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A CO MAP OF THE DWARF STARBURST GALAXY NGC 5253

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ABSTRACT

We have mapped CO and 2.6 mm continuum emission in the dwarf galaxy NGC 5253 with the Owens Valley Millimeter Array. CO is detected along the prominent dust lane in the nucleus. The CO emission is extremely weak: NGC 5253 appears to be the most CO-poor starburst known. The CO flux appears to be low by factors of ~100 compared to star-forming regions of similar radio and infrared luminosity in large spiral galaxies and as much as a factor of 10 weaker than those in other metal-poor dwarf galaxies. This unusually weak CO emission, together with the observed morphology of the CO gas and its unusual kinematical properties, lead us to suggest that NGC 5253 has recently accreted gas of extremely low metallicity, significantly lower than that of the galaxy itself.
Subject headings: galaxies: individual (NGC 5253) — galaxies: ISM — galaxies: starburst — galaxies: structure

1. INTRODUCTION

Starburst activity on global scales is not well understood even in gas-rich spiral galaxies like our own; star-forming dwarf galaxies present a considerably more difficult problem. They have less gas than spirals and lack the triggering mechanism of spiral arms, but they contain some of the most intense and luminous starbursts. An example of an extreme starburst in a dwarf galaxy is NGC 5253. This nearby (2.8 Mpc) I0/S0 galaxy has total mass 2×10^9 $M_\odot$ (Bottinelli, Gougenheim, & Heidemann 1972; corrected to 2.8 Mpc), only ~1% of the Milky Way's mass, yet has a nuclear starburst of luminosity $\sim 3 \times 10^9$ $L_\odot$ (Beck et al. 1996, hereafter B96), which is more than 100 times more luminous than the largest star-forming regions in the Milky Way. The central region requires some 10^4–10^5 massive young stars and is largely concentrated in a compact cluster of stars, a "super–star cluster," with properties similar to those of globular clusters (Meurer et al. 1995; B96; Gorjian 1996). Rieke, Lebofsky, & Walker (1988) suggested, based on the weak CO band head absorption, that NGC 5253 has the youngest starburst known. Radio continuum observations (B96) also suggest that the central star cluster is young and coevel to a high degree.

The molecular gas contents of dwarf galaxies are of great interest since in general molecular gas is the fuel for the star formation process. We have mapped the emission in the CO $J = 1-0$ line at 2.6 mm in NGC 5253 using the Owens Valley Millimeter Array. The CO emission from NGC 5253 is extremely weak. Although CO is known to be a poor tracer of star-forming gas in dwarf galaxies, in no other galaxy is CO as weak compared to the star formation rate as it is in NGC 5253. We attempt to estimate the relative underluminosity of CO with respect to the star-forming gas mass through comparison with other gas tracers. We discuss these results and their significance for the central starburst cluster in NGC 5253.

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2. OBSERVATIONS

The CO $J = 1-0$ line at 115.271 GHz was observed in NGC 5253 with the Owens Valley Millimeter Array in 1993 December and 1994 January. System temperatures referred to above the atmosphere ranged from 300 to 800 K (single-sideband) at source elevations of ~20° during the observations. The line data have 8 MHz (20.8 km s^{-1}) velocity resolution, and the continuum channel has bandwidth 1 GHz. Absolute flux calibration was based on observations of Mars and Uranus and is good to ~15%. Phase center was at $\alpha = 13^h37^m05\overset{s}{.}2$, $\delta = -31°23'15''$ (1950). The maps are corrected for the attenuation of the primary beam. Natural weighting produced a synthesized beam of $14\overset{''}{.}0 \times 6\overset{''}{.}5$ (FWHM) at p.a. −7° for the continuum map; this corresponds to a size scale of 190 × 90 pc at 2.8 Mpc. The line maps were tapered to a beam size of $14\overset{''}{.}9 \times 11\overset{''}{.}4$, p.a. −37° to improve the signal-to-noise ratio. Owing to lack of short spacings, the maps are sensitive only to structures $\lesssim 20''$. The rms noise in the continuum map is 2.5 mJy $beam^{-1}$, and in the 8 MHz channel maps is 0.04 K, or 70 mJy $beam^{-1}$. Errors quoted are the larger of 2 σ or the absolute uncertainty of 15%. The red image of NGC 5253 was taken with the 1 m telescope of the Wise Observatory in Mitzpe Ramon.

