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DETECTION OF STRONG CARBON MONOXIDE EMISSION FROM THE HOST GALAXY OF THE QUASAR I Zw 1

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ABSTRACT

We have observed the radio-quiet quasar I Zw 1 in the $J = 1$–0 and $J = 2$–1 lines of CO and obtained clear detections in both transitions. The $J = 1$–0 line appears much more luminous than the $J = 2$–1 line. If the CO is optically thick and thermalized, as it is in galactic molecular clouds, this implies that the CO is extended on the scale of the larger $J = 1$–0 beam size (26 kpc). This is roughly the same scale as the optically visible disk of the host galaxy of I Zw 1, so the CO emission must originate throughout the host galaxy's disk. This is substantiated by the CO profile shape, which is double-horned and symmetric like those seen in the rotating disks of the spiral galaxies.

In a plot of CO luminosity versus far-infrared luminosity, I Zw 1 lies well within the distribution of luminous *IRAS* galaxies, demonstrating the plausibility of the hypothesis that the far-infrared emission in I Zw 1 is thermal. If more than about half of the far-infrared is attributed to a nonthermal mechanism, I Zw 1 moves into an unoccupied zone on the diagram. Therefore, despite the quasi–power-law infrared spectrum, the far-infrared may be dominated by dust emission.

Subject headings: infrared: sources — interstellar: molecules — quasars

I. INTRODUCTION

About three dozen radio-quiet quasars (RQQs) were detected by the *Infrared Astronomy Satellite* (*IRAS*) in one or more of its four wavebands (Neugebauer *et al.* 1986). These observations gave us our first look at the far-infrared continua of this important class of objects, whose numbers comprise some 85%–90% of all known quasars (e.g., Kellerman *et al.* 1985). However, it appears that the *IRAS* data do not provide enough information to allow us to discern the infrared emission mechanism(s) in RQQs with any degree of certainty (e.g., Barvainis and Antonucci 1989, hereafter BA89). This is in contrast to the situation for blazars and some other radio-loud quasars, where there exists strong evidence favoring the dominance of synchrotron emission from radio to optical wavelengths (Landau *et al.* 1986). In order to develop a coherent picture of the infrared emission in RQQs, further diagnostic measurements are needed in order to supplement *IRAS*.

Future satellite missions may someday provide such measurements, but for the present we are limited to whatever information we can garner from the ground (almost all of these objects are too weak to be studied using the Kuiper Airborne Observatory). One important diagnostic which is now becoming accessible is the location and slope of the far-infrared-submillimeter cutoff, which must occur shortward of 1.3 mm (BA89). For example, the cutoff slope, whether greater or less than 2.5 ($f_\nu \propto \nu^\alpha$), will distinguish between synchrotron and thermal dust emission mechanisms.

Another diagnostic which may prove useful in discriminating infrared emission mechanisms is the level of carbon monoxide line emission present in RQQs. Regions rich in molecules, both galactic and extragalactic, are strong thermal emitters in the far-infrared as a result of the cohabitation of molecules and dust. The far-infrared emission from normal galaxies and infrared luminous *IRAS* galaxies is almost certainly due to dust, and in these objects CO is readily detected (e.g., Sanders *et al.* 1986). In a plot of CO luminosity versus far-infrared luminosity for high-luminosity *IRAS* galaxies, there is an obvious correlation between these two quantities, but with a fair amount of scatter (see below). Measurements of CO in quasars might best be viewed as a consistency check on our ideas about the infrared emission mechanism. We can ask: Are the measured levels (or upper limits) on CO emission consistent with thermal emission (within the range seen in galaxies), or are they sufficiently out of line as to indicate a nonthermal explanation?

This is the question we address in this *Letter*, using new CO observations of the RQQ I Zw 1.

II. OBSERVATIONS AND RESULTS

The observations were carried out with the IRAM 30 m telescope on Pico Veleta near Granada, Spain, over the period 1988 July 22–25. For details regarding the telescope, see Baars *et al.* (1987). The CO $J = 1$–0 line at rest frequency 115.271 GHz was observed using an SIS receiver with noise temperature 180 K. The antenna beam size is 21″ at 115 GHz. Measurements of the CO $J = 2$–1 line at rest frequency 230.538 GHz were performed with an SIS receiver having a noise temperature of 260 K. At this frequency, the antenna beam size is 12″. The pointing procedure consisted of cross-scans on a nearby continuum emitting quasar (MR

2251 + 158). Pointing was checked every 1–2 hr, and was found to be better than ±2″.

