EXTENDED DUST EMISSION AND ATOMIC HYDROGEN: A RESERVOIR OF DIFFUSE H$_2$ IN NGC 1068

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ABSTRACT

We report on sensitive submillimeter imaging observations of the prototype Seyfert 2/starburst galaxy NGC 1068 at 850 and 450 μm using the Submillimeter Common-User Bolometer Array on the James Clerk Maxwell Telescope. We find clear evidence of dust emission associated with the extended H i component that, together with the very faint $^{12}$CO J = 1–0 emission, gives a gas-to-dust ratio of $M_{\text{gas}}/M_{\text{dust}} \sim 70–150$. This contrasts with the larger ratio $M_{\text{gas}}/M_{\text{dust}} \sim 330$ that is estimated within a galactocentric radius of $r \leq 1.36$ kpc, where the gas is mostly molecular and starburst activity occurs. The large gas-to-dust ratio that is found for the starburst region is attributed to a systematic overestimate of the molecular gas mass in starburst environments when the luminosity of the $^{12}$CO J = 1–0 line and a standard Galactic conversion factor are used. On the other hand, submillimeter imaging proves to be a more powerful tool than conventional CO imaging for revealing the properties of the diffuse H$_2$, that coexists with H i. This molecular gas phase is characterized by low densities [$n$(H$_2$) < 10$^4$ cm$^{-3}$], very faint emission from subthermally excited CO, and contains more mass than H i, namely, $M$(H$_2$)/$M$(H i) ~ 5.

Subject headings: dust, extinction — galaxies: individual (NGC 1068) — ISM: atoms — ISM: molecules

1. INTRODUCTION

In the standard way to estimate molecular gas mass in galaxies, we would use the luminosity of the $^{12}$CO J = 1–0 line and convert it to molecular gas mass by using the so-called standard Galactic conversion factor $X_{\text{co}}$ (see, e.g., Young & Scoville 1982, 1991; Bloemen 1985; Dickman, Snell, & Schloerb 1986). The dependence of $X_{\text{co}}$ on the ambient conditions of the molecular gas has been explored extensively. The main factors are (a) metallicity and the intensity of the ambient UV radiation field (see, e.g., Israel 1988, 1997; Wilson 1995; Arimoto, Sofue, & Tsujimoto 1996), (b) the density, temperature, and kinematic state of the average molecular cloud, and (c) the effects of particular geometries (see, e.g., Bryant & Scoville 1996 and Sakamoto 1996 for a recent exposition). In the environments of extreme starbursts, it has been clearly demonstrated that the standard method overestimates $M$(H$_2$) since it yields masses comparable to or larger than the dynamical ones (see, e.g., Downes, Solomon, & Radford 1993; Bryant & Scoville 1996; Solomon et al. 1997; Downes & Solomon 1998). In low-metallicity environments with high-UV intensities, the larger rate of CO dissociation with respect to H$_2$ produces a lower CO luminosity per H$_2$ and thus underestimates $M$(H$_2$).

In principle, the aforementioned effects can be taken into account by a combination of observational and theoretical work studying a wide range of galactic environments, which can then provide “adjusted” $X_{\text{co}}$ factors to be used for the appropriate set of conditions. However, little can be done if the H$_2$ is so diffuse and/or cold that the $^{12}$CO J = 1–0 line is very faint or not luminous at all. Hints of such physical conditions have not luminous at all. Hints of such physical conditions have been reported recently for the outer parts of the Milky Way (Usuda et al. 1998), and cold dense clouds have been reported for M31 (Loinard & Allen 1998). In such cases, the advantage of easily detecting and mapping a bright CO line, and thus the distribution of H$_2$, is lost. Here we report deep submillimeter imaging of the prototype Seyfert 2/starburst galaxy NGC 1068 that reveals extended emission from dust well beyond the CO-bright regions and that is associated with the H i.