3. MILLIMETER CONTINUUM: IONIZED GAS AND DUST IN THE STARBURST

The 2.6 mm continuum map is shown in Figure 1 (*gray contours*). Its north-south elongation is an artifact of the beam; the millimeter spatial distribution and position is consistent with the compact ($\lesssim 5''$ diameter) nuclear source seen at centimeter wavelengths (B96), $\alpha = 13^h37^m05\overset{s}{.}13$, $\delta = -31°23'15\overset{''}{.}4$ (1950). The flux density of the compact nuclear source is 38 ± 6 mJy, with an extended halo of emission amounting to 52 ± 8 mJy, for the central 20″ region. This can be compared to a 2 cm peak flux of 37 ± 1 mJy for the central source and 54 ± 3 mJy for the inner 20″ (B96 maps, convolved to the same resolution). The total 2.6 mm flux is 72 ± 11 mJy, of which at least 46 mJy (see below) is from free-free emission.

The central source has a flat spectral index from 20 cm (B96 and references therein) to 2.6 mm. This is most unusual for a starburst, which more typically has a dominant synchrotron component at wavelengths of 6 cm and beyond. B96 suggest

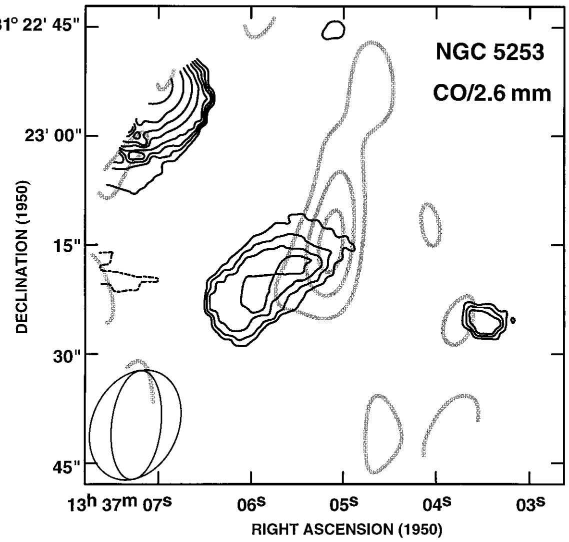

FIG. 1.—The 2.6 mm continuum (*gray contours*) map and CO integrated intensity map (*black contours*) of NGC 5253 made with the Owens Valley Millimeter Array. Beams are plotted in the lower left-hand corner: the synthesized beam size is 14″.0 × 6″.5 (FWHM), p.a. −7° for the continuum map, and 14″.9 × 11″.4, −37°, for the CO map. Continuum contour levels are multiples of 10 mJy beam^{-1}, which is 4 σ. CO integrated intensity contour levels are multiples of 10^6 mJy beam^{-1} Hz, or 0.54 K km s^{-1}.

that this lack of synchrotron emission indicates that the cluster is extremely young, less than 10^7 yr in age. Another unusual feature is that the spectrum in the millimeter appears to be more rising ($\alpha = 0$; $S_\nu \sim \nu^\alpha$) than would be expected for optically thin thermal free-free emission ($\alpha = -0.1$), although the data are marginally consistent with this value.

There is a weak secondary source located 20″ north of the nuclear cluster, at $\alpha = 13^h37^m04^s.7$, $\delta = -31°22'52''$ (1950). The flux of the northern continuum component is 15 ± 5 mJy at 2.6 mm but is <0.2 mJy at 2 cm (Turner, Ho, & Beck 1997), so that $\alpha \gtrsim +2$. This millimeter plume could conceivably be optically thick free-free emission, in which case the implied emission measure would be quite large, EM $\gtrsim 10^{11}$ cm^{-6} pc, for electron temperatures of 12,000 K (Walsh & Roy 1989). If so, the source is 1–2 orders of magnitude larger in size than optically thick Galactic H II regions, which would require a large ($N_{\rm Lyc} \sim 10^{52}$ s^{-1}) ionizing luminosity. There is no other evidence to date for such a source, although there is diffuse Hα emission in the area (Atherton et al. 1982). The other possibility is that this emission is from dust, which is discussed below.

