

## DETECTION OF ABUNDANT MOLECULAR GAS IN THE UV-EXCESS QUASAR MARKARIAN 1014

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### ABSTRACT

CO(1 → 0) emission has been detected from the UV-excess quasar Mrk 1014 (= PG 0157+001 = IRAS 01572+0009) at  $z = 0.163$ . Assuming the same empirical relationship between CO brightness and H<sub>2</sub> surface mass density as has been found for giant molecular clouds in the Milky Way, the mass of H<sub>2</sub> gas is  $\sim 4 \times 10^{10} M_{\odot}$ —more than 10 times the H<sub>2</sub> content of our Galaxy. The infrared and molecular gas properties of Mrk 1014 are similar to other “warm,” ultraluminous infrared galaxies such as Mrk 231, and IRAS 15206+3342 ( $z = 0.125$ ) from which CO(1 → 0) emission is also reported. The trigger for the intense infrared activity in both Mrk 1014 and IRAS 15206+3342 appears to be a recent galaxy merger. It is suggested that objects such as these represent an important link in the evolution of ultraluminous infrared galaxies into UV-excess quasars.

*Subject headings:* galaxies: individual (Mrk 1014) — infrared: sources — interstellar: molecules — quasars

### I. INTRODUCTION

There is accumulating evidence that gas-rich galaxies may play an important role in the origin and evolution of quasars. Much of the evidence so far has come from studies of ultraluminous infrared galaxies, objects that plausibly represent the initial dust-enshrouded stages of quasars (*cf.* Sanders *et al.* 1988*b*). The detection of CO(1 → 0) line emission at 2.6 mm from ultraluminous infrared galaxies (Young *et al.* 1984; Sanders and Mirabel 1985; Sanders *et al.* 1987) has demonstrated that a common property of these objects is an abundant supply of molecular gas. Interferometer observations show that a large fraction of this gas is concentrated in the centers of these galaxies where it appears to be fueling both a luminous starburst and an active nucleus (Scoville *et al.* 1986; Sargent *et al.* 1987; Sanders *et al.* 1988*a*).

To explore the connection between molecular gas and quasars we have begun to search for CO emission from “warm,” ultraluminous infrared galaxies (Sanders *et al.* 1988*c*). These “warm” infrared galaxies have been found in the IRAS data base to be preferentially Seyfert galaxies (Miley, Neugebauer, and Soifer 1985) or quasars (Low *et al.* 1988) and are thought to represent a transition phase between the heavily dust-obscured ultraluminous infrared galaxies and the optical quasars. These “warm” objects span many of the well-known classes of active galactic nuclei including radio-loud and UV-loud objects. Several have infrared properties similar to the “infrared quasars” that have been discovered in comparatively large numbers in the IRAS survey (*e.g.*, Beichman *et al.* 1986; Vader and Simon 1987; Kleinmann and Keel 1987; Low *et al.* 1988). In this *Letter* we report the first detection of CO(1 → 0) emission from a UV-excess quasar Mrk 1014 (= PG 0157+00) observed as part of the CO survey of IRAS warm galaxies. CO emission was also detected from the Seyfert 2, warm, infrared galaxy IRAS 15206+3342.

### II. OBSERVATIONS

The CO observations were made during two observing runs in 1987 October, with the NRAO<sup>1</sup> 12 m telescope equipped

<sup>1</sup> The NRAO is operated by Associated Universities, Inc., under contract with the National Science Foundation.

with a dual polarization SIS receiver with a receiver temperature of  $\sim 90$  K in each channel. Two 256 channel filterbanks of 2 MHz filters, one for each polarization, provided a total velocity coverage of  $\sim 1550$  km s<sup>-1</sup> with a resolution of  $\sim 6$  km s<sup>-1</sup>. The filterbanks were centered at the frequency corresponding to CO(1 → 0) emission in the object rest frame. At the redshifted CO(1 → 0) frequency of  $\sim 99$  GHz the system temperature was  $\sim 400$  K and the beam size was 62" (FWHM). Mrk 1014 was observed during four separate 6 hr intervals. The observations were made using a nutating subreflector chopped at a frequency of 1.25 Hz. This observing mode provided flat baselines. Calibration was provided by a chopper wheel, and pointing (monitored by observations of the planets) was estimated to be accurate to  $\sim 5''$ .

In addition, CO(1 → 0) emission was detected from IRAS 15206+3342 ( $z = 0.125$ ), the only other object from our warm infrared galaxy list to be observed during the October runs. The redshift for IRAS 15206+3342 was determined from an optical spectrum obtained with the double spectrograph (Oke and Gunn 1982) on the Palomar 5 m telescope. IRAS 15206+3342 was observed during three separate 6 hr intervals. At the redshifted CO(1 → 0) frequency of  $\sim 102$  GHz, the system temperature was  $\sim 430$  K and the beam size was 61".

