Galaxy: Herschel SPIRE-FTS Observations of the central region of M51 (NGC 5194)

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ABSTRACT

We present Herschel SPIRE-FTS intermediate-sampled mapping observations of the central $\sim 8 \text{kpc}$ ($\sim 150\prime\prime$) of M51, with a spatial resolution of 40\prime\prime. We detect 4 \textsuperscript{12}CO transitions ($J = 4-3$ to $J = 7-6$) and the [CI] $^3P_2 - ^3P_1$ and $^3P_1 - ^3P_0$ transitions. We supplement these observations with ground based observations of \textsuperscript{12}CO $J = 1-0$ to $J = 3-2$ and perform a two-component non-LTE analysis. We find that the molecular gas in the nucleus and central regions has a cool component ($T_{\text{kin}} \sim 10 - 20 \text{ K}$) with a moderate but poorly constrained density ($n(\text{H}_2) \sim 10^{3} - 10^{6} \text{ cm}^{-3}$), as well as significant molecular gas in a warmer ($T_{\text{kin}} \sim 300 - 3000 \text{ K}$), lower density ($n(\text{H}_2) \sim 10^{1.6} - 10^{2.5} \text{ cm}^{-3}$) component. We compare our CO line ratios and calculated densities along with ratios of CO to total infrared luminosity to a grid of photon dominated region (PDR) models and find that the cold molecular gas likely resides in PDRs with a field strength of $G_0 \sim 10^2$. The warm component likely requires an additional source of mechanical heating, from supernovae and stellar winds or possibly shocks produced in the strong spiral density wave. When compared to similar two-component models of other star-forming galaxies published as part of the Very Nearby Galaxies Survey (Arp 220, M82 and NGC 4038/39), M51 has the lowest density for the warm component, while having a warm gas mass fraction that is comparable to those of Arp 220 and M82, and significantly higher than that of NGC 4038/39.

Key words: galaxies: individual(NGC 5194), galaxies: ISM, ISM: molecules

1 INTRODUCTION

M51 (NGC 5194) is a well-studied, relatively normal, nearby spiral galaxy. Its recent interaction with the nearby lenticular galaxy NGC 5195 has led to triggered star formation throughout the galaxy (Nikola et al. 2001), and this interaction may be responsible for the prominent spiral arms of M51 (Zaritsky, Rix & Rieke 1993; Dobbs et al. 2010). Rose & Searle (1982) first suggested the presence of a non-stellar nuclear source of radiation at the centre of M51: it has been

classified as a Seyfert type 2 galaxy without a hidden broad-line region detected in polarized light (Tran 2001) and as a Low Ionization Nuclear Emission Region (LINER) galaxy (e.g., Satyapal, Sambruna & Dudik 2004). The Seyfert-2 activity may have been triggered as a result of the interaction (Koulouridis 2014).

M51 is an excellent source in which to study both cold and warm molecular gas, due to its nearly face-on orientation, the prominence of its spiral arms, and its recent interaction with NGC 5195. Observations of H$_2$ rotational lines have found that the ratio of warm ($T = 100 - 300$ K) to hot ($T = 400 - 1000$ K) molecular gas varies across the system, which may suggest a varying excitation mechanism (Brunner et al. 2008). Roussel et al. (2007) found that the H$_2$ is generally excited in photon dominated regions (PDRs, also known as photodissociation regions). Recently, Parkin et al. (2013) modelled PDRs in M51 using various transitions of [O], [CII] and [NII], along with the total infrared luminosity, and found that the far-ultraviolet field strength necessary to reproduce PDRs in M51 varies between $G_0 \sim 10^{-5} - 10^{-4}$, with the highest values occurring in the nucleus.

The cold molecular gas has been studied predominantly through observations of $^{12}$CO (hereafter CO), and its isotopologues $^{13}$CO and C$^{18}$O. M51 has been observed using ground-based single-dish telescopes in CO $J = 1 - 0$ (Scoeville & Young 1983; García-Burillo, Günel & Cernicharo 1993; Nakai et al. 1994; Kramer et al. 2005; Koda et al. 2009), $J = 2 - 1$ (García-Burillo, Günel & Cernicharo 1993; Kramer et al. 2005; Israel, Tielens & Baas 2006; Schuster et al. 2007; Leroy et al. 2009), $J = 3 - 2$ (Israel, Tielens & Baas 2006; Vlahakis et al. 2013) and $J = 4 - 3$ (Israel, Tielens & Baas 2006), and in $^{13}$CO $J = 1 - 0$ (Kramer et al. 2005), $J = 2 - 1$ (Kramer et al. 2005; Israel, Tielens & Baas 2006) and $J = 3 - 2$ (Israel, Tielens & Baas 2006). In addition, Israel, Tielens & Baas (2006) presented observations of [CII] in the $^{4}$P$_1 - ^{4}$P$_0$ (hereafter $J = 1 - 0$) transition at 492 GHz, which has also been proposed as a molecular gas tracer (e.g. see Papadopoulos, Thi & Viti 2004 and Offner et al. 2014).

Higher-resolution interferometric observations of CO $J = 2 - 1$, $^{13}$CO $J = 1 - 0$ and $^{12}$C$^{18}$O $J = 1 - 0$ in M51 have been performed using the Owens Valley Radio Observatory (OVRO) by Schinnerer et al. (2010). These observations were limited to two regions within the spiral arms of M51. Using non-local thermodynamic equilibrium (non-LTE) excitation models with an escape probability formalism, they found that the temperature of the molecular gas in the observed giant molecular clouds (GMCs) is $T_{kin} \sim 20$ K. This temperature is similar to clouds in the Milky Way when observed at the same resolution ($\sim 180$ pc).

More recently, M51 was observed at arcsecond resolution in CO $J = 1 - 0$ and $^{13}$CO $J = 1 - 0$ as part of the Plateau de Bure Interferometer (PdBI) Arcsecond Whirlpool Survey (PAWS, Schinnerer et al. 2013; Pety et al. 2013; Hughes et al. 2013b; Meidt et al. 2013; Hughes et al. 2013a; Colombo et al. 2014a,b). These observations were corrected for short-spacings using single dish observations. Colombo et al. (2014a) detect 1507 objects in CO $J = 1 - 0$, and find that the mass distribution, brightness and velocity dispersion of GMCs vary across the different environments in M51. Some of these differences seem to be dynamically driven (Meidt et al. 2013). Pety et al. (2013) detect extended CO $J = 1 - 0$ emission that resides in a thick molecular disk with a scale height $\sim 200$ pc, and accounts for $\sim 50$ percent of the total CO $J = 1 - 0$ emission. Pety et al. (2013) suggest that this thick, extended disk could be the result of galactic fountains or chimneys due to the ongoing star formation. In this paper, we present observations of M51 using the Spectral and Photometric Imaging Receiver (SPIRE; Griffin et al. 2010) Fourier Transform Spectrometer (FTS; Naylor et al. 2010) on board the ESA Herschel Space Observatory (Herschel; Pilbratt et al. 2010). The SPIRE-FTS is a low spatial and spectral resolution imaging spectrometer covering a spectral range from 194$\mu$m to 671$\mu$m ($\sim 450$ GHz to $1545$ GHz). At the redshift of M51 ($z \sim 0.002$), this spectral range includes a total of 10 CO transitions ($J = 4 - 3$ to $J = 13 - 12$), 10 $^{13}$CO transitions ($J = 5 - 4$ to $J = 14 - 13$) and 2 [CI] transitions ($^{3}$P$_1 - ^{3}$P$_0$ and $^{3}$P$_2 - ^{3}$P$_1$, hereafter $J = 1 - 0$ and $J = 2 - 1$, respectively) of which trace molecular gas. The SPIRE-FTS [NI]205$\mu$m data were previously published by Parkin et al. (2013); in this paper we present the detected CO and [CI] transitions for the first time. We adopt a distance to M51 of 9.9$\pm$0.7 Mpc (Tikhonov, Galazutdinova & Tikhonov 2009), based on observations of the tip of the red giant branch.

These observations were performed as part of the Very Nearby Galaxies Survey (VNGS; PI: C.D. Wilson) whose primary goal is to study the interstellar medium (ISM) of very nearby galaxies using both SPIRE and the Photocathode Array Camera and Spectrometer (PACS; Poglitsch et al. 2010). From the sample of 13 galaxies in the VNGS, SPIRE-FTS CO data have been published for five: Arp 220 (Rangwala et al. 2011), M82 (Kamenetzky et al. 2012), NGC 1068 (Spinoglio et al. 2012), NGC 4038/39 (Schirm et al. 2014), and M83 (Wu et al. 2015). We present the observations and data reduction in Section 2. In Section 3, we present the non-LTE analysis of our detected CO and [CI] transitions, while in Section 4 we present models of photon dominated regions (PDRs) in M51. We discuss the implications of the solutions of our non-LTE models and our PDR models in Section 5, along with a comparison of the results for M51 with previously studied galaxies within our sample.

## 2 OBSERVATIONS

### 2.1 FTS Data Reduction

M51 was observed using the SPIRE-FTS on OD 438 (July 25th, 2010) in intermediate sampling mode, with 32 repetitions per jiggle position (Observation ID 1342201202). The observation is centered at (13h29m52.71s, +47°11′42.60″), covering a region roughly $160′′ \times 180′′$ with a total integration time of 17603 seconds ($\sim 5$ hours). These data were reduced with the Herschel Interactive Processing Environment (HIPE) version 11.0 and SPIRE calibration 11.0. We used a modified version of the standard mapping pipeline (Swinyard et al. 2014), with the primary difference that we skip the map making step, instead saving each individual jiggle position as a level 1 spectrometer point source (SPS) product.