The free-free flux of 46 mJy at 2.6 mm requires an ionization rate of $N_{\rm Lyc} = 4 \times 10^{52}$ s^{-1}, and as much as 7×10^{52} s^{-1}, if optically thick free-free emission is present. This is consistent with centimeter-wave and mid-infrared recombination line observations (Ho, Beck, & Turner 1990; Kawara, Nishida, & Phillips 1989). For a standard Salpeter initial mass function (IMF) of OB stars only, with an upper mass cutoff of 30–35 $M_\odot$ (B96), this implies a luminosity of $L_{\rm OB} \sim 2$–$5 \pm 1 \times 10^9$ $L_\odot$. The OB luminosity could be a factor of 2 lower if the upper mass cutoff is 60 $M_\odot$. The infrared luminosity is $L_{\rm IR} = 8 \times 10^8$ $L_\odot$, inferred from *IRAS* fluxes (see below). The factor of 3–6 discrepancy between the dust luminosity and the H II luminosity could be due to an very top-heavy IMF, with no stars later than O4 ($M \gtrsim 70$ $M_\odot$). Another possibility is that the dust-to-gas ratio is lower than usual. There are two factors that could lower the dust-to-gas ratio in NGC 5253: one is the low metallicity, and the other is the intense radiation field in the central starburst which could destroy dust.

Although the general agreement between the centimeter and millimeter fluxes indicates that most of the 2.6 mm continuum is free-free emission, there may be a contribution from cool dust. *IRAS* HIRES images show the emission to be unresolved at all bands, which implies that the 60 and 100 μm region is localized to the central arcminute of the starburst while the 12 and 25 μm emission is concentrated within the central half-arcminute, consistent with the fact that the *N*-band emission (Rieke 1976) in a 6″ beam is more than 70% of the *IRAS* 12 μm flux. We find that the 12, 25, 60, and 100 μm *IRAS* fluxes of 3, 12, 31, and 30 Jy may be reasonably fitted with two blackbody components of temperatures 40 ± 5 K and 120 ± 10 K, which contribute roughly equal amounts to $L_{\rm IR}$. For a dust opacity of 0.4 cm^2 g^{-1} at 100 μm (extrapolated from the 1 mm opacity of Pollack et al. 1994), the 40 K component indicates a molecular gas mass of approximately 3×10^6 $M_\odot$, with a factor of 4 uncertainty owing to the dust opacity (Pollack et al.). This component is undetectable at 2.6 mm.

There is, however, almost certainly a cooler component that dominates the molecular cloud mass (see, e.g., Scoville & Good 1989), which is not detected at 100 μm by *IRAS*. We may place limits on the mass of this component using our 2.6 mm continuum fluxes. We detect a flux of $S_{2.6\ \rm mm} \sim 72 \pm 11$ mJy for the central arcminute, whereas the total optically thin free-free contribution, extrapolated from 2 cm flux, is ∼46 mJy. The 2.6 mm "excess" above the free-free value is therefore ∼26 ± 10 mJy. If this excess were all due to emission from dust at a temperature of 10 K, we obtain, for a 2.6 mm opacity of 1×10^{-3} cm^2 g^{-1}, a molecular mass of 2×10^8 $M_\odot$. The actual mass could be lower if there is a contribution to the 2.6 mm flux from H II regions that are optically thick at frequencies of ∼115 GHz. We therefore adopt as an upper limit to the molecular mass of $M_{\rm H_2} < 2 \times 10^8$ $M_\odot$ based on dust emission.

