CO IN HIGH REDSHIFT GALAXIES

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1. Introduction

Study of molecular gas in distant galaxies during the last twenty years has followed the steady progress in mm wave receiver sensitivity. In 1975, CO was detected in M 82, NGC 253, and several other galaxies with redshifts of a few hundred $\mathrm{km\,s^{-1}}$ (Rickard et al. 1975; Solomon & de Zafra 1975). Over the next fifteen years, the CO detection horizon increased steadily, reaching $z \approx 0.22$ by 1990 (Downes et al. 1991). The discovery that the large population of infrared luminous galaxies detected by IRAS are very gas rich (e.g., Sanders, Scoville, & Soifer 1991) was especially significant. In the last few years, CO has been detected in two high redshift objects, IRAS FSC 10214+4724 at $z = 2.3$ (Brown & Vanden Bout 1992b) and the Cloverleaf quasar (H 1413+117) at $z = 2.6$ (Barvainis et al. 1994; Barvainis 1996). These objects offer glimpses of galaxies' properties when the Universe was only about 15% of its present age. The presence and conditions of molecular gas in galaxies at such an early epoch are clues to understanding galaxy formation and evolution in the early Universe.

Despite much observational effort, however, no other high redshift sources have confirmed detections of CO. Indeed molecular gas in both 10214+4724 and the Cloverleaf is visible only because they are gravitationally lensed. In intrinsic molecular content, gas distribution, and IR luminosity, these galaxies resemble gas rich, ultraluminous IR galaxies in the local universe. They may be powered by ongoing bursts of massive star formation in the gas rich interstellar medium or by active nuclei fueled by gas accretion. Whatever the power source, substantial processing by massive stars must have already taken place to create the observed heavy elements, dust, and molecular gas. These galaxies indicate the existence of a high redshift parent population similar to nearby ultraluminous galaxies.

2. IRAS FSC 10214+4724

2.1. APPARENT PROPERTIES

The apparent luminosity of 10214+4724, about[1] $10^{14}h^{-2}\,L_\odot$ emitted primarily in the far infrared (Rowan-Robinson et al. 1991, 1993), places it among the most luminous objects known. It exceeds the quasar luminosity threshold by two orders of magnitude. Although 10214+4724 is not strictly speaking a primordial galaxy, because there has been sufficient processing of material through stars to produce metals, it obviously has not had much time to convert its gas to stars. It clearly formed at least a few $\times 10^7$ yr, and more probably $> 10^8$ yr, earlier.

To date, CO in 10214+4724 has been detected with six different telescopes. Since the first observations (Brown & Vanden Bout 1991), however, the CO line flux, precise redshift, and source size have all been disputed. Follow up observations with the IRAM and Nobeyama telescopes (Fig. 1) have all indicated a much smaller line flux, 4 ± 1 Jy km s^{-1}, than first measured with the NRAO 12 m telescope, 21 ± 5 Jy km s^{-1} (Brown & Vanden Bout 1991). The lower measurements imply an apparent mass $M(\mathrm{H_2}) \approx 10^{11}h^{-2}\,M_\odot$ (Solomon, Downes, & Radford 1992), as much gas as the total mass of stars in a large spiral galaxy or the core of a giant elliptical galaxy. The discrepancy with the original measurement led to suggestions (Brown & Vanden Bout 1992b; Sakamoto et al. 1992; Tsuboi & Nakai 1992) the molecular gas is extended over a diameter as large as $60''$ ($240h^{-1}$ kpc) with an apparent molecular mass of about $10^{12}\,M_\odot$. With smaller beams, the large telescopes and interferometers would see, therefore, only the central peak, while the smaller telescope would detect the more extended component. Although it cannot be ruled out a priori, such a large source seems unlikely since only a few molecular clouds have been observed > 20 kpc from the center of the Milky Way and CO has never been detected > 100 kpc from the center of any other galaxy.

To resolve the observational quandry, then, we reobserved CO($3\rightarrow2$) from 10214+4724 with the NRAO 12 m telescope (Radford et al. 1996). We found an integrated line flux of 6.7 ± 1.4 km s^{-1}. This is 3 ± 1 times smaller than the first measurement and is consistent, within its uncertainties, with observations at other telescopes. No evidence remains for an extended source larger than a couple of arcseconds. Molecular gas in 10214+4724 is concentrated in a small central region.

