ALMA SUB-ARCSEC-RESOLUTION 183 GHZ H$_2$O AND DENSE MOLECULAR LINE OBSERVATIONS OF NEARBY ULTRALUMINOUS INFRARED GALAXIES

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ABSTRACT

We present the results of ALMA $\sim$2 mm, $\lesssim$1”-resolution observations of ten (ultra)luminous infrared galaxies ([U]LIRGs; infrared luminosity $\gtrsim 10^{11.7}$L$_{\odot}$) at $z < 0.15$, targeting dense ($>10^4$ cm$^{-3}$) molecular (HCN, HCO$^+$, and HNC J=2–1) and 183 GHz H$_2$O 3$_{1,3}$–2$_{2,0}$ emission lines. Higher HCN to HCO$^+$ J=2–1 flux ratios are observed in some, but not all, AGN-important ULIRGs than in starburst-classified sources. We detect 183 GHz H$_2$O emission in almost all AGN-important ULIRGs, and elevated H$_2$O emission is found in two sources with elevated HCN J=2–1 emission, relative to HCO$^+$ J=2–1. Except one ULIRG (the Superantennae), the H$_2$O emission largely comes from the entire nuclear regions ($\sim$1 kpc), rather than AGN-origin megamaser at the very center ($<<1$ kpc). Nuclear ($\sim$1 kpc) dense molecular gas mass derived from HCO$^+$ J=2–1 luminosity is $\gtrsim$a few $\times 10^8$M$_{\odot}$, and its depletion time is estimated to be $\gtrsim 10^6$ yr in all sources. vibrationally excited J=2–1 emission lines of HCN and HNC are detected in a few (U)LIRGs, but those of HCO$^+$ are not. It is suggested that in mid-infrared-radiation-exposed innermost regions around energy sources, HCO$^+$ and HNC are substantially less abundant than HCN. In our ALMA $\sim$2 mm data of ten (U)LIRGs, two continuum sources are serendipitously detected within $\sim$10″, which are likely to be an infrared luminous dusty galaxy at $z > 1$ and a blazar.

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1. INTRODUCTION

Ultraluminous infrared galaxies (ULIRGs) with infrared (8–1000 µm) luminosity $L_{\text{IR}} \gtrsim 10^{12} L_{\odot}$ and luminous infrared galaxies (LIRGs) with $L_{\text{IR}} \sim 10^{11–12} L_{\odot}$ are characterized by strong dust thermal emission that is heated by energy sources (Sanders & Mirabel 1996). The infrared luminosity is typically much greater than UV-optical luminosity, suggesting that the energy sources, either starbursts and/or active galactic nuclei (AGNs), are mostly hidden behind dust. (U)LIRGs are almost exclusively observed as gas-rich galaxy mergers in the local universe at $z < 0.3$ (e.g., Sanders et al. 1988; Clements et al. 1996; Murphy et al. 1996; Duc et al. 1997). Numerical simulations of gas-rich galaxy mergers predict that supermassive black holes (SMBHs) grow rapidly in mass through accretion and become luminous AGNs at nuclear regions (Hopkins et al. 2006). However, high concentrations of dust and gas in merging (U)LIRGs’ nuclei (e.g., Downes & Eckart 2007; Scoville et al. 2015; Sakamoto et al. 2017; Imanishi et al. 2019) preclude clear distinction of hidden energy sources, particularly if compact AGNs are deeply buried (=obscured in virtually all directions) because the AGN signatures become elusive in extensively used optical spectroscopic classification (Maiolino et al. 2003; Imanishi et al. 2006). Observing at wavelengths of small dust extinction effects is indispensable to properly understand the energetic roles of buried AGNs in merging (U)LIRGs.