4. CO EMISSION IN NGC 5253: FUEL FOR THE STARBURST

The CO emission from NGC 5253 is *remarkably* weak for a starburst of its size. The Owens Valley Radio Observatory (OVRO) map of the CO emission in the nucleus of NGC 5253 is shown in Figure 1 (*black contours*) and in Figure 2. The central CO source is barely detectable, with an integrated intensity of 14 Jy km s^{-1}. The peak intensities in the individual 8 MHz channel maps are 0.2 K, or ∼4–5 σ; the effective signal-to-noise ratio in the final integrated map is slightly higher, ∼6–8 σ. The radial velocity of the emission is $v_{\rm lsr} \sim 400$–420 km s^{-1}, with the lower velocity gas to the north. Although the source is weak, the positional coincidence with the optical dust lane, and the kinematic coincidence with H I velocities in this region (Kobulnicky & Skillman 1996), are further evidence that this feature is real. The extent of the map is limited by the primary beam of the 10.4 m antennas, which is 56″, FWHM. The emission at the northeast edge of the primary beam appears to be real. The position of the optical supernova Z Cen (SN 1895B; Caldwell & Phillips 1989) is located at the southwest edge of this cloud. However, since this CO feature is strongly affected by enhanced noise at the edge of the primary beam, we shall not consider it further here. CO was first detected in NGC 5253 by Wiklind & Henkel (1989) with the Swedish-ESO Submillimeter Telescope. They find an

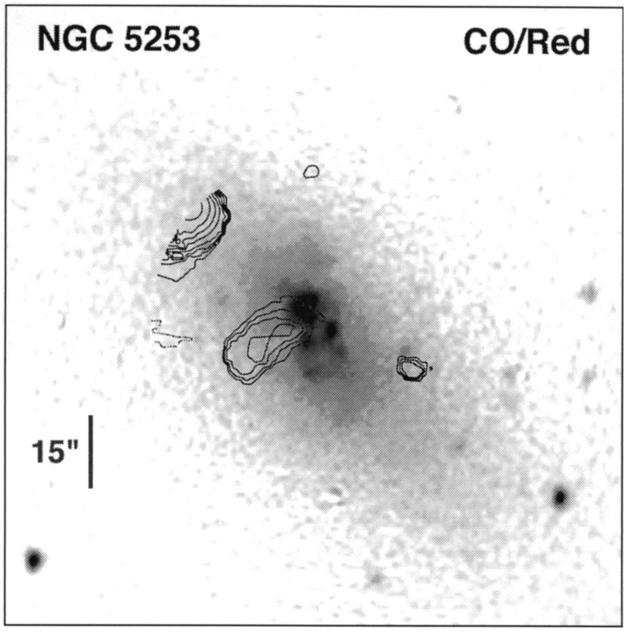

FIG. 2.—CO image (*contours*) overlaid on a red image of NGC 5253 (*gray scale*) taken at the Wise Observatory. The uncertainty in registration is determined by the uncertainty in the optical astrometry, which is ∼1″–2″.

integrated intensity a factor of 2 higher than we do for the nuclear source, which could in part be due to the observational uncertainty in our interferometer flux or resolved-out flux; however, their 44″ beam may also include some of the other nonnuclear sources, particularly the relatively bright source to the northeast.

That the CO detection is only ∼6–8 σ means that the flux cannot be determined very reliably, but the weakness of the emission is more interesting than its precise value. For comparison, the integrated intensity of the emission in M83, which has a starburst of similar magnitude, is 1610 Jy km s^{-1} (J. L. Turner 1996, private communication), 2 orders of magnitude higher than in NGC 5253. Generally, where there is strong radio continuum emission, there is strong CO emission. This is not the case in NGC 5253.

CO appears to be a good tracer of molecular gas mass, mostly M_{H_2}, in the Galaxy (Strong et al. 1988; Solomon et al. 1987) and on global scales in large spiral galaxies (Devereux & Young 1990). However, in metal-poor galaxies, CO is known to be underluminous, i.e., the local $X_{CO} = N_{H_2}/I_{CO}$ conversion factor is higher than the Galactic value, for which we adopt $X_{CO} \sim 2.3 \times 10^{20}$ cm^{-2} (K km s^{-1})$^{-1}$ (Strong et al. 1988), generally by factors of a few. In the LMC, the conversion factor is 4–7 times higher than the Galactic value, or $X_{CO} \sim 17 \times 10^{20}$ cm^{-2} (K km s^{-1})$^{-1}$ (Israel et al. 1986; Cohen et al. 1988). In the SMC, the conversion factor is nearly 30 times the Galactic value, or $X_{CO} = 60 \times 10^{20}$ cm^{-2} (K km s^{-1})$^{-1}$ (Rubio et al. 1991). There seems to be a correlation between metallicity and X_{CO} for metal-poor galaxies (Wilson 1995; Verter & Hodge 1995; Arimoto, Sofue, & Tsujimoto 1996; Sakamoto 1996). NGC 5253 is metal poor, but not extremely so. At 12 + log (O/H) ∼ 8.0–8.2 (Walsh & Roy 1989), it lies between the LMC (8.4) and SMC (8.0) in metallicity (Pagel et al. 1978). Based on this metallicity, one might then expect the CO in NGC 5253 to be underluminous in CO by factors of a few to 30 times compared to Galactic clouds, with $X_{CO} \sim 20$–60×10^{20} cm^{-2} (K km s^{-1})$^{-1}$.