In high redshift objects, submm lines usually difficult to study can be observed at mm wavelengths through the standard atmospheric windows. In 10214+4724, the CO($3\rightarrow2$), ($4\rightarrow3$) (Brown & Vanden Bout 1992b), ($6\rightarrow5$)

[1] $H_0 = 100h$ km s^{-1} Mpc^{-1}, $q_0 = 0.5$

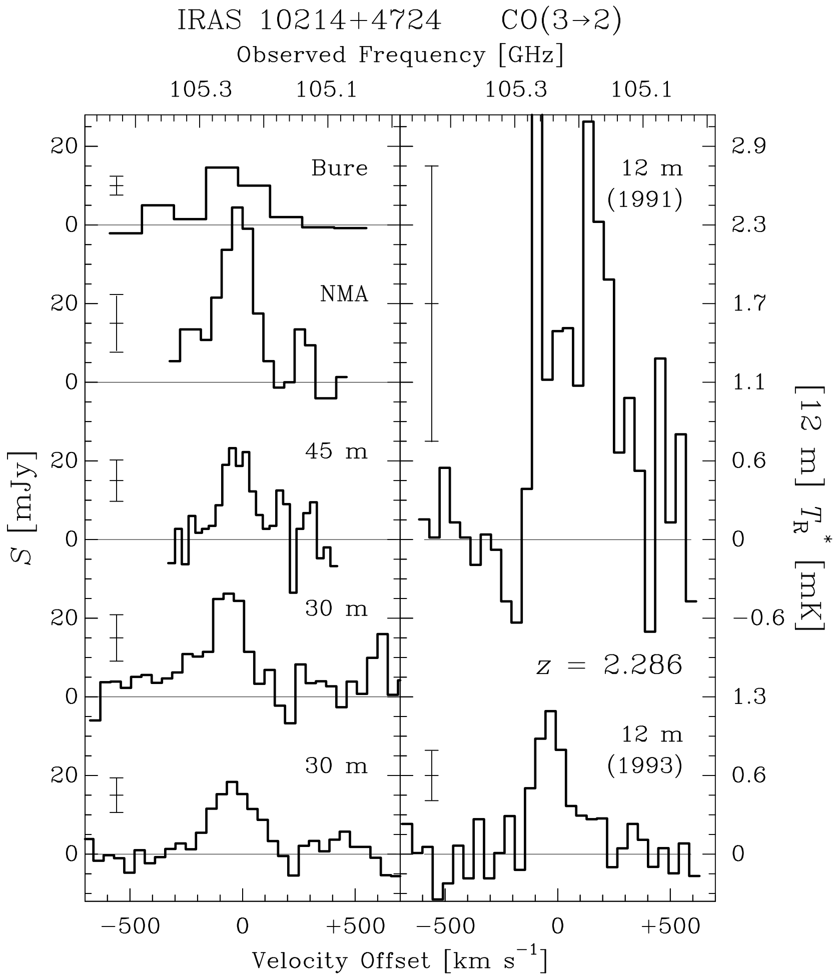

Figure 1. Spectra of CO(3→2) emission at $z = 2.286$ from IRAS 10214+4724 observed with the NRAO 12 m telescope at 16 MHz resolution in 1991 (Brown & Vanden Bout 1991) and in 1993 (Radford et al. 1996), the IRAM 30 m telescope at 16 MHz resolution (upper: Brown & Vanden Bout 1992b; lower: Solomon et al. 1992), the Nobeyama 45 m telescope at 10.5 MHz resolution (Tsuboi & Nakai 1992), the Nobeyama Millimeter Array at 32.5 MHz resolution (Kawabe et al. 1992; Sakamoto et al. 1992), and the IRAM interferometer (Bure) at 50 MHz resolution (Radford et al. 1993). The $\pm 1\sigma$ error bars represent the per channel uncertainty.

(Solomon, Downes, & Radford 1992), and, tentatively, (7→6) (Solomon private communication) lines have all been detected. The line ratios are consistent with a single component LVG model that indicates the gas is warmer, $T_{\rm kin} \approx 50\,$K, and denser, $n(\mathrm{H_2}) \approx 5000\,\mathrm{cm^{-3}}$, than the bulk of the gas in the Milky Way (Solomon, Downes, & Radford 1992), where CO($6 \rightarrow 5$) is only observed in molecular cloud cores near sites of massive star formation (Jaffe et al. 1989). An upper limit to the CO($1 \rightarrow 0$) line flux (Barvainis 1995) is also consistent with this excitation model.

