A SEARCH FOR C i J = 2–1 EMISSION IN IRAS F10214+4724

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ABSTRACT

This paper presents sensitive new observations of the fine-structure line \( ^3P_2 \rightarrow ^3P_1 \) (\( J = 2–1 \)) of the neutral atomic carbon C i (\( \nu_{\text{rest}} \approx 809 \) GHz) in the strongly lensed ultraluminous infrared galaxy (ULIRG) IRAS F10214+4724 at \( z = 2.3 \) obtained with the millimeter/submillimeter James Clerk Maxwell telescope (JCMT). These do not confirm the presence of emission from this line at the flux levels or angular extent previously reported in the literature. The new 2 \( \sigma \) upper limits are \( S_{\nu_{\text{rest}}} \leq 7 \) Jy km s\(^{-1} \) (central position), and \( \langle S_{\nu_{\text{rest}}} \rangle \leq 8.5 \) Jy km s\(^{-1} \) (average over the two \( \Delta \alpha = 0'', \Delta \delta = \pm 10'' \) positions). C i emission assumed to be fully concomitant with the bulk of H\(_2\) and confined entirely within the strongly lensed object yields an upper limit of \( M_{\text{C}_i}(\text{H}_2) \leq 1.5 \times 10^{10} \ M_\odot \), compatible with the reported CO-derived H\(_2\) gas mass, within the uncertainties of the two methods. A comparison is made with the recent detection of the \( ^3P_1 \rightarrow ^3P_0 \) (\( J = 1–0 \)) line in this galaxy by Weiss et al., and the large discrepancy with the previous C i measurements is briefly discussed.

Subject headings: galaxies: individual (IRAS F10214+4724) — galaxies: starburst — ISM: atoms — ISM: molecules — submillimeter

1. INTRODUCTION

The detection of CO \( J = 3–2 \) emission in the IRAS F10214+4724 galaxy at \( z \approx 2.3 \) (Brown & Vanden Bout 1991; Solomon et al. 1992) was the first detection of a molecular gas mass tracer at high redshifts, initiating a series of largely fruitful efforts to detect CO lines in QSOs (e.g., Barvainis et al. 1994; Omont et al. 1996; Ohta et al. 1996), submillimeter-bright galaxies (e.g., Frayer et al. 1998; Neri et al. 2003), and Lyman-break galaxies (Baker et al. 2004) at increasingly high redshifts. The current record stands at \( z \approx 6.42 \) (Walter et al. 2003), dramatically expanding the domain over which such standard ISM probes can be used to deduce H\(_2\) mass, its average physical conditions, and (when sufficient angular resolution is available) to provide information about total versus H\(_2\) gas mass. On occasion such observations reveal that, unlike local ultraluminous infrared galaxies (ULIRGs), high-\( z \) starbursts can have star formation activity extending over tens of kiloparsecs, fueled by large reservoirs of molecular gas whose mass dominates the total dynamic mass (Papadopoulos et al. 2000).

The importance of detecting the two C i lines at any redshift stems from extensive evidence for fully concomitant \( ^1\text{CO}, ^1\text{CO}, \) and C i emission in Galactic molecular clouds (Keene et al. 1996 and references therein; Ikeda et al. 2002). Thus C i can be an alternative, optically thin molecular gas tracer, which also remains sensitive for gas with low excitation conditions (Papadopoulos et al. 2004). Previous work reported the presence of CO \( J = 3–2 \) and C i \( J = 1–0 \), 2–1 emission in the strongly lensed IRAS F10214+4724, possibly extending in regions around it and beyond the amplification power of the gravitational lens (Brown & Vanden Bout 1991, 1992a, 1992b). This raised the possibility of a massive amount of reservoir molecular gas present near this high-\( z \) galaxy, but follow-up CO \( J = 3–2 \) observations assigned all the observed CO emission to the strongly lensed object (Downes et al. 1995), and this issue was considered resolved (see Radford et al. 1996 for a summary). Observations of the C i \( J = 1–0 \) line in IRAS F10214+4724 and a few other high-\( z \) objects have been recently reported in the literature in which the emission from the former is found to be \( \sim 10 \) times weaker than originally reported (Weiss et al. 2005). Here it must be emphasized that C i observations at any redshift are important in their own right and are not a trivial variation of CO observations, since C i line emission remains luminous for low-excitation gas that may be underluminous in the CO \( J +1 \rightarrow J, J +1 \geq 3 \) lines (see, e.g., Kaufman et al. 1999). This provided the main motivation for the follow-up observations to search for C i \( J = 2–1 \) emission in and around this high-\( z \) ULIRG that are presented in this paper. A Hubble constant of \( H_0 = 75 \) km s\(^{-1}\) Mpc\(^{-1}\) and \( q_0 = 1/2 \) are assumed throughout.