The standard mapping pipeline assumes either that the source is a point source or that the source is fully-extended, filling the entire beam uniformly. As with many of the
sources in the VNGS sample, M51 cannot be characterized as either a point-source or a fully-extended source relative to the FTS beam. In addition, the beam size and shape of the SPIRE-FTS varies with frequency, with the size varying from $\sim 17''$ to $\sim 43''$. In previous works where we had fully Nyquist sampled maps of our sources (e.g. see Kamenetzky et al. 2012; Spinoglio et al. 2012; Schirm et al. 2014), we convolved our point-source calibrated integrated intensity maps using custom convolution kernels. The same technique cannot be used here as our map is not Nyquist sampled. Instead, we match the beam size across the entire spectrum using the recently developed semi-extended correction tool (SECT) in HIPE version 11.0 (Wu et al. 2013).

When a source is semi-extended, correcting for the FTS beam requires correcting for the source-beam coupling at every frequency. The SECT corrects for the source-beam coupling by assuming that the distribution of the emitting gas, whether it is [CI]- and CO-emitting molecular gas or [NII]-emitting ionized gas, follows the same spatial distribution as the selected reference image (Wu et al. 2013). It first calculates the source-beam coupling in the form of a forward coupling efficiency, $\eta(\nu, \Omega_{source})$, for each bolometer at a given jiggle position using derived FTS beam profiles and the normalized reference map. This source-beam coupling is frequency-dependent, and so must be calculated at every frequency. It then multiplies the intensity at each frequency by this factor. The resulting data cube has an equivalent beam size and shape of a 40$''$ Gaussian beam. For our reference image, we opt to use the PACS 70$\mu$m image, which correlates strongly with star formation (Calzetti et al. 2010) and also has the advantage of having a significantly higher resolution than any of the FTS data (beam size $\sim 6''$). We expect that the molecular gas traced by CO and [CI] correlates well with the ongoing star formation in a relatively normal galaxy like M51. We perform this correction on the level 1 SPS products at each jiggle position using the SECT, with the correction varying between $\sim 0.5$ and $\sim 1.6$. The correction is dependent upon the frequency and the location of the bolometer.

We create a level 2 data cube for each set of detectors, the SPIRE Long Wavelength Spectrometer Array (SLW) and the SPIRE Short Wavelength Spectrometer Array (SSW), from the semi-corrected level 1 products using the spireProjection task. We chose a pixel size of 10$''$ for both cubes. It is important to note that the pixel size will have no significant effect on our data cubes, provided we limit the pixel size such that only one detector is assigned to an individual pixel for each of the SLW and SSW level 2 data cubes. The resulting SLW and SSW data cubes contain 28 and 68 pixels with spectra, respectively. The complete semi-extended corrected FTS spectrum for the centre of M51 is shown in Figure 1.

2.1.1 Regions

One of the aims of the VNGS is to investigate any regional variations in the interstellar medium of the galaxies which we resolve. In the case of M51, we resolve the central $\sim 2'$ at a beam size of 40$''$. We investigate the regional variations in the physical state and heating mechanisms of the molecular gas by assigning each pixel in our FTS map into one of four regions (see Figure 2): the nucleus, centre, arm and inter-arm. We use the same region definitions as Parkin et al. (2013) to facilitate comparison with their results.

2.1.2 Line Fitting

We wrote a custom line fitting routine in HIPE to fit all of the detected atomic and molecular transitions; a list of detected transitions is shown in Table 1. The intrinsic line profile of the FTS is a Sinc function with a fixed full-width half-maximum of 1.4305 GHz in high resolution mode, which corresponds to 280 – 450 km s$^{-1}$ for the SSW, and 440 – 970 km s$^{-1}$ for the SLW in velocity space. The maximum measured line width from observations from the James Clerk Maxwell Telescope (JCMT) of CO J = 3 – 2 convolved to a beam size of 40$''$ (see Section 2.2.1) is only $\sim 50$ km s$^{-1}$ in the FTS field of view, less than the intrinsic line width of the instrument. Therefore, we do not resolve the line width in our observations.

For each pixel in our cubes, the routine fits each of the lines listed in Table 1 with a Sinc function using a Levenberg-Marquardt fitter, keeping the width of the line fixed to 1.4305 GHz, with the amplitude and centroid varying. The surrounding 30 GHz is fit with a quadratic at the same time in order to account for the continuum emission. With the exception of the CO J = 7 – 6 and [CI] J = 2 – 1 transitions, all of the lines listed in Table 1 are fit individually. In the case of the CO J = 7 – 6 and [CI] J = 2 – 1 transitions, both lines are fit concurrently, each with a Sinc function, along with the continuum emission. We integrate the resulting Sinc functions to calculate the total integrated intensity for each line, while the uncertainty is calculated from the uncertainty in the fitting parameters. The CO J = 10 – 9 line is detected only in the nucleus with a flux of 0.6±0.2 K km s$^{-1}$. The calibration uncertainty of the SPIRE-FTS is 7 percent, while we add a total of 10 percent in quadrature to account for uncertainties in fitting the baseline, and uncertainties in the semi-extended source correction. The resulting maps for CO and [CI] are shown in Figures 3 and 4, respectively.

For each region, we perform an unweighted average for each CO and [CI] transition, including all pixels where all of the transitions are detected with a signal-to-noise ratio (SNR) > 1. We opt for an unweighted average as the fluxes within an individual region are similar (Figure 5). With the exception of the CO J = 8 – 7 line, all of the transitions listed in Table 1 are detected with a SNR > 3 for all pixels in the nucleus and centre regions. For the arm/inter-arm region, only a single pixel satisfies the same SNR > 3. As such, we choose a SNR > 1 in order to explore the parameter space in the arm and inter-arm regions of M51 (Figure 5). Even with this low SNR cut, few pixels are included from the arm and inter-arm regions (see Figure 5), while the included pixels all contain a portion of both regions within the 40$''$ beam. Therefore, we combine the arm and inter-arm regions into a single arm/inter-arm region. Finally, we combine the pixels included in the nucleus, centre and arm/inter-arm regions into a single “All” region.

---

Figure 1. FTS spectrum for the nucleus of M51 in units of Jy beam$^{-1}$. All of the detected atomic and molecular transitions are indicated by a dashed line, while undetected CO transitions are indicated by a dotted line at the expected location. This spectrum has been corrected for the semi-extended nature of the emission (see Section 2.1 for details). The peak of the [NII] line is at $\sim 100$ Jy beam$^{-1}$, beyond the scale of the plot. Note that CO $J = 10 - 9$ is detected only in the nucleus.

2.2 Ancillary Data

2.2.1 Ground based CO

We supplemented our FTS observations of M51 using previously published CO $J = 1 - 0$ to $J = 3 - 2$ maps from ground based instruments. M51 was observed in CO $J = 1 - 0$ and $^{13}$CO $J = 1 - 0$ using the Institut de Radioastronomie Millimétrique (IRAM) 30 m telescope as part of the PAWS program (Schinnerer et al. 2013). As we are interested only in the very large scales ($\sim 40$ pc) in M51, we use the single-dish CO $J = 1 - 0$ and $^{13}$CO $J = 1 - 0$ data cubes published in Pety et al. (2013)$^2$, with a beam size of 22.5". M51 was observed in CO $J = 2 - 1$ with the IRAM 30 m as part of the HERA CO Line Extragalactic Survey$^3$ (Schuster et al. 2007; Leroy et al. 2009). The publicly available data cube

$^2$ Downloaded from http://www.mpia.de/PAWS/PAWS/Data.html
$^3$ http://www.mpia-hd.mpg.de/HERACLES/Overview.html
Table 1. Line integrated intensity measurements

<table>
<thead>
<tr>
<th>Species</th>
<th>Transition</th>
<th>Rest frequency (GHz)</th>
<th>Average measured integrated intensity (K km s(^{-1}))</th>
<th>Calibration uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Nucleus</td>
<td>Centre</td>
</tr>
<tr>
<td>CO (ancillary)</td>
<td>(J = 1 \rightarrow 0)</td>
<td>115.27</td>
<td>47.2 ± 0.2</td>
<td>41.2 ± 0.1</td>
</tr>
<tr>
<td></td>
<td>(J = 2 \rightarrow 1)</td>
<td>230.54</td>
<td>37.8 ± 0.2</td>
<td>32.2 ± 0.2</td>
</tr>
<tr>
<td></td>
<td>(J = 3 \rightarrow 2)</td>
<td>345.80</td>
<td>25.9 ± 0.2</td>
<td>20.9 ± 0.2</td>
</tr>
<tr>
<td>CO (FTS)</td>
<td>(J = 4 \rightarrow 3)</td>
<td>461.04</td>
<td>12 ± 1</td>
<td>9 ± 1</td>
</tr>
<tr>
<td></td>
<td>(J = 5 \rightarrow 4)</td>
<td>576.27</td>
<td>5.5 ± 0.9</td>
<td>4.2 ± 0.9</td>
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<tr>
<td></td>
<td>(J = 6 \rightarrow 5)</td>
<td>691.47</td>
<td>2.2 ± 0.1</td>
<td>1.5 ± 0.4</td>
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<tr>
<td></td>
<td>(J = 7 \rightarrow 6)</td>
<td>806.65</td>
<td>1.10 ± 0.06</td>
<td>0.6 ± 0.1</td>
</tr>
<tr>
<td></td>
<td>(J = 8 \rightarrow 7)</td>
<td>921.80</td>
<td>&lt; 0.4 ± 0.2</td>
<td>&lt; 0.3 ± 0.1</td>
</tr>
<tr>
<td>(^{13})CO (ancillary)</td>
<td>(J = 1 \rightarrow 0)</td>
<td>110.20</td>
<td>5.87 ± 0.06</td>
<td>5.09 ± 0.07</td>
</tr>
<tr>
<td>[CI] (FTS)</td>
<td>(J = 1 \rightarrow 0)</td>
<td>492.16</td>
<td>8 ± 1</td>
<td>6 ± 2</td>
</tr>
<tr>
<td></td>
<td>(J = 2 \rightarrow 1)</td>
<td>809.34</td>
<td>3.08 ± 0.06</td>
<td>1.9 ± 0.1</td>
</tr>
</tbody>
</table>

\(^1\)Quoted uncertainties are measurement uncertainties only
\(^2\)Kramer, Moreno & Greve (2008)
\(^3\)Leroy et al. (2009)
\(^4\)Vlahakis et al. (2013)

Figure 2. Left: Schematic of M51 as defined in figure 6 of Parkin et al. (2013) with CO \(J = 2 \rightarrow 1\) contours overlaid. Right: The same regions of M51 defined for the pixels of our FTS maps with the same CO \(J = 2 \rightarrow 1\) contours overlaid. In both figures, the colors correspond to the nucleus (black), centre (green), arm (red) and inter-arm (blue) regions of M51.

has been smoothed to 13\(^\prime\), the smallest beam size of all the CO maps used in this work. Finally, M51 was observed in CO \(J = 3 \rightarrow 2\) with 15\(^\prime\) resolution by Vlahakis et al. (2013) using the HARP-B instrument on the JCMT. We use the data cube released as part of the JCMT Nearby Galaxies Legacy Survey\(^4\) (NGLS, Wilson et al. 2012).

