IMAGING ATOMIC AND HIGHLY EXCITED MOLECULAR GAS IN A $z = 6.42$ QUASAR HOST GALAXY: COPIOUS FUEL FOR AN EDDINGTON-LIMITED STARBURST AT THE END OF COSMIC REIONIZATION

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ABSTRACT

We have imaged CO($J = 7→6$) and C$\text{II}$($P_2→3P_1$) emission in the host galaxy of the $z = 6.42$ quasar SDSS J114816.64+525150.3 (hereafter J1148+5251) through observations with the Plateau de Bure Interferometer. The region showing CO($J = 7→6$) emission is spatially resolved, and its size of 5 kpc is in good agreement with earlier CO($J = 3→2$) observations. In combination with a revised model of the collisional line excitation in this source, this indicates that the highly excited molecular gas traced by the CO $J = 7→6$ line is subthermally excited (showing only 58% ± 8% of the CO $J = 3→2$ luminosity), but not more centrally concentrated. We also detect C$\text{II}$($P_2→3P_1$) emission in the host galaxy of J1148+5251, but the line is too faint to enable a reliable size measurement. From the C$\text{II}$($P_2→3P_1$) line flux, we derive a total atomic carbon mass of $M_{\text{C,}1} = 1.1 \times 10^7 M_{\odot}$, which corresponds to $\sim 5 \times 10^{-4}$ times the total molecular gas mass. We also searched for H$_2$O($J_{K_aK_c} = 2_{12}\rightarrow 1_{01}$) emission, and obtained a sensitive line luminosity limit of $L_{\text{H}_2\text{O}} < 4.4 \times 10^8$ K km s$^{-1}$ pc$^2$, i.e., <15% of the CO($J = 3→2$) luminosity. The warm, highly excited molecular gas and dust in this quasar host at the end of cosmic reionization maintain an intense starburst that reaches surface densities as high as predicted by (dust opacity) Eddington limited star formation over kiloparsec scales.

Key words: cosmology: observations – galaxies: active – galaxies: formation – galaxies: high-redshift – galaxies: starburst – radio lines: galaxies

Online-only material: color figures

1. INTRODUCTION

Detailed studies of individual quasars at the highest redshifts are vital to shed light on how today’s most massive galaxies are formed and to investigate whether or not the tight correlation between black hole mass and stellar bulge mass seen today was formed and to investigate whether or not the tight correlation between black hole mass and stellar bulge mass seen today was formed and to investigate whether or not the tight correlation between black hole mass and stellar bulge mass seen today was formed and to investigate whether or not the tight correlation between black hole mass and stellar bulge mass seen today was formed and to investigate whether or not the tight correlation between black hole mass and stellar bulge mass seen today was formed and to investigate whether or not the tight correlation between black hole mass and stellar bulge mass seen today was formed and to investigate whether or not the tight correlation between black hole mass and stellar bulge mass seen today was formed and to investigate whether or not the tight correlation between black hole mass and stellar bulge mass seen today was formed and to investigate whether or not the tight correlation between black hole mass and stellar bulge mass seen today was formed and to investigate whether or not the tight correlation between black hole mass and stellar bulge mass seen today was formed and to investigate whether or not the tight correlation between black hole mass and stellar bulge mass seen today was formed and to investigate whether or not the tight correlation between black hole mass and stellar bulge mass seen today was formed and to investigate whether or not the tight correlation between black hole mass and stellar bulge mass seen today was formed and to investigate whether or not the tight correlation between black hole mass and stellar bulge mass seen today was formed and to investigate whether or not the tight correlation between black hole mass and stellar bulge mass seen today was formed and to investigate whether or not the tight correlation between black hole mass and stellar bulge mass seen today was formed and to investigate whether or not the tight correlation between black hole mass and stellar bulge mass seen today was formed and to investigate whether or not the tight correlation between black hole mass and stellar bulge mass seen today was formed and to investigate whether or not the tight correlation between black hole mass and stellar bulge mass seen today was formed and to investigate whether or not the tight correlation between black hole mass and stellar bulge mass seen today was formed and to investigate whether or not the tight correlation between black hole mass and stellar bulge mass seen today was formed and to investigate whether or not the tight correlation between black hole mass and stellar bulge mass seen today was formed and to investigate whether or not the tight correlation between black hole mass and stellar bulge mass seen today was formed.