2. OBSERVATIONS AND RESULTS

The 15 m James Clerk Maxwell Telescope (JCMT) on Mauna Kea, Hawaii, was utilized to observe the C i \( J = 2–1 \) line (\( \nu_{\text{rest}} = 809.3432 \) GHz) toward IRAS F10214+4724 (\( z = 2.2854 \) from CO lines; Downes et al. 1995) in numerous observing sessions, namely in 2003 January 17 and 20–22, and during several sessions between 2004 June 15 and 28, and on 2004 July 7. The DBS receiver A3 yielded typical effective system temperatures of \( T_{\text{sys}} \approx 350 \) K during the 2003 observing period and somewhat higher ones, \( T_{\text{sys}} \approx 450–600 \) K, during the 2004 period. In the former period A3 was tuned at \( \nu_{\text{cen}}(z) = 246.4954 \) GHz, and the Digital Autocorrelation Spectrometer (DAS) was set at its widest bandwidth of 1.84 GHz (\( \approx 2240 \) km s\(^{-1}\)), while in the latter a bandwidth of 920 MHz (\( \approx 1120 \) km s\(^{-1}\)) centered at \( \nu_{\text{cen}} = 246.3454 \) GHz (the exact line center as expected from the CO lines), was used. The wide bandwidth mode of the DAS was initially used to allow for a C i line wider than expected from the high-\( J \) CO transitions (since more gas may be excited in C i), while maintaining ample baseline to define the zero level.\(^1\) The telescope pointing and focus were checked regularly using Saturn and the spectral-line standard IRC +10216 (for spectral-line

\(^{1}\) The receiver tuning in the wide-band DAS mode was deliberately set slightly away from the expected line center in order to avoid positioning the line in the joining section of the two spectrometer sectors that form the bandwidth in this mode. This proved to be an unnecessary precaution, since ample channel overlap makes for a smooth joining of the two DAS sectors, evident in the co-added spectra in Figs. 1 and 2.

763
pointing), and the estimated rms pointing error was ~3″ (~1/7 of the θ_{HPBW} = 21″ beam at this frequency). Frequent observations of IRC+10216 at CO J = 2−1 verified the proper receiver tuning and yielded a spectral line calibration uncertainty of ~15%. Rapid beam switching at ν_{IF} ~ 1−2 Hz and an azimuthal throw of ~60° were employed. Finally, in order to search for the purported extended C I emission along the north−south direction (Brown & Vanden Bout 1992a), the points Δα = 0″, Δδ = ±10″ were also observed during the 2003 observing period. The final co-added spectra are shown in Figures 1 and 2, respectively.

The quantity I = \int_{ΔV} ΔT_A dV, where ΔT_A = T_A(V) − T_A, bas is the spectral line profile, has a thermal rms error of

$$\sigma(I) = \sqrt{N_{ΔV}} \left( \frac{1 + \frac{1}{N_{bas}}} {N_{bas}} \right)^{1/2} \delta T_{A, ch} ΔV_{ch},$$

where N_{ΔV} = ΔV / ΔV_{ch} is the number of channels ΔV_{ch} comprising ΔV, and N_{bas} is the total number of channels used to define the line-free offset T_A, bas (N_{bas}/2 channels placed on each side of the line). The rms error per channel, δT_{A, ch}, is assumed to be uniform over the band.