All four of the ground-based CO transitions were reduced in the same manner using the Starlink software package (Currie et al. 2008) and a similar method as for the CO \(J = 3 \rightarrow 2\) observations of NGC 4038/39 in Schirm et al. (2014). First, we convolved the data cubes to a 40\(^\prime\) gaussian beam using the gaussian command. We then smoothed the cubes with a top hat with a width 2.5 times the half-power beam-width of the 40\(^\prime\) beam and smoothed to a velocity width of 20 km/s. Using the clumpfind command, we identified regions of emission above 2\(\sigma\) in our smoothed cube to create a mask which we then used to create moment 0, 1 and 2 maps, corresponding the intensity-weighted integrated intensity, velocity and line-width maps, respectively, from our original, 40\(^\prime\) HPBW, data cubes. We estimated the noise in our moment 0 maps using the emission free channels from our 40\(^\prime\) HPBW data cubes. Finally, we re-gridded the ground based data using the wcsalign task in Starlink, using our CO \(J = 4 \rightarrow 3\) integrated intensity map as a reference. The resulting spectral line energy distributions (SLEDs) for CO and [CI] are shown in Figures 5 (individual pixels) and 6 (region averages).

2.2.2 Infrared data

The total infrared luminosity, \(L_{\text{TIR}}\), can be combined with the CO line strengths to provide useful constraints on photon dominated region (PDR) models. We calculate the total infrared luminosity (\(L_{\text{TIR}}\), \(\lambda = 3 – 1100 \mu m\)) using the following empirical relation from Galametz et al. (2013)

\[
L_{\text{TIR}} = c_{24} \nu_{24} L_{24} + c_{70} \nu_{70} L_{70} + c_{160} \nu_{160} L_{160} \tag{1}
\]

where the subscripts 24, 70, and 160 correspond to the 24 \(\mu m\), 70 \(\mu m\), and 160 \(\mu m\) maps respectively, while \(c_{24} = 2.133 \pm 0.095\), \(c_{70} = 0.681 \pm 0.028\) and \(c_{160} = 1.125 \pm 0.010\). We use the Spitzer Space Telescope MIPS 24 \(\mu m\) map reprocessed by Bendo, Galliano & Madden (2012), and the Herschel PACS 70 \(\mu m\) and 160 \(\mu m\) maps from Mentuch Cooper et al. (2012). We beam-match and align all the maps using appropriate kernels from Aniano et al. (2011) before calculating the \(L_{\text{TIR}}\) map. We then beam-match and align the \(L_{\text{TIR}}\) map to our FTS observations using gaussian kernels with the imsmooth command to beam-match, and the imregrid command to regrid, in the Common Astronomy Software Package (CASA) version 4.2.1. The calculation of \(L_{\text{TIR}}\)

\(^4\) http://www.physics.mcmaster.ca/~wilson/xfer/NGLS/
Figure 3. CO integrated intensity maps in units of K km s\(^{-1}\) from the Herschel SPIRE-FTS for the \(J = 4 - 3\) (top left), \(J = 5 - 4\) (top right), and \(J = 6 - 5\) (bottom left), \(J = 7 - 6\) (bottom right) transitions. The CO \(J = 2 - 1\) contours from the IRAM 30 m telescope at a beam size of 13′′ are overlaid (Leroy et al. 2009). The CO integrated intensity maps shown here have been corrected for the semi-extended nature of the source (see Section 2.1). The native FTS beam size at the observed frequencies is shown as a blue circle in the bottom-right corner for each of the CO maps, while the centre of M51 is denoted by a black box. The semi-extended corrected maps have a 40′′ gaussian beam, which is approximately the size of the CO \(J = 7 - 6\) beam.

using the 24 \(\mu\)m, 70 \(\mu\)m, and 160 \(\mu\)m photometric waveband provides a reliable estimate of \(L_{\text{TIR}}\) to within 25 percent (Galametz et al. 2013).

3 NON-LTE EXCITATION ANALYSIS

We use the methods presented in Kamenetzky et al. (2014) to perform a non-LTE excitation analysis to determine the physical state of the molecular gas. Here, we present the highlights of the method used, along with any differences from the previous work. We use the non-LTE excitation code RADEX (van der Tak et al. 2007) along with a Bayesian likelihood code (Kamenetzky et al. 2014) to determine the kinetic temperature (\(T_{\text{kin}}\)), molecular gas density (\(n(\text{H}_2)\)), area filling factor (\(\Phi_A\)) and CO column density per unit line width (\(N_{\text{CO}}\)). In this work, we also include the [CI]/CO column density ratio (\(N_{\text{CI}}/N_{\text{CO}}\)) as one of the fitted parameters. The range of each parameter used in the models is given in Table 2. We compare our measured fluxes to the RADEX models to calculate the likelihood distribution for each of the physical parameters. The code determines the median and 1σ range for each of the physical parameters from the marginalized likelihood distribution, along with the most probable “best-fit” (“4DMax”) solution from the combined multi-dimensional likelihood distribution. By using Bayesian inference, we are able to include priors on the physical parameters based upon the physical characteristics of the observed region.
Figure 4. [CI] integrated intensity maps in units of K km s\(^{-1}\) from the Herschel SPIRE-FTS observations of M51 for the \(^3\)P\(_1\) – \(^3\)P\(_0\) transition at 492 GHz (left) and the \(^3\)P\(_2\) – \(^3\)P\(_1\) transition at 809 GHz (right) transitions. For more details see Figure 3.

Table 2. RADEX grid parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinetic Temperature, cold component ((T_{\text{kin}}, \text{Cold}))</td>
<td>(10^{0.5} - 10^{1.5})</td>
<td>[K]</td>
</tr>
<tr>
<td>Kinetic Temperature, warm component ((T_{\text{kin}}, \text{Warm}))</td>
<td>(10^{0.7} - 10^{3.8})</td>
<td>[K]</td>
</tr>
<tr>
<td>H(_2) density (n(H_2))</td>
<td>(10^{1.0} - 10^{7.0})</td>
<td>[cm(^{-3})]</td>
</tr>
<tr>
<td>Area filling factor ((\Phi_A))</td>
<td>(10^{-5.0} - 1)</td>
<td>...</td>
</tr>
<tr>
<td>CO column density per unit line width ((N_{\text{CO}}/\Delta V)^a)</td>
<td>(10^{12.0} - 10^{18.0})</td>
<td>[cm(^{-2}) (km s(^{-1}))(^{-1})]</td>
</tr>
<tr>
<td>[CI]/CO column density ratio ((N_{\text{[CI]}}/N_{\text{CO}}))</td>
<td>(10^{-2.0} - 10^{2.0})</td>
<td>...</td>
</tr>
<tr>
<td>Line width ((\Delta V))</td>
<td>1.0</td>
<td>[km s(^{-1})]</td>
</tr>
</tbody>
</table>

\(^a\) Column density is calculated per unit linewidth, while the linewidth is held fixed at 1 km s\(^{-1}\) in the calculations (see text).

Table 3. Non-LTE Model Constraints

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO abundance ((x_{\text{CO}}))</td>
<td>(3 \times 10^{-4})</td>
<td>...</td>
</tr>
<tr>
<td>Mean molecular weight ((\mu))</td>
<td>1.5</td>
<td>...</td>
</tr>
<tr>
<td>Angular size scale</td>
<td>48.9 pc/(^{\prime\prime})</td>
<td></td>
</tr>
<tr>
<td>Source size</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>Length ((L))</td>
<td>(\leq 160) pc</td>
<td></td>
</tr>
</tbody>
</table>

3.1 Priors

We introduce three priors into our modeling: the length along the line of sight, the total molecular gas mass and the optical depth. These are the same priors used in Schirm et al. (2014); however the derivation of some of the physical parameters differs. The physical parameters used to calculate the priors are given in Table 3. Note that the line width, which is used to calculate the total column density \(N_{\text{CO}}\), is taken as the average from the CO \(J = 3 - 2\) moment 2 map for all the pixels included in the regional averages.

The first prior is on the total length \((L)\) of the CO and [CI] emitting regions along the line of sight. This prior limits the column density, area filling factor, and molecular gas density such that

\[
\frac{N_{\text{CO}}}{\sqrt{\Phi_A x_{\text{CO}} n(H_2)}} \leq L
\]

(2)

As with all grand design spiral galaxies, the molecular gas in M51 resides predominantly in a disk. We derive our length prior based upon measurements of the scale height of this disk. Pety et al. (2013) calculated the scale height for their extended and compact components to be \(\sim 190 - 250\) pc and \(\sim 10 - 40\) pc, respectively (figure 17 of their work). Their extended component corresponds to a warm, diffuse component, which we do not include in our models. (We discuss the implications of including a diffuse component in Section 5.1.3.) We use the scale height of their compact component and adopt a length prior of 160 pc, a factor of 4 times the maximum scale height (40 pc) derived for the compact component.