Follow-up observations revealed that this gas is centered on the AGN, but distributed on scales of 5 kpc (Walter et al. 2004). This large molecular reservoir harbors a compact 1.5 kpc size region that emits bright emission from the [C$\text{II}$]($P_2→3P_1$) interstellar medium (ISM) cooling line, which is presumably due to active star formation at an enormous star formation rate (SFR) surface density of $\sim 1000 M_{\odot}$ yr$^{-1}$ kpc$^{-2}$ (Walter et al. 2009a). The dense, star-forming molecular gas component as traced by hydrogen cyanide (HCN) is comparatively faint, given the source’s high SFR and FIR luminosity (Riechers et al. 2007).

In addition, it was found that J1148+5251 is radio-quiet and follows the radio–FIR correlation for star-forming galaxies, providing additional evidence that the FIR dust emission is dominated by young stars rather than the AGN (Carilli et al. 2004; Wang et al. 2008). To further investigate on which scales the star formation takes place, we here aimed at resolving the neutral atomic and the warm, highly excited molecular gas components in the host galaxy of this unique quasar.

2. OBSERVATIONS

We observed the CO($J = 7→6$) ($v_{\text{rest}} = 806.6518$ GHz), C$\text{II}$($P_2→3P_1$) (809.3435 GHz), and H$_2$O($J_{K_aK_c} = 2_{12}\rightarrow 1_{01}$) (1669.9048 GHz) emission lines toward J1148+5251 using the IRAM Plateau de Bure Interferometer (PdBI). At $z = 6.419$, these lines are redshifted to 108.7278, 109.0907, and 225.0849 GHz (2.8 and 1.3 mm). First observations were carried out with the PdBI’s previous generation receivers in the old 6D configuration in 2003 May, June, and November (May...
observations published by Bertoldi et al. (2003b), and in 2004 April–June and September–November (23 tracks total). Further observations were carried out with the new generation receivers in the new 6A configuration (longest baseline: 760 m) in 2007 February and March (seven tracks total). All tracks were taken under good 3 mm observing conditions. Of the tracks taken with dual frequency setup in 2003/2004, 12 were taken under conditions sufficient for 1 mm observing. The nearby source 1150+497 (distance to J1148+5251: 3′4) was observed every 22.5 minutes for pointing, secondary amplitude, and phase calibration. For primary flux calibration, several nearby standard calibrators were observed during all runs, leading to a calibration that is accurate within 10%–15% (3 mm) and 15%–20% (1 mm), respectively.

Observations with the previous generation receivers were set up using a total bandwidth of 580 MHz (single polarization, dual frequency; corresponding to ∼1600 km s$^{-1}$ at 2.8 mm and ∼770 km s$^{-1}$ at 1.3 mm). This setup requires two separate tunings at 3 mm to observe the CO$(J = 7→6)$ (14 tracks) and C$^3\text{H}_2$$(P_2→3P_1)$ (nine tracks) emission lines (1 mm receivers were tuned to the redshifted H$_2$O$J_{K_aK_c} = 2_{12}→1_{01}$ frequency). Observations with the new generation receivers were set up using a total bandwidth of 1 GHz (dual polarization; corresponding to ∼2800 km s$^{-1}$ at 2.8 mm). This setup allows to observe the CO$(J = 7→6)$ and C$^3\text{H}_2$$(P_2→3P_1)$ lines simultaneously (selecting a tuning frequency of 108.894 GHz centered between both lines). All observations were taken with sufficient bandwidth to cover the underlying continuum simultaneously.

For data reduction and analysis, the IRAM GILDAS package was used. All data were mapped using “natural” weighting unless mentioned otherwise. The CO$(J = 7→6)$ data result in a final rms of 0.33 mJy beam$^{-1}$ per 28 km s$^{-1}$ channel (resolution: 1″38 × 1′′17). To optimize the spatial resolution, these data were also mapped using “uniform” weighting, leading to a synthesized clean beam size of 0′′86 × 0′′61 (4.8 kpc × 3.4 kpc) and an rms of 0.12 mJy beam$^{-1}$ over 414 km s$^{-1}$ (150 MHz).

To maximize the signal-to-noise ratio (S/N), the C$^3\text{H}_2$(P$_2→3P_1$) data were tapered to a resolution of 2′278 × 2′42, leading to an rms of 0.17 mJy beam$^{-1}$ over 316 km s$^{-1}$ (115 MHz). The 2.8 mm continuum data (combined from all CO$J = 7→6$ and C$^3\text{H}_2$$(P_2→3P_1$) observations) result in a 1′′20 × 0′′99 beam and an rms of 0.046 mJy beam$^{-1}$ over 563.75 MHz. The H$_2$O$(J_{K_aK_c} = 2_{12}→1_{01})$ data result in an rms of 0.76 mJy beam$^{-1}$ over 303 km s$^{-1}$ (227.5 MHz), and the (double sideband) 1.3 mm continuum data result in an rms of 0.34 mJy beam$^{-1}$ over 2 × 563.75 MHz.