Can we deduce the CO conversion factor in NGC 5253? First, the Galactic value can be rejected. For NGC 5253, it gives $M_{H_2} = 1 \times 10^6$ $M_\odot$. This can be compared with the minimum mass in O stars alone of $M_O \sim 10^5$–10^6 $M_\odot$ (B96). Since there are almost certainly lower mass stars (such as B stars), the total stellar mass must be close to $M_{stars} \sim 10^7$–10^8 $M_\odot$. In the Milky Way, star formation efficiencies are at most a few percent on these size scales, from which we infer a total gas mass of close to 10^9 $M_\odot$. This would imply that we are underpredicting the amount of star-forming gas by at least 2 orders of magnitude by employing the Galactic CO conversion factor.

We cannot directly measure the molecular gas content through observations of H_2, so we are left with indirect means of estimating the CO conversion factor in NGC 5253. Our estimate of the total stellar mass in the starburst depends heavily on the IMF, so we consider now less model-dependent means of estimating the molecular gas mass. One possibility is to assume a infrared light–to–molecular mass ratio, L_{IR}/M_{H_2}, which is related to the efficiency of star formation. In Galactic molecular clouds, L_{IR}/M_{H_2} is a stable quantity, ranging from about 1–4 for quiescent molecular clouds to 10–20 for star-forming clouds (Scoville & Good 1989), with similar values for starbursts in large spiral galaxies (Young & Scoville 1991). The highest values of L_{IR}/M_{H_2} are found in ultraluminous infrared galaxies: Arp 220 has $L_{IR}/M_{H_2} = 100$ (Scoville et al. 1991). If we apply the standard conversion factor to our observed CO flux, the CO-predicted molecular mass of $M_{H_2} = 10^6$ $M_\odot$ and the observed infrared luminosity from *IRAS* fluxes give an "observed" value of $L_{IR}/M_{H_2} = 800$ for NGC 5253. If we assume that L_{IR}/M_{H_2} is actually 10–20, as in Galactic star-forming clouds and other nearby starbursts of similar size (see, e.g., Hurt & Turner 1991), we would infer that the gas mass is seriously underestimated by the Galactic value of the conversion factor and that X_{CO} in NGC 5253 is at least 40–80 times higher than the Galactic value, or $X_{CO} = 90$–180×10^{20} cm^{-2} (K km s^{-1})$^{-1}$. However, as discussed previously, L_{IR} in NGC 5253 is unusually low compared to other measures of starburst activity, possibly owing to a low dust-to-gas ratio. If instead one considers the luminosity in OB stars inferred from the radio continuum and Brackett line fluxes, L_{OB}, then the ratio becomes $L_{OB}/M_{H_2} = 3000$–5000! This would imply that $X_{CO} = 350$–1200×10^{20} cm^{-2} (K km s^{-1})$^{-1}$. The upper limits to dust emission at 2.6 mm that we obtained in § 3 constrain the gas mass, for a Galactic dust-to-gas ratio, to be $<2 \times 10^8$ $M_\odot$ and would imply a conversion factor at most 200 times the Galactic value, or $X_{CO} \lesssim 500 \times 10^{20}$ cm^{-2} (K km s^{-1})$^{-1}$, and higher if the dust to gas ratio is low. These results suggest that the value for X_{CO} in NGC 5253 is nearly an order of magnitude higher than the value observed for the SMC, in spite of the fact that it has a slightly higher metallicity.