The second prior is on the total mass of molecular gas in a single beam. In previous publications (e.g. Rangwala et al. 2011; Kamenetzky et al. 2012; Schirm et al. 2014), we used the dynamical mass to limit the total molecular gas mass within a single beam. This assumption was sensible for systems contained entirely within a single FTS beam, such as Arp 220 (Rangwala et al. 2011). However,
Figure 5. Measured CO (circles), [CI] (triangles), and $^{13}$CO(squares) spectral line energy distribution in units of K km s$^{-1}$ for each pixel in our FTS data cube. The y-axis corresponds to the integrated intensity in units of K km s$^{-1}$ and the x-axis corresponds to $J_{\text{up}}$. The vertical and horizontal scales are the same for each box and are shown in the lower-left box. The CO $J = 1 - 0$ to $J = 3 - 2$ and $^{13}$CO $J = 1 - 0$ transitions are from ground based instruments (see Section 2.2.1). The error bars shown here do not include calibration uncertainties (see Table 1 for the calibration uncertainties). The letter in the upper right corner indicates the pixel's region, where “N” corresponds to the nucleus, “C” the centre, “A” the arm and “I” the inter-arm regions. Only the bolded letters are included in our region averages.
in the case of galaxies which span multiple beams, such as NGC 4038/39 (Schirm et al. 2014) or M51, it is more difficult to determine the dynamical mass per beam. Instead, we calculate an upper limit to the molecular gas mass for each pixel using the CO J = 1 − 0 map along with an \( \alpha_{\text{CO}} \) value of 9 M\(_{\odot}\) pc\(^{-2}\) (K km s\(^{-1}\))\(^{-1}\). This value for the conversion factor corresponds to the largest value for \( \alpha_{\text{CO}} \) seen in the Milky Way and other Local Group Galaxies (\( \alpha_{\text{CO}} \sim 3−9\) M\(_{\odot}\) pc\(^{-2}\) (K km s\(^{-1}\))\(^{-1}\), Leroy et al. 2011). The mass prior for each region is the average from all the pixels included in the region average.

The mass prior places a limit on the beam-averaged column density (\( N_{\text{CO}} = N_{\text{CO}} \Phi_A \))

\[
N_{\text{CO}} \Phi_A < \frac{M_{\text{mol}} x_{\text{CO}}}{\mu m_{\text{H}_2} A_{\text{CO}}}
\]

where \( M_{\text{mol}} \) is our derived mass from the CO J = 1 − 0 map, \( x_{\text{CO}} \) is the CO abundance relative to H\(_2\), \( \mu \) is the mean molecular weight, \( m_{\text{H}_2} \) is the mass of the H\(_2\) molecule, and \( A_{\text{CO}} \) is the area of the CO emitting region, which is the area covered by one beam at the distance of M51.

The third prior limits the optical depth of each line such that \( -0.9 < \tau < 100 \). An optical depth \( \tau \) < 0 is indicative of a maser, and we do not expect CO or [CI] masers to contribute appreciably to the emission on the observed size scales (the limit of -0.9 allows for computational error). Furthermore, the line intensities calculated by RADEX become more uncertain the further the optical depth drops below 0. In addition, van der Tak et al. (2007) suggest limiting the optical depth to an upper limit of 100, as the one-zone approximation implied by its escape probability formalism breaks down at optical depths greater than \( \tau > 100 \).

### 3.2 Non-LTE Excitation Modelling

CO, [CI] and \(^{13}\)CO are all tracers of molecular gas; all three species are excited via collisions with H\(_2\). In the classic slab-geometry model of a photon dominated region (PDR) by Tielens & Hollenbach (1985), [CI] arises from the surfaces of molecular clouds, while CO does not begin to form until deeper into the cloud. In this model, some of the molecular gas is “CO dark” (Wolfire, Hollenbach & McKee 2010). However, there is strong evidence that [CI] and CO are co-spatial (Papadopoulos, Thi & Viti 2004), as supported by observations of the Orion molecular cloud (Plume et al. 1999; Ikeda et al. 2002; Shimajiri et al. 2013) and more recent simulations of molecular clouds (e.g. Offner et al. 2014, Gaches et al. 2015). Furthermore, [CI] may be less sensitive to temperature than CO (Offner et al. 2014), and so may help constrain the density.

We fit a two-component model to our measured CO and [CI] intensities in the nucleus, centre, and arm/inter-arm regions of M51. (A single-component model fit, which does not produce a physically realistic solution, is discussed in Appendix A.) We include the CO transitions from J = 1 − 0 to J = 7 − 6, while leaving the J = 8 − 7 transition as an upper limit. The total uncertainty used is the line fitting and calibration uncertainties added in quadrature. The molecular gas in M51 is unlikely to populate two distinct components in terms of the physical state of the gas, so our two-component fit will represent an average of the state of all the molecular gas within the 3 distinct regions. We are therefore investigating the bulk properties of the molecular gas in the three regions. (For an extensive discussion of one- and two-component modelling, see Kamenzetzky et al. 2014.)

Our two-component fit to the molecular gas consists of a “cold” component which can dominate the lower-J CO transitions, and a “warm” component which dominates the upper-J CO transitions. We include the [CI] in the cold component model only. Our initial tests fitting both components simultaneously while constraining the temperature of the cold component to be \( < 100 \) K resulted in a bimodal temperature distribution, with high probabilities at the upper (100 K) and lower (10 K) ends of the range and a minimum probability around 30 K. Therefore, to isolate better the cold component from the warmer component, we reran the fits while constraining the temperature of the cold component to be \( < 10^{4.5} \) K. The derived physical parameters are given in Table 4; we give both the median value for each parameter as well as the “best fit” value, which is the set of values in the multi-dimensional parameter space with the highest probability. The resulting measured and calculated SLEDs are shown in Figure 6, while the calculated optical depths are shown in Figure 7. The 1\( \sigma \) ranges are shown in Figure 8 and an example of the probability distributions for four of the fit parameters is given in Appendix B.
Table 4. Results from two-component non-LTE excitation analysis

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Nucleus</th>
<th>Centre</th>
<th>Arm/inter-arm</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
<td>Median (-1σ → +1σ; best fit)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cold component:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Log(T_kin)</td>
<td>1.1 (1.0 → 1.3; 1.3)</td>
<td>1.1 (1.0 → 1.3; 1.4)</td>
<td>1.0 (0.9 → 1.4; 1.3)</td>
<td>1.1 (0.9 → 1.4; 1.5)</td>
</tr>
<tr>
<td>Log(n(H_2))</td>
<td>4.0 (3.0 → 5.7; 3.6)</td>
<td>4.3 (3.0 → 6.1; 3.4)</td>
<td>4.3 (2.9 → 6.1; 3.0)</td>
<td>4.1 (2.9 → 6.0; 2.4)</td>
</tr>
<tr>
<td>Log(N(CO))</td>
<td>19.1 (18.6 → 19.5; 19.1)</td>
<td>19.0 (18.6 → 19.4; 19.0)</td>
<td>18.8 (18.3 → 19.2; 18.4)</td>
<td>18.9 (18.4 → 19.3; 18.8)</td>
</tr>
<tr>
<td>Log(Φ_A)</td>
<td>-1.8 (-2.1 → -1.6; -2.1)</td>
<td>-1.8 (-2.1 → -1.5; -2.2)</td>
<td>-1.5 (-1.8 → -1.1; -1.7)</td>
<td>-1.6 (-2.0 → -1.4; -1.5)</td>
</tr>
<tr>
<td>Log(&lt; N(CO) &gt;)</td>
<td>17.2 (16.8 → 17.6; 17.0)</td>
<td>17.2 (16.8 → 17.6; 16.8)</td>
<td>17.3 (16.8 → 17.8; 16.7)</td>
<td>17.2 (16.8 → 17.6; 17.3)</td>
</tr>
<tr>
<td>Log(P)</td>
<td>5.2 (4.2 → 6.7; 4.9)</td>
<td>5.3 (4.3 → 7.1; 4.7)</td>
<td>5.3 (4.2 → 7.0; 4.3)</td>
<td>5.1 (4.2 → 6.9; 3.9)</td>
</tr>
<tr>
<td>Log(N(CII)/N(CO))</td>
<td>1.2 (0.4 → 1.7; 0.4)</td>
<td>1.0 (0.1 → 1.6; 0.2)</td>
<td>1.0 (0.1 → 1.6; 0.2)</td>
<td>0.9 (0.0 → 1.6; -0.2)</td>
</tr>
</tbody>
</table>

Warm component:
| Log(T_kin) | 3.2 (2.8 → 3.5; 3.0) | 2.9 (2.5 → 3.3; 2.9) | 2.8 (2.2 → 3.4; 2.4) | 2.8 (2.4 → 3.4; 2.1) |
| Log(n(H_2)) | 2.1 (1.7 → 2.4; 2.4) | 2.1 (1.6 → 2.5; 1.9) | 2.5 (1.7 → 4.5; 2.4) | 2.3 (1.7 → 3.3; 4.1) |
| Log(N(CO)) | 17.9 (16.9 → 18.7; 16.5) | 17.8 (16.9 → 18.6; 16.4) | 17.6 (16.3 → 18.6; 18.4) | 17.7 (16.6 → 18.6; 16.6) |
| Log(Φ_A) | -1.4 (-1.8 → -0.5; -0.1) | -1.3 (-1.8 → -0.6; 1.6) | -1.7 (-3.0 → -0.7; -2.4) | -1.4 (-2.2 → -0.6; -1.4) |
| Log(< N(CO) >) | 16.5 (16.3 → 16.9; 16.4) | 16.5 (16.3 → 16.9; 16.8) | 15.9 (14.6 → 16.4; 16.4) | 16.3 (15.5 → 16.7; 15.2) |
| Log(P) | 5.3 (4.9 → 5.6; 5.4) | 5.1 (4.6 → 5.3; 4.7) | 5.3 (4.8 → 6.9; 4.8) | 5.1 (4.7 → 6.0; 6.2) |

1 Units for the parameters are as follows: (T_kin): K; (n(H_2)): cm^{-3}; (N(CO)): cm^{-2}; (P): K cm^{-3}; (Φ_A), (N(CII)/N(CO)): dimensionless.