3. RESULTS

In Figure 1, the velocity-integrated CO$(J = 7→6)$ emission is shown at a linear resolution of ∼4 kpc (0′′7). From elliptical Gaussian fitting to the 1σ detection of the source in the $u−v$ plane, it is found that the emission is spatially resolved on a scale of 0′′9 ± 0′′16 (5.0 kpc) in the north–south direction, and marginally resolved (0′′54 ± 0′′11; 3.0 kpc) in east–west direction. The peak, extent, and orientation of the emission are in remarkable agreement with the lower-excitation CO$(J = 3→2)$ line emission (color scale in Figure 1; Walter et al. 2004), and the peak is coincident with the position of the optical quasar (cross in Figure 1; White et al. 2005). This demonstrates that the relative astrometry between the CO$(J = 7→6)$ PdBI and CO$(J = 3→2)$ VLA observations is accurate within <0′′1. It also indicates that, even though the CO$(J = 7→6)$ line is only subthermally excited (see discussion below), the emission is apparently not more centrally concentrated than the CO$(J = 3→2)$ emission.

In Figure 2, the spectrum of the CO$(J = 7→6)$ emission is shown. The line is detected at a peak flux of $S_\nu = 1.99 ± 0.23$ mJy and a width of 297 ± 35 km s$^{-1}$, leading to an integrated line flux of 0.63 ± 0.06 Jy km s$^{-1}$, and a line luminosity of $L_{\text{CO}(7→6)} = 1.7 ± 0.2 \times 10^{10}$ K km s$^{-1}$ pc$^2$.
a line peak flux of 0.7 mJy when accounting for the underlying (see Table 1). The sensitivity of the observations is sufficient to detect, for the first time, the underlying 2.8 mm continuum emission (0.28 ± 0.07 mJy). Figure 3 shows a map of the 2.8 mm continuum emission integrated over all line-free channels of the combined CO and CII observations at ~6 kpc (1.1') linear resolution. The continuum emission is detected at a flux level consistent with the simultaneous line/continuum fit to the CO(J = 7→6) spectrum within the errors.

In Figure 4, a velocity-integrated map of the CII(J = 3→2) emission over 316 km s$^{-1}$ toward J1148+5251. At 2σ resolution, the line is still marginally detected, but the peak flux decreases. This may indicate that the CII(J = 3→2) emission is resolved on similar scales as the CO emission, and thus emerges from the same (molecular) gas phase on a global (galactic) scales. However, this conclusion remains tentative at the present S/N.

No evidence for H$_2$O(J = 2→1) emission is found in the 1.3 mm data. Assuming that the line has the same width as CO(J = 7→6), we derive a 3σ upper limit of <0.69 Jy km s$^{-1}$ for the integrated line flux, and a line luminosity limit of $L_{H_2O}$ < 4.4 × 10$^4$ K km s$^{-1}$ pc$^2$ (i.e., $L_{H_2O}/L_{CO}(3→2) < 0.15$). We clearly detect the underlying 225 GHz continuum emission at 3.9 ± 0.8 mJy.

4. DISCUSSION

4.1. Properties of the Molecular and Atomic ISM in J1148+5251

4.1.1. Resolved CO(J = 7→6) Emission

We successfully resolved emission from the high-J CO(J = 7→6) line toward the z = 6.42 quasar J1148+5251. The structure and size of the gas reservoir are consistent with what was derived from previous CO(J = 3→2) line mapping (Walter et al. 2004). The line width derived from our high S/N CO(J = 7→6) spectrum is consistent with that of previous observations of the CO(J = 6→5) and CO(J = 7→6) lines (Bertoldi et al. 2003b). Although the molecular gas emission appears to be more extended than that from the neutral ISM as traced by the 158 µm [CII] 2$→$1 line, the linewidths and centroids are consistent to high precision (Maiolino et al. 2005; Walter et al. 2009a).