Searches for C I($^3P_1 \rightarrow {}^3P_0$) and ($^3P_2 \rightarrow {}^3P_1$) emission from 10214+4724 have been made, but a claimed detection of C I($^3P_2 \rightarrow {}^3P_1$) (Brown & Vanden Bout 1992a) remains unconfirmed and controversial. In the Cloverleaf quasar, on the other hand, C I($^3P_1 \rightarrow {}^3P_0$) has been detected (Barvainis 1996) with a C I/CO level similar to the nearby galaxy IC 342 (Büttgenbach et al. 1992).

The observed mm and submm spectral energy distribution peaks near $150\,\mu$m, corresponding to a rest frame peak of 46 μm and a dust temperature of about 80 K. In addition, the $60\,\mu$m flux observed by IRAS corresponds to $18\,\mu$m in the rest frame and indicates the presence of hotter dust at about 200 K. These components each have an apparent luminosity of $4 \times 10^{13} h^{-2}\,L_\odot$. The apparent gas-to-dust ratio, inferred from the CO line flux and the $350\,\mu$m (rest frame) continuum flux, is about 500, similar to the Milky Way and to nearby ultraluminous galaxies. This suggests the metal abundance is already approximately Solar (Downes et al. 1992).

2.2. GRAVITATIONAL LENS AND INSTRINSIC PROPERTIES

Optical and infrared images suggest 10214+4724 is magnified 5–50 times by an intervening gravitational lens (Matthews et al. 1994; Elston et al. 1994; Januzzi et al. 1994; Broadhurst & Lehár 1995; Graham & Liu 1995; Eisenhardt et al. 1996). This means, of course, the galaxy's intrinsic luminosity and mass of H_2 are proportionally smaller, but it still ranks among the most luminous and gas rich IR galaxies (Downes, Solomon, & Radford 1995). There is still copious molecular gas, comparable to that in an ultraluminous IR galaxy, to fuel vigorous star formation.

The $2.2\,\mu$m (Matthews et al. 1994; Graham & Liu 1995) and red HST (Eisenhardt et al. 1996) images of 10214+4724 show a $1.5''$ long arc about $1.2''$ south of the intervening galaxy. At the center of the arc is a bright, compact, $0.7''$ diameter core that has a faint counterimage just north of the intervening galaxy. This apparent morphology suggests the intrinsic source has at least two components: a compact source almost coincident with a cusp of the lens caustic and an extended envelope or disk that appears as the extended arc (Broadhurst & Lehár 1995). Because the lens magnification depends on the intrinsic source size, the lens may be chromatic since different spectral components are emitted by sources with different intrinsic sizes. Differential magnification may alter, then, the observed spectrum so it no longer accurately represents the intrinsic spectrum.

Current mm wave interferometers do not have the sub arcsecond resolution available in the near IR and optical and necessary to see details of the CO distribution in 10214+4724. Nevertheless, it is possible to gauge its overall extent.

In a CO($3\rightarrow2$) image made with the IRAM interferometer, the source is clearly more extended east-west than the beam, but it is no wider north-south. Convolving the $2.3'' \times 1.6''$ synthesized beam with the 15% contour of the $2.2\,\mu$m arc reproduces the observed CO distribution well (Downes, Solomon, & Radford 1995). Convolving the beam with a small compact source, such as the bright, compact $2.2\,\mu$m core, on the other hand, produces a much more condensed distribution than observed in the CO image.

A CO($6\rightarrow5$) image made with the OVRO interferometer (Fig. 2) offers better resolution and shows somewhat more directly the east-west extent of the CO distribution. Regardless of the weighting of the visibility data, natural or uniform, this image indicates the apparent CO distribution is $1.5''$ long. We identify the CO distribution with the extended arc in the $2.2\,\mu$m image and, hence, with an extended part of the intrinsic source.