Figure 7. Best-fit line optical depths for the two-component fit for the nucleus (top-left), centre (top-right), and arm/inter-arm (bottom-left) regions, and for all the regions combined (bottom right). The cold component and warm component CO optical depths are shown by the blue and red dashed lines and circles, respectively. The [CI] optical depths are indicated by the solid magenta line and triangles.

4 PHOTON DOMINATED REGIONS

PDRs are regions of molecular gas illuminated by FUV radiation (6.20 eV < E_{ph} < 13.6 eV, Tieless & Hollenbach 1985). While FUV photons are typically not the right energy to dissociate molecular hydrogen, this radiation can have a significant effect on the chemistry and heating of the illuminated region. Indeed, the FUV radiation will liberate electrons from dust grains through the photoelectric effect, which in turn will heat the molecular gas through collisions.

Using a PDR model grid (Hollenbach et al. 2012 and M. Wolfire, private communication), we model the ratio of CO transitions (e.g. CO J = 3 → 2/J = 2 → 1, etc.) for the nucleus, centre and arm/inter-arm regions of M51, along with the combination of all three regions. The model uses the molecular gas density (n(H_2)) and FUV field strength (G_0) in units of the Habing field (FUV flux = 1.3 × 10^{-4} G_0 ergs cm^{-2} s^{-1} sr^{-1}). The model grid spans a large range of density (n(H_2) = 10^{1.0} cm^{-3} to 10^{6.0} cm^{-3}) and FUV field strengths (G_0 = 10^{-5} to 10^{-5}) to calculate the CO fluxes for the transitions from J = 1 → 0 up to J = 29 → 28. We show the CO model grid along with the line ratios measured for the nucleus of M51 in Figure 9. We also show the cold component density range calculated from our two-component RADEX fit overlaid on the low J line ratios (Figure 9, left column) and the warm component density range overlaid on the high J line ratios (Figure 9, right column).

The CO ratios alone are unable to constrain both the density and FUV field strength (Figure 9). The ratio of L_{CO}/L_{TIR} provides an upper limit to the FUV field strength. We calculate a grid of the ratio of L_{CO,J→3−2}/L_{TIR} and L_{CO,J→6−5}/L_{TIR} by estimating L_{TIR} as twice the FUV field strength (Kaufman et al. 1999). We show the resulting grid in the bottom panel of Figure 9, along with the measured ratio for the nucleus of M51. We correct the measured CO-to-TIR line ratios by multiplying the ratio by 2 to account for the fact that the measured CO emission from the PDR model is only from one side of the PDR, while the TIR emission as estimated is assumed to originate from both sides of the PDR. We show the measured L_{CO,J→3−2}/L_{TIR} ratios for the remaining regions in Figure 10, and the L_{CO,J→6−5}/L_{TIR} ratios in Figure 11.

For the low-J CO line ratio PDR model, the CO line ratios coupled with the ratio of L_{CO,J→3−2}/L_{TIR} constrain
The field strength to $G_0 < 10^2$ in all the modelled regions, while the PDR model density agrees with the low end of the range of density from our non-LTE analysis ($n({H_2}) \sim 10^3 - 10^{3.5}$ cm$^{-3}$, Figure 10). For the high-J CO line ratio PDR model, the CO line ratios limit the density to $n({H_2}) \gtrsim 10^4$ cm$^{-3}$, while the ratio of $L_{CO,J=6-5}/L_{TIR}$ limits the field strength to $G_0 \lesssim 10^n$ for all the modelled regions (Figure 11). For the nucleus and centre regions, these densities are significantly higher than the densities calculated from our non-LTE analysis ($n({H_2}) \sim 10^2 - 10^{3.5}$ cm$^{-3}$) and so these PDR models do not provide a good fit to the data. For the arm/interarm region, both low ($n({H_2}) \sim 10^2$ cm$^{-3}$) and high ($n({H_2}) \sim 10^4$ cm$^{-3}$) density solutions exist; tighter constraints on the density are required to distinguish between the two solutions.

5 DISCUSSION

5.1 Physical state of the molecular gas

5.1.1 Regional variations

The physical state of both the cold and warm molecular gas can vary significantly from source to source, depending upon the environment in which the molecular gas resides. The results for the cold and warm components for the nucleus, centre and arm/inter-arm regions of M51 are shown in Table 4 and Figure 8. For each of the components, no significant differences between regions are seen among any of the physical parameters. The density of the cold molecular gas in all 3 regions ($n({H_2}) \sim 10^4$ cm$^{-3}$) is typical for GMCs in the Milky Way (e.g. Tielens 2005), but is uncertain by three orders of magnitude (Table 4). The temperature of the cold component in all 3 regions is very similar to the typically quoted value of $\sim 10$K for Milky Way GMCs. Given the $1\sigma$ ranges for the beam-averaged column densities in Table 4, any differences would need to be greater than a factor of $\sim 5$ ($\sim 10$ for the arm/inter-arm region) to be seen in our results. Similarly for the warm component, we detect...
Figure 9. PDR model line ratios for CO $J=3−2$ (top-left), $J=2−1$ (middle-left), $J=8−7$ (top-right), and $J=7−6$ (middle-right) for the nucleus of M51 in units of W m$^{-2}$. Note that the ratio of $J=8−7$ to $J=6−5$ is an upper limit. In the top two rows, the dotted contours correspond to constant CO line ratios. The blue (top-row) and yellow (middle-row) shaded regions correspond to the uncertainty in the measured line ratio for the nucleus. In the bottom row, the dotted contours correspond to constant value of $L_{CO}J=3−2/L_{TIR}$ (bottom-left) and $L_{CO}J=6−5/L_{TIR}$ (bottom-right), while the solid purple line is the measured ratio for each. The shaded regions in the bottom-row panels correspond to the same CO line ratios of the two panels directly above, while the green region indicates where the two line ratios overlap. The blue (left-column) and red (right-column) dashed vertical lines correspond to the cold and warm component 1σ ranges for the densities from the two-component RADEX solutions.
Figure 10. Same as the bottom-left panel of Figure 9 except for the cold-component PDR solutions for the nucleus (top-left), centre (top-right), and arm/inter-arm (bottom-left) regions of M51, and for all four regions combined (bottom-right). Note that the line ratios are calculated in units of W m$^{-2}$.

Figure 11. Same as the bottom-right panel of Figure 9 except for the warm-component PDR solutions for the nucleus (top-left), centre (top-right), and arm/inter-arm (bottom-left) regions of M51, and for all four regions combined (bottom-right). Note that the line ratios are calculated in units of W m$^{-2}$.

no differences between the temperature, density or beam-averaged column density across the 3 regions. The warm molecular gas has a temperature of $\sim 1000$ K. In the nucleus and centre, the density of the warm component is quite low ($n(H_2) \sim 10^{1.6} - 10^{2.5}$ cm$^{-3}$), while for the arm/inter-arm region the density is not very well constrained.

The similarities in the nucleus and centre of M51 are likely due to contamination of the beam at the nucleus position by emission from the centre region. Parkin et al. (2013) used data with a 12$''$ beam and defined the nucleus to be a square $\sim 12''$ across. Given the 40$''$ beam of our observations, our nucleus region will be somewhat contaminated by emission from the centre region, and vice versa.

### 5.1.2 Comparison to previous studies

Both Israel, Tilanus & Baas (2006) and Schinnerer et al. (2010) modelled various ratios of CO and $^{13}$CO in M51. Schinnerer et al. (2010) used a non-LTE analysis to model ratios of $^{12}$CO $J = 1 - 0$ and $J = 2 - 1$, and $^{13}$CO $J = 1 - 0$ at multiple positions of the western arm and southern regions of M51 at resolutions of 2$''$.9 and 4$''$.5; however these regions lie beyond our FTS maps. They recovered cold (14 – 20 K), moderately dense ($n(H_2) \sim 10^{2.5} - 10^{3.0}$ cm$^{-3}$) gas.

Israel, Tilanus & Baas (2006) modelled $^{12}$CO $J = 1 - 0$ to $J = 4 - 3$ and $^{13}$CO $J = 1 - 0$ to $J = 3 - 2$ line ratios at two locations in M51: the centre and in a giant molecular association (GMA) offset from the nucleus. Using an LVG model, they fit two components to the CO line ratios, assuming that $[^{12}$CO]/$[^{13}$CO] $\approx 40$. For the offset GMA, they find a warm ($\sim 100$ K), relatively diffuse ($\sim 10^{2.0}$ cm$^{-3}$) component, and a warmer ($\sim 150$ K), more dense ($\sim 10^{3.0}$ cm$^{-3}$) component. For the centre, they find a relatively warm ($\sim 100 - 1000$ K), lower density ($\sim 10^{2.0} - 10^{3.0}$ cm$^{-3}$) component, and a cooler ($\sim 20 - 60$ K), higher density ($10^{3.0} - 10^{4.0}$ cm$^{-3}$) component. The cold component from our two-component fit agrees with their centre results in both density and temperature, although our models do not constrain the density particularly well. Our warm component fit also agrees with their centre results in both density and temperature. Unlike Israel, Tilanus & Baas (2006), we have observations of CO beyond the $J = 4 - 3$ transition and so are able to place significantly tighter constraints on the temperature of the warm component.

Brunner et al. (2008) probed the warm and hot molecular gas in M51 using the mid-infrared H$_2$ rotational transitions $S(0) - S(5)$ in a strip. They found that the low-J H$_2$ transitions ($S(0) - S(2)$) trace warm ($\sim 100 - 300$ K) molecular gas, while the high-J H$_2$ transitions ($S(2) - S(5)$) trace hot molecular gas ($\sim 400 - 1000$ K). The temperature ranges for the warm and hot H$_2$ gas agree quite well with the warm component from our fit to the CO data.

