C I EMISSION IN ULTRALUMINOUS INFRARED GALAXIES AS A MOLECULAR GAS MASS TRACER

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ABSTRACT

We present new sensitive wide-band measurements of the fine-structure line $^3P_j \rightarrow ^3P_i$ ($J = 1–0$, 492 GHz) of neutral atomic carbon (C I) in the two typical ultraluminous infrared galaxies (ULIRGs) NGC 6240 and Arp 220. We then use them along with several other C I measurements in similar objects found in the literature to estimate their global molecular gas content under the assumption of a full C I–H$_2$ concomitance. We find excellent agreement between the H$_2$ gas mass estimated with this method and the standard methods using $^{12}$CO. This may provide a new way to measure H$_2$ gas mass in galaxies and one that may be very valuable in ULIRGs since in such systems the bright $^{13}$CO emission is known to systematically overestimate the gas mass while their $^{12}$CO emission (an often-used alternative) is usually very weak. At redshifts $z \geq 1$ the C I $J = 1–0$ line shifts to much more favorable atmospheric windows and can become a viable alternative tracer of the H$_2$ gas, fueling starburst events in the distant universe.

Subject headings: galaxies: individual (NGC 6240, Arp 220) — galaxies: starburst — ISM: atoms — ISM: molecules

1. INTRODUCTION

The C I $J = 1–0$ line emission emerging from molecular clouds has been detected early (Phillips & Huggins 1981), but its interpretation as emanating from only a narrow C I/C O transition zone at the surface of these clouds (e.g., Tielens & Hollenbach 1985a, 1985b) seems to preclude its use as a bulk H$_2$ gas tracer, except perhaps to derive lower limits. Nevertheless, despite the considerable difficulties involved in imaging wide areas in C I emission (caused by an unfavorable atmospheric window at 492 GHz and the small beams of single-pixel detectors mounted on large aperture submillimeter telescopes), early work has shown C I to be widely distributed and well correlated with other H$_2$ gas mass tracers such as $^{13}$CO (Keene et al. 1985, 1996 and references therein). Further observational efforts have confirmed this CO–C I concomitance in molecular clouds together with a remarkably constant N(C I)/N(C O) ratio over the bulk of the CO-bright gas (Ojha et al. 2001; Ikeda et al. 2002). A new comprehensive study has shown how this could be established and advocated the use of C I line emission as a molecular gas mass tracer in galaxies (Papadopoulos et al. 2004).

Ultraluminous infrared galaxies (ULIRGs) are powered mainly by starburst events (Genzel et al. 1998) that yield $L_{\text{FIR}} \geq 10^{12} L_\odot$, making them the most luminous objects in the local universe (Sanders et al. 1988; Sanders & Mirabel 1996). A number of reasons make them a good sample to test C I emission as a bulk H$_2$ gas mass tracer in galaxies, namely:

1. They are gas-rich systems but with their H$_2$ distributions usually so compact (e.g., Downes & Solomon 1998; Bryan & Scoville 1999) that single pointings with single-dish telescopes are adequate to record all of their C I/C O flux density (of prime importance for the difficult C I observations).
2. Their H$_2$ gas mass has been estimated using several methods other than the standard one based solely on the $^{12}$CO $J = 1–0$ line luminosity (e.g., Solomon et al. 1997; Downes & Solomon 1998; Glenn & Hunter 2001; Yao et al. 2003). Thus they constitute an ideal test bed for any new H$_2$ mass-tracing method.
3. In these merger/starburst systems, intense far-ultraviolet radiation and powerful tidal fields drive a two-phase differentiation of the molecular gas (Aalto et al. 1995). The diffuse, $^{13}$CO-bright, and nonvirialized intercloud phase is probably responsible for the systematic overestimate of H$_2$ gas mass by factors of ~4–5 in starburst environments (Solomon et al. 1997; Downes & Solomon 1998). It is thus interesting to see how a new method of measuring H$_2$ gas mass will fare under such conditions.
4. Early applications of this method in Arp 220 (Gerin & Phillips 1998) and the Cloverleaf QSO at $z = 2.5$ (Weiss et al. 2003) have yielded an H$_2$ mass that is in good agreement with the standard methods that use $^{13}$CO and dust continuum emission.
5. ULIRGs, as possible precursors of optically bright QSOs (Sanders et al. 1988; Tacconi et al. 2002) or as the nearby templates for starburst dust-enshrouded galaxies observed at high redshifts (Smail et al. 1997; Hughes et al. 1998), are interesting systems in their own right. Molecular gas being the “fuel” of their prodigious star-forming activity makes any new method of estimating its mass particularly valuable.