Radiative energy in a starburst originates from nuclear fusion inside stars, while in an AGN, a mass-accreting SMBH produces huge radiative energy from a compact (<<1 pc) accretion disk. In an AGN, (1) >2 keV X-rays and (2) mid-infrared 3–35 µm emission are much stronger than a starburst when normalized to intrinsic UV or bolometric luminosity (e.g., Shang et al. 2011), because in the vicinity of a mass-accreting SMBH, (1) UV photons from the accretion disk are upscattered to X-rays by inverse Compton process and (2) the amount of mid-infrared emitting hot (>100 K) dust is much greater because of considerably higher UV radiation density than in star-forming regions. Because hard X-rays ($\gtrsim$10 keV) and infrared 3–35 µm have strong penetrating power into dust and gas, spectroscopy in these wavelengths can be used as an effective tool to identify luminous buried AGN signatures, by distinguishing from starbursts, in gas/dust-rich (U)LIRGs’ nuclei. Such spectroscopy of nearby ($z < 0.3$) (U)LIRGs has been conducted systematically and signatures of luminous buried AGNs have been revealed in many sources with no obvious optical AGN signatures, at $\gtrsim 10$ keV hard X-rays (e.g., Teng et al. 2015; Oda et al. 2017; Ricci et al. 2017; Yamada et al. 2021) and at infrared 3–35 µm (e.g., Genzel et al. 1998; Imanishi et al. 2006; Armus et al. 2007; Imanishi et al. 2007a, 2008; Nardini et al. 2008, 2009; Veilleux et al. 2009; Nardini et al. 2010; Imanishi et al. 2010b). The presence of theoretically hypothesized deeply buried AGNs (actively mass-accreting SMBHs) in many merging (U)LIRGs has been observationally uncovered. However, there remain many nearby (U)LIRGs that have no significant AGN signatures even in the hard X-rays and infrared. It is important to distinguish whether (1) they contain no energetically important AGNs, or (2) they do, but are elusive even in hard X-rays and infrared owing to extremely large extinction (e.g., Downes & Eckart 2007; Matsushita et al. 2009; Scoville et al. 2017; Pereira-Santaella et al. 2021). Observations at wavelengths of even lower extinction can provide useful information.

(Sub)millimeter at 0.8–3.5 mm is one such wavelengths, with $\lesssim 1/20$ extinction effects than hard X-rays at $\sim 10$ keV and infrared $\sim 20$ µm (Hildebrand 1983). Because energy generation mechanisms are different for a starburst (nuclear fusion inside stars) and an AGN (mass-accreting SMBH), their effects on the surrounding mass-dominating dense ($> 10^4$ cm$^{-3}$) molecular gas at (U)LIRGs’ nuclei (Gao & Solomon 2004) can be different, possibly producing different rotational J-transition line flux
ratios among dense molecular gas tracers at (sub)millimeter. (Sub)millimeter dense molecular line flux ratios (J=1–0, J=3–2, and J=4–3 of HCN and HCO+) characteristic to known optically identified luminous AGNs (e.g., Kohno 2005; Krips et al. 2008; Izumi et al. 2015; Imanishi et al. 2016c), are also observed in a number of (U)LIRGs that show no discernible AGN signatures in the optical, infrared, and X-rays (e.g., Imanishi et al. 2007b, 2009; Privon et al. 2015; Izumi et al. 2016; Imanishi et al. 2016c, 2018b, 2019). Considering that independent (sub)millimeter AGN signatures are observed in some of these (U)LIRGs, they can be considered as candidates of optically/infrared/X-ray-elusive, but (sub)millimeter-detectable extremely deeply buried luminous AGNs (Imanishi et al. 2018b, 2019).

ALMA is an ideal observing facility to apply this (sub)millimeter dense molecular line energy diagnostic method to nearby (U)LIRGs, owing to very high sensitivity and high spatial resolution which enables to (1) pinpoint nuclear (≲1 kpc) regions where the putative luminous buried AGNs are expected to be present and (2) investigate AGN effects, by minimizing the contaminations from surrounding spatially extended (≳a few kpc) starburst emission. However, owing to the current ALMA frequency coverage of >84 GHz (band 3–10), HCN and HCO+ J=1–0 lines cannot be observed for (U)LIRGs at z > 0.06 where many interesting nearby (U)LIRGs are found (Kim & Sanders 1998). Thus, we observed at J=3–2 and J=4–3 lines of HCN, HCO+, and HNC (Imanishi & Nakanishi 2014; Izumi et al. 2016; Imanishi et al. 2016c, 2018b, 2019). A trend of elevated HCN emission, relative to HCO+, is observed in (U)LIRGs with luminous AGN signatures, compared to those without (Imanishi & Nakanishi 2014; Izumi et al. 2016; Imanishi et al. 2016c, 2018b, 2019). An enhanced HCN abundance in AGN-affected dense molecular gas (e.g., Aladro et al. 2015; Saito et al. 2018; Takano et al. 2019; Nakajima et al. 2018; Kameno et al. 2020; Imanishi et al. 2020) is one possibility. However, higher rotational excitation of HCN by warm and dense molecular gas in the vicinity of a luminous AGN than in a starburst is another scenario (Imanishi et al. 2018b), because the critical density of HCN is higher by a factor of ∼5 than that of HCO+ (Shirley 2015). Addition of different J-transition line data can help distinguish the physical origin of the elevated HCN emission in luminous AGNs.