4.1.2. Atomic Carbon

We also detected the upper fine structure line of neutral carbon, CII(J = 3→2), toward J1148+5251. This represents the highest $z$ detection of atomic carbon (or, indeed, any neutral atomic medium) to date, and the first CII detection in an unlensed high-redshift galaxy. As the lower fine structure line (which...
is redshifted to 66.3 GHz cannot be observed with current facilities, it is not possible to derive an excitation temperature for C1. However, for $T_\text{ex} > 20$ K, the derived C1 mass only weakly depends on $T_\text{ex}$ (Weiß et al. 2005a). Assuming an excitation temperature of $T_\text{ex} = 36$ K (the average of the Cloverleaf and IRAS F10214+4724, the only high-$z$ galaxies for which both transitions have been detected; Barvainis et al. 1997; Weiß et al. 2003, 2005a; Ao et al. 2008), we derive a C1 mass of $M_{\text{C1}} = 1.1 \times 10^7 M_\odot$. From the CO luminosity, a total molecular gas mass of $M_\text{H}_2 = 2.4 \times 10^{10} M_\odot$ can be derived (Walter et al. 2003). We thus find a C1/H2 mass fraction of $5 \times 10^{-4}$. Assuming $\alpha^\text{[CII]}/H_2$ abundance ratio of $5 \times 10^{-5}$ (Weiß et al. 2003, 2005a), the C1 mass translates to a total molecular gas mass of $M_\text{H}_2 = 3.7 \times 10^{10} M_\odot$. This is somewhat higher than the value derived from the CO luminosity, and may indicate either a higher atomic carbon abundance, or that the CO luminosity to H2 mass conversion factor is higher than that assumed above (possibly due to different molecular abundances relative to nearby ultra-luminous infrared galaxies (ULIRGs)).

By comparing the line luminosities (in units of $L_\odot$), one finds that the C1($P_2\rightarrow P_1$) line provides only ∼2% of the cooling capacity of the [CII]($P_{3/2}\rightarrow P_{1/2}$) line (Maiglio et al. 2005; Walter et al. 2009a), the latter thus clearly remains the strongest detected coolant of the neutral atomic ISM. This also implies $L_{\text{C1}}/L_{\text{FIR}} \sim 5 \times 10^{-6}$. This ratio is comparable to those found in nearby star-forming and starbursting galaxies, where it is considered to be a measure for the strength of the non-ionizing stellar UV radiation field (e.g., Gérin & Philips 2000; Bayet et al. 2006). This supports the assumption that the bulk of the dust and gas heating in this system is powered by star formation.

4.1.3. Limits on Water Emission

We have also searched for H2O($J_{K_aK_c}=2_{12}\rightarrow1_{01}$) emission toward J1148+5251, but only obtained a sensitive upper limit. Radiative transfer calculations show that, assuming the known gas and dust properties of J1148+5251, H2O($J_{K_aK_c}=2_{12}\rightarrow1_{01}$) emission is expected to be optically thick over a substantial range of the permitted parameter space. Thus, the line luminosity limit can be directly translated to a surface filling factor limit (relative to CO $J = 3\rightarrow2$) of <15% (assuming both lines are in thermal equilibrium).

Sensitive searches for water emission from dense molecular gas were performed for two other $z > 3$ galaxies (Riechers et al. 2006a; Wagg et al. 2006), reaching comparable depths. A search for H2O($J_{K_aK_c}=3_{13}\rightarrow2_{02}$) emission ($v_{\text{rest}} = 183,310$ GHz) toward the $z = 3.20$ quasar MG 0751+2716 provided a surface filling factor limit of <12% relative to CO($J = 4\rightarrow3$) (Wigg et al. 2006; Weiß et al. 2007a; Riechers et al. 2009).

The $J_{K_aK_c}=3_{13}\rightarrow2_{02}$ transition was detected toward the nearby ULIRG Arp 220, at about one third of its HCN($J = 1\rightarrow0$) line luminosity (Cernicharo et al. 2006). This suggests a small surface filling factor even within dense molecular cloud cores as traced by HCN. This is, again, assuming optically thick emission in thermal equilibrium from both lines. Note that the H2O line emission in Arp 220 (and the high-$z$ sources) is likely maser-enhanced, which would even predict substantially smaller surface filling factors (Cernicharo et al. 2006; Riechers et al. 2006a). Although different H2O and HCN transitions were observed toward J1148+5251, the observed H2O($J_{K_aK_c}=2_{12}\rightarrow1_{01}$) luminosity limit would be consistent with a H2O/HCN line luminosity ratio similar to Arp 220.