The spectrometer consisted of a filterbank with 512 channels of 1 MHz width. All observations were made with a wobbling secondary (wobbler frequency 0.25 Hz). The sky references (taken alternately on each side of the source) were 90″ away from I Zw 1, and the beams were exchanged every 30 s. Spectra were calibrated using hot and cold loads, after each 5 minute source observation. The main beam efficiency is 0.60 at 110 GHz and 0.45 at 230 GHz. System temperatures were about 450 K for CO $J = 1\text{–}0$ and 700 K for CO $J = 2\text{–}1$.

The data were reduced using the CLASS software package developed at IRAM and Grenoble Observatory. The wobbler switch mode used for the observations resulted in straight baselines, ideal for CO profile analysis in cases where the CO line is a substantial fraction of the baseline width. The spectra have been corrected for the main beam efficiencies, because source size is similar to the beam size, and are in units of T_r^*.

I Zw 1 (= 0050 + 124) was clearly detected in CO on each night of observation (a preliminary report of our results was given by Antonucci *et al.* 1989). The averaged and smoothed spectra are shown in Figure 1 and represent total integration times of 7 and 3.5 hr in $J = 1\text{–}0$ and $J = 2\text{–}1$, respectively. The $J = 1\text{–}0$ profile is double-horned and symmetric and is nearly identical to the H I profile obtained by Condon, Hutchings, and Gower (1985). The $J = 1\text{–}0$ and $J = 2\text{–}1$ profiles are similar, but the limited baseline region available for the $J = 2\text{–}1$ line makes its precise shape somewhat uncertain. Observed and derived quantities are summarized in Table 1. Assuming that the CO is thermalized and optically thick in both transitions (as it is in many galactic molecular clouds), the higher luminosity seen in the $J = 1\text{–}0$ transition means that substantial emission arises outside the 12″ (= 15 kpc for H_0 = 75 km s^{-1} Mpc^{-1}, $q_0 = 0$) $J = 2\text{–}1$ beam. (A relative calibration error of almost a factor or 2 between the $J = 1\text{–}0$ and $J = 2\text{–}1$ observations would be required to nullify this conclusion, so we consider it to be firm.) Some degree of central concentration may be indicated by ratio of $J = 2\text{–}1$ to $J = 1\text{–}0$ luminosities, which is larger than what would be obtained from a uniform source.

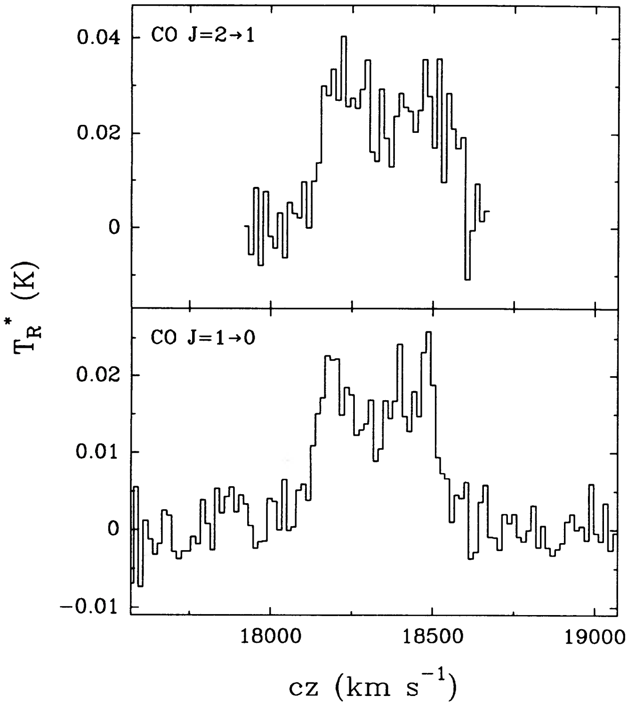

FIG. 1.—Observed CO spectra for I Zw 1, smoothed to a resolution of 15 km s^{-1}.

