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EXTENDED MOLECULAR GAS IN FSC 10214+4724

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ABSTRACT

We report high resolution imaging of the CO (3–2) emission in the luminous infrared source FSC 10214+4724 at $z = 2.2853$. Maps at resolutions of $2''.3 \times 3''.0$ and $45\text{--}90 \text{ km s}^{-1}$ show the CO emission peak coinciding with those of H α and radio continuum. Two components are identified in the CO emission: an unresolved core and an extended source ($\sim 1''.9 \times 4''.4$)—elongated southeast-northwest. The implied size is $9 \times 24 \text{ kpc}$ for $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $q_0 = 0.5$. The extent of the CO emission is significantly greater than that of either the optical or the radio continuum ($\sim 1''$) and the CO extent varies between the line core and the wings. If the gravitational lensing is occurring in FSC 10214+4724 (as has been suggested based on the near infrared morphology), the magnification factor for the CO emission is likely to be lower than for the near-infrared and the observed CO extent is probably an upper limit to the true source size.

The mass of molecular gas implied by the observed CO line flux is $\sim 2 \times 10^{11} M_\odot$, assuming no lens magnification. In order that the derived gas mass does not exceed the dynamical mass, the gas would have to be in a nearly face-on ($i < 20^\circ$) disk. However, this configuration appears inconsistent with the elongated morphology of the CO (which suggests an inclined disk or an interacting galaxy system). We suggest that the “dynamical” mass might be reconciled with the derived gas mass if substantial support for the gas is provided by radiation pressure from the nucleus of FSC 10214+4724. For the observed ratio of infrared luminosity-to-gas-mass ($10^3 L_\odot M_\odot^{-1}$), we find that a column density $\leq 2.4 \times 10^{22} \text{ H}_2 \text{ cm}^{-2}$ ($A_V \sim 24$) could be supported; this is consistent with the average gas column that is observed. The very high luminosity-to-mass ratio strongly also favors a nonthermal origin for the luminosity since a starburst would require consumption of the entire ISM on a timescale significantly shorter than the dynamical times ($2 \times 10^7\text{--}2 \times 10^8 \text{ yr}$) estimated from the CO data. These conclusions are not critically dependent on the presence or absence of gravitational lensing since the molecular emission, the far-infrared flux, and the “dynamical” mass are similarly affected and the ratios therefore remained almost unchanged.

Subject headings: galaxies: active — galaxies: individual (FSC 10214+4724)— galaxies: interactions — ISM: molecules

1. INTRODUCTION

The *IRAS* galaxy FSC 10214+4724 at $z = 2.286$ has a total luminosity of $\sim 2 \times 10^{14} L_\odot$ ($H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $q_0 = 0.5$), making it one of the most luminous objects yet detected in the universe (Rowan-Robinson et al. 1991). It also has an extraordinarily massive concentration of molecular hydrogen ($1\text{--}3 \times 10^{11} M_\odot$ —Brown & Vanden Bout 1991; Solomon et al. 1992a, b). At present the nature of this object and the ultimate source of its luminosity are very uncertain, be it a primeval galaxy undergoing an early ultraluminous starburst or a young dust-embedded quasar. In both scenarios the rich interstellar medium (ISM) can play a pivotal role, feeding a starburst or supplying accretion material to a central active galactic nucleus (AGN). An additional complication in understanding this object is revealed by near infrared imaging which shows a companion source $1''.5$ to the north of the H α emission peak which could be an intervening galaxy acting as a gravitational lens (Matthews et al. 1994; Elston et al. 1994). More recent *HST* images have been used to model the lens/source geometry, indicating magnification factors ~ 50 (Eisenhardt et al. 1995).

In this Letter we report high resolution aperture synthesis imaging of the molecular emission in FSC 10214+4724. These observations clearly show the molecular emission to be ex-

tended over $\sim 24 \text{ kpc}$. This distribution of emission is very different from the highly concentrated nuclear gas distributions seen in lower redshift ultraluminous infrared galaxies such as Mrk 231 and Arp 220 (see Scoville et al. 1991), consistent with the notion that FSC 10214+4724 is much earlier in its evolution and is, perhaps undergoing a period of rapid collisional agglomeration and mass accumulation. Our new data enable estimates of the dynamical timescales and masses of the system and, hence, the luminosity-to-mass ratio with greater certainty than before. These parameters provide constraints on the evolutionary status of the system.