In this work we present new sensitive observations of the C I $J = 1–0$ line in two prominent ULIRGs, namely, Arp 220 and NGC 6240, and collect available C I measurements in similar objects from the literature, which are then used to estimate their H$_2$ gas mass content. Throughout this Letter we adopt an $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$ and $q_0 = 1/2$.

2. OBSERVATIONS AND RESULTS

We used the 15 m James Clerk Maxwell Telescope (JCMT) on Mauna Kea, Hawaii, to observe the $^3P_2 \rightarrow ^3P_1 (J = 1–0)$ fine-structure line at $\nu_{\text{rest}} = 492.160$ GHz in the ULIRGs Arp 220 (2003 January 3) and NGC 6240 (1999 February 27). Cold
and extremely dry weather with $\tau_{225 \text{ GHz}} \approx 0.035$ ensured excellent conditions for high-frequency observations with overall system temperatures of the single-sideband–tuned W-receiver of $T_{\text{sys}} \sim 700–900 \text{ K}$. Rapid beam switching at a chop-throw of 30° (Az) with a frequency of 1 Hz produced stable baselines, and the use of the Digital Autocorrelation Spectrometer at its widest mode of 1.8 GHz ($\sim 1100 \text{ km s}^{-1}$) enabled the full velocity coverage of the wide extragalactic lines often observed in such galaxies. This is particularly important since, e.g., Arp 220 has a FWHM $\sim 500 \text{ km s}^{-1}$ and in the past multiple frequency settings of the spectrometer were necessary in order to cover the entire C $\text{I}$ $J = 1–0$ line (Gerin & Phillips 1998). The aperture efficiency was measured repeatedly using Mars, an important task in submillimeter telescopes operating at such high frequencies since residual thermal distortions and mechanical deformations of the dish can then affect their performance significantly. We deduced $(\eta_{s}) = 0.35$, lower than the one quoted in the JCMT Observer’s Guide $(\eta_{s} = 0.45)$ but within the expected variations (P. Friberg 2004, private communication). The beam size at these frequencies (used to estimate the aforementioned efficiencies) is $\theta_{\text{FWHM}} = 10^\circ$. Frequent pointing checks showed the pointing error to be $\sim 3\arcmin$.

Frequent observations of strong spectral line sources yielded a calibration uncertainty of $\sim 20\%$, which along with the $\sim 25\%$ uncertainty of the adopted value of aperture efficiency dominate the error in the reported velocity-integrated line fluxes. These are estimated from

$$S_{\text{C}\text{I}} = \int_{\Delta v} S_{\text{v}} \, dv = \frac{8\pi}{\eta_{s}(1-\epsilon_{\text{source}})} \frac{K(x)}{T_{\text{A}}} \int_{\Delta v} T_{\text{A}}^* \, dv,$$

where $K(x) = x^2/(1 - e^{-x^2})$, $x = \theta_{\text{FWHM}} (1.2\theta_{\text{FWHM}})$ ($\theta_{\text{FWHM}}$ = source diameter) accounts for the geometric coupling of the Gaussian part of the beam with a finite-sized disklike source. For NGC 6240 it is $K(x) = 1.15$, while for all other sources $K(x) \sim 1$.

The C $\text{I}$ spectra are shown in Figures 1 and 2 along with overlaid $^{12}\text{CO}$ and $^{13}\text{CO}$ $J = 2–1$ spectral lines. The correspondence is excellent, while the weakness of the observed $^{12}\text{CO}$ emission (an often-used alternative to the much more optically thick $^{13}\text{CO}$) elevates C $\text{I}$ emission (if indeed fully concomitant with H$_{2}$) to a good alternative H$_{2}$ gas tracer in ULIRGs.