TABLE 1

CO PARAMETERS FOR I ZW 1

Transition	W^a	z^b	$I_{CO}{}^c$ (K km s^{-1})	$L_{CO}{}^d$ (K km s^{-1} pc^2)
$J = 1\text{–}0$..........	413	0.0611	7.0	3.4×10^9
$J = 2\text{–}1$..........	...	...	11.0	1.8×10^9

[a] Width of CO $J = 1\text{–}0$ line, $W = c\Delta\nu(1 + z)/\nu_e$ km s^{-1}, where ν_e is the emitted CO $J = 1\text{–}0$ frequency (Condon, Hutchings, and Gower 1985).

[b] CO redshift derived from the midpoint between the outer edges of the $J = 1\text{–}0$ profile at the half-power points.

[c] CO intensity.

[d] CO luminosity, calculated using $L_{CO} = \pi/4\ I_{CO}\, d_{\rm beam}{}^2$, where $d_{\rm beam}$ is the beam diameter in pc at the distance of the source.

III. DISCUSSION

I Zw 1 is surrounded by a large and very luminous host galaxy, which has been modeled as a disk system by Smith *et al.* (1986; the following galactic and nuclear parameters are from this reference). The galaxy's blue magnitude, $M_B{}^{\rm gal} = -21.5$ (for H_0 = 75 km s^{-1} Mpc^{-1}, $q_0 = 0$), puts it near the upper end of the spiral galaxy luminosity function (Holmberg 1975). The host is 1.6 mag fainter than the quasar nucleus ($M_B{}^{\rm QSO} = -23.1$). The average isophotal radius of the host, out to 25 mag arcsec^{-2}, is R_{25} = 18.5 kpc (= 15″); the galaxy thus extends somewhat beyond the CO $J = 1\text{–}0$ beam. The system is accompanied by two stellar appearing objects, one being a foreground star and the other a companion galaxy (Heckman *et al.* 1984). According to Smith *et al.* (1986), the host galaxy's isophotes are distorted at low levels, and an armlike feature is visible near the companion. The symmetric CO and H I profiles argue, however, against serious disruption of the disk.

Our motivation in making CO observations of quasars is to obtain clues regarding the origin of the far-infrared emission. One plausibility test for thermal emission is to compare the levels of CO and far-infrared power in our program quasars with the levels seen in *IRAS* galaxies of similar luminosity (BA89). In the latter objects, the far-infrared is almost certainly thermal emission from dust, based upon the similarity between their infrared spectral shapes and those of known thermal sources. Furthermore, there is a rough correlation between CO and far-infrared luminosities in these galaxies. In Figure 2 we plot CO luminosity (L_{CO}) versus far-infrared luminosity (L_{FIR}, calculated according to the prescription of Appendix B of *Cataloged Galaxies Observed in the IRAS Survey* [1985]) for luminous *IRAS* galaxies and for I Zw 1. Our CO detection of I Zw 1 places it comfortably within the distribution of *IRAS* galaxies, demonstrating the plausibility of thermal far-infrared emission in this quasar. If we assume that some fraction of the emission is nonthermal in character, then plotting only the remaining (thermal) part will shift the position of I Zw 1 to the left in Figure 2. The open stars on the plot show the location of I Zw 1 if only 50% or 25% of the far infrared is thermal. It can