Since ALMA Cycle 5, band 5 (163–211 GHz or ∼1.8 mm) observations have become available for openuse programs. HCN, HCO+, and HNC J=2–1 transition lines can be observed in band 5 for nearby (U)LIRGs. Because the excitation energy level is lower at J=2 than at J=3 or J=4, we can (1) discuss dense molecular line flux ratios at J=2–1 less affected by uncertainty of excitation conditions than at J=3–2 and J=4–3, and (2) J=2–1 lines of HCN, HCO+, and HNC may be more reliable dense molecular gas mass tracers, by reasonably assuming that J=2–1 lines are thermalized and optically thick (i.e., same luminosity as J=1–0 in units of [K km s−1 pc2]) in (U)LIRGs’ nuclei, where warm and dense molecular gas is highly concentrated (e.g., Downes & Eckart 2007; Scoville et al. 2015; Sakamoto et al. 2017; Imanishi et al. 2019). Further, addition of J=2–1 lines of HCN, HCO+, and HNC, to J=3–2 and J=4–3 lines, can be used to better constrain physical properties of dense molecular gas at (U)LIRGs’ nuclei.

In addition, the para-H2O 31,3–22,0 line at rest frequency νrest ∼ 183 GHz with an upper energy level of Eu ∼ 205 K. (hereafter “183 GHz H2O”) is present in close proximity to the HNC J=2–1 line (νrest ∼ 181 GHz), so they are simultaneously observable using ALMA. In warm and dense molecular gas illuminated by a luminous AGN, it is theoretically predicted that the 183 GHz H2O emission line can be very bright through maser amplification (e.g., Deguchi 1977; Neufeld & Melnick 1991; Yates et al. 1997; Maloney et al. 2002) and/or elevated thermal (non-maser) emission owing to
enhanced H$_2$O abundance caused by AGN’s X-ray illumination (Neufeld et al. 1994; Meijerink et al. 2012). Although sensitive observations of the 183 GHz H$_2$O lines are difficult for very nearby sources at $z \sim 0$ owing to the poor atmospheric transmission of Earth at $\sim$183 GHz, we can observe this line without severe Earth’s atmospheric H$_2$O absorption for (U)LIRGs at $z > 0.02$, rendering this H$_2$O line as another potentially good AGN indicator.

In this paper, we present the results of ALMA band 5 (163–211 GHz) and 4 (125–163 GHz) dense molecular (HCN, HCO$^+$, and HNC J=2–1) and 183 GHz H$_2$O line observations of ten (U)LIRGs (Table 1), for which the J=3–2 and J=4–3 line data of HCN, HCO$^+$, and HNC are available (Imanishi & Nakanishi 2013a,b, 2014; Imanishi et al. 2016b,c, 2017, 2018b). Results of a ULIRG, the Superantennae (IRAS 19254–7245) at $z = 0.0617$, where strong signatures of AGN-megamasers-origin luminous 183 GHz H$_2$O emission were found, have previously been published by Imanishi et al. (2021). In this manuscript, we report our band 4–5 ($\sim$2 mm) observational results of ten (U)LIRGs and discuss general properties of their nuclear dense molecular gas. Compilation of the J=2–1, J=3–2, and J=4–3 line data of HCN, HCO$^+$, and HNC, and detailed discussion of the physical properties of dense molecular gas at (U)LIRGs’ nuclei, with the aid of non-LTE modeling (van der Tak et al. 2007), will be presented in a separate paper (M. Imanishi in preparation). We adopt the cosmological parameters, $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_M = 0.27$, and $\Omega_\Lambda = 0.73$, throughout this paper. Unless otherwise mentioned, “H$_2$O emission” indicates “183 GHz H$_2$O 3$_{1,3}$–2$_{2,0}$ line emission”, while “molecular line flux ratio” indicates “rotational J-transition line flux ratio at the vibrational ground level (v=0)”.