4.2. Continuum Emission

The new detections of the observed-frame 225 GHz (rest-frame: 1.67 THz) and 109 GHz (807 GHz) continuum emission are consistent with the overall dust spectral energy distribution (SED) of J1148+5251 (Beelen et al. 2006). In particular, the detection of 2.8 mm continuum emission allows us to better constrain both the CO($J = 7\rightarrow6$) and CO($J = 6\rightarrow5$) line fluxes. From the shape of the SED, we derive an estimated continuum flux of 0.19 mJy at the wavelength of the CO($J = 6\rightarrow5$) emission, by which we reduce the CO($J = 6\rightarrow5$) flux relative to the original estimate (Bertoldi et al. 2003b) in the following.

5. MODELING AND CONCLUSIONS

5.1. CO Line Excitation

Given the high S/N of the CO($J = 7\rightarrow6$) observations and the fact that we successfully detected the (observed-frame) 2.8 mm continuum emission (which also provided an updated CO($J = 6\rightarrow5$) line flux), we have calculated new large velocity gradient (LVG) models of the line excitation in this system (see Bertoldi et al. 2003b for the original study). In this LVG model study, the kinetic gas temperature and density are treated as free parameters. For all calculations, the H2 ortho-to-para ratio was fixed to 3:1, the cosmic microwave background temperature was fixed to 20.25 K (at $z = 6.42$), and the Flower (2001) CO collision rates were used. We adopted a CO abundance per velocity gradient12 of $[\text{CO}]/(dv/dr) = 1 \times 10^{-5}$ pc (km s$^{-1}$)$^{-1}$ (e.g., Weiß et al. 2005c, 2007a; Riechers et al. 2006b), and a CO disk radius of 2.5 kpc as found from the spatially resolved CO($J = 3\rightarrow2$) and CO($J = 7\rightarrow6$) observations. The best solution was obtained for a spherical, single-component model with a CO disk filling factor of 0.16, $T_\text{kin} = 50$ K, and $\rho_{\text{gas}}(H_2)=10^{4.2}$ cm$^{-3}$ (Figure 5). These values are comparable to those found for other high-$z$ quasars (e.g., Riechers et al. 2006b; Weiß et al. 2007b). This model predicts that the CO($J = 3\rightarrow2$) line emission is thermalized. Also, the model-predicted gas

10 CO in high-$z$ quasar hosts is more widespread than in nearby ULIRGs, but shows similar physical properties. We thus adopt a low ULIRG CO luminosity to H2 mass conversion factor of $\alpha = 0.8 M_\odot/(K\text{ km s}^{-1}\text{ pc}^{-2})$ (Downes & Solomon 1998) rather than $\alpha = 4.5 M_\odot/(K\text{ km s}^{-1}\text{ pc}^{-2})$ as in nearby spirals (e.g., Scoville & Sanders 1987; Solomon & Barrett 1991). Such low $\alpha$ are also found for $z \sim 2.5$ submillimeter galaxies (Tacconi et al. 2008).

11 Only the ratio of [CO] and $\text{H}_2$ line fluxes are used in the LVG model calculations. Thus, our solutions can account for the factor of a few variations in [CO] found between nearby star-forming galaxies by adjusting the “internal” parameter $dv/dr$ accordingly. Here, [CO]$(dv/dr)$ is fixed to that of the nearby starburst M82 (Weiß et al. 2005c).

12 This is due to the relative statistical weights of the symmetrical (ortho) and antisymmetrical (para) eigenstates of the wavefunction: there are three symmetrical combinations of the spins of both H nuclei, but there is only one antisymmetrical combination.
temperature is consistent with that of the dust (55 ± 5 K; Beelen et al. 2006).

5.2. Star Formation Rate and its Surface Density

The dust reservoir in J1148+5251 exhibits a FIR continuum luminosity of $L_{\text{FIR}} = 2.2 \times 10^{13} \, L_\odot$ (Bertoldi et al. 2003a; Beelen et al. 2006), about half of which emerges from a compact, 0.75 kpc radius region (Walter et al. 2009a). Its molecular gas, dense gas, radio continuum, and dust properties are consistent with $L_{\text{FIR}}$ being dominantly powered by star formation (e.g., Beelen et al. 2006; Riechers et al. 2007; Walter et al. 2009a). Assuming that the AGN contribution to $L_{\text{FIR}}$ is small, we thus derive an integrated SFR of 3300 $M_\odot \, \text{yr}^{-1}$, about half of which takes place within a 0.75 kpc radius region. This high SFR is consistent with the high luminosity of the [C ii]$(\lambda P_{3/2} \rightarrow 3 P_{1/2})$ ISM cooling line (Maiolino et al. 2005), which emerges from a region of 0.75 kpc radius within the molecular gas reservoir (Walter et al. 2009a). An intense, kpc-scale starburst is also needed to explain the fact that the molecular gas is warm and highly excited over a large, 5 kpc size region (as shown by the new, spatially resolved CO $J=7 \rightarrow 6$ data), which requires a heating source of similar size (given that radiation from a compact heating source such as the AGN likely cannot penetrate the dense molecular reservoir out to such large scales).

