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Probing the molecular interstellar medium of M82 with *Herschel*-SPIRE spectroscopy

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**ABSTRACT**

We present the observations of the starburst galaxy M82 taken with the *Herschel* SPIRE Fourier-transform spectrometer. The spectrum (194–671 μm) shows a prominent CO rotational ladder from $J = 4$–$3$ to $13$–$12$ emitted by the central region of M82. The fundamental properties of the gas are well constrained by the high $J$ lines observed for the first time. Radiative transfer modeling of these high-S/N $^{12}$CO and $^{13}$CO lines strongly indicates a very warm molecular gas component at ~500 K and pressure of $3 \times 10^5$ K cm$^{-3}$, in good agreement with the $H_2$ rotational lines measurements from *Spitzer* and ISO. We suggest that this warm gas is heated by dissipation of turbulence in the interstellar medium (ISM) rather than X-rays or UV flux from the starburst. This paper illustrates the promise of the SPIRE FTS for the study of the ISM of nearby galaxies.

**Key words.** galaxies: ISM – galaxies: starburst – galaxies: individual: M82 – ISM: molecules – submillimeter: galaxies

**1. Introduction**

Starburst galaxies provide us with the opportunity to study star formation and its effect on the interstellar medium (ISM) in extreme environments. These galaxies combine large central gas concentrations and high ionizing radiation fields, resulting in bright molecular, neutral and ionized gas emission lines.

At a distance of 3.9 Mpc (Sakai & Madore 1999), M82 is the most well-studied starburst galaxy in the local universe, and it is widely used as a starburst prototype in cosmological studies. Its infrared luminosity (5.6 × 10$^{10}$ L$_\odot$, Sanders et al. 2003) corresponds to a star-formation rate of 9.8 $M_\odot$ yr$^{-1}$, which has almost certainly been enhanced by its interaction with M81 and NGC 3077 (Yun et al. 1993). With a reported molecular gas content of 1.3 × 10$^9$ $M_\odot$ (Walter et al. 2002), its bright emission lines of CO and other molecules allow us to study its ISM in great detail (Shen & Lo 1995; Walter et al. 2002; Ward et al. 2003).

Far-infrared fine structure lines were used to constrain the physical properties of the ionized gas and photo-dissociation regions (PDRs) in M82. Colbert et al. (1999) found that the ionized gas emission can be reproduced with a 3–5 Myr old instantaneous starburst and a gas density of 250 cm$^{-3}$, while the PDR component is best fit with a density of 2000 cm$^{-3}$, in pressure equilibrium with the ionized phase.

Stellar evolution and photoionization models (Förster Schreiber et al. 2003) indicate a series of a few, Myr-duration starbursts with a peak of activity 10 Myr ago in the central regions, and 5 Myr ago in the circumnuclear ring. Models of the PDR and molecular emission as a set of non-interacting hot bubbles driving spherical shells of swept-up gas into a surrounding uniform medium also predict a starburst age of 5–10 Myr, but fail to match the observed far-infrared luminosity (Yao 2009).

The strengths of the CO lines place fundamental constraints on the physical properties of the molecular gas. Tilanus et al. (1991) fitted $^{12}$CO and $^{13}$CO lines from the central starburst up to $J = 3$–$2$ with a single-component model with temperatures of 30–55 K and densities of $3 \times 10^5$ cm$^{-3}$ (Wild et al. 1992) used lines up to the CO $J = 6$–$5$ transition to refine these parameters to 40–50 K and $10^5$ cm$^{-3}$, while HCN and HCO$^+$ lines suggest densities greater than $3 \times 10^5$ cm$^{-3}$ are present. Petitpas & Wilson (2000) showed evidence for a temperature or density gradient across the starburst region. Weiss et al. (2005) showed that CO emission up to $J = 3$–$2$ is dominated by more extended regions while higher $J$ transitions originate in the central disk.

In this paper, we present observations of M82 with *Herschel* (Pilbratt et al. 2010) using the SPIRE Fourier-transform spectrometer (FTS) (Griffin et al. 2010), which measures the complete far-infrared spectrum from 194 to 671 μm. This spectral region is particularly interesting for probing the peak of the CO spectral line energy distribution (SLED) in gas-rich galaxies. The wealth of lines across a continuous spectral region allows...
for unprecedented precision in modeling the physical and chemical properties of the molecular ISM. Here, we focus on the measurement and analysis of the CO rotational transitions from the central starburst in M82.