From the spectra shown in Figures 1 and 2 it is estimated that \sigma(I_{0,0}) = 0.14 K km s^{-1} and \delta(I) = 0.17 K km s^{-1} for the average spectrum of the two (0″, ±10″) offset positions. The FWZI of the C I line was assumed to be ΔV ≈ 2 × ΔV_{FWHM} ≈ 400 km s^{-1} (from multiple, high-S/N CO line observations; Radford et al. 1996). Upper limits can be alternatively expressed in terms of velocity-integrated flux densities from

$$S_C = \int_{ΔV} S_{ν} dV = \frac{8πν_0}{η_ν πD^2} \int_{ΔV} ΔT_A dV = \frac{15.6(Jy/K)}{η_ν} \int_{ΔV} ΔT_A dV,$$

where η_ν = 0.63 is the aperture efficiency of JCMT at this frequency (a point source was assumed with a source size ≤ 1.5′′; Downes et al. 1995). The 2 σ upper limits obtained from the present observations are S_C(0″, 0″) ≤ 7 Jy km s^{-1} and \langle S_C(0″, ±10″) \rangle ≤ 8.5 Jy km s^{-1} (where a ~15% line calibration uncertainty was also added in quadrature along with the thermal rms error).

2.1. Comparison with the J = 1−0 Transition and an Upper Limit on M(H2)

The galaxy F10214+4724 has had several of its CO lines and thermal dust continuum frequencies detected (Solomon et al. 1992; Downes et al. 1995 and references therein), from which \theta_k = 50−65 K and n(H2) ≥ 5 × 10^3 cm^{-3} are deduced. Recently, Weiss et al. (2005) have measured the flux of the J = 1−0 line toward the central position using the IRAM 30 m telescope and found it to be S_{C}(1−0) = 1.6 ± 0.2 Jy km s^{-1}. In principle, measurements of both C I J = 2−1 and J = 1−0 lines can yield constraints on the gas excitation properties independent of those deduced from the CO lines. Indeed, assuming a collisional excitation of the C I three-level system (and that the lines are optically thin), it is

$$\frac{S_C(2−1)}{S_C(1−0)} = \frac{A_{21} Q_{21}(n, T_k)}{A_{10} Q_{10}(n, T_k)} × \frac{Q_{21}(n, T_k)}{Q_{10}(n, T_k)} = 3.38,$$

where A_{21} = 2.68 × 10^{-7} s^{-1} and A_{10} = 7.93 × 10^{-8} s^{-1} are the Einstein coefficients of the two transitions, and Q_{n0}(n, T_k) = N_n/N_{tot} express the relative population levels (their full expressions can be found in Papadopoulos et al. 2004). The upper limit on the C I J = 2−1 line emission reported here and the measurement by Weiss et al. for J = 1−0 yield Q_{21}/Q_{10} ≤ 1.29, which is fully compatible with the values expected for the conditions reported for the molecular gas in this galaxy (Downes et al. 1995), but hardly constraining by itself. However, somewhat more sensitive C I J = 2−1 measurements would yield nontrivial constraints, e.g., for Q_{21}/Q_{10} ~ 1/2 × 1.29 = 0.64 (corresponding to ~1 σ limit of the current measurements) one finds \theta_k ~ 40 K (for LTE) to \theta_k ~ 55 K (for n = 5 × 10^3 cm^{-3}), which now probes the temperature range deduced from CO and dust measurements.

Assuming that CO, dust, and C I emission are fully concomitant and tracing the same H2 gas reservoir allows us to express S_C in terms of H2 mass by using

$$\frac{M_C(H_2)}{M_C} = 8.75 × 10^{10} \left[ \frac{1 + z − \sqrt{1 + z}}{1 + z} \right]^{-1} \left( \frac{X_C}{10^{-5}} \right)^{-1} \left( \frac{A_{21}}{10^{-7} \text{ s}^{-1}} \right)^{-1} \left[ \frac{S_C (2−1)}{\text{Jy km s}^{-1}} \right].$$
EMISSION IN IRAS F10214+4724

3. CONCLUSIONS

The results of this work can be summarized as follows:

1. New sensitive observations of the $C_{\text{i}}J = 2–1$ line emission in IRAS F10214+4724 at $z \sim 2.3$ do not confirm its presence at the intensity or the angular extent previously reported in the literature.