Thus, the (peak) size and brightness of the resolved [C ii]$(\lambda P_{3/2} \rightarrow 3 P_{1/2})$ line and FIR continuum emission are consistent with a nuclear “hyper”-starburst as the main heating source for the gas and dust, i.e., a starburst that exhibits a flux of $F_{\text{FIR}} = 10^{13} \, L_\odot \, \text{kpc}^{-2}$, produced by an enormous SFR surface density of $\Sigma_{\text{SFR}} = 1000 \, M_\odot \, \text{yr}^{-1} \, \text{kpc}^{-2}$ (Walter et al. 2009a). Such high $F_{\text{FIR}}$ and $\Sigma_{\text{SFR}}$ are typically observed in the most extreme star-forming environments in the local universe. As a reference, the Galactic star forming cloud Orion exhibits a FIR luminosity of $1.2 \times 10^5 \, L_\odot$ within its central arcmin$^2$ (0.013 pc$^2$; Werner et al. 1976). This corresponds to a $F_{\text{FIR}}$ of $\sim 10^{13} \, L_\odot \, \text{kpc}^{-2}$. Nearby ULIRGs exhibit a FIR luminosity of typically $3 \times 10^{11} \, L_\odot$ within their most active $\sim 100$ pc size regions (Downes & Solomon 1998). This, again, corresponds to a $F_{\text{FIR}}$ of $\sim 10^{13} \, L_\odot \, \text{kpc}^{-2}$. Nearby ULIRGs exhibit a FIR luminosity of typically $3 \times 10^{11} \, L_\odot$ within their most active $\sim 100$ pc size regions (Downes & Solomon 1998). This, again, corresponds to a $F_{\text{FIR}}$ of $\sim 10^{13} \, L_\odot \, \text{kpc}^{-2}$. Nearby ULIRGs exhibit a FIR luminosity of typically $3 \times 10^{11} \, L_\odot$ within their most active $\sim 100$ pc size regions (Downes & Solomon 1998). This, again, corresponds to a $F_{\text{FIR}}$ of $\sim 10^{13} \, L_\odot \, \text{kpc}^{-2}$. Nearby ULIRGs exhibit a FIR luminosity of typically $3 \times 10^{11} \, L_\odot$ within their most active $\sim 100$ pc size regions (Downes & Solomon 1998). This, again, corresponds to a $F_{\text{FIR}}$ of $\sim 10^{13} \, L_\odot \, \text{kpc}^{-2}$. Nearby ULIRGs exhibit a FIR luminosity of typically $3 \times 10^{11} \, L_\odot$ within their most active $\sim 100$ pc size regions (Downes & Solomon 1998). This, again, corresponds to a $F_{\text{FIR}}$ of $\sim 10^{13} \, L_\odot \, \text{kpc}^{-2}$. Nearby ULIRGs exhibit a FIR luminosity of typically $3 \times 10^{11} \, L_\odot$ within their most active $\sim 100$ pc size regions (Downes & Solomon 1998). This, again, corresponds to a $F_{\text{FIR}}$ of $\sim 10^{13} \, L_\odot \, \text{kpc}^{-2}$ (Tacconi et al. 2006), which are by about an order of magnitude smaller.

Intriguingly, recent high-resolution molecular gas and radio continuum observations of the $z = 4.4$ merging quasar host of BRI 1335-0417 indicate $\Sigma_{\text{SFR}}$ comparable to those in J1148+5251 (assuming that the FIR-emitting dust is not more extended than the molecular gas; Riechers et al. 2008b; Momjian et al. 2007).