2. Observations and data reduction

The galaxy M82 was observed by the SPIRE FTS in the high spectral resolution ($FWHM = 0.048 \text{ cm}^{-1}$), point-source mode, on 2009 September 21 as a performance verification target. The total integration time was 1332 s. The data were processed and calibrated as described in Swinyard et al. (2010). Only data from the central detectors in the two FTS bands are presented here.

The beam size of the FTS bolometers varies with wavelength across the individual bands (see Swinyard et al. 2010), and the spatial extent of the M82 central starburst is comparable to the beam size (mean $FWHM \sim 19''$ and $35''$ for the short- and the long-wavelength bands respectively). For a proper comparison with models, the spectrum must be scaled appropriately to a single beam size by a source-beam coupling factor ($\eta(v)$). This factor was obtained by convolving the M82 SPIRE photometer map at 250 $\mu$m (Roussel et al. 2010), which has a beam $FWHM$ of 18''1 (Griffin et al. 2010), with appropriate Gaussian profiles to reproduce the light distribution as seen by FTS bolometers at different beam sizes. The value of $\eta(v)$ is then given by the ratio of the beam-integrated flux density of the map convolved to the beam size corresponding to the given frequency ($v$) to the beam-integrated flux density of the map with the largest beam size (43''4); its values goes from 1 to 0.42. This implicitly assumes that the dust and CO emission distributions within the beam are the same at all frequencies.

We opted to use the extended-source calibrated$^1$ spectrum because the point-source calibration was more noisy and suffered from significant uncertainties below 600 GHz. We found, however, that the extended-source calibrated spectrum corrected for source-beam coupling is around a factor of 2 fainter than photometry for the same beam. We thus scaled the spectrum to match the photometry in the three bands by applying a single constant scaling factor for the short-wavelength band and a factor with a linear dependence on frequency for the long-wavelength band. The resulting spectrum is shown in Fig. 1 (for clarity, we show the spectrum apodized using the extended

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$^1$ Extended-source flux calibration is derived from telescope emission measurements, while the point-source flux calibration is based on observations of known astronomical point sources.

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Notes. Errors are 1σ only from line fitting procedure, not including other uncertainties (see text). The $^{12}$CO $J = 6$–5 line is missing due to fringing.
for each variable, marginalizing over ). Both Lord et al. 1995 and 6
an and and 30%
weight in units of
. The modeling only depends on the relative
masses. The main inputs to RADEX are the gas density (nH₂),
the kinetic temperature (T_{kin}), and the CO column density per
unit line width (N(12CO)/Δν). We ran the code for a large par-

table grid in T_{kin} (20–1000 K), nH₂ (10^2–10^6 cm^{-3}),
N(12CO) (10^{15}–10^{18} cm^{-2}), and N(13CO) (10^{15}–10^{18} cm^{-2}). From
this grid of
models, we generated likelihood distributions by adapting the
method described in W03, for (T_{kin}, nH₂, N(12CO), N(13CO),
and pressure by comparing the RADEX and observed line
fluxes.

To avoid any non-physical situation we applied two priors
in this analysis following W03. The first one limits the
density by comparing the RADEX and observed line fluxes.

\[ N(12CO) < \frac{M_{dyn,xCO}}{\mu m_{H_2}} \rho_{R_d} = 2.3 \times 10^{20} \text{ cm}^{-2}, \]

where the dynamical mass of the disk \( M_{dyn} = 2.4 \times 10^9 M_\odot \),
the radius of the disk \( R_d = 250 \) pc, the abundance of CO relative to
H₂, \( x_{CO} = 3 \times 10^{-4} \) (W03), and \( \mu = 1.4 \) is the mean molecular
weight in units of m_{H_2}. The second prior limits the column length
below than that of the entire molecular region according to
\( \rho_{R_d} = 1.5 \times 10^{31} \) cm. In this analysis we used all the 12CO
and 13CO lines in Table 1 along with their 1σ statistical errors. It
was necessary to add 20% and 10% uncertainties for the CO J ≤
8–7 and J > 8–7 lines, respectively, to avoid un-physically nar-
row and noisy distributions (consistent with the additional 30%
line flux uncertainty estimate in Sect. 2). The resulting distribu-
tions are shown in Fig. 3 for each variable, marginalizing over
the other variables. The modeling only depends on the relative
line fluxes, therefore the results will not be affected by the un-
certainties in the absolute flux calibration.

4. Results and discussion

We found that the highest likelihood model (dotted line in Fig. 4)
provides a good fit to our data (open squares), in particular for the
higher J lines (J ≥ 6–7). The likelihood contour plot of tem-
perature and density in Fig. 3 (last panel) strongly indicates that
the observed emission is coming from very warm gas with a ki-
netic temperature of ∼540 K and a pressure of ∼3 × 10^6 K cm^{-3}.