2. OBSERVATIONS

The observations were made on two nights in 1997 August 4 and 1998 January 26 with the Submillimeter Common-User Bolometer Array (SCUBA) at the 15 m James Clerk Maxwell Telescope (JCMT). SCUBA is a dual camera system that is cooled well below 1 K and that allows sky background—limited simultaneous observations with two arrays. The short-wavelength array contains 91 pixels, and the long-wavelength array contains 37 pixels. Both arrays have approximately the same field of view on the sky ~2.3 (for a full description of the instrument, see Holland et al. 1998).

We performed dual-wavelength imaging at 450 and 850 μm using the 64 point jiggle-mapping mode that allows Nyquist sampling of the field of view (Holland et al. 1998). We employed the recommended rapid beam switching at a frequency of 8 Hz and a beam throw of 120° in azimuth. The pointing and focus of the telescope were monitored frequently using Mars, Jupiter, and CRL 618, with an expected rms pointing error of ≤3″. All the NGC 1068 maps were bracketed by sky dops that were used to correct for atmospheric extinction. Typical opacities at 850 μm were $\tau$ ~ 0.14 for our 1998 run and $\tau$ ~ 0.6 for our 1997 run. Frequent photometric measurements and beam maps of CRL 618 and Mars allowed us to monitor the gains closely (in units of Jy beam$^{-1}$ V$^{-1}$). These can vary significantly, especially at 450 μm if the dish has not thermally relaxed, and can even be elevation dependent (Sandell 1998).

The individual jiggle maps are consistent in terms of peak and integrated intensities and were co-added after flat-fielding, correcting for atmospheric extinction, and editing out bad bo-
Where the starburst occurs. This ratio and its variations acrossometers/integrations using the standard reduction package SURF (Jenness & Lightfoot 1998). Special care was taken to remove sky noise by using bolometers at the edge of the field of view that “look” at sky emission only (Jenness, Lightfoot, & Holland 1998). As a result, the final maps have exceptional sensitivity, close to the one expected from the total integration time and the noise-equivalent flux densities at the sky conditions of our runs. Flux calibration of the final maps, in units of mJy beam$^{-1}$, was obtained from beam maps of CRL 618 that were obtained with the same chop throw as our NGC 1068 maps. The corresponding beam profiles were obtained from beam maps of CRL 618 and Mars. The calibration information is summarized in Table 1.

3. EXTENDED SUBMILLIMETER EMISSION: CO, H I, AND DUST

The clear association of the submillimeter emission from dust and H I gas is demonstrated in Figure 1, where the 850 and 450 μm maps are overlaid with an H I map (Brinks et al. 1994) at a common resolution of ~15″. Figure 2 shows the bright central 450 μm emission and the associated $^{12}$CO $J = 1$–$0$ integrated brightness (Helfer & Blitz 1995) that lie within the central H I “hole” seen in Figure 1. This wealth of imaging data for the interstellar medium (ISM) in NGC 1068 and the wide range of conditions that are present because of the existence of the central starburst (Telesco et al. 1984) make it an ideal testing “ground” for our standard ideas about the distribution and mass of the various ISM phases on large scales. We adopt a distance to NGC 1068 of 14 Mpc ($H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$), where $1'' = 68$ pc.

A remarkable property of the submillimeter emission is that it extends over the entire bright H I emission where the estimated $R = S_{450}/S_{850}$ ratio is lower than in the CO-bright region where the starburst occurs. This ratio and its variations across the image can be a good temperature indicator as long as the average dust temperature is $T \leq 30$ K. Indeed, assuming a single average dust component, this ratio can be expressed as

$$\frac{S_{450}}{S_{850}} = 1.88^{\beta+1} \left( \frac{e^{16/3T} - 1}{e^{31/8T} - 1} \right),$$

where $\beta$ is the emissivity law. It can be easily seen that the ratio tends to the Raleigh-Jeans limit for dust temperatures of $T \geq 30$ K and is no longer temperature sensitive. Nevertheless, for a range of $T = 10$–$30$ K, it varies by a factor of ~2. This temperature range is particularly interesting since it “marks” the transition between cool and warm dust, the latter dominating the IRAS 100 and 60 μm bands.