5.3. Radiation–Pressure Supported Starburst Disks

An SFR surface density of $\Sigma_{\text{SFR}} = 1000 \, M_\odot \, \text{yr}^{-1} \, \text{kpc}^{-2}$ is consistent with theories of “maximum starbursts” (Elmegreen 1999). At such high surface densities, feedback from star formation is likely to occur, which may (self-)regulate the starburst. If the maximum intensity of a radiation pressure-supported, galaxy scale starburst is determined by the Eddington limit for dust, a number of characteristic limits arise in these “maximum starburst” theories (Thompson et al. 2005). Assuming a Salpeter-like initial mass function (IMF), a constant gas-to-dust ratio with radius, and that the disk is self-regulated (i.e., Toomre- $Q \sim 1$), such an Eddington-limited starburst has
\[ \Sigma_{\text{SFR}} \sim 1000 \, M_\odot \, \text{yr}^{-1} \, \text{kpc}^{-2}, \quad F_{\text{FIR}} \sim 10^{13} \, L_\odot \, \text{kpc}^{-2}, \quad \text{and an effective temperature of} \, 88 \, \text{K} \quad \text{(equations (34)-(36) of Thompson et al. 2005). As shown above, J1148+5251 has} \, \Sigma_{\text{SFR}} \quad \text{and} \, F_{\text{FIR}} \quad \text{close to these theoretical limits over a} \, 0.75 \, \text{kpc radius region.} \]

For a flat disk as assumed here, \[ F_{\text{FIR}} = L_{\text{FIR}}/\pi r^2 = \sigma_{\text{SB}} \tau_v T_{\text{eff}}^4, \]
where \( r \) is the disk radius, and \( \sigma_{\text{SB}} \) is the Stefan–Boltzmann constant. \(^{14}\) About half of \( L_{\text{FIR}} \) comes from a 0.75 kpc radius region in J1148+5251. This corresponds to \( T_{\text{eff}} \approx 82 \, \text{K} \), which is also consistent with the limit. Note that, integrated over the whole 5 kpc region traced by CO (and full \( L_{\text{FIR}} \)), this simplified calculation predicts \( T_{\text{eff}} \approx 53 \, \text{K} \), which is in good agreement with the kinetic temperature of the molecular gas as derived above, and the dust temperature obtained from fitting the SED of the source.

The vertical optical depth of a disk is given by \( \tau_v = \Sigma_{\text{gas}} \kappa / 2 \), where \( \Sigma_{\text{gas}} \) is the gas surface density, and \( \kappa \approx \kappa_0 T_{\text{eff}}^2 \) (valid for \( T_{\text{eff}} \lesssim 200 \, \text{K} \), \( \kappa_0 \approx 2.4 \times 10^{-4} \, \text{cm}^2 \, \text{g}^{-1} \, \text{K}^{-2} \); see Thompson et al. 2005) is the Rosseland mean opacity for dust. The assumption of a constant gas-to-dust ratio with radius implies that about half of the gas mass is found within a 0.75 kpc radius region in J1148+5251. Together with the \( T_{\text{peak}} \) derived above, this implies \( \tau_V \approx 1.03 \) (i.e., moderately optically thick), consistent with the assumptions of the Eddington-limited starburst model.

From the dynamical \( [\text{CII}]^{\lambda} (P_{3/2} \rightarrow P_{1/2}) \) line map of J1148+5251, we can derive a dynamical mass of \( M_{\text{dyn}} \sim 1.5 \times 10^{10} \, M_\odot \) within a 0.75 kpc radius region. Assuming that \( M_{\text{dyn}} \) traces the total mass within that region, this corresponds to a gas mass fraction of \( \Sigma_{\text{gas}} / \Sigma_{\text{SB}} \approx 0.72 \). Using Equation (37) of Thompson et al. (2005), this suggests that the disk is optically thick out to a radius of \( \sim 400 \, \text{pc} \). \(^{15}\) This value is by almost a factor of 2 smaller than 750 pc. This may indicate that the potential is not isothermal, as assumed in the model. It may also indicate that the three-dimensional distribution of the gas and dust is more complicated than assumed here. However, the model reproduces a number of the observed properties of J1148+5251 fairly well. Our observations thus are, indeed, consistent with a kiloparsec-scale “maximum starburst,” radiating close to its characteristic Eddington limit. This hyper-starburst is harbored by a large, 5 kpc size, overall warm and highly excited molecular gas reservoir that hosts \( 2.4 \times 10^{10} \, M_\odot \) of molecular hydrogen and \( 1.1 \times 10^7 \, M_\odot \) of atomic carbon.