Optical images of Mrk 1014 and IRAS 15206+3342 were obtained with the CCD direct imaging camera on the Palomar 1.5 m telescope as part of the study of Sanders *et al.* (1988*c*). A deep optical image and an optical spectrum of Mrk 1014 have previously been reported by MacKenty and Stockton (1984).

### III. RESULTS

The CO spectrum of Mrk 1014 is shown in Figure 1. The CO line was verified by offsetting the filterbank center velocity either +50 or -50 km s<sup>-1</sup> for each of the four 6 hr observing blocks. The line was marginally detected in each 6 hr block of data, and the line centroid channel moved in the direction expected for the applied velocity shift. Data from each observing block were shifted, co-added, and then smoothed to a resolution of 20 km s<sup>-1</sup>. The resulting noise level was  $\sim 0.3$  mK (rms). The CO line parameters are summarized in Table 1.

The CO luminosity for Mrk 1014 of  $8.1 \times 10^9$  (K km s<sup>-1</sup> pc<sup>2</sup>) is within the range of values ( $3\text{--}11 \times 10^9$  [K km s<sup>-1</sup> pc<sup>2</sup>])

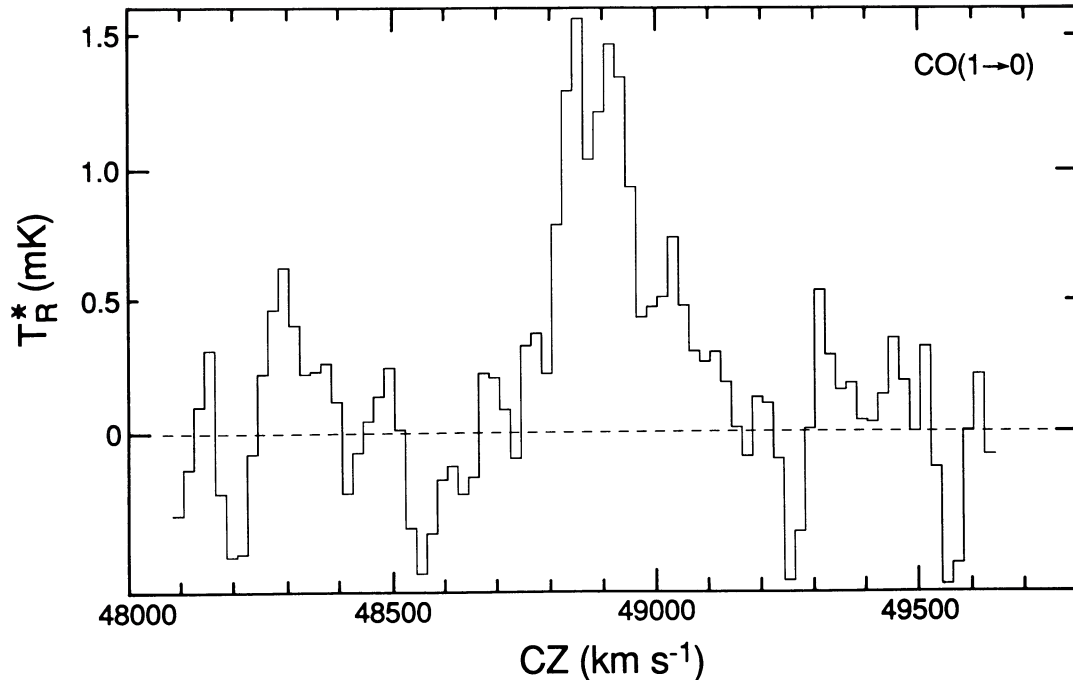


FIG. 1.—CO(1  $\rightarrow$  0) emission spectrum of the UV-excess quasar Mrk 1014 obtained with the NRAO 12 m telescope. The spectrum has been smoothed to a velocity resolution of 20 km s<sup>-1</sup>.