3. GLOBAL MOLECULAR GAS MASS ESTIMATES USING THE C $\text{I}$ LINE EMISSION

We use the measured $S_{\text{C}\text{I}}$, to deduce the global molecular gas mass from

$$M_{\text{C}\text{I}}(\text{H}_2) = \frac{4.92 \times 10^{10} h^{-2} (1 + z - \sqrt{1 + z})^2 (X_{\text{C}\text{I}})^{-1}}{1 + z} \times \left(\frac{A_{10}}{10^{-7} \text{ s}^{-1}}\right)^{-1} \frac{S_{\text{C}\text{I}}}{\text{Jy km s}^{-1}},$$

where $h' = 0.75$, the Einstein $A$-coefficient $A_{10} = 7.93 \times 10^{-8} \text{ s}^{-1}$, and $Q_{10} = Q_{10}(n, T_{s})$ depends on the gas excitation conditions (see Papadopoulos et al. 2004). The [C $\text{I}$]/[H$_{2}$] abundance chosen here is $X_{\text{C}\text{I}} = 3 \times 10^{-5}$, identical to that used by Weiss et al. (2003) in their H$_{2}$ mass estimate in the Cloverleaf. This value is the average between the minimum found for the bulk of the Orion A and B clouds ($\sim 10^{-5}$; Ikeda et al. 2002) and in the starburst environment of the nucleus of M82 ($\sim 5 \times 10^{-5}$; White et al. 1994; assuming [CO]/[H$_{2}$] = 10$^{-4}$). The results are shown in Table 1, where $M_{\text{C}\text{I}}(\text{H}_2)$ can be directly compared with the best available $M_{\text{CO}}(\text{H}_2)$ estimates. In the cases in which a range of physical conditions is reported for the gas, the average $Q_{10}$ excitation factor is adopted.

The agreement is remarkable, especially given that the CO-derived H$_{2}$ masses reported here are based on much better methods than the mere application of the Galactic X-factor (which in ULIRGs overestimates the H$_{2}$ mass by a factor of $\sim 5$). It must be noted, although, that even such methods leave uncertainties of a factor of $\sim 2$ in their $M(\text{H}_2)$ estimates (see, e.g., Tacconi et al. 1999). In the one case of IRAS 10565+2448 it is $M_{\text{C}\text{I}}(\text{H}_2)/M_{\text{CO}}(\text{H}_2) \sim 4$, possibly too large a difference to be attributed solely to the aforementioned uncertainties of the CO-based methods. In starburst environments higher $X_{\text{C}\text{I}}$ values are possibly more appropriate (e.g., Schilke et al. 1993 and references therein). Indeed, assuming that C $\text{I}$ is as abundant as in the center of M82 would keep the C $\text{I}$ and CO-deduced H$_{2}$ mass estimates in agreement within factors of $\sim 2$, while bringing $M_{\text{C}\text{I}}(\text{H}_2)$ in IRAS 10565+2448 in better accord with...
the CO-deduced value. Nevertheless, the latter case highlights an irreducible uncertainty when using optically thin emission from any molecular or atomic species to trace H$_2$ gas mass.

It is important to note that unlike quiescent spirals, ULIRGs can have $\geq$50% of their H$_2$ mass at densities $n$(H$_2$) $> 10^4$ cm$^{-3}$ (Gao & Solomon 2004), for which one-dimensional static photodissociation region models predict much lower $X_{C_1}$ values, effectively rendering C$\alpha$ emission incapable of tracing its mass. This does not seem to be happening, lending further support to a full C$\alpha$--H$_2$ concomitance over most of the parameter space characterizing the physical conditions of H$_2$ in galaxies. Furthermore, C$\alpha$ emission may be a good alternative molecular gas tracer particularly in ULIRGs because the often-used optically thin $^{13}$CO emission is very weak, while $^{12}$CO $1\rightarrow 0$ and a Galactic conversion factor overestimates $M$(H$_2$) because of the presence of nonvirialized $^{12}$CO-bright H$_2$ gas. Apart from the uncertainty of the assumed $X_{C_1}$ (which plagues also the $^{13}$CO measurements since C and $^{13}$CO emerge from tightly coupled chemical routes), the C$\alpha$ $1\rightarrow 0$ line is a more straightforward H$_2$ mass tracer than CO because of a simpler partition function and a significantly reduced sensitivity to the ambient gas excitation conditions.