The ISM of this galaxy has been well-studied using ground-
based observations – in particular the lowest-lying CO rota-
tional lines that provide constraints on the physical state of the
cold molecular gas. Several studies from ground-based CO ob-
servations, including W03, have identified cold gas at ∼30 K.
We show W03 data (open circles) over-plotted in Fig. 4. From
J ≤ 7–6 lines, W03 deduced the presence of a warm component,

\[ J \leq 7–6 \]

whereby the uncertainty on
\( T_{dust} \geq 1.5 \); from dust models of
Laor & Draine (1993) extrapolated to our wavelengths) of the S(1) line, we find it to be
consistent with our mass range.

Our inferred thermal pressure (3 × 10^6 K cm^{-3}) is com-
parable to both that of the M82 atomic gas as probed by the CII
and O1 transitions (Kaufman et al. 1999; Lord et al. 1995),

\[ \frac{1}{\mu m_{H_2}} \rho_{R_d} = 2.3 \times 10^{20} \text{ cm}^{-2}, \]

with a pressure of ∼3 × 10^6 K cm^{-3}.

The detailed physical characteristics of the warm gas are listed in
Table 2, which are obtained from the likelihood distributions
shown in Fig. 3.

Mid-IR H₂ rotational lines are optically-thin and easily ther-
malized, so they provide an independent constraint on the mass
of warm gas. Several transitions have been studied with ISO
(Rigopoulou et al. 2002) and Spitzer (Beirão et al. 2008). Both
studies agree that the S(1) to S(2) line ratio suggests T ∼ 500 K
(assuming an ortho-to-para ratio of 3), in excellent agreement
with our temperature. Using the Spitzer measurement of S(1)
line flux corrected for our larger beam we calculate a mass of
\( \sim 2 \times 10^6 M_\odot \). Given the uncertainty on x_{CO}, and considerable ex-
tinction (τ_{dust} ≥ 1.5); from dust models of
Laor & Draine (1993) extrapolated to our wavelengths) of the S(1) line, we find it to be
consistent with our mass range.

Fig. 3. Left panel: likelihood distributions of kinetic temperature, density, CO column density and pressure. Right panel: likelihood contour plot of temperature and density. Dashed lines show constant pressure (Log_{10} P (K cm^{-3})) relations.

Fig. 4. Comparing the highest likelihood model (dotted line) with our CO line intensities. The model shown by a dashed line was obtained by using only J ≥ 7–6 CO lines. The W03 data are shown by open circles. The inset highlights the deviations from models at the lower J end.

3. Radiative transfer modeling

We used RADEX (van der Tak et al. 2007), a non-LTE code that
computes the intensities of molecular lines by iteratively solving
for statistical equilibrium using an escape-probability formalism
assuming a uniform expanding sphere, to model the CO line in-
tensities. The main inputs to RADEX are the gas density (nH₂),

\[ \frac{1}{\mu m_{H_2}} \rho_{R_d} = 2.3 \times 10^{20} \text{ cm}^{-2}, \]

where the dynamical mass of the disk \( M_{dyn} = 2.4 \times 10^9 M_\odot \),
the radius of the disk \( R_d = 250 \) pc, the abundance of CO relative to
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tions are shown in Fig. 3 for each variable, marginalizing over
the other variables. The modeling only depends on the relative
line fluxes, therefore the results will not be affected by the un-
certainties in the absolute flux calibration.
Table 2. Model results and their uncertainties for the warm gas.

| Quantity | Most probable value | Range† |
|----------|---------------------|--------|
| $T_{int}$ (K) | 545 | 350–825 |
| $\log_{10} n(H_2)$ (cm$^{-3}$) | 3.7 | 3.0–4.1 |
| $\log_{10} \Phi(N(12CO))$ (cm$^{-3}$) | 19.0 | 18.5–19.8 |
| $\log_{10} \Phi (N(12CO))$ (cm$^{-3}$) | 17.4 | 17.2 – 17.9 |
| $\Phi(N(12CO)/N(12CO))$ | 20 | 15 – 37 |
| $\log_{10} P$ (K cm$^{-2}$) | 6.4 | 5.8–6.7 |
| $M_{warm}/(x10^7 M_\odot)$ | 1.2 | 0.7–3.6 |

Notes. (†) Ranges for 95% confidence intervals; (††) Beam averaged column density where $\Phi_A$ is an area filling factor.

