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CO EMISSION IN THE RADIO-LOUD QUASAR 3C 48

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ABSTRACT

We have used the Owens Valley Millimeter Array to conduct a sensitive search for CO ($1 \rightarrow 0$) emission in the radio-loud quasar 3C 48. An emission feature is detected (4σ) at the redshift of the narrow optical emission lines ($z = 0.3695$). The width of this feature is $\sim 250 \text{ km s}^{-1}$ (FWHM) similar to that expected for a galactic disk, and the integrated CO line flux implies an H_2 mass of $7 \times 10^{10} M_\odot$ (assuming the same CO to H_2 conversion factor found for giant molecular clouds in the Milky Way). This H_2 mass is ~ 30 times that for the Galaxy, and about twice that estimated for ultraluminous *IRAS* galaxies such as Arp 220 and the UV-excess quasar Mrk 1014. These data support previous suggestions that 3C 48 may have formed from the recent merger of gas-rich galaxies and that the extended nebulosity surrounding the quasar is largely due to a population of young stars which could have been formed from the gas detected here.

Subject headings: galaxies: active — galaxies: interactions — galaxies: starburst — ISM: molecules — quasars: general — quasars: individual (3C 48)

1. INTRODUCTION

Several observational studies over the last 5 years have suggested an evolutionary link between the luminous galaxies detected in the *IRAS* survey and quasars. At the highest luminosities ($> 10^{12} L_\odot$) the infrared luminous galaxies have a space density similar to that of quasars (at $z < 0.1$; Soifer et al. 1987) and the nuclei of the ultraluminous infrared galaxies often exhibit optical emission line ratios similar to those seen in active galactic nuclei with nonstellar ionization (Sanders et al. 1988b). Virtually all of the luminous infrared galaxies have abundant interstellar gas, predominantly in molecular form (cf. Sanders, Scoville, & Soifer 1991) and generally concentrated at the centers of these galaxies (cf. Scoville et al. 1991; Okumura et al. 1991).

To further probe the link between luminous infrared galaxies and quasars, molecular line observations of standard optical quasars are vital. At present CO emission has been detected in the UV-excess quasars: Mrk 1014 (= PG 0157+00), PG 0838+77, Mrk 876 (= PG 1613+65), and IZw 1 (Sanders, Scoville, & Soifer 1988a; Barvainis, Alloin, & Antonucci 1989; Alloin et al. 1992). None of these objects is a strong source of radio continuum emission, and it is of importance to extend the detection of molecular gas to radio-loud QSOs. In this *Letter* we report a sensitive search for CO ($1 \rightarrow 0$) emission in the strong radio source 3C 48. 3C 48 was the first optically identified quasar (Matthews & Sandage 1963) and the second object (after 3C 273) to have its redshift measured (Greenstein & Matthews 1963). Despite its high redshift ($z = 0.37$), it is a prime candidate for the detection of CO, in view of its strong infrared excess (Neugebauer, Soifer, & Miley 1985) and the presence of extended emission-line gas and a possible double nucleus (cf. Stockton & Ridgway 1991). The detection of strong Balmer absorption lines in the extended nebulosity indicate a luminous young stellar population (Boroson & Oke 1984), possibly an aging starburst.

2. OBSERVATIONS

The CO observations of 3C 48 were made using the three-element Owens Valley millimeter array between 1991 November and 1992 March. Each of the 10.4 m telescopes was equipped with an SIS receiver with receiver temperature ~ 50 – 100 K (DSB). Spectral resolution was provided by a new digital cross-correlator system (Padin et al. 1983) with four independent bands encompassing 464 MHz at 4 MHz resolution; that is a total velocity range of 1200 km s^{-1} at 10.4 km s^{-1} resolution. The spectrometers were centered at 84.170 GHz which corresponds to the $J = 1 \rightarrow 0$ CO transition in the quasar rest frame. For 3C 48 we adopted the redshift of the narrow optical emission lines ($z = 0.3695$; Boroson & Oke 1984; Wampler et al. 1975) which is significantly different from the redshift, $z = 0.367$, of the broad emission lines.

Phase calibration was provided by observations of the quasar 0234+285 every half hour, and absolute flux calibration was determined from observations of 3C 273, 3C 84, Neptune and Uranus. The relative gains of individual channels in the spectrometer was taken from the observations of 3C 273 and the shape of the residual passband during the 3C 48 observations was further refined by fitting a polynomial to the average spectrum of 0234+285 during each track and dividing this into the 3C 48 spectra. Since the objective of the experiment was the detection of CO emission rather than producing an aperture synthesis image, data were obtained in array configurations without regard for the resulting UV coverage. Most of the data was obtained in two compact configurations with maximum baselines of 60 m and the synthesized (uniform) beam was $8''.6 \times 10''.5$. A total of 44 hr of integration on 3C 48 were obtained with three telescopes.

After gain, passband, and flux calibration the data were analyzed in two ways: a simple vector average of all the on-source spectra and aperture synthesis maps using the NRAO AIPS package. Both procedures yielded consistent results in the sense that the maps exhibit no significant emission outside the central resolution element containing the radio continuum source and the vector-average spectrum agreed with that obtained using AIPS to measure the spectrum by integrating each channel map over the area of the synthesized beam centered on 3C 48.

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FIG. 1.—The vector average spectrum for 3C 48 is shown centered at 84.170 GHz corresponding to CO (1 → 0) transition at $z = 0.3695$. The spectrum is an average of 44 hr of on-source integration with the three-element array. The dashed line corresponds to a continuum level of 0.266 Jy. The crosses correspond to the average phase (continuum + line) for each spectral channel with the full vertical scale being 20° .