It can be argued that a proper comparison between the various tracers of molecular gas must be between transitions within the same frequency domain because of the significant variations in the atmospheric absorption (and thus in the resulting effective system sensitivity) across the millimeter/submillimeter wavelengths. For C$\alpha$ and CO this is presented by Papadopoulos et al. (2004), where it is shown that while the $^{12}$CO $J = 4\rightarrow 3$ (461 GHz) transition can be indeed much stronger than C$\alpha$ $1\rightarrow 0$, the latter offers decisive advantages for cooler and/or diffuse gas ($T_e \leq 20$ K, $n < 10^4$ cm$^{-3}$) where the emission of the former is significantly suppressed. In ULIRGs the very weak $^{12}$CO emission makes the much brighter C$\alpha$ $1\rightarrow 0$ a better alternative H$_2$ mass tracer when using the same telescope to observe unresolved sources. This of course assumes C$\alpha$ observations conducted during suitable dry weather conditions, which occur much less frequently than those needed for sensitive $^{13}$CO observations. However, this situation is expected to change drastically when the new generation of millimeter/submillimeter single-dish telescopes (the Atacama Pathfinder Experiment [APEX]) and interferometer arrays (the Atacama Large Millimeter Array [ALMA]) become operational in the excellent sites in the Atacama Desert plateau in Northern Chile.

There dry atmospheric conditions, suitable for C$\alpha$ $1\rightarrow 0$ observations, are expected for $\sim$50% of the time and with much less pronounced diurnal variations (Radford & Nyman 2001 and references therein).

More C$\alpha$ $1\rightarrow 0$ observations of ULIRGs are urgently needed to further test the notion of C$\alpha$ as a bulk H$_2$ gas mass tracer. Application of this technique to quiescent nearby galaxies is also of prime importance, but then extensive C$\alpha$ imaging may be needed to match the CO and C$\alpha$ imaged areas. Finally, C$\alpha$ observations of galaxies at high redshifts with known CO detections can further test the effectiveness of this method while circumventing the problem of the low atmospheric transmission at 492 GHz ($J = 1\rightarrow 0$) and 809 GHz ($J = 2\rightarrow 1$).

4. CONCLUSIONS

We report on new sensitive C$\alpha$ $1\rightarrow 0$ measurements in the two prominent ULIRGs NGC 6240 and Arp 220 and collect C$\alpha$ measurements available for similar objects from the literature. We then use them to derive the molecular gas mass under the assumption of fully concomitant C$\alpha$, CO, and H$_2$, and find very good agreement between the C$\alpha$ and the CO-based estimates within the uncertainties of the two methods. The faintness of the $^{13}$CO emission (often used instead of the more optically thick $^{12}$CO) in these two galaxies and in similar systems makes C$\alpha$ emission a good alternative tracer of their molecular gas mass. However, given the much stricter constraints on the atmospheric conditions needed for sensitive C$\alpha$ observations (very dry weather) than those for $^{13}$CO, the practical advantages of C$\alpha$ as a good optically thin H$_2$ gas mass tracer will be fully realized when the new generation of millimeter/submillimeter single-dish telescopes (APEX) and interferometer arrays (ALMA) become operational in Cerro Chajnantor in the Atacama Desert plateau. We advocate more C$\alpha$ $1\rightarrow 0$ observations of similar objects at low as well as high redshifts (where C$\alpha$ lines are redshifted to more transparent atmospheric windows) in order to further test the potential of C$\alpha$ to trace bulk H$_2$ gas mass in galaxies.

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