After carefully correcting the integrated flux densities for the error-beam contribution (Sandell 1998) by using the correction factors tabulated in Table 1, we obtain $R(r \leq 20''') = 7.10 \pm 1.77$. For $\beta = 2$, this agrees well with the range of gas temperatures $T \sim 20$–$30$ K found from studying the CO excitation within this region (Papadopoulos & Seaquist 1999) and the minimum temperature of ~20 K implied from the observed $^{12}$CO $J = 1$–$0$ brightness temperatures in high-resolution maps (see, e.g., Planesas, Scoville, & Myers 1991). For the submillimeter emission that is associated with the H I distribution, we find $R(20'' \leq r \leq 60'') = 4.70 \pm 1.17$. This ratio suggests colder gas, in the range of $T \sim 10$–$15$ K, but rules out any M31-type clouds (Loinard & Allen 1998) where $T_{\text{vis}} < 10$ K.

| Wavelength (μm) | $\theta_{\text{beam}}$ (arcsec) | $S_{\text{vis}}$ (Jy beam$^{-1}$) | $G$, $\delta G/G^2$ (%$^2$) | $\sigma_{\text{rms}}$ (mJy beam$^{-1}$) | $f_{20''}$ | $f_{30''}$ | $f_{60''}$ |
|-----------------|---------------------------------|---------------------------------|---------------------------|-----------------------------|-------------|-------------|-------------|
| 850 ……….      | 15.25                           | 4.56 ± 0.17                     | 265, 15                  | 10, 1.03, 1.30              | 1.45, 2.45  |
| 450 ……….      | 8.75                            | 11.5 ± 1.2                      | 670, 30                  | 50, 1.45, 1.65              | 1.45, 2.45  |

$^a$ The total flux of CRL 618 in units of Jansky, taken from the JCMT secondary calibrators list (Sandell 1998).

$^b$ The flux gain in units of Jy beam$^{-1}$ V$^{-1}$ and its fractional uncertainty estimated from an extensive set of beam maps and photometry on CRL 618 and Mars.

$^c$ The thermal rms error of the final maps in units of mJy beam$^{-1}$.

$^d$ The flux correction factor for a circular area with $r = 20''$ and $r = 60''$ radius, estimated from beam maps of CRL 618 (see Sandell 1998). If $S$ is the integrated flux density within that area, the error-beam–corrected flux is $S = S + \sigma^2$.
Fig. 2.—Gray scale: velocity-integrated $^{12}$CO $J=1$–0 brightness from Helfer & Blitz (1995), convolved to a resolution of ~9" and a range of 100–307 Jy beam$^{-1}$ km s$^{-1}$. Contours: the bright 450 μm emission is at a resolution of ~9", and the contours are 8, 10, 12, 14, 16, 18, 20, 22, 24, 26, 28, and 30 × σ, where σ = 50 mJy beam$^{-1}$.

Here we must emphasize that the main uncertainty in the estimate of $R$ is due to systematic factors (~25%) that stay unchanged across the maps. The thermal rms uncertainty is ≤5%, and thus the observed change of $R$ between the CO-bright and the H$\textsc{i}$-bright regions is much more significant than the total quoted uncertainties imply.

4. THE GAS-TO-DUST RATIO

The spatial resolution of our submillimeter maps and the H$\textsc{i}$, $^{12}$CO $J=1$–0 maps from the literature permits us to estimate the gas-to-dust ratio as a function of position in this galaxy. Combining the standard expressions for the H$\textsc{i}$, H$_2$, and dust mass, the gas-to-dust ratio in astrophysical units is expressed as follows:

$$\frac{M_{\text{gas}}}{M_{\text{dust}}} \approx 1.25 \times 10^3 \left(\frac{v}{v_0}\right)^{\beta+3} (e^{h\nu/T} - 1)^{-1} \times \left(\frac{S_{\text{HI}} + 10^{-2}X_{\text{CO}}S_{\text{CO}}}{S_{\text{dust}}}\right).$$  \hspace{1cm} (2)

where $S_{\text{HI}}$ and $S_{\text{CO}}$ are the velocity-integrated flux densities of the H$\textsc{i}$ hyperfine transition and the $^{12}$CO $J=1$–0 line, respectively, in units of Jy km s$^{-1}$, $X_{\text{CO}}$ is the standard Galactic conversion factor in units of $M_\odot$ (K km s$^{-1}$ pc$^2$)$^{-1}$, and $S_{\text{dust}}$ is the submillimeter flux density at frequency $\nu$ in units of jansky. We adopted the emissivity law given by Hildebrand (1983), namely, $k(\nu) = k(\nu_0)(\nu/\nu_0)^{\delta}$, where $k(\nu_0) = 10$ cm$^2$ g and $\nu_0 = 1196$ GHz (250 μm).

For a galactocentric radius of $r = 20''$, where most of the far-infrared emission arises (Telesco et al. 1984), we estimate $S_{\text{CO}} = 2800 \pm 800$ Jy km s$^{-1}$ (from the $^{12}$CO $J=1$–0 channel maps: Helfer & Blitz 1995), $S_{\text{HI}} = 0.82 \pm 0.20$ Jy km s$^{-1}$, $S_{\text{850}} = 8.74 \pm 1.95$ Jy, and $S_{\text{800}} = 1.23 \pm 0.13$ Jy. For $\beta = 2$ and $X_{\text{CO}} = 5 M_\odot$ (K km s$^{-1}$ pc$^2$)$^{-1}$ (i.e., the standard galactic value), the observed 850 μm flux density implies

$$\frac{M_{\text{gas}}}{M_{\text{dust}}} \approx 315(e^{16.8/T} - 1)^{-1},$$  \hspace{1cm} (3)

for $T = 25$ K yields $M_{\text{gas}}/M_{\text{dust}} \sim 330$, which is similar to the molecular gas-to-dust ratio found in spiral galaxies using IRAS 100 and 60 μm fluxes (Young et al. 1986, 1989).

Assuming that the actual gas-to-dust ratio in NGC 1068 is similar to that for the Milky Way, namely, 100:150, we conclude that the application of equation (3) leads to a significant overestimate of this ratio for the inner region ($r \leq 20''$) of NGC 1068. There is indeed independent evidence (see, e.g., Downes & Solomon 1998) suggesting that the standard Galactic conversion factor that is applied to starburst nuclei leads to significant overestimates of the H$_2$ content in these regions. In addition, Papadopoulos & Seaquist (1999) provide indications that $M$(H$_2$) in the inner region of NGC 1068 is overestimated by a factor of 2, which would then produce an agreement between the ratio for the nuclear region NGC 1068 and the Milky Way.

For $r > 20''$, no bright CO emission is detected (see Fig. 2 of Helfer & Blitz 1995). However, there is evidence for faint CO emission. By integrating over the area 20'' ≤ $r \leq 60''$, we find $S_{\text{CO}} = 1570 \pm 470$ Jy km s$^{-1}$. Over the same area, we
estimate \( S(\text{H} \alpha) = 16 \pm 1 \) Jy km s\(^{-1}\) and \( S_{\text{CO}} = 4.0 \pm 0.9 \) Jy, and \( S_{\text{SO}} = 0.85 \pm 0.09 \) Jy. Using these figures, together with equation (2) and the standard value for \( X_{\text{H}} \), we obtain
\[
\frac{M_{\text{gas}}}{M_{\text{dust}}} \approx 300(e^{16.87/T} - 1)^{-1}.
\] (4)

For \( T \approx 10-15 \) K, we obtain \( M_{\text{gas}}/M_{\text{dust}} = 70-150 \) and \( M(\text{H})/M(\text{H} \alpha) \sim 5 \). The good agreement of the gas-to-dust ratio with that of the Milky Way suggests that most of the gas/dust mass is accounted for.