observed for ultraluminous infrared galaxies (Sanders *et al.* 1988b). The mass of interstellar molecular gas in Mrk 1014 was computed from the measured CO luminosity using a “standard” CO  $\rightarrow$  H<sub>2</sub> conversion factor of  $3.6 \times 10^{20}$  H<sub>2</sub> cm<sup>-2</sup> (K km s<sup>-1</sup>)<sup>-1</sup> determined from the virial theorem (Scoville *et al.* 1987), and  $\gamma$ -ray measurements (Bloemen *et al.* 1986) of molecular clouds in the Milky Way. This is equivalent to the relation  $M(\text{H}_2)[M_\odot] = 5.8 L_{\text{CO}} [\text{K km s}^{-1} \text{ pc}^2]$  (Sanders, Solomon, and Scoville 1984). Nearly all empirical measures of the CO  $\rightarrow$  H<sub>2</sub> conversion factor in Galactic GMCs are within a factor of 2 of this value (cf. Scoville and Sanders 1987; Dame *et al.* 1987). In one instance, the nucleus of M82, it has been assumed that the conversion ratio is somewhat lower since the high observed ratios of CO(2–1)/CO(1–0) (Knapp *et al.* 1980) and <sup>13</sup>CO(1–0)/CO(1–0) (Stark and Carlson 1982) seemed to indicate partial optical thinness. However, more recent measurements indicate a substantially lower value for the CO(2–1)/CO(1–0) ratio (Sutton, Masson, and Phillips

1983), and other possible interpretations of the CO line ratios involving hot, optically thick clouds (Young and Scoville 1984) seem equally probable. The CO conversion factor actually depends on both the average CO brightness temperature and the mean gas density, with  $M(\text{H}_2)/L_{\text{CO}} \propto \rho^{0.5}/T_{\text{CO}}$  (Scoville and Sanders 1987; Solomon *et al.* 1987). Since hotter clouds (e.g., in galactic nuclei) tend to be denser (Bally *et al.* 1987), the temperature and density dependences will to some extent cancel. Additional evidence that the CO emission from luminous infrared galaxies is optically thick has been provided by the first measurements of the CO(2–1)/CO(1–0) ratio in extremely luminous infrared galaxies—Arp 220 and NGC 2623 (Casoli *et al.* 1988) and Mrk 231 (P. M. Solomon, private communication)—showing that the ratio of CO(2–1)/CO(1–0) is near unity for each galaxy, similar to what is found for the bulk of the CO emission in the disk of the Milky Way.

The derived mass of H<sub>2</sub> in Mrk 1014 is  $4.4 \times 10^{10} M_\odot$ , approximately 10 times the mass of H<sub>2</sub> in the Milky Way, but slightly less than the H<sub>2</sub> mass derived for the most gas-rich infrared galaxy IRAS 14348–1447 (Sanders, Scoville, and Soifer 1988). Large masses of H I have previously been reported for several nearby UV-excess quasars (Condon, Hutchings, and Gower 1985); however, the current sensitivity of 21 cm observations is insufficient to detect even  $10^{11} M_\odot$  of H I at the distance of Mrk 1014.

More data on Mrk 1014, including optical imaging, spectroscopy, and the far-infrared to UV spectral energy distribution, can be found in Sanders *et al.* (1988c). The host galaxy shows distorted spiral features extending over 90 kpc, that could plausibly be the remnants of a galaxy merger as first suggested by MacKenty and Stockton (1984). The spectral energy distribution exhibits the characteristic ultraviolet excess of optically selected quasars; however, Mrk 1014 has an anomalously large infrared excess which accounts for over half the bolometric luminosity.

TABLE 1  
CO(1  $\rightarrow$  0) LINE PARAMETERS

Parameter	Mrk 1014	IRAS 15206 + 3342
$\alpha_{1950}$ .....	01 <sup>h</sup> 57 <sup>m</sup> 16 <sup>s</sup> .6	15 <sup>h</sup> 20 <sup>m</sup> 38 <sup>s</sup> .3
$\delta_{1950}$ .....	00°09'08"	33°42'12"
$\langle CZ(\text{CO}) \rangle$ (km s <sup>-1</sup> ) .....	48,913	37,485
Distance (Mpc) <sup>a</sup> .....	650	505
$\theta_{\text{beam}}$ .....	62"	61"
$T_R^*$ (peak) (mK) .....	1.6	3.2
$I_{\text{CO}}$ (K km s <sup>-1</sup> ) <sup>b</sup> .....	0.24	0.47
$\log [L_{\text{CO}} (\text{K km s}^{-1} \text{ pc}^2)]$ .....	9.91	9.89
$\Delta(cz_{\text{FWHM}})$ (km s <sup>-1</sup> ) .....	130	200
$\Delta(cz_{\text{FWZI}})$ (km s <sup>-1</sup> ) .....	390	320

<sup>a</sup> Luminosity distance calculated from  $\langle cz(\text{CO}) \rangle$  assuming  $H_0 = 75$  km s<sup>-1</sup> Mpc<sup>-1</sup>.