2. OBSERVATIONS

FSC 10214+4724 was observed using the Owens Valley Millimeter Array in three configurations between 1993 October and 1994 January. At the time the array consisted of five 10.4 m telescopes, and the longest baseline observed was 200 m E-W. For FSC 10214+4724 for which the systemic redshift is $z = 2.286$, the CO (3–2) transition occurs at 105.2 GHz. The synthesized beams were $2''.2 \times 2''.3$ (uniform weighted) and $2''.3 \times 3''.0$ (natural) at PA = -87° . The phase center, central redshift, and adopted angular size and luminosity distances for FSC 10214+4724 are given in Table 1. The single sideband system temperatures were typically 250 K in the signal sideband corrected for antenna and atmospheric losses. Spectral resolution was provided by a digital correlator configured with $120 \times 4 \text{ MHz}$ channels (11.4 km s^{-1}), covering

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TABLE 1
IRAS FSC 10214+4724

Parameter	Value	
α_{1950}	$10^{\text{h}}21^{\text{m}}31.^{\text{s}}40$	
δ_{1950}	$47^{\circ}24'23''.0$	
$\langle z \rangle_{\text{CO}}$	2.2853 ± 0.0003	
Luminosity distance ^a (Gpc)	11.8	
Angular-size distance ^a (Gpc)	$1.09 (1'' \rightarrow 5.29 \text{ kpc})$	
Masses ^b	$M_{\text{H}_2}(10^{10} M_{\odot})$	$M_{\text{DYN}} \sin^2 i (10^{10} M_{\odot})$
Total	22 ± 3	1.1 ± 0.3
Core	15 ± 2	$< 0.8 \pm 0.2$
Extended	7 ± 1	1.1 ± 0.3

^a $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $q_0 = 0.5$.

^b For the molecular mass estimate, we use $\alpha = 4 M_{\odot} (\text{K km s}^{-1} \text{ pc}^2)^{-1}$ (Solomon et al. 1992b). Given reasonable constraints on the physical conditions in the gas, the maximum viable range in α is 1–10 and the mass range is therefore 0.25 to 2.5 times the values listed in the table. For the dynamical mass estimates, the numeric values are for $\sin^2 i = 1$.

a total velocity range of 1300 km s^{-1} . In addition, the continuum emission was measured in a 1 GHz bandwidth analog correlator. The total integration time on source was 37 hours distributed over six tracks in the three different telescope configurations. The nearby quasar 0923+392 was used to track the phase and gain variations, and Uranus ($T_b = 125 \text{ K}$) and 3C 345 (4.5 Jy) were observed for absolute flux calibration. The positional accuracy of the resulting maps is $\sim 0''.3$. For 0923+392 the measured flux density was $\sim 4.9 \text{ Jy}$ at 105 GHz during the period of the observations. The data were calibrated using the standard Owens Valley array program mma (Scoville et al. 1992) and mapped using DIFMAP (Shepherd 1994) and the NRAO AIPS package.

In Figure 1 the vector-average interferometric spectrum on FSC 10214+4724 is shown smoothed to a velocity resolution of 34 km s^{-1} . This spectrum should represent the total CO emission since it was obtained by averaging only data with fringe spacing $\geq 5''$. The peak flux is $14 \pm 2 \text{ mJy}$ and the full line width $250 \pm 15 \text{ km s}^{-1}$. Both numbers are in good agreement with previous single-dish and interferometric spectra (Solomon et al. 1992a, b; Radford, Brown, & Vanden Bout 1993).

In Figure 2 maps of the CO emission over velocity ranges with $\Delta v = 90 \text{ km s}^{-1}$ are shown and in Figure 3 (Plate L12) the

FIG. 1.—Vector averaged spectrum of CO (3–2) emission in FSC 10214+4724 smoothed to 12 MHz (34 km s^{-1}) resolution is shown including all data with interferometer fringe spacing $\geq 5''$.

total integrated CO line flux is shown superposed on the redshifted $\text{H}\alpha$ emission. The cross in the maps indicates the position of the 8 GHz continuum peak which also coincides with the redshifted $\text{H}\alpha$ peak (Lawrence et al. 1993; Matthews et al. 1993). The flux in the integrated map is $4.8 \pm 0.7 \text{ Jy km s}^{-1}$ and the peak flux in the individual maps for the narrow velocity ranges is $13 \pm 2 \text{ mJy beam}^{-1}$. The peak flux corresponds to a beam averaged brightness temperature excess of 0.21 K at $\lambda = 2.8 \text{ mm}$ or 0.68 K in the rest frame of the source. This corresponds to an absolute brightness temperature of 9.9 K in the rest frame after adding in the cosmic background radiation.