It is possible that L_{IR}/M_{H_2} is higher in NGC 5253 than it is in the Galaxy simply because the efficiency of star formation (M_{stars}/M_{gas}) is extremely high? This has been suggested to explain the lack of CO emission toward 30 Doradus in the LMC (Israel et al. 1986). The nature of the star formation process may well be different in NGC 5253. An obvious difference is that it appears to be forming protoglobular clusters (Meurer et al. 1995; B96; Gorjian 1996) rather than open clusters. Given the observed N_{Lyc}, a factor of 10 increase in star formation efficiency, to $M_{gas} \sim 0.1$–1 M_{stars}, would be required, in addition to an SMC conversion factor.

Can it be that the starburst in NGC 5253 is fueled by dense atomic clouds rather than molecular clouds, so that molecular gas mass is not the appropriate quantity to measure? H I probably plays a more prominent role in the star-forming regions in NGC 5253, where the radiation field is intense and where the low metallicity will reduce the extinction and in turn lower both the CO/H_2 ratio (Sternberg & Dalgarno 1995) and, to a lesser extent, the hydrogen atomic/molecular ratio (Maloney & Black 1988). Lequeux et al. (1994) have shown in their models for the low-metallicity molecular clouds in the Magellanic Clouds that CO does not become abundant until $A_v = 1$ (for dense gas) to $A_v = 8-10$ (for diffuse gas) and that the H_2 abundance is down as well, although not nearly as much as CO. Therefore, dense clouds in low-metallicity galaxies may have a higher atomic fraction than usual. However, the H I mass in the central (1′) region of NGC 5253 has been measured and is $\sim$1–3 $\times 10^7\ M_\odot$ (Bottinelli et al. 1972). This is still an order of magnitude less gas mass than what would be required on the basis of the ionizing fluxes.

5. AN ACCRETED BODY OF VERY LOW METAL GAS?

There are a number of models that can explain the unusual characteristics of the star formation in the center of NGC 5253, to wit, the low infrared luminosity and even lower CO luminosity as compared with the derived ionizing luminosity. The first model, that all the stars formed are earlier than spectral type O4, will not be considered further here. A second model is that the stars are forming from H_2 gas; that the CO/H_2 conversion factor is 10 times higher than it is in the Galaxy, consistent with a Magellanic metallicity; and that the star formation efficiency is at least an order of magnitude higher than it is in the Galaxy, or $M_{\rm stars} \sim 1$–$10\ M_{\rm gas}$. A third possibility is what we find most interesting, and may be true even if the second model holds, and that is that the starburst in NGC 5253 is caused by accretion of relatively unprocessed gas with superlow metallicity. In this model, the molecular gas clouds in the nucleus of NGC 5253 have not Magellanic but 1/10 Magellanic metallicity. That NGC 5253 has accreted material recently is not a new idea; van den Bergh (1980), Graham (1981), Caldwell & Phillips (1989), and Moorwood & Glass (1982) have all suggested that an accretion event might be responsible for the large number of intermediate-age clusters surrounding the galaxy and the recent starburst event.

There are three pieces of evidence here to support the accretion scenario. First is the extremely weak CO emission that could be most easily explained by unusually low metallicity of the star-forming gas. Second is the orientation of the CO along the dust lane perpendicular to the disk of the galaxy and roughly along its rotation axis. This suggests that the gas did not originate in the galaxy and cannot have persisted in this configuration for very long. Third is the kinematics of the gas in the dust lane. Both the H I and the CO give a velocity range for this gas of $v_{\rm LSR} \sim 400-420$ km s^{-1}. This is redshifted with respect to the disk velocity field at this location, where the average velocity in the diffuse Hα-emitting gas is 380 km s^{-1} (Atherton et al. 1982). There is evidence for a velocity gradient along the dust lane; in H I, the gradient persists to the northwest of the galaxy as well (Kobulnicky & Skillman 1996). Although this gradient suggests rotation, the location of the starburst at the end of the dust lane suggests that this gas is passing through the disk, and perhaps the star formation was initiated by the passage. It is interesting to note that there is a region of anomalous velocity in the Hα map of Atherton et al. at the location of our faint northern continuum source. The velocity of this emission, $\sim$400 km s^{-1}, is similar to that of the gas at the northern end of the dust lane gas and further suggests a link between the two.

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