However, the CO becomes exceedingly faint and essentially undetectable at \( r \approx 30^\circ \). If we assume the lowest gas/dust temperature of \( T \approx 10 \) K allowed by the \( S_{\text{CO}}/S_{\text{SO}} \) ratio, the inferred gas-to-dust ratio for \( 30^\circ \leq r \leq 60^\circ \) would be \( \sim 40 \) with \( M(\text{H})/M(\text{H} \alpha) \sim 1 \) (using the standard \( X_{\text{H}} \)). Thus, the use of the standard conversion factor in this region may underestimate \( M(\text{H}) \) by a factor of \( \sim 5 \). It seems possible that this molecular gas phase is not CO bright mainly because of low densities \( [n(\text{H})] < 10^3 \) cm\(^{-3}\) rather than low gas/dust temperatures. A thermalized \( ^{12}\text{CO} \) \( J = 1-0 \) line would remain luminous as long as \( T \geq \Delta E_{\text{th}}/k \approx 5 \) K, and lower temperatures would yield \( S_{\text{CO}}/S_{\text{SO}} \leq 1.13 \), which is not observed. Assuming similar spatial and velocity filling factors, we estimate that the average \(^{12}\text{CO} \) \( J = 1-0 \) brightness temperature for the outer regions is \( T_b \approx 0.07T_b(r \leq 20^\circ) \). For the various molecular clouds (with a size of \( \sim 200 \) pc) within the \( r \approx 20^\circ \) radius, \( T_b(r \leq 20^\circ) \sim 10-20 \) K (see, e.g., Planesas et al. 1991); hence, for similar size molecular clouds in the \( \text{H} \beta \)-bright regions, it would be \( T_b \sim 1 \) K. This is significantly lower than the gas/dust temperature inferred by the \( S_{\text{CO}}/S_{\text{SO}} \) ratio over the same regions, thus implying subthermally excited \(^{12}\text{CO} \) \( J = 1-0 \).

These characteristics of the diffuse \( \text{H}_2 \) phase make submillimeter measurements very valuable since, while CO is very faint and may underestimate the \( \text{H}_2 \) mass, the dust/gas temperature is still high enough to allow submillimeter imaging to reveal the distribution and mass of the \( \text{H}_2 \) mixed with \( \text{H} \alpha \), under the assumption of a canonical gas-to-dust ratio. We expect this gas phase to be a general feature in spiral galaxies, and sensitive submillimeter imaging of the regions with high \( \text{H} \alpha \) column densities is a new tool for studying its properties through the associated dust emission.

5. CONCLUSIONS

The results of deep submillimeter imaging of the archetypal Seyfert 2/starburst galaxy NGC 1068 can be summarized as follows:

1. Extended submillimeter emission due to dust, with a temperature of \( T \approx 10-15 \) K, is found to be associated with the regions with the highest \( \text{H} \alpha \) column densities. A more spatially concentrated and warmer (\( T \approx 20-30 \) K) component is found in the inner starburst region where most of the gas is molecular.

2. The estimated gas-to-dust ratio for the inner region is \( M_{\text{gas}}/M_{\text{dust}} \sim 330 \), while for the dust emission associated with the \( \text{H} \alpha \) gas, we find \( M_{\text{gas}}/M_{\text{dust}} \sim 70-150 \), depending on the value of the gas/dust temperature.

3. Under the assumption that a Milky Way value of \( M_{\text{gas}}/M_{\text{dust}} \sim 100-150 \) applies also to NGC 1068, we conclude that the high value of \( M_{\text{gas}}/M_{\text{dust}} \) in its starburst region is a result of an overestimate of the molecular gas mass. This seems to be a systematic effect of using the standard Galactic conversion factor to convert \(^{12}\text{CO} \) \( J = 1-0 \) luminosity to molecular gas mass in starburst environments.

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