3. DISCUSSION

On the basis of the morphology seen in the channel maps, we decompose the CO emission into two components: an

FIG. 2.—Maps of the CO emission over 90 km s^{-1} velocity ranges are shown as a function of coordinate offset from 1.4 GHz continuum peak in FSC 10214+4724 (Lawrence et al. 1994). The contours are at 4, 6, 8, 10 mJy beam^{-1} , and the natural weighted beam is shown. The lowest contour is $\sim 3 \sigma$. The velocities are relative to $z = 2.2853$. No significant continuum emission was detected at the level greater than 2σ (3 mJy beam^{-1}).

elongated structure possibly a disk or a galaxy interaction trail, and an unresolved core component. Both are centered on the redshifted H α peak. For the elongated component, the deconvolved size is $1.9 \times 4''.4$ ($\pm 0''.2$) at PA = 115° , which corresponds to 9×24 kpc. The extended component is approximately outlined by the 4σ (6 mJy beam^{-1}) contour in $v = +45 \text{ km s}^{-1}$ channel map of Figure 2, and the quoted uncertainty reflects the maximum and minimum sizes inferred from the deconvolution. This feature comprising approximately one-third of the total CO line flux is seen only in the central velocity map ($v = +45 \text{ km s}^{-1}$). Its full width is $\Delta v \approx 125 \text{ km s}^{-1}$ based on higher spectral resolution channel maps. The observed extent is qualitatively similar but larger than the size inferred by Radford et al. (1993). Our new observations with higher frequency resolution should be more sensitive to this narrow velocity feature. The compact core containing two-thirds of the CO line flux is visible in six of the $\Delta v = 45 \text{ km s}^{-1}$ channel maps, and the full line width is $\Delta v = 228 \text{ km s}^{-1}$. This compact component is spatially unresolved and we adopt an upper limit corresponding to less than $1''$ or a diameter of 5.3 kpc.

The center frequency of the CO(3–2) emission is 105.258 GHz corresponding to a mean redshift of $z = 2.2853 \pm 0.0003$. This is significantly different from the mean redshift $z = 2.2835$ for the optical/UV emission lines (Elston et al. 1994). A similar offset with higher redshifts for the radio versus optical lines has been noted for lower redshift, high luminosity galaxies (Mirabel & Sanders 1989). The offset, corresponding to 180 km s^{-1} , might be explained if the optical/UV lines originate from gas flowing out of the galaxy and the symmetric redshifted emission is extinguished by dust within the system. If the system is gravitationally lensed, then the offset probably implies different spatial extents in the source for the optical and CO emission; this is consistent with their different apparent sizes.

From the integrated line flux of $4.8 \pm 0.7 \text{ Jy km s}^{-1}$, we obtain a total CO luminosity (both components) of $L'_{\text{CO}} = 5.5 \times 10^{10} \text{ K km s}^{-1} \text{ pc}^2$, using equation (3) from Solomon et al. (1992b). For a conversion factor $\alpha = 4 M_\odot (\text{K km s}^{-1} \text{ pc}^2)^{-1}$, the total molecular mass is $2.2 \times 10^{11} M_\odot$. Apportioning this mass according to the CO emission from the two components, $M_{\text{H}_2} = 1.5 \times 10^{11}$ and $0.7 \times 10^{11} M_\odot$ for the compact core and extended components, respectively. The mass surface density of molecular gas within the central core is $\Sigma_{\text{H}_2} \geq 3.4 \times 10^3 M_\odot \text{ pc}^{-2}$.

Based on the measured sizes and line widths, it is also possible to estimate dynamical masses associated with the two source components. Using

$$M_{\text{dyn}} = \frac{RV_{1/2}^2}{G \sin^2 i}, \quad (1)$$

where $V_{1/2}$ is half of the measured line full width, we obtain $8.0 \pm 1.9 \times 10^9$ and $1.1 \pm 0.3 \times 10^{10} M_\odot$ for the core and extended components, with no correction for inclination.