### 5.1.3 Diffuse molecular gas

As part of the PAWS collaboration, Pety et al. (2013) mapped the CO $J = 1 - 0$ emission in M51 at arcsecond resolution. By combining the Plateau de Bure Interferometer (PdBI) interferometric data with the IRAM 30m data,
they were able to correct for the “missing flux” from the interferometric observations. They find that \~\~ 50 percent of the CO $J = 1 - 0$ emission is from molecular gas located in a thick, extended disk with a scale height \~\~ 200 pc. Pety et al. (2013) argue that this emission originates from a warm (\~\~ 50 - 100 K), diffuse (\~\~ 100 - 500 cm$^{-3}$) molecular component.

We investigate the possible effects of this extended CO emission on our two-component non-LTE model by fitting various combinations of the CO and [CI] transitions (Table 5). We begin by setting the CO $J = 1 - 0$ flux to half of the measured flux and fitting it along with the remaining CO and [CI] transitions as before (half$10^1$). Additionally, to investigate any contributions from the warm, diffuse component to the CO $J = 2 - 1$ transition, we set the CO $J = 2 - 1$ transition as an upper limit while fitting half of the CO $J = 1 - 0$ flux (half$10^2$ul). We compare these solutions to our original two-component solutions (all lines) for the centre region in Table 5. For the cold component, the 1σ ranges for the kinetic temperatures do not shift significantly among the models, while the 1σ ranges for the molecular gas density narrow slightly for both the half$10$ and half$10^2$ul solutions compared to the all lines solution. However, the half$10$ and half$10^2$ul warm component solutions have significantly higher densities, higher pressures, and lower beam-averaged column densities compared to the all lines solution.

The changes in the warm component density for both the half$10$ and half$10^2$ul solutions suggest that the diffuse molecular gas component from Pety et al. (2013) contributes to the CO $J = 1 - 0$ emission, and possibly the CO $J = 2 - 1$ emission. However, determining the physical characteristics of this component using a non-LTE model, such as the one presented in Section 3, would be difficult. The CO $J = 1 - 0$ emission from the diffuse, extended component is subthermally excited and there would be even less contribution from the diffuse component to higher J CO transitions. While Pety et al. (2013) use the ratio of $^{12}$CO/$^{13}$CO to argue for the existence of this diffuse component, including only a single $^{13}$CO transition in a non-LTE analysis requires assuming a relative abundance ratio of $^{12}$CO and $^{13}$CO in the diffuse component.

The existence of an extended, diffuse component does not preclude the diffuse molecular gas, at least in part, being contained within GMCs. Diffuse GMCs exhibiting high ratios of $^{12}$CO/$^{13}$CO have been observed at high latitudes within our own Galaxy (Blitz, Magnani & Mundy 1984). In this scenario, the limited sensitivity of the interferometer along with the unresolved nature of the brightest clumps of the diffuse GMCs would lead to the interferometer filtering out these diffuse GMCs (Pety et al. 2013).

The critical densities of the [CI] $J = 1 - 0$ and $J = 2 - 1$ transitions are $n_{10} \sim 500$ cm$^{-3}$ and $n_{21} \sim 10^3$ cm$^{-3}$, respectively (Papadopoulos, Thi & Viti 2004). These are comparable to the critical density of CO $J = 1 - 0$ ($n_{cr} \sim 1.1 \times 10^3$ cm$^{-3}$), which indicates that [CI] could also, at least in part, be tracing a diffuse molecular component. High-resolution observations of [CI] in galaxies like M51 coupled with single dish observations, as for CO in Pety et al. (2013), may be useful in constraining the physical state of this diffuse gas. Combining such observations with interferometric observations of dense gas tracers, such as HCN and HCO$^+$ would allow us to discriminate between dense and diffuse GMCs. Finally, high-sensitivity, flux-recovered observations of a combination of these molecular gas-tracing species using the Atacama Large Millimeter Array (ALMA) would help differentiate between a truly extended component or a collection of diffuse GMCs. Unfortunately, M51 itself is not a viable target for ALMA due to its high declination.

### 5.2 PDR modelling

Our comparison of the PDR and non-LTE models suggests that the warm component of the molecular gas in the nucleus and centre of M51 is unlikely to reside primarily in simple PDRs. The LINER nucleus (Satyapal, Samburua & Dudik 2004) may produce a small X-ray dominated region that could affect the excitation in the vicinity of the nucleus. On larger scales, Kazandjian et al. (2015) has shown that a relatively small amount of mechanical heating from supernovae and stellar winds can have significant effects on the temperature of the molecular gas. The presence of active star formation in M51 certainly suggests that supernovae will be present in the disk. However, we cannot easily estimate the mechanical heating due to supernovae and stellar winds for M51 as the necessary supernova rate data do not exist. The strong spiral density wave in M51 may also create shocks that are themselves a potential source of mechanical heating. We also note that our efforts to estimate the effect of the diffuse molecular component proposed by Pety et al. (2013) result in models with higher warm component densities that would be consistent with PDR models. We therefore focus our discussion in this section on the cold component of the molecular gas, for which the PDR models are able to reproduce the CO data.

Both Kramer et al. (2005) and Parkin et al. (2013) previously modelled PDRs in M51. Kramer et al. (2005) modelled various ratios of [CI]$^{158\mu m}$, [OI]$^{63\mu m}$, [CI] $J = 1 - 0$, CO $J = 1 - 0$ and CO $J = 3 - 2$ using the PDR models from Kaufman et al. (1999). They found that the best fit solution to their line ratios at all 3 pointings was consistent with density of $n(H_2) \sim 4 \times 10^4$ cm$^{-3}$ and a field strength of $18 < G_0 < 32$ in an 80" beam. While their value of $G_0$ is comparable to the results for our cold component, their value for the density is an order of magnitude larger than our result.

Parkin et al. (2013) used the [CII]/[OI]$63\mu m$ and ([CII] + [OI]$63\mu m$)/TIR ratios along with the PDR models from Kaufman et al. (1999) and Kaufman, Wolfe & Hollenbach (2006) to constrain the density and field strength in the nucleus, centre, arm and inter-arm regions of M51 (see Figure 2). They corrected the [CII] emission for the ionized gas fraction and [OI]$^{63\mu m}$ for orientation effects due to the plane-parallel slab-nature of the models (see Section 4.1 of Parkin et al. 2013 for details). Their results for the nucleus ($n(H_2) = 10^{3.75} - 10^{4.0}$ cm$^{-3}$, $G_0 = 10^{3.25} - 10^{3.75}$) do not agree with our “cold” PDR solution, falling above the range allowed by our CO line ratios and our CO/TIR ratios. Their density for the centre ($n(H_2) = 10^{3.0} - 10^{3.75}$ cm$^{-3}$) agrees with our “cold” PDR solution density, while their field strength ($G_0 = 10^{2.75} - 10^{3.0}$) exceeds what is allowed by our ratio of CO/TIR combined with various CO line ratios (Figure 10). Their results for both the arm and inter-
arm regions are similar: the ranges reported for the density \((n(H_2) = 10^{2.75} - 10^{3.60} \text{ cm}^{-3})\) agree with our results, while the FUV field strength \((G_0 = 10^{2.25} - 10^{2.3})\) is larger than our allowed solutions.

Our “cold” PDR results suggest a density of \(n(H_2) \sim 10^3 \text{ cm}^{-3}\) and FUV field strength of \(G_0 < 10^2\). In the Kaufman et al. (1999) and Kaufman, Woffilee & Hollenbach (2006) PDR models, this would correspond to \(T_{\text{kin}}(\text{HI}) > 1.7\) and \(\frac{\text{[CI]}}{\text{[OI]}(63\mu\text{m})} > 1.3 \times 10^{-2}\). The average values of these ratios in each of the nucleus, centre, arm and inter-arm regions from Parkin et al. (2013) vary between \(0.2 \sim 1.2\) and \(\frac{\text{[CI]}}{\text{[OI]}(63\mu\text{m})} \sim (5.0 - 8.1) \times 10^{-3}\). For both ratios, the values for our “cold” PDR solution are a factor of \(\sim 1.5\) greater than the values measured in Parkin et al. (2013). Smoothing the Parkin et al. (2013) data to our 40\arcsec beam and remeasuring these ratios does not change the average values significantly. However, including the \(\sim 30\%\) percent calibration uncertainty of the PACS spectrometer\(^5\) leads to a range of \(\frac{\text{[CI]}}{\text{[OI]}(63\mu\text{m})} \sim (3.5 - 10.5 \times 10^{-3})\), which agrees within 50 percent with the range necessary to reproduce our results using the Kaufman, Woffilee & Hollenbach (2006) PDR models. Accounting for the calibration uncertainty leads to a range of \(\sim 0.4 - 1.8\) for the ratio of \(\frac{\text{[CI]}}{\text{[OI]}(63\mu\text{m})}\), which agrees within uncertainties with the model value of \(> 1.7\).

We attribute the remaining disagreement to the simplified geometries assumed by the PDR models, which can lead to differences in the model results (Röllig et al. 2007). Both the model used in Parkin et al. (2013) and the model used here assume a semi-infinite slab of gas illuminated by an FUV field. In reality, PDRs are clumpy media which are affected by other physical processes concurrently. Mechanical heating, for example, can have a significant effect on the atomic and ion line ratios, as well as on the overall shape of the CO SLED (Kazandjian et al. 2015). Combining the measurements from Parkin et al. (2013) and our measured CO SLED, along with observations of other molecular gas tracers such as HCN and HCO\(^+\) would be necessary to quantify the contributions of mechanical heating to the PDRs in M51.