2. TARGETS

Detailed properties of the observed ten (U)LIRGs in Table 1 are described by Imanishi et al. (2016b,c, 2018b). In short, we selected nearby (U)LIRGs that (1) had different levels of AGN’s energetic contributions to the bolometric luminosity, based on optical/infrared/(sub)millimeter spectroscopic energy diagnostic methods and (2) were expected to show bright molecular emission lines, to investigate their flux ratios with small statistical uncertainty. We regard NGC 1614 and IRAS 13509+0442 as starburst-dominated, because there are no luminous buried AGN signatures in the infrared as well as (sub)millimeter. IRAS 06035–7102, IRAS 08572+3915, IRAS 12127–1412, IRAS 15250+3609, the Superantennae, and IRAS 20551–4250 are diagnosed to contain luminous obscured AGNs based on 3–35 $\mu$m infrared spectroscopy (e.g., Armus et al. 2007; Imanishi et al. 2007a, 2008; Veilleux et al. 2009; Nardini et al. 2009, 2010). IRAS 12112+0305 and IRAS 22491–1808 display no obvious luminous AGN signatures in the optical and infrared, but possible signatures of (sub)millimeter-detected extremely deeply buried luminous AGNs were found in IRAS 12112+0305 NE (north eastern primary nucleus) and IRAS 22491–1808 (Imanishi et al. 2018b). IRAS 12112+0305 SW (south western secondary nucleus) is considered starburst-dominated (Imanishi et al. 2018b). Although our sample is not statistically unbiased, nor complete, it can provide useful information on the possible variation of molecular line flux ratios, depending on different AGN’s energetic contributions.

3. OBSERVATIONS AND DATA ANALYSIS

We conducted band 5 (163–211 GHz) and 4 (125–163 GHz) observations of nine ULIRGs and one LIRG NGC 1614 (Table 1) in our ALMA Cycle 5 programs 2017.1.00022.S and 2017.1.00023.S (PI = M. Imanishi). Data of dense molecular gas tracers, HCN J=2–1 ($\nu_{\text{rest}} = 177.261 \text{ GHz}$) and HCO$^+$
Table 1. Basic Properties of Observed (Ultra)luminous Infrared Galaxies

| Object              | Redshift | $d_L$ | Scale    | $f_{12}$ | $f_{25}$ | $f_{60}$ | $f_{100}$ | $\log L_{IR}$ | Optical      | IR/(sub)mm   | Class   | Class   |
|---------------------|----------|-------|----------|----------|----------|----------|-----------|---------------|-------------|-------------|---------|---------|
| NGC 1614 (IRAS 04315–0840) | 0.0160   | 68    | 0.32     | 1.38     | 7.50     | 32.12    | 34.32     | 11.7          | HII$^{a,b}$ | Sy2$^{c}$   | SB      | AGN    |
| IRAS 06035–7102     | 0.0795   | 356   | 1.5      | 0.12     | 0.57     | 5.13     | 5.65      | 12.2          | LI$^d$      |             | AGN     |         |
| IRAS 08572+3915     | 0.0580   | 256   | 1.1      | 0.32     | 1.70     | 7.43     | 4.59      | 12.1          | LI$^e$ (Sy2$^e$) | AGN + SB   |         |         |
| IRAS 12112+0305     | 0.0730   | 326   | 1.4      | 0.12     | 0.51     | 8.50     | 9.98      | 12.3          | LI$^e$      |             | AGN     |         |
| IRAS 12127–1412     | 0.1332   | 620   | 2.3      | <0.13    | 0.24     | 1.54     | 1.13      | 12.2          | Li$^f$ (HII$^f$) | AGN     |         |         |
| IRAS 13509+0442     | 0.1364   | 636   | 2.4      | 0.10     | <0.23    | 1.56     | 2.53      | 12.3          | HII$^f$     |             | SB      |         |
| IRAS 15250+3609     | 0.0552   | 243   | 1.1      | 0.16     | 1.31     | 7.10     | 5.93      | 12.0          | Li$^e$ (Cp$^e$) |             |         |         |
| Superantennae (IRAS 19254–7245) | 0.0617 | 273   | 1.2      | 0.22     | 1.24     | 5.48     | 5.79      | 12.1          | Sy2$^{b,d,f-g}$ | AGN     |         |         |
| IRAS 20551–4250     | 0.0430   | 188   | 0.84     | 0.28     | 1.91     | 12.78    | 9.95      | 12.0          | LI or HII$^d$ (Cp$^e$) | AGN     |         |         |
| IRAS 22491–1808     | 0.0776   | 347   | 1.5      | 0.05     | 0.55     | 5.44     | 4.45      | 12.2          | HII$^{c-e}$ |             | AGN     |         |