5. Conclusions

We have presented the Herschel-SPIRE spectroscopic observations of the starburst galaxy M82. The spectra show a prominent CO emission-line ladder along with C1 and N II lines. Radiative transfer modeling of CO lines clearly indicates a warm gas component at ~500 K in addition to the cold (~30 K) component derived from ground-based studies. The properties of the warm gas are strongly constrained by the high $J$ lines, observed here for the first time. The temperature and mass of warm gas agree with the $H_2$ rotational line observations from Spitzer and ISO. At this temperature $H_2$ is the dominant coolant instead of CO, and we argue that turbulence from stellar winds and supernovae may be the dominant heating mechanism.

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References

Beirão, P., Brandl, B. R., Appleton, P. N., et al. 2008, ApJ, 676, 304
Bradford, C. M., Stacey, G. J., Nikola; T., et al. 2005, ApJ, 623, 866
Colbert, J. W., Malkan, M. A., Clegg, P. E., et al., 1999, ApJ, 511, 721
Falgarone, E., & Puget, J.-L. 1995, A&A, 293, 840
Forster Schreiber, N. M., Genzel, R., Dutz, D., et al., 2003, ApJ, 599, 193
Goldsmith, P. F., & Langer, W. D. 1978, ApJ, 222, 881
Griffin, M. J., et al. 2010, A&A, 518, L3
Kaufman, M. J., Wolfire, M. G., Hollenbach, D. J., & Luhman, M. L. 1999, ApJ, 527, 795
Kaufman, M. J., Wolfire, M. G., & Hollenbach, D. J. 2006, ApJ, 644, 283
Mac Low, M. M. 1999, ApJ, 524, 169
Maloney, P. R., Hollenbach, D. J., & Tielens, A. G. G. M. 1996, ApJ, 466, 561
Naylor, B. J., Bradford, C. M., Aguirre, J. E., et al., 2010, ApJ, submitted
Naylor, D. A., & Tacit M. K. 2007, J. Opt. Soc. Am. A, 24, 3644
Neufeld, D. A., Lepp, S., & Mclnnich, G. J. 1995, ApJS, 100, 132
Laor, A., & Draine, B. T. 1993, ApJ, 402, 441
Le Bourlot, J., Pineau des Forêts, G., & Flower, D. R. 1999, MNras, 305, 802
Lord, S. D., Hollenbach, D. J., Colgan, S. W. J., et al. 1995, ASPC, 73, 151
Pan, L., & Padoan, P. 2009, ApJ, 692, 594
Petitpas, G. R., & Wilson, C. D. 2000, ApJ, 538, L117
Pilbratt, G. L., et al. 2010, A&A, 518, L1
Rigopoulou, D., Kunze, D., Lutz, G., Genzel, R., & Moorwood, A. F. M. 2002, A&A, 389, 374
Roussel, H., et al. 2010, A&A, 518, L66
Sakai, S., & Madore, B. F. 1999, ApJ, 526, 599
Sanders, D. B., Mazzarella, J. M., Kim, D.-C., Surace, J. A., & Soifer, B. T. 2003, AJ, 126, 1607
Seaquist, E. R., Lee, S. W., & Moriarty-Schieven, G. H. 2006, ApJ, 638, 148
Shen, J., & Lo, K. Y. 1995, ApJ, 445, L99
Strickland, D. K., & Heckman, T. M. 2007, ApJ, 658, 258
Suchkov, A., Allen, R. J., & Heckman, T. M. 1993, ApJ, 413, 542
Swinyard, B. G., et al. 2010, A&A, 518, L4
Tilanus, R. P. J., Tacconi, L. J., Sutton, E. C., et al. 1991, ApJ, 376, 500
van der Tak, F. F. S., & Black, J. H., 2002, ApJ, 568, 258
van der Werf, P. P., & Black, J. H., 2006, ApJ, 648, 627
van der Werf, P. P., et al. 2010, A&A, 518, L42
van Dishoeck, E. F., & Black, J. H. 1986, ApJS, 60, 109
Walter, F., Weiss, A., & Scoville, N. 2007, ApJ, 668, 795
Walter, F., & Scoville, N. 2002, ApJ, 580, L21
Ward, J. S., Zmuidzinas, J., Harris, A. I., et al. 2003, ApJ, 587, 171 (W03)
Weiss, A., Walter, F., & Scoville, N. 2005, A&A, 438, 533
Wild, W., Harris, A. I., Eckart, A., et al. 1999, A&A, 265, 447
Yao, L. 2009, ApJ, 705, 766
Yun, M. S., Ho, P. T. P., & Lo, K. Y. 1993, ApJ, 411, L17

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