5 PACS Observers Manual is available for download from the ESA Herschel Science Centre.

5.3 Comparison to other VNGS galaxies

M51 is the 6th galaxy in the VNGS sample for which the analysis of the SPIRE-FTS observations of CO have been published, and is the first normal, quiescent spiral galaxy from the sample. Only a single-component fit was to the CO SLED for M83 (Wu et al. 2015), while for NGC 1068 (Spinoglio et al. 2012), the extended (star-forming ring) and compact (circumnuclear disk) CO emission was fit separately, taking advantage of the varying beam size of the SLW and SSW. In the case of Arp 220 (Rangwala et al. 2011), M82 (Panuzzo et al. 2010; Kamenetzky et al. 2012) and NGC 4038/39 (Schirm et al. 2014), a two-component fit was performed for the CO, \(^{13}\)CO(M82) and [CI](NGC 4038/39) emission. Arp 220, M82 and NGC 4038/39 are all examples of either an interaction or an ongoing merger. Arp 220 \((D = 77 \text{ Mpc}, \text{Scoville, Yun & Bryant } 1997)\) is an ultra luminous infrared galaxy and is an advanced merger between two galaxies. M82 \((D = 3.4 \text{ Mpc}, \text{Dalcanzon et al. 2009})\) is a starburst galaxy (Yun, Ho & Lo 1993) whose increased star formation rate is due to a recent interaction with the nearby M81. Finally, NGC 4038/39 \((D = 22 \text{ Mpc}, \text{Schweizer et al. 2008})\) is an ongoing merger between two gas rich spiral galaxies.

We compare our two-component fit for the centre region of M51 to those of Arp 220, M82 and NGC 4038/39 (Table 6 and Figure 12). We also compare our results to the mean values for the two-component fits of Kamenetzky et al. (2014) for 17 galaxies, including the 5 galaxies from the VNGS. For NGC 4038/39, we distinguish between the region where the two merging gas disks overlap (the “overlap region”) and the nucleus of NGC 4038 (hereafter NGC 4038). For NGC 4038, the physical size corresponding to the beam of the observations \((\sim 43''\) is \(\sim 4.6 \text{ kpc}\). In comparison, our analysis of M51 covers the central \(\sim 5 \text{ kpc}\) \((\sim 100''\). Note that for Arp 220, the CO emission is point-like within the FTS beam (Rangwala et al. 2011) and the actual column density is reported in Table 6. (Rangwala et al. 2011) only report best fit values for the parameters for Arp 220 (rather than medians); however, the probability distributions for the Arp 220 fits are quite narrow and so the difference between median and best fit is likely small for this galaxy.)

The characteristics of the cold component for the centre region of M51 are very similar to the two regions in...
Table 6. Comparing radiative transfer solutions

<table>
<thead>
<tr>
<th>Comp.</th>
<th>Source</th>
<th>Log((n(\text{H}_2))) [Log(cm(^{-3}))]</th>
<th>(T_{\text{kin}}) [K]</th>
<th>Log(&lt; (N_{\text{CO}})&gt; [Log(cm(^{-2})])</th>
<th>Log((P)) [Log(K cm(^{-2}))]</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold</td>
<td>Centre of M51</td>
<td>4.3 (3.0 – 6.1)</td>
<td>12 (10 – 21)</td>
<td>17.2 (16.8 – 17.6)</td>
<td>5.3 (4.3 – 7.1)</td>
<td>This work</td>
</tr>
<tr>
<td></td>
<td>Arp220(^1)</td>
<td>2.8 (2.6 – 3.2)</td>
<td>50 (34 – 67)</td>
<td>20.3 (19.9 – 20.3)</td>
<td>4.5 (4.5 – 4.8)</td>
<td>Rangwala et al. (2011)</td>
</tr>
<tr>
<td></td>
<td>M82</td>
<td>3.2 (2.4 – 4.8)</td>
<td>40 (12 – 472)</td>
<td>18.2 (17.6 – 18.8)</td>
<td>5.1 (4.6 – 5.8)</td>
<td>Kamenetzky et al. (2012)</td>
</tr>
<tr>
<td></td>
<td>NGC4038</td>
<td>3.7 (3.1 – 4.3)</td>
<td>24 (18 – 33)</td>
<td>17.1 (16.6 – 17.6)</td>
<td>5.0 (4.5 – 5.6)</td>
<td>Schirm et al. (2014)</td>
</tr>
<tr>
<td></td>
<td>Overlap region</td>
<td>3.7 (2.9 – 4.4)</td>
<td>20 (15 – 27)</td>
<td>17.4 (16.8 – 17.9)</td>
<td>4.9 (4.3 – 5.6)</td>
<td>Schirm et al. (2014)</td>
</tr>
</tbody>
</table>

| Warm       | Centre of M51         | 2.1 (1.6 – 2.5)                          | 755 (347 – 2089)        | 16.5 (16.3 – 16.9)              | 5.1 (4.6 – 5.3)                 | This work           |
|            | Arp220\(^1\)         | 3.2 (3.0 – 3.2)                          | 1343 (1247 – 1624)      | 19.4 (19.4 – 19.5)              | 6.3 (6.2 – 6.4)                 | Rangwala et al. (2011) |
|            | M82                   | 4.0 (3.5 – 4.2)                          | 414 (335 – 518)         | 16.7 (16.4 – 17.2)              | 6.6 (6.2 – 6.8)                 | Kamenetzky et al. (2012) |
|            | NGC4038               | 5.8 (4.8 – 6.6)                          | 1065 (347 – 3397)       | 14.4 (14.2 – 14.8)              | 9.3 (8.2 – 10.2)                | Schirm et al. (2014)  |
|            | Overlap region        | 4.2 (4.0 – 4.7)                          | 1425 (430 – 3811)       | 14.6 (14.4 – 14.7)              | 7.4 (7.3 – 7.7)                 | Schirm et al. (2014)  |

1 “Best fit” values and actual \(N_{\text{CO}}\) reported for Arp 220; see text.

Figure 12. Comparison of results from the Very Nearby Galaxies Survey. The error bars represent the 1\(\sigma\) ranges reported in Table 6 and the symbols are placed at the median of the distribution. The values for the temperature (y-axis) and molecular gas density (x-axis) are the non-LTE excitation analysis results from this work (centre of M51), Rangwala et al. (2011) (Arp 220), Kamenetzky et al. (2012) (M82), and Schirm et al. (2014) (NGC 4038 and the overlap region). The cold and warm components are represented by the blue and red data points, respectively.

NGC 4038/39. Aside from the large temperature range for M82 (\(T_{\text{kin}} = 12 – 472\) K), the cold molecular gas in M51 is also similar to that of M82. The temperature of the cold molecular gas in Arp 220 (\(T_{\text{kin}} = 34 – 67\) K) is above the temperature range we adopted in fitting the cold component in M51. The cold component fits to the 17 galaxies from Kamenetzky et al. (2014) cover a similar range in temperature (\(T_{\text{kin}} = 12 – 250\) K).

The warm component of M51 shows more differences than the cold component when compared to the other galaxies, with a lower density (\(n(\text{H}_2) = 10^{3.6} – 10^{5.5}\) cm\(^{-3}\)) than any of the other 3 systems (\(10^3 < n(\text{H}_2) < 10^{6.6}\) cm\(^{-3}\)). The warm component fits from Kamenetzky et al. (2014) have a similar temperature range to M51, but densities (\(10^{2.3} < n(\text{H}_2) < 10^{4.9}\) cm\(^{-3}\)) that only just overlap the M51 solution.

The molecular gas mass is proportional to the beam size multiplied by the beam-averaged column density. Since the beam-size in any one system will be the same for the cold and warm components, we can calculate the warm gas mass as a fraction of the cold gas mass using the beam-averaged column densities. In M51, the \(1\sigma\) range for the warm gas mass is 7-65 percent (mean 20 percent) of the cold gas mass for the nucleus and centre regions, and 0.2-30 percent (mean 3 percent) for the arm/interarm region. Interestingly, these fractions are comparable to the warm gas mass fractions of \(\sim 10\) percent in Arp 220 (Rangwala et al. 2011) and \(\sim 3\) percent in M82 (Kamenetzky et al. 2012) but are significantly larger than the warm gas mass fraction of \(\sim 0.1\) percent in NGC 4038 and the overlap region (Schirm et al. 2014). The average ratio of warm to cold gas mass in the Kamenetzky et al. (2014) sample is 12 percent, with a range from 0.4 percent (for NGC 4038) to 40 percent.

The global star formation rates in Arp 220 (\(\sim 200\) M\(_\odot\) yr\(^{-1}\), Barcos-Munoz et al. 2015) and M82 (\(\sim 10\) M\(_\odot\) yr\(^{-1}\), Yun, Ho & Lo 1993) are larger than the global star formation rates in M51 (\(\sim 2.6\) M\(_\odot\) yr\(^{-1}\) Schuster et al. 2007) and NGC 4038/39 (\(> 5\) M\(_\odot\) yr\(^{-1}\), Stanford et al. 1990) by factors of 2 – 80. In addition, the gas and star formation rate surface densities are significantly higher in Arp 220 (Rangwala et al. 2011) and M82 (Kamenetzky et al. 2012), where the active regions are roughly 1 kpc in size, than in M51 and the Antennae, where the activity is spread over the entire disk. The primary heating source for the warm molecular gas in Arp 220 (Rangwala et al. 2011) and M82 (Kamenetzky et al. 2012) was found to be mechanical heating due primarily to supernova and stellar winds (Maloney 1999). The higher warm gas mass fraction in Arp 220 and M82 compared to NGC 4038/39 was attributed to an increase in the efficiency by which energy from supernova and
stellar winds is injected as thermal energy into the molecular gas (Schirm et al. 2014). It is unclear whether stellar feedback can also explain the high warm gas mass fraction in M51. Perhaps shocks produced by the strong spiral density wave in M51 can provide an efficient source of turbulent energy.