<sup>b</sup> CO integrated intensity =  $\int T_R^* dv$ .

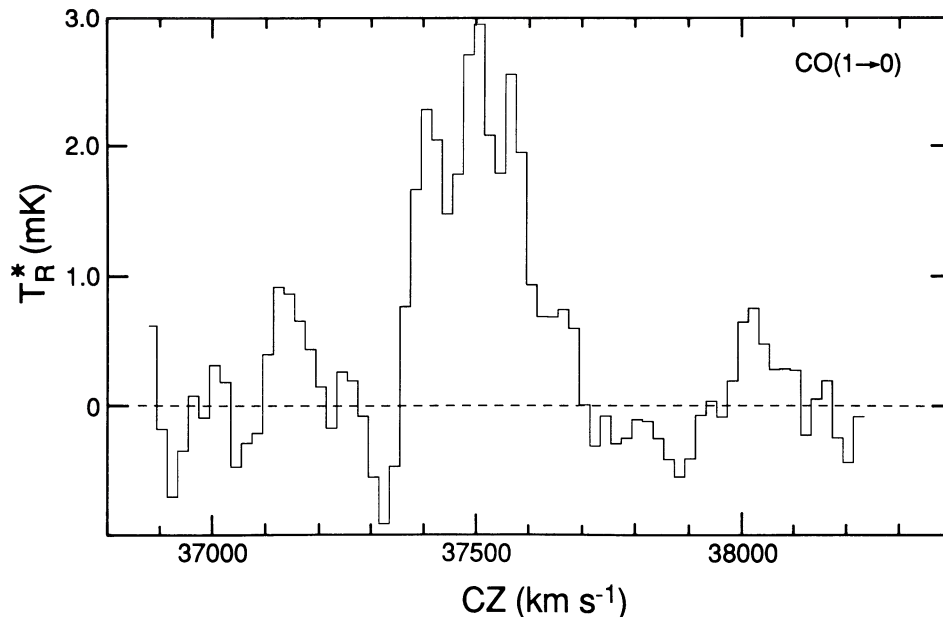


FIG. 2.—CO(1 → 0) emission spectrum of the ultraluminous, warm infrared galaxy IRAS 15206 + 3342 smoothed to a velocity resolution of  $20 \text{ km s}^{-1}$

The CO spectrum for IRAS 15206 + 3342 is shown in Figure 2. The spectrum was co-added from the raw data scans as described for Mrk 1014, and the line parameters are summarized in Table 1. The derived mass of  $\text{H}_2$  is  $4.6 \times 10^{10} M_\odot$ . An optical image of IRAS 15206 + 3342 (Sanders *et al.* 1988c) shows a large ( $\sim 60$  kpc) distorted disk suggesting that this object may be a recent merger. Although the integrated luminosity over the wavelength range  $0.01\text{--}100 \mu\text{m}$  of IRAS 15206 + 3342 meets the minimum bolometric luminosity criteria for quasars derived from adopting the criterion  $M_B < -23$  (Schmidt and Green 1983), and  $L_{\text{bol}} = 9\nu(L_\nu)_B$  (Soifer *et al.* 1986), there is no ultraviolet excess emission from this object; over 85% of its energy emerges longward of  $1 \mu\text{m}$ . The optical spectrum of IRAS 15206 + 3342 is classified Seyfert 2 (Sanders *et al.* 1988c).

#### IV. DISCUSSION

The CO observations of Mrk 1014 provide direct evidence of an extremely gas-rich ISM in a *UV-excess* quasar. Large masses of interstellar molecular gas in quasars are consistent with the idea that a large fraction of quasars are interacting *spiral* galaxies (cf. Hutchings, Crampton, and Campbell 1984), but these data provide the first direct detection of this gas.

The total mass of  $\text{H}_2$  in Mrk 1014 is large, but not so large that it could not be supplied by the merger of two very gas-rich spirals. Further support for a large mass of interstellar gas in Mrk 1014 comes from considering the mass of dust required to produce the observed infrared excess. A lower limit to the total dust mass is obtained by fitting the *IRAS*  $60 \mu\text{m}$  and  $100 \mu\text{m}$  fluxes to a single-temperature dust model. Assuming a standard grain emissivity  $\epsilon \propto \lambda^{-1}$ , and a gas-to-dust mass ratio of 150 yields a *lower* limit to the mass of gas of  $1.2 \times 10^{10} M_\odot$ , a factor of 3.5 less than, but consistent with, the mass derived from the CO data. It is expected that the mass obtained from the *IRAS* data will be less than that from CO since the *IRAS* data is insensitive to the colder component of the ISM.