### 5.4. Dense Molecular Gas and Gas Surface Density

There are additional lines of evidence that suggest that \( \Sigma_{\text{SFR}} \) as high as \( 1000 \, M_\odot \, \text{yr}^{-1} \, \text{kpc}^{-2} \) on kpc scales (as observed in J1148+5251) are not unreasonable. Recent investigations of the (in the nearby universe linear) HCN–FIR luminosity correlation at high \( z \) (including J1148+5251) show tentative evidence for an excess in \( L_{\text{FIR}} \) relative to the observed \( L_{\text{HCN}} \) toward the highest \( L_{\text{FIR}} \) systems (both with and without AGN; Carilli et al. 2005; Gao et al. 2007; Riechers et al. 2007). Such an excess can be explained by higher median gas densities (comparable to the critical density of HCN \( J = 1 \rightarrow 0 \)) in the most FIR-luminous galaxies (Krumholz & Thompson 2007; Narayanan et al. 2008a). Even when assuming a constant efficiency of forming a unit mass of molecular gas into stars among all galaxies, this would imply a higher SFR per unit area for the most FIR-luminous systems.

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\(^{14}\) Assuming a blackbody, which the dust SED only approximates.

\(^{15}\) As \( M_{\text{gas}} \approx \sigma_{\text{SHM}} \) was used to determine the gas fraction, this value is independent of the assumed disk inclination.
with a picture in which the molecular ISM in ULIRGs and even more FIR-luminous systems is dominantly in a rather dense, relatively continuous phase (rather than in individual, moderately dense molecular clouds), exhibiting optically thick emission. While the measured (peak) gas surface densities are comparable, the gas is spread out over larger areas in the high-z quasar host galaxies relative to the (dense) nuclei of nearby ULIRGs, consistent with the higher total gas masses and SFRs, and higher median gas densities (integrated over the whole galaxies). Overall, this may suggest that a tighter correlation would be found if $\Sigma_{\text{gas}}^{(\text{peak})}$ is compared to $\Sigma_{\text{SFR}}$ instead of the integrated $L_{\text{FIR}}$ (as a proxy of SFR).

5.5. Evolution of the Gaseous and Stellar Components

Assuming that the massive amounts of molecular material available on 5 kpc scales in J1148+5251 are converted into stars at an efficiency of 5%-10% as in GMC cores (e.g., Myers et al. 1986; Scoville et al. 1987), the SFR corresponds to a gas depletion timescale of only $(0.7-1.4) \times 10^8$ yr. This is about one-third of the value found for BRI 1335-0417 (Riechers et al. 2008b), suggesting a rapid buildup of the stellar component in both galaxies. Still, this gas depletion timescale is a few times larger than the dynamical and free-fall times of both the 0.75 kpc radius region traced by [CII], and the full 5 kpc size molecular reservoir. In this regard, the ongoing star formation may still be considered slow.

The [CII]$(3P_{1/2} \rightarrow 3P_{1/2})$ dynamical mass estimate suggests that J1148+5251 hosts a total mass of $\sim 1.5 \times 10^{10} M_\odot$ within a $\sim 0.75$ kpc radius region. A present day, massive elliptical galaxy with a black hole mass comparable to J1148+5251 and a velocity dispersion of 300 km s$^{-1}$ hosts a total mass of $\sim 5-8 \times 10^{10} M_\odot$ within a central region of the same size (and a total stellar mass of $\sim 2 \times 10^{12} M_\odot$ distributed over its entire spheroid; e.g., Häring & Rix 2004). Even assuming that the whole amount of molecular material in J1148+5251 were to eventually contribute to the assembly of the stellar spheroid within this small central region leaves a factor of a few difference between the central mass budgets of the $z = 6.42$ quasar and a $z = 0$ massive elliptical galaxy. This suggests that J1148+5251 has to accrete additional material by $z = 0$ (e.g., through subsequent mergers) to grow a spheroid mass comparable to its (likely) present-day counterparts.

On the other hand, the widths of the CO($J = 7 \rightarrow 6$) and [CII]$(3P_{1/2} \rightarrow 3P_{1/2})$ lines are the same within the uncertainties, while the sizes of the CO and [CII]-emitting regions appear to be different by a factor of $\sim 3$. Thus, [CII] traces a smaller dynamical mass than CO, corresponding to a shallower potential well. This difference may indicate that the gas in J1148+5251 has not yet fully coalesced, possibly due to an ongoing merger. This would be consistent with the high star formation efficiency found in the central region of this galaxy (Walter et al. 2009a), and the comparatively high fraction of dense gas (Riechers et al. 2007).

We conclude that the highly excited, several kpc scale size gas reservoirs in dust- and gas-rich high-z quasar host galaxies are dominantly heated by the large-scale starbursts that they maintain, consistent with cosmological simulations of merger-driven $z \sim 6$ quasar formation (Li et al. 2008; Narayanan et al. 2008b). These starbursts reach surface densities as predicted by Eddington-limited star formation over kpc scales, accompanied (and probably supported) by ongoing major, “wet” merger activity in some cases.

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