An upper limit to the magnification of the CO image can be determined because the gravitational lens stretches the source image in one dimension, preserving surface brightness, and we can estimate the intrinsic CO brightness temperature from the line ratios (Downes, Solomon, & Radford 1995). The observed luminosity in the CO($3\rightarrow2$) line is $L_{\rm CO} = 2.6 \times 10^{10} h^{-2}\,{\rm K\,km\,s^{-1}\,pc^2}$. For the smallest possible intrinsic CO distribution, an optically thick thermal source, $L_{\rm CO} = m_{\rm CO} \pi r^2 T_b \Delta v$, where r is the intrinsic source radius, T_b is the rest frame brightness temperature of the line, $\Delta v = 220 \pm 30\,{\rm km\,s^{-1}}$ is the linewidth, and $m_{\rm CO}$ is the source magnification. Since the magnification is one dimensional, $m_{\rm CO} = a/r$, where $2a$ is the apparent extent of the CO distribution. The observed CO line ratios clearly indicate the molecular gas is warm. If the gas kinetic temperature is 60 K, slightly cooler than the 80 K dust, an LVG excitation model that fits the observed CO line intensities and ratios indicates the CO($3\rightarrow2$) and ($6\rightarrow5$) brightness temperatures are 43 ± 7 and $27 \pm 5\,$K, respectively, and the opacities are 6, 37, and 41 for the CO($1\rightarrow0$), ($3\rightarrow2$), and ($6\rightarrow5$) lines. At $z = 2.3$, the apparent extent of the CO distribution $2a = 1.5'' \times (4h^{-1}\,{\rm kpc\ arcsec^{-1}}) = 6h^{-1}\,{\rm kpc}$, so $m_{\rm CO} \approx 10$, independent of h.

With this modest lens magnification, 10214+4724 still has a molecular gas content comparable to the most CO rich, IR luminous galaxies (Graham & Liu 1995), but is not extraordinary for that class. The galaxy's intrinsic CO($3\rightarrow2$) luminosity is $2.6 \times 10^9 h^{-2}\,{\rm K\,km\,s^{-1}\,pc^2}$ and the true radius of the CO distribution $r \approx 300h^{-1}\,{\rm pc}$. For comparison, Arp 220 has a CO($1\rightarrow0$) luminosity of $4 \times 10^9 h^{-2}\,{\rm K\,km\,s^{-1}\,pc^2}$ (Solomon, Radford, & Downes 1990),

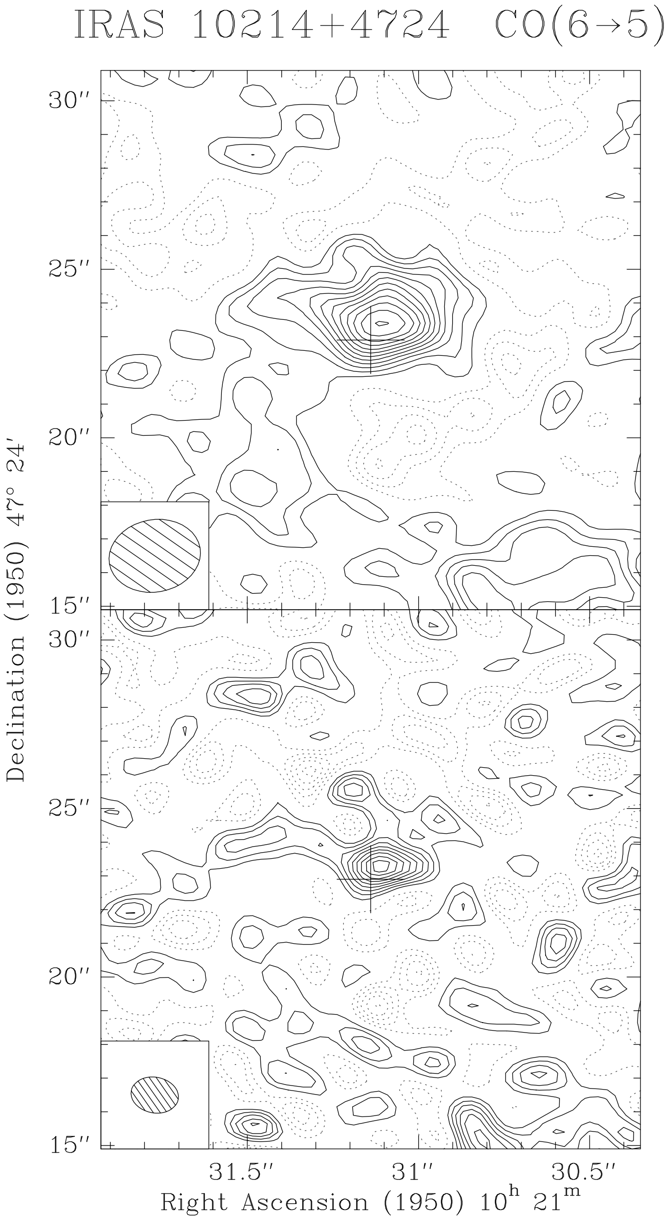

Figure 2. Integrated emission maps of CO(6→5) at $z = 2.286$ from IRAS 10214+4724 observed with OVRO interferometer at 210 GHz. The contour interval is $2\,\mathrm{mJy\,beam^{-1}}$ and the synthesized beam (insert) is $2.7'' \times 2.1''$ for natural weighting (top) and $1.4'' \times 1.1''$ for uniform weighting (bottom). The source is more extended than the beam; the deconvolved source size is about $1.5''$ east-west.