The overlap region of NGC 4038/39 provides us with a comparison of the effects of an early stage major merger to the less pronounced interaction seen in M51. The most striking differences are in the density and pressure of the warm molecular gas, which are both roughly two orders of magnitude smaller in M51 compared to the overlap region of NGC 4038/9. In NGC 4038/39, supernova and stellar winds were found to be sufficient to heat the warm molecular gas (Schirm et al. 2014). For the densest gas, there is also evidence that PDRs with at least 5 percent mechanical heating contribute to the overall heating budget (Schirm et al. 2016). In M51, there is strong evidence to suggest that PDRs are fundamental to the molecular gas heating (e.g. see Roussel et al. 2007 and Parkin et al. 2013), although PDR models may not be sufficient to explain the heating of the warm component (§5.2). Both PDRs and mechanical heating, however, are tied to the star formation rate as both require the formation of O and B stars which are relatively short lived. A relatively small amount of mechanical heating compared to heating due to PDRs (∼ 1 percent) is able to produce a significant effect on the temperature of the molecular gas (e.g. Kazandjian et al. 2012). In NGC 4038/39, the turbulent motion due to both the ongoing merger and stellar feedback should exceed this minimum threshold (Schirm et al. 2014). It is possible that similar effects are also at work in M51, which is itself an interacting system. Using more sophisticated PDR models which include contributions from mechanical heating, along with dense gas tracers such as HCN and HCO+, may allow us to calculate the contributions to the total gas heating from PDRs and mechanical heating in M51, NGC 4038/39, and other systems.

6 SUMMARY AND CONCLUSIONS

In this paper, we have presented intermediate-sampled SPIRE-FTS observations of CO from \( J = 4 - 3 \) to \( J = 8 - 7 \) and both [CI] transitions of the central region of M51. We supplemented these observations with ground-based observations of CO \( J = 1 - 0 \) to \( J = 3 - 2 \). We separate M51 into 3 regions, the nucleus, centre and arm/inter-arm regions, by performing an unweighted average of the emission for each pixel contained with a region. We also combine all the pixels within the three into a single “All” region.

(i) Using the non-LTE excitation code RADEX along with a Bayesian likelihood code, we perform a two-component fit to the CO and [CI] emission in the nucleus, centre and arm/inter-arm regions of M51, along with all three regions combined. We find that the results do not vary beyond 1σ for all three regions. The results for the nucleus and centre regions of M51 consist of a cold component (\( T_{\text{kin}} \sim 10 - 20 \text{ K} \)) with a moderate but poorly constrained density (\( n(H_2) = 10^3 - 10^6 \)) and a warm, somewhat lower density component (\( T_{\text{kin}} \sim 300 - 3000 \text{ K}, n(H_2) = 10^{1.6} - 10^{2.5} \)). The results for the arm/inter-arm region, and for all regions combined are not as well constrained. The warm gas mass fraction for the centre of M51 is ∼ 20 percent.

(ii) Pety et al. (2013) argue that ∼ 50 percent of the CO \( J=1-0 \) emission in M51 arises from warm diffuse gas. We investigate the possible effect of this extended component by re-running our models with the CO \( J = 1 - 0 \) flux set to half of the measured flux in our non-LTE analysis. The density range of the cold molecular gas narrows somewhat in these models, while the warm component shifts to significantly higher density and pressure. This analysis is consistent with the remaining CO \( J = 1 - 0 \) emission originating from a more diffuse, possibly extended component of the molecular gas. We suggest that this diffuse molecular gas may still arise from GMCs. High-resolution, high-sensitivity, flux-recovered observations of multiple molecular gas-tracing species, such as [CI], HCN and HCO+ along with CO would allow us to distinguish between dense and diffuse GMCs.

(iii) We compare line ratios of CO along with the \( \frac{CO_{J=3-2}}{TIR} \) and \( \frac{CO_{J=6-5}}{TIR} \) ratios to a PDR model. Using the densities calculated from our non-LTE excitation analysis, our PDR modelling suggest a density of \( n(H_2) = 10^3 \text{ cm}^{-3} \) and a field strength \( G_0 < 10^2 \) for the cold component. Although the warm component in the arm/interarm regions is consistent with PDR heating, additional heating sources beyond PDRs seem to be required for the nucleus and centre regions. We compare our results to previous results (Parkin et al. 2013) which used various atomic line ratios and the total infrared flux to model the FUV field strength and gas density, and find that their FUV field strength (\( G_0 > 10^2 \)) is greater than what is allowed by our models. We attribute the differences to calibration uncertainties in the atomic line ratios used by Parkin et al. (2013) and the simple geometry assumed by the PDR models.

(iv) We compare our two-component model for the centre region of M51 to similar models for the ULIRG Arp 220, the starburst galaxy M82 and the on-going merger NGC 4038/39. The characteristics of the cold component are comparable across all 4 systems, with the exception of the temperature of Arp 220, which is slightly higher. In the case of the warm component, the density in the centre region of M51 (\( n(H_2) \sim 10^4 - 10^5 \)) is lower than the other 3 systems (\( n(H_2) \sim 10^3 - 10^6 \)), while the temperatures are comparable. Interestingly, the warm gas mass fraction in M51 is higher than in the NGC 4038/9 merger and comparable to what is seen in Arp 220 and M82. We suggest that a more complete multi-phase analysis of the molecular gas in M51 including both PDR models and mechanical heating would increase our understanding of this iconic system.

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Appendices

APPENDIX A: SINGLE-COMPONENT FIT

We fit a single-component to the 7 detected CO transitions ($J = 1 - 0$ to $J = 7 - 6$), and both [CI] transitions, setting the CO $J = 8 - 7$ transition as an upper limit, in the nucleus, centre and arm/inter-arm regions of M51, along with all 3 regions combined. We show the calculated fluxes from the “best fit” solution compared to the measured fluxes in Figure A1. We report the best-fit solution for each of the physical parameters in Table A1, along with the $1\sigma$ ranges for each parameter.

For all of the modelled regions, our single-component fits suggest that the CO emission is dominated by warm ($\sim 100 - 300$ K), relatively diffuse ($\ll 10^{2.4} - 10^{2.8}$ cm$^{-3}$) molecular gas. While diffuse, CO emitting molecular gas has been observed within the Milky Way (e.g. see Pety, Lucas & Liszt 2008 and Liszt, Pety & Tachihara 2009), most of the star-forming molecular gas is much colder than 200 K. Furthermore, GMC scale observations of CO $J = 1 - 0$ in M51 by Hughes et al. (2013b) find that the CO peak brightness temperature ranges from $T_{mb} = 1 - 10$ K on spatial scales of $\sim 50$ pc ($\sim 1''$). Assuming the CO emission fills the beam, the CO peak brightness temperature corresponds to the molecular gas temperature. If the molecular gas were at a temperature of $\sim 200$ K, as recovered in our single-component model, only $\sim 0.5 - 5$ percent of the $1''$ beam would be filled. Given the typical sizes of GMCs ($10 - 100$ pc), our single-component model does not appear likely to represent accurately the bulk of the molecular gas in M51.

APPENDIX B: PARAMETER DISTRIBUTIONS

Figure B1 shows the probability distributions from the two-component Bayesian RADEX model fits to the centre region of M51. The distributions for the cold component fit are shown in blue while the distributions for the warm component fit are shown in red. Many of the distributions are decidedly asymmetric. In particular, the density distribution for the cold component fit is very broad (see also Table 4). The probability distributions for the fits to the nucleus and arm/interarm regions as well as to the average of all the data are very similar to the distributions for the centre region shown in Figure B1.
Table A1. Results from single-component non-LTE excitation analysis

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Nucleus</th>
<th>Centre</th>
<th>Arm/inter-arm</th>
<th>All</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{\text{kin}}$</td>
<td>234 (162–320)</td>
<td>141 (112–256)</td>
<td>104 (90–236)</td>
<td>141 (110–277)</td>
<td>[K]</td>
</tr>
<tr>
<td>$\log(n(\text{H}_2))$</td>
<td>2.37 (2.36–2.74)</td>
<td>2.54 (2.41–2.82)</td>
<td>2.46 (2.38–2.84)</td>
<td>2.54 (2.36–2.82)</td>
<td>[Log(cm$^{-3}$)]</td>
</tr>
<tr>
<td>$\log(N_{\text{CO}})$</td>
<td>18.68 (17.85–18.64)</td>
<td>18.70 (17.69–18.67)</td>
<td>18.74 (17.05–18.53)</td>
<td>18.56 (17.36–18.57)</td>
<td>[Log(cm$^{-2}$)]</td>
</tr>
<tr>
<td>$\log(\Phi_A)$</td>
<td>$-1.57 (-1.72–-1.26)$</td>
<td>$-1.64 (-1.74–-1.18)$</td>
<td>$-1.71 (-1.76–-0.82)$</td>
<td>$-1.64 (-1.74–-0.99)$</td>
<td>[...]</td>
</tr>
<tr>
<td>$\log(&lt;N_{\text{CO}}&gt;)$</td>
<td>16.92 (16.57–17.02)</td>
<td>17.00 (16.49–17.01)</td>
<td>16.31 (16.21–16.83)</td>
<td>16.51 (16.35–16.91)</td>
<td>[Log(cm$^{-2}$)]</td>
</tr>
<tr>
<td>$\log(P)$</td>
<td>5.09 (4.71–5.13)</td>
<td>5.09 (4.61–5.08)</td>
<td>4.96 (4.52–5.01)</td>
<td>5.09 (4.58–5.08)</td>
<td>[Log(K cm$^{-2}$)]</td>
</tr>
</tbody>
</table>

Figure A1. Measured and calculated spectral line energy distributions for the single component fit for the nucleus (top-left), centre (top-right), and arm/inter-arm (bottom-left) regions, and for all the regions combined (bottom right). The measured fluxes are shown by black circles (CO) and triangles ([CI]), while the calculated fluxes are shown by the green (CO) and magenta ([CI]) solid lines.

Figure B1. Probability distributions of 4 fitted parameters from the two-component RADEX model for the centre region of M51. The cold component distributions are shown in blue and the warm component distributions are shown in red for molecular gas density (top left), kinetic temperature (top right), column density (bottom left), and filling factor (bottom right).