The derived estimates for the gas and dynamical masses are clearly inconsistent—the dynamical masses being a factor of 10 lower than the H $_2$ masses. Since the true CO luminosity, the source diameter, and the dynamical mass will all decrease similarly, this inconsistency remains even if there is significant gravitationally lensing. Two possible resolutions for the inconsistency are that the gas is configured in a nearly face-on ($i \leq 20^\circ$) disk so that the true rotational velocities are 3 times

greater than observed or that the molecular mass has been overestimated from the CO emission by an order of magnitude. Such face-on geometry has been previously suggested to reconcile the large difference between the derived H $_2$ mass and the dynamical mass (e.g., Solomon et al. 1992a), but we note that the elongated appearance of the extended component, specifically its greater than 2:1 axis ratio, is in fact more suggestive of a nearly edge-on system ($i > 66^\circ$ if it is a thin circular disk). The probability of having the required $i < 20^\circ$ is only 7% for randomly oriented disks. We also note that if this is an interacting system, it would be highly unlikely for the gas during the interaction to remain narrowly confined in a plane nearly perpendicular to the line of sight. Nevertheless, we cannot rule out the possibility that the system is nearly face-on since such an orientation might be observationally selected due to the low optical extinction expected.

A possible overestimate of the gas mass from the CO emission might arise in two ways: if the observed CO emission has been artificially enhanced by gravitational lensing, or if the physical conditions within the molecular gas are sufficiently extreme that the CO to H $_2$ conversion ratio is a factor of 10 lower than the value adopted above. Recent high-resolution *HST* images by Eisenhardt et al. (1995) support the lensing hypothesis. On the other hand, the morphology of the CO and its position angle (115°) are not seen in any other optical/IR (or radio continuum) tracer. The concave arc seen in redshifted H α extends over $\sim 1''$ whereas the CO emission extends diagonally across and is three times more extensive than that of H α . Thus, if the molecular gas and the optical emission are both undergoing gravitational focusing, their distributions in the background galaxy must be very different, presumably with the true CO extent being larger than that of the rest-frame optical emission. Amplification factors ~ 50 are suggested for the optical emission (Eisenhardt et al. 1995) but if the CO is more extensive the amplification could be much less. In any case, the observed CO extent is probably an upper limit to the true source size. A detailed model for the lensing is obviously required in order to accurately assess the relative effects on the fluxes versus the linear sizes.

Solomon et al. (1992b) discussed the CO excitation and its effects on the conversion ratio, α . Making use of constraints provided by the measured CO line ratios, they find $1.3 < \alpha < 10$ for $200 \text{ K} > T_{\text{kin}} > 20 \text{ K}$. The conversion ratio from optically thick CO emission to H $_2$ mass scales approximately as $n_{\text{H}_2}^{1/2}/T_x$. The value of $\alpha = 4 M_\odot (\text{K km s}^{-1} \text{ pc}^2)^{-1}$ adopted by us is in the middle of this range, and it is difficult to see how the conversion factor could be reduced by a full order of magnitude in order to bring the derived gas mass in line with the “apparent” dynamical mass. If the metallicity is low as expected for high redshift objects, then the inferred gas mass would be even larger. Lastly, it is worth noting that if the ISM mass estimates are reduced by an order of magnitude to match the inferred dynamical mass, the problem of maintaining the luminosity in this system for a reasonable time become even more severe than they already are.

In view of the apparent inconsistency between the dynamical mass and the molecular gas mass (which is not resolved by invoking gravitational focussing since both must be decreased similarly), we have investigated the possibility that the gas might be supported against self-gravity by pressure forces. Given the high luminosity-to-mass ratio for this system, it is natural to consider the pressure provided by radiation. Under the assumption that the gas is uniformly distributed about a

central luminosity source, the gas column density at which radiation pressure forces balance the gravitational attraction, assuming that the gas and dust are optically thick and absorb all the radiative momentum is

$$N_{\text{H}_2} < \frac{L}{4\pi G c m_{\text{H}_2} M} \quad (2a)$$

$$< 2.4 \times 10^{22} (L/M)_{10^3 L_\odot / M_\odot} \text{ cm}^{-2}. \quad (2b)$$

Using the observed far-infrared luminosity ($L \sim 2 \times 10^{14} L_\odot$) and the derived molecular mass ($2 \times 10^{11} M_\odot$), we have scaled equation (2a) to the parameters appropriate to FSC 10214+4724 in equation (2b). For these parameters, we find that a column of approximately $2.4 \times 10^{22} \text{ cm}^{-2}$ of H_2 can be supported, corresponding to $A_V \sim 24$ mag for a standard gas-to-dust ratio. This column density is similar to the mean column densities actually inferred for this system, assuming the molecular mass is uniformly spread out over the derived source sizes of the two components. It is also similar to typical column densities of Galactic GMCs; however, if the gas is in fact radiatively supported, the physical structures in which the gas resides are likely to be quite different from the standard GMCs. Elston et al. (1994) inferred substantial reddening ($A_V > 5.5$) based on $\text{H}\alpha/\text{H}\beta$ ratio greater than 20 ($\text{H}\beta$ not detected), and the new near-IR and optical spectroscopic study by Soifer et al. (1995b) also find evidence for heavy extinction. The gas will be Rayleigh-Taylor unstable, probably breaking up into small structures down to the point at which their individual column densities become less than the critical density derived in equation (2a). When their column densities decrease below this limit, it is anticipated that the material will be lifted back up to larger radii where it accumulates into larger structures with column density exceeding the limit. This gas will then start to rain down once again toward the nucleus. Thus, the material might be continually recycled up and down in a misty halo of the galaxy. In the event that there is significant gravitational lensing in FSC 10214+4724, these conclusions may still hold since the infrared luminosity and the CO emission are probably similarly amplified if the far-infrared emission arises from dust associated with the molecular gas, as seems reasonable.