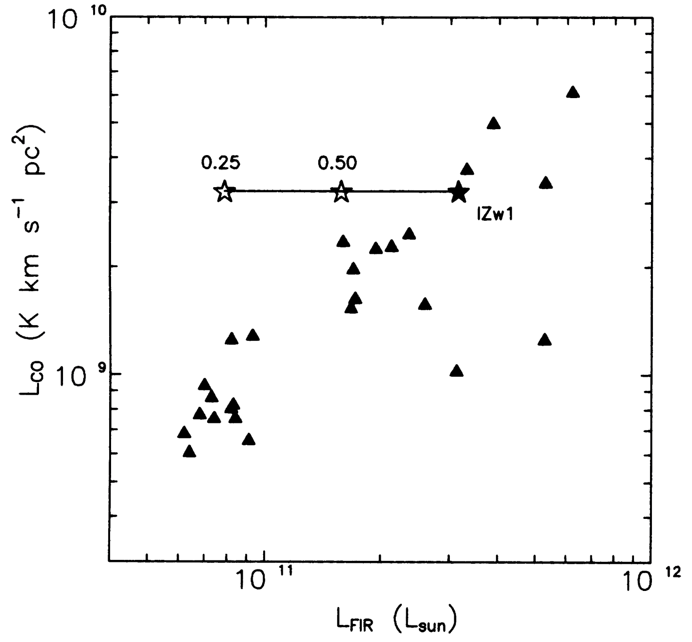

FIG. 2.—Plot of CO luminosity vs. far-infrared luminosity for I Zw 1 and the *IRAS* galaxy sample (*triangles*) observed by Sanders *et al.* (1986). The filled star gives the actual position for I Zw 1 on the diagram, while the open stars show its hypothetical location if only 50% or 25% of the far-infrared emission is thermal (see text).

be seen that by the 25% mark I Zw 1 would lie well outside the distribution of luminous *IRAS* galaxies. Therefore, if the analogy with *IRAS* galaxies is valid, a significant and perhaps dominant fraction of the far-infrared emission is likely to be thermal. The infrared and CO luminosities of the host galaxy are both extremely large, being typical of *IRAS* galaxies rather than normal galaxies.

Some differences, aside from the quasar nucleus, are evident between the properties of I Zw 1 and those typical of luminous *IRAS* galaxies. The infrared spectral energy distribution (SED) of I Zw 1 is fairly flat in νF_ν (Edelson and Malkan 1986; BA89). Most galaxies show a sharp rise between 25 and 60 μm. Two counterexamples, NGC 1068 and NGC 3227, can be found in the Sanders *et al.* (1986) sample plotted in Figure 2, but both are Seyfert 2's rather than typical *IRAS* galaxies. Furthermore, high-resolution observations (both spectral and spatial) of NGC 1068 show that the infrared emission consists of two or more dust components at different temperatures, which conspire to produce a roughly flat SED between about 10 and 100 μm in the undersampled *IRAS* data (Edelson and Malkan 1986; Hildebrand *et al.* 1977).

In fact, the most interesting aspect of this evidence for thermal emission in I Zw 1 is that this object has a quasi–power-law infrared spectrum, like those of many luminous quasars (Edelson and Malkan 1988; BA89). Sanders, Scoville, and Soifer (1988) report copious CO emission from the quasar Mrk 1014, but in that case the infrared spectrum is unusual for a quasar, and clearly thermal.

Another possible difference between I Zw 1 and *IRAS* galaxies is in the CO profiles. Infrared-luminous galaxies tend to have convex profiles (e.g., Sanders and Mirabel 1985; Sanders *et al.* 1986), in contrast to the classic, double-horned rotating disk profile seen in I Zw 1. Most of the highly luminous *IRAS* galaxies appear to be involved in interactions or mergers, which can both disturb systematic rotation in the disks and confuse the observed CO profiles as a result of the contribution from the two systems. Also, the bulk of the infrared and CO from some *IRAS* galaxies may arise from the nuclear regions rather than from the whole disk (e.g., Arp 220, Joy *et al.* 1986 and Casoli *et al.* 1988; M82 and NGC 253, Rieke *et al.* 1980). H I profiles in *IRAS* galaxies show a similar propensity for convex shapes (Garwood, Helou, and Dickey 1987). However, more quasar CO profiles will have to be obtained to determine whether they differ systematically from *IRAS* galaxies.

The optical spectrum of I Zw 1 is unusual. Line ratios indicate that the permitted lines come from a high-density region, which is normal for quasars and Seyfert 1 nuclei, but the permitted and forbidden lines are comparable in width (Phillips 1976; Oke and Lauer 1979). It is similar in this way to some of the "narrow-line Seyfert 1 galaxies" of Osterbrock and Pogge (1985). It is also a strong Fe II emitter.