The relationship of the molecular gas to the active nucleus in

Mrk 1014 is currently an open question given the lack of spatial resolution in the current single-dish observation. The centrally peaked CO line profile for Mrk 1014 is most likely due to a relatively face-on orientation of the merger disk, although it could be due to a centrally peaked gas distribution similar to what is often seen in other ultraluminous infrared galaxies. If the gas is centrally concentrated near the AGN, then a large fraction of the observed infrared excess may be due to direct heating of the gas by the active nucleus. Although there must be a relatively dust-free line of sight toward the active nucleus given that the broad-line region is observed optically, it may be that a significant fraction of the molecular gas is within the central few kpc as observed in the Seyfert 1 galaxy NGC 7469 (Sanders *et al.* 1988a), or in NGC 1068 (Meyers and Scoville 1987).

Based upon the observed  $f_\nu(60 \mu\text{m})/f_\nu(100 \mu\text{m})$  color temperature of the far-infrared emission ( $T = 57 \text{ K}$  assuming  $\epsilon_\lambda \propto \lambda^{-1}$ ), an upper limit to the distance of the dust from a central heating source is  $\sim 2$  kpc. The alternative hypothesis, that the dust is heated by an extended population of young stars, cannot be ruled out. In this case, the observed dust temperature does not constrain the radius of the far-infrared emitting dust. However, given that there is nearly equal luminosity in the UV-X-ray and far-infrared components of Mrk 1014, this latter model then requires the fortuitous coincidence of the energy generation in the AGN and starburst components.

In Table 2 the infrared, optical, and CO properties of Mrk 1014 and IRAS 15206 + 3342 are compared with those of the extreme infrared excess galaxy Arp 220 (Soifer *et al.* 1984) and the classic UV-excess/radio-loud quasar 3C 48 (Greenstein and Schmidt 1964), and the “IR-loud quasar” Mrk 231 (Rieke and Low 1972). In terms of infrared, optical, and UV continuum properties, the two pairs, IRAS 15206 + 3342 and Arp 220 on the one hand and Mrk 1014 and 3C48 on the other, are remarkably similar. In terms of molecular gas properties, the two galaxies reported here both have approximately 3 times the CO luminosity of Arp 220. Due to its larger redshift, there do not yet exist meaningful limits on the molecular gas in 3C

TABLE 2  
COMPARISON OF PROPERTIES OF ULTRALUMINOUS INFRARED GALAXIES/QUASARS

Parameter	Arp 220	IRAS 15206 + 3342	Mrk 231 <sup>a</sup>	Mrk 1014	3C 48 <sup>b</sup>
$\log(L_{\text{bol}}/L_{\odot})$ .....	12.23	12.26	12.66	12.79	12.76
$\log(L_{\text{IR}}/L_{\odot})^c$ .....	12.19	12.18	12.52	12.49	12.51
$v_{f,(80)}/v_{f,(B)}$ .....	60	25	22	5	7
$T_{\text{dust}} \text{ (K)}^d$ .....	45	45	54	57	57
$\log[M(\text{H}_2)/M_{\odot}]$ .....	10.15	10.67	10.15	10.65	...
$L_{\text{FIR}}/M(\text{H}_2) [L_{\odot}/M_{\odot}]$ .....	95	22	150	43	...
Seyfert type .....	2	2	1	1	1

<sup>a</sup> Sanders *et al.* 1987.

<sup>b</sup> Neugebauer, Soifer, and Miley 1985.

<sup>c</sup>  $L(8\text{--}1000 \mu\text{m})$  in the object rest frame.

<sup>d</sup> Single temperature fit to  $f_{\lambda}(60)/f_{\lambda}(100)$  in the rest frame, assuming dust emissivity  $\epsilon \propto \lambda^{-1}$ .

48. Nevertheless, based on the essentially identical infrared continuum properties of 3C 48 and Mrk 1014, it is plausible that abundant molecular gas will be detected in 3C 48. Mrk 231 seems to share many properties of these two extremes, the high effective IR temperature of the UV-excess quasars, and high IR/visible ratio of the ultraluminous infrared galaxies.

The objects in Table 2 span many of the well-known classes of active galactic nuclei, ranging from ultraluminous infrared galaxies like Arp 220 to bona fide radio and/or UV-loud quasars. It is plausible that all of these objects have a common origin and source of energy. The rich ISM in these galaxies may play a fundamental role in the genesis of these objects. Ultimately the dust and gas may be evaporated and expelled

from the host galaxy; however, the results presented here suggest that more gas-rich objects like Mrk 1014 will be discovered among the list of known optical quasars.

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