2. Under the assumption that $C_{\text{i}}$ emission traces the bulk of the $H_2$ gas mass located in the strongly lensed object, an upper limit of $M_{C_i}(H_2) \leq 1.5 \times 10^{10} M_\odot$ is deduced. This is compatible with the CO-derived $H_2$ mass, within the uncertainties of the two methods. However, any differential lensing effects between the easier-to-excite and possibly more extended $C_{\text{i}}$ emission (with respect to $CO J = 3–2$) would act to raise the $C_{\text{i}}$-derived $H_2$ mass limit.

3. A comparison with the recently reported $C_{\text{i}}J = 1–0$ line intensity in this object by Weiss et al. (2005) allows us to place an upper limit on the $C_{\text{i}}(2–1)/(1–0)$ ratio. Its value, while compatible with the average CO-derived excitation conditions of the molecular gas, does not offer any useful independent constraints by itself. Nevertheless, only a modest improvement of any future $C_{\text{i}}J = 2–1$ measurements (a factor of 2) is needed in order to yield a good independent constraint.

4. The discrepancy between the measurements presented here and those of Brown & Vanden Bout is attributed to the low S/N and baseline instabilities affecting their data. The latter source of error can be particularly insidious, as demonstrated by an affected part of the data set presented here, in which such an instability could easily be construed as a line detected at $\sim 4–5 \sigma$.

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REFERENCES

Baker, A. J., Tacconi, L. J., Genzel, R., Lehnert, M. D., & Lutz, D. 2004, ApJ, 604, 125
Barvainis, R., Tacconi, L., Antonucci, R., Alloin, D., & Coleman, P. 1994, Nature, 371, 586
Brown, R. L., & Vanden Bout, P. A. 1991, AJ, 102, 1956
———. 1992a, ApJ, 397, L11
Brown, R. L., & Vanden Bout, P. A. 1992b, ApJ, 397, L19
Downes, D., Solomon, P. M., & Radford, S. J. E. 1995, ApJ, 453, L65
Frayer, D. T., Ivison, R. J., Scoville, N. Z., Yun, M., Evans, A. S., Smail, I., Blain, A. W., & Kneib, J.-P. 1998, ApJ, 506, L7
Ikeda, M., Oka, T., Tatematsu, K., Sekimoto, Y., & Yamamoto, S. 2002, ApJS, 139, 467
Kaufman, M. J., Wolfire, M. G., Hollenbach, D. J., & Luhman, M. L. 1999, ApJ, 527, 795
Keene, J., Lis, D. C., Phillips, T. G., & Schilke, P. 1996, in IAU Symp. 178, Molecules in Astrophysics: Probes and Processes, ed. E. F. van Dishoeck (Dordrecht: Kluwer), 129
Neri, R., et al. 2003, ApJ, 597, L113
Ohta, K., Yamada, T., Nakanishi, K., Kohno, K., Akiyama, M., & Kawabe, R. 1996, Nature, 382, 426
Omont, A., Petitjean, P., Guilloteau, S., McMahon, R. G., Solomon, P. M., & Pecontal, E. 1996, Nature, 382, 428
Papadopoulos, P. P., Röttgering, H. J. A., van der Werf, P. P., Guilloteau, S., Omont, A., van Breugel, W. J. M., & Tilanus, R. P. J. 2000, ApJ, 528, 626
Radford, S. J. E., Downes, D., Solomon, P. M., & Barrett, J. 1996, AJ, 111, 1021
Solomon, P. M., Downes, D., & Radford, S. J. E. 1992, ApJ, 398, L29
Weiss, A., Downes, D., Henkel, C., & Walter, F. 2005, A&A, 429, L25
Weiss, A., Henkel, C., Downes, D., & Walter, F. 2003, A&A, 409, L41