Mirabel and Wilson (1984) studied neutral hydrogen in Seyfert galaxies and found that about 60% have H I profiles similar to normal spirals. They also found that there is a systematic shift of about 60 km s^{-1} between the nuclear narrow emission-line velocities and the systemic velocities derived from H I. Hutchings, Gower, and Price (1987), in a study of H I in quasars, find a similar difference of 50 km s^{-1} between the narrow emission line region and H I velocities ($v_{\rm H\,I} > v_{\rm NLR}$). A velocity difference much larger, but in the same sense, has been noted for I Zw 1 by Condon, Hutchings, and Gower (1985). The H I and CO lines are at nearly the same redshift as the off-nuclear stellar absorption lines (Boroson and Oke 1987), as well as the permitted nuclear emission lines (Hβ, Fe II, etc.), but the forbidden nuclear lines ([O III] and [Ne III]) are blueshifted by 700 km s^{-1} relative to these systems. This may be due to inflow or outflow of the narrow-line region combined with some sort of symmetry-breaking absorption (Condon, Hutchings, and Gower 1985). This difference between systemic (CO and H I) and forbidden line velocities is very large and conflicts with the common assumption that the narrow line region is near systemic.

IV. CONCLUSIONS

Our detection of CO in I Zw 1 adds to the suddenly growing body of evidence suggesting that the far-infrared radiation in RQQs is thermal. Several of the *IRAS*-detected RQQs recently studied by Chini, Kreysa, and Biermann (1988) have cutoff slopes between 100 μm and 1.3 mm that exceed 2.5. This group includes I Zw 1, for which $\alpha > 2.6$. The critical slope $\alpha = 2.5$ is fairly definitive, because this is the maximum slope allowed for self-absorbed synchrotron emission, while on the other hand all known dust sources have larger cutoff slopes. Other mechanisms for steep cutoff slopes, such as free-free absorption, are possible but require fine tuning of parameters (Antonucci and Barvainis 1986; Chini, Kreysa, and Biermann 1988). Cool dust sources cut off naturally in the far-infrared/submillimeter region, precisely where the quasar cutoff is found.

If the far-infrared in RQQs is indeed thermal emission from dust, why do RQQ infrared SEDs generally differ from the SEDs of known dust sources such as galaxies and molecular clouds? As mentioned above, the primary difference in the mid-infrared to far-infrared is that the relatively flat SEDs characteristic of *most* RQQs contrast with the sharp rise between 25 and 60 μm seen in *most* galaxies. While RQQ SEDs are indeed flatter globally than those of galaxies, they can also be quite bumpy in many cases, without the smooth appearance of a single power law (BA89; Chini, Kreysa, and Biermann 1988). This suggests multiple emitting components, each fairly localized in frequency. The far-infrared thermal component in RQQs, perhaps from a galactic disk, may be supplemented by another source of emission in the ~ 1–20 μm region, a source that may be more intimately related to the quasar nucleus. One possibility is a very compact synchrotron source that turns over in the mid-infrared. Another candidate is dust within a few hundred parsecs of the nucleus, which has been heated directly by the powerful quasar ultraviolet radiation. The nearest grains, heated almost to their evaporation temperature, begin to emit strongly between about 1 and 3 μm, explaining the inflection (Neugebauer *et al.* 1987) seen in optically selected quasars near 1 μm; more distant grains, at lower temperatures, contribute emission at longer wavelengths (Barvainis 1987). This idea has recently been confirmed for the near-infrared emission, in variability observations of the Seyfert 1 galaxy Fairall 9 (Clavel, Wamsteker, and Glass 1989). One possible problem with invoking dust to explain the mid-infrared is the observed absence of the 10 μm silicate feature in Seyfert 1's and quasars (Roche *et al.* 1984). The similar absence of the narrow unidentified near-infrared features can be explained by the destruction of small grains in the quasar's hard ultraviolet radiation field (Aitken and Roche 1985).

Most of the RQQs detected by *IRAS* are nearby and relatively low in luminosity, really not much more powerful than the most luminous galaxies. The underlying galaxies can compete with the quasar emission in the far-infrared if they are as luminous as *IRAS* galaxies. But what of the more luminous quasars, which can outshine galaxies optically by orders of magnitude? By far the most luminous *IRAS* RQQ is PG 1634+706, with $M_V = -29.6$ and $z = 1.334$. For this object the infrared SED rises gently to 25 μm, flattens, and then turns down sharply between 60 and 100 μm (BA89). Perhaps significantly, this apparent turnover occurs between 26 and 43 μm in the quasar rest frame. Luminous RQQs may be relatively weak in far-infrared emission compared with the optical, *if* the results for I Zw 1 prove to be generalizable. Although this is our only CO detection of a quasar so far, the limits on the others (BA89) are not yet constraining, and much more sensitive data should be available soon.

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