with 2/3 of that concentrated within a radius of $240h^{-1}$ pc (Scoville et al. 1991). In a sample of 37 ultraluminous IR galaxies out to $z = 0.27$, the highest CO($1 \rightarrow 0$) luminosity is $9 \times 10^9 h^{-2}$ K km s^{-1} pc^2 and the median is $5 \times 10^9 h^{-2}$ K km s^{-1} pc^2 (Solomon et al. 1996).

The far IR magnification can be determined by a similar argument, although in this case we have no direct measurement of the source size (Downes, Solomon, & Radford 1995). In 10214+4724, the apparent far IR luminosity of $4 \times 10^{13} h^{-2}$ L$_\odot$, observed at 450 to 1300 μm, is emitted by optically thick dust at ≈ 80 K (Downes et al. 1992). In nearby, non-lensed ultraluminous galaxies, the far IR source is 0.6–1.0 times the the size of the CO source. This suggests the 80 K dust source in 10214+4724 has a radius of 200–$300h^{-1}$ pc, the far IR magnification is 10–13, and the intrinsic far IR luminosity is 3–$4 \times 10^{12} h^{-2}$ L$_\odot$. Again, this is similar to nearby ultraluminous galaxies, albeit at the high end of the distribution. Arp 220, for example, has a far IR luminosity of $6 \times 10^{11} h^{-2}$ L$_\odot$. In our sample of 37 galaxies, the most luminous has $2 \times 10^{12} h^{-2}$ L$_\odot$. Since the CO and far IR have similar magnifications, their ratio, which indicates the gas-to-dust ratio and the metal abundance, is largely unaffected.

The mid IR radiation, on the other hand, is emitted by a hotter, 200 K source that may be much smaller. If it corresponds to the compact, $0.7''$ diameter core in the 2.2 μm images, it may be magnified 50 times (Broadhurst & Lehár 1995). Then the intrinsic mid IR luminosity would be $8 \times 10^{11} h^{-2}$ L$_\odot$ and the true radius of the core would be $30h^{-1}$ pc. This is a typical radius for an AGN Narrow Line Region (NLR), but is much too small to account for the thermal far IR emission at 80 K. Hence the far IR dominates the intrinsic luminosity of 10214+4724, as it does in nearby ultraluminous galaxies.

Although 10214+4724 has a Seyfert 2 spectrum lacking the usual signatures of star formation (Rowan-Robinson et al. 1991, 1993; Lawrence et al. 1993, Elston et al. 1994; Januzzi et al. 1994; Soifer et al. 1995; Goodrich et al. 1996), this may be an artifact of differential magnification by the intervening lens rather than an intrinsic property. If the galaxy harbors both an extended starburst and an AGN, the small nucleus will be magnified much more than the larger region of star formation where the H II regions are. Since the observed optical spectrum is dominated by the compact $0.7''$ core, which is the magnified image of the nucleus, the AGN characteristics overshadow the starburst signatures.

Even with true bolometric and CO luminosities ten times lower than earlier estimates (Downes et al. 1992; Solomon, Downes, & Radford 1992), the nature of the energy source remains a problem. Is 10214+4724 powered by star formation in the molecular region itself, or are the gas and dust just part of a massive envelope heated by the AGN (Sanders et al. 1989)?

The amount of dense molecular gas in ultraluminous IR galaxies indicates they harbor huge starbursts. To explain even the intrinsic luminosity of 10214+4724 with a starburst, however, time scale constraints (Heckman 1994) imply there must be an IMF of high mass stars only and a high star formation efficiency – 20% of all the gas converted to stars in 10^7 yr. Nevertheless, in intrinsic molecular content and IR luminosity, 10214+4724 resembles a typical nearby ultraluminous IR galaxy. Whatever its current power source, the heavy elements, dust, and molecular gas must all have been produced by massive stars.

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