In Figure 1 the vector-average spectrum for 3C 48 is shown after convolution to 90 km s^{-1} resolution. The amplitude and phases are shown as solid lines and crosses, respectively. For this average the individual spectra were weighted proportional to T_{SSB}^{-2} . The horizontal dashed line in Figure 1 corresponds to a continuum amplitude of 0.266 Jy determined from the average of 300 km s^{-1} at each end of the spectrum. Based on the noise determined from the individual channel maps, the integrated emission excess seen in Figure 1 corresponds to $\sim 4 \sigma$. The correlation of the phases with the amplitude excess provides further evidence that the emission is probably real. (When the data set is split in halves, the positive feature at the center is present in both subsets although not equally strong.) The peak excess of 7 mJy is just 2.6% of the 84.17 GHz continuum flux and the phase deviation is $\sim 2^\circ$. Achieving this low spectral noise ($\sim 0.1 \text{ mK}$) in the presence of radio continuum would be very difficult with single-dish spectroscopy; however, with interferometry only the cross-correlated signals are detected and temporal variations in the bandpasses of the individual receivers are removed to first order. The full width at half-intensity of the apparent CO emission excess is $\sim 250 \text{ km s}^{-1}$ and the integrated line flux is 2.0 Jy km s^{-1} .

3. DISCUSSION

If the observed emission excess is indeed CO emission from 3C 48 the integrated CO line flux provides an estimate of the molecular gas content in the host galaxy. Adopting a Galactic $\text{CO} \rightarrow \text{H}_2$ conversion factor of $3 \times 10^{20} \text{ H}_2 \text{ cm}^{-2} (\text{K km s}^{-1})^{-1}$, the derived H_2 mass is $7 \times 10^{10} M_\odot$ (for $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $q = 0$, using eq. [A15] in Sanders et al. 1991). The molecular mass estimate could be reduced somewhat if the physical conditions were such that the mean temperature is higher or the gas density lower than those of Galactic GMCs (cf. Sanders et al. 1991). On the other hand, this large mass of interstellar medium is consistent with the estimate of more than $10^{10} M_\odot$ derived from the far-infrared emission assuming a gas-to-dust ratio of ~ 200 (Neugebauer et al. 1985). This

gas-to-dust ratio (and hence the mass estimate) is a lower limit since *IRAS* was sensitive only to dust warmer than $\sim 30 \text{ K}$.

From the *IRAS* pointed observations of 3C 48, Sanders, Scoville, & Soifer (1988; see also Neugebauer et al. 1985) estimate infrared, $8\text{--}1000 \mu\text{m}$, and bolometric luminosities of $3.2 \times 10^{12} L_\odot$ and $6 \times 10^{12} L_\odot$, respectively when scaled to $H_0 = 75$. For the H_2 mass derived above we obtain $L_{\text{IR}}/M_{\text{H}_2} = 46 L_\odot M_\odot^{-1}$. Although the H_2 mass and luminosity-to-mass ratio are both approximately a factor of 20 higher than the average values obtained in the Galaxy (Scoville & Good 1989), they are entirely consistent with estimates derived for other ultraluminous infrared galaxies and optically selected QSOs. The H_2 mass for 3C 48 is ~ 3 times that derived under similar assumptions for the nearest ultraluminous infrared galaxy, Arp 220; it is only slightly larger than the H_2 mass derived for the most gas-rich galaxy in the *IRAS* Bright Galaxy sample IRAS 14349–1447 at $z = 0.087$ (Sanders et al. 1991) and is a factor of 3–5 less than that derived for IRAS 10214+4724 at $z = 2.3$ (see Brown & Vanden Bout 1991 and Solomon, Radford, & Downs 1992). The infrared and molecular gas properties of 3C 48 are almost identical to the first optically selected QSO detected in CO, the radio-quiet object Mrk 1014 (PG 0157+001 = IRAS 01572+0009) at $z = 0.163$ (Sanders et al. 1988a). The derived infrared luminosity-to- H_2 mass ratio for 3C 48 and Mrk 1014 are in fact less extreme than the $80 L_\odot M_\odot^{-1}$ obtained for Arp 220.

4. CONCLUSIONS

Sensitive millimeter interferometer measurements have been used to place constraints and probably detect CO emission in the radio-loud quasar 3C 48. Although the emission excess at the expected redshift 3C 48 is statistically significant ($\sim 4 \sigma$), follow-up observations in other CO transitions to confirm the detection and constrain the physical properties of the molecular gas are critical. Such follow-up observations are important since this is the first radio-loud quasar in which molecular gas has been shown to be probably present; it therefore extends one of the extraordinary characteristics of the ultraluminous *IRAS* galaxies (the massive ISM) to the first radio-loud QSO.

Most of the ultraluminous *IRAS* galaxies exhibit optical and near-infrared morphologies suggestive of a recent galactic interaction or merger (i.e., double nuclei or tidal tails; see Sanders et al. 1988b and Carico et al. 1990). 3C 48 seems also to be a nearly completed merger (Stockton & Ridgeway 1991), as does Mrk 1014 (MacKenty & Stockton 1984). It is plausible that all of these objects ranging from ultraluminous infrared galaxies like Arp 220 to bona fide radio-loud and radio-quiet QSOs have a common origin and source of energy. In such galactic mergers, the ISM abundance plays a critical role. Being much more dissipative than the stellar component, the ISM can concentrate strongly in the nucleus of the merged system (Hernquist 1989; Norman & Scoville 1988), fueling a nuclear starburst or AGN. The molecular gas and dust should ultimately be expelled from the nuclear regions, but depending on the clearing time, it seems reasonable to expect that abundant molecular gas may eventually be discovered in many more optical and radio-selected QSOs.

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