In assessing the energy source for the luminosity in FSC 10214+4724, the dynamical timescale provides a strong constraint on realistic models. In scenarios in which the ISM plays an important role, either fueling a massive starburst or in feeding a central AGN, it is reasonable to expect that the timescale for the current high-luminosity phase must be at least equal to the dynamical time. From the derived sizes and line widths in the two molecular gas components, we can estimate dynamical timescales ($\tau_{\text{DYN}} = 2r/\Delta V_{\text{FW}}$) of 2.3×10^7 and 1.9×10^8 yr for the unresolved and extended components. If the observed luminosity is generated by accretion onto a black hole with an efficiency for conversion of mass into energy

of 10%, then the accretion rate must be $140 M_\odot \text{ yr}^{-1}$. If this accretion is to last for at least the dynamical time in the compact component, then the total accreted mass amounts to $3 \times 10^9 M_\odot$ over 2.3×10^7 yr. This corresponds to 40% of the apparent dynamical mass in the core component! If instead the luminosity is generated from the formation of high-mass stars, as in a starburst, we can estimate the required rate of star formation from simple stellar evolution considerations. For upper main sequence stars, approximately 15% of the original stellar mass is processed through hydrogen burning, while the stars are on the main sequence and for hydrogen fusion, 0.7% of the mass is converted into energy. For these stars, most of their energy output occurs while on the main sequence and thus, we derive a total star-formation rate of $1.3 \times 10^4 M_\odot \text{ yr}^{-1}$ from the observed luminosity ($2 \times 10^{14} L_\odot$). Within the dynamical time for the compact core, the implied total star formation rate would be $M_* = 2.9 \times 10^{11} M_\odot$ which is 36 times greater than the apparent dynamical mass of the core and similar to the molecular gas content of the entire system. The gas depletion time scale would also be implausibly short ($\sim 10^7$ yr—see also Elston et al. 1994). If the star formation is heavily biased toward upper main-sequence stars, a significant fraction of the material going into those stars will be recycled back into the interstellar medium during and at the end of stellar evolution; however, the material cannot be recycled more than ~ 3 times without the abundances becoming too enriched in processed gas. On the basis of the very extreme total mass which is required under star formation scenarios to account for the luminosity and on the basis of the optical spectra which show no evidence of a starburst component (see Elston et al. 1994), it seems unlikely that star formation can account for the energetics and optical characteristics of this system.

For very high luminosity-to-mass ratio systems such as FSC 10214+4794 in which the interstellar gas provides a fuel supply for accretion (or starbursts) and in which the gas may be partially supported by radiation pressure, the activity can be self-regulating as in Eddington-limited accretion. This arises because once the luminosity-to-mass ratio in the system exceeds $100 L_\odot M_\odot^{-1}$, the accretion of optically thin interstellar gas and dust is prohibited by radiation pressure forces on the dust. (In FSC 10214+4724, the luminosity to mass ratio is 10 times higher, and an order of magnitude larger column density can be supported.) In this situation, the only means to maintain the accretion is by lowering the luminosity and hence, reducing the radiation pressure, or by packing the interstellar medium into optically thick clouds with larger column densities. On the other hand, if the central accretion rate increases and the luminosity rises, the minimum column density of clouds which can be accreted will increase to the point at which radial infall will be reduced.

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FIG. 3.—CO (3–2) emission ($z = 2.286$) is shown integrated over all channels containing significant line emission ($v = -160$ to $+200$ km s $^{-1}$). CO emission contours are superposed on redshifted H α emission (Matthews et al. 1994) and the cross indicates the position of the 1.4 GHz continuum peak (Lawrence et al. 1994). The contours are spaced by 0.4 Jy km s $^{-1}$ beam $^{-1}$ for the natural weighted beam.

SCOVILLE et al. (see 449, L110)