Note—Col.(1): Object name. Col.(2): Redshift adopted from ALMA dense molecular line data (Imanishi et al. 2016c), which are slightly different from the optically derived ones (Kim & Sanders 1998) in some cases. Col.(3): Luminosity distance (in Mpc). Col.(4): Physical scale (in kpc arcsec$^{-1}$). Col.(5)–(8): $f_{12}$, $f_{25}$, $f_{60}$, and $f_{100}$ are IRAS fluxes at 12, 25, 60, and 100 $\mu$m, respectively, taken from Kim & Sanders (1998) or Sanders et al. (2003) or the IRAS Faint Source Catalog (FSC). Col.(9): Decimal logarithm of infrared (8–1000 $\mu$m) luminosity in units of solar luminosity ($L_\odot$), calculated with $L_{IR} = 2.1 \times 10^{39} \times D(Mpc)^2 \times (13.48 \times f_{12} + 5.16 \times f_{25} + 2.58 \times f_{60} + f_{100})$ (ergs s$^{-1}$) (Sanders & Mirabel 1996). Col.(10): Optical spectroscopic classification. “Sy2”, “LI”, “HII”, and “Cp” mean Seyfert 2, LINER, HII-region, and starburst+AGN composite, respectively. $^a$: Veilleux et al. (1995). $^b$: Kewley et al. (2001). $^c$: Yuan et al. (2010). $^d$: Duc et al. (1997). $^e$: Veilleux et al. (1999). $^f$: Mirabel et al. (1991). $^g$: Colina et al. (1991). Col.(10): Infrared and (sub)millimeter energy diagnostic result. “AGN” and “SB” mean AGN-important (AGN signatures significantly detected) and starburst-dominated (no AGN signature), respectively. IRAS 12112+0305 consists of two galaxy nuclei, AGN-important primary nucleus and starburst-dominated secondary nucleus ($^g$).}
Table 2. Log of Our ALMA Observations

| Object       | Line                  | Date            | Antenna Number | Baseline [m] | Integration [min] | Bandpass | Flux | Phase |
|--------------|-----------------------|-----------------|----------------|--------------|-------------------|----------|------|-------|
| NGC 1614     | HCN/HCO+ J=2–1 (J21a) | 2018 September 12 | 41             | 15–1231      | 13                | J0423–0120 |      |       |
| HNC J=2–1/183 GHz H2O (J21b) | 2018 September 12 | 41 | 15–1231 | 20 | J0423–0120 |                      |      |       |
| IRAS 06035–7102 | HCN/HCO+ J=2–1 (J21a) | 2018 August 26 | 42             | 15–782       | 6                 | J0519–4546 |      |       |
| HNC J=2–1/183 GHz H2O (J21b) | 2018 September 21 | 43 | 15–1398 | 15 | J0635–7516 |                      |      |       |
| IRAS 08572+3915 | HCN/HCO+ J=2–1 (J21a) | 2018 April 1 | 41             | 15–704       | 19                | J0854+2006 |      |       |
| HNC J=2–1/183 GHz H2O (J21b) | 2018 September 19 | 41 | 15–1398 | 19 | J0854+2006 |                      |      |       |
| IRAS 12112+0305 | HCN/HCO+ J=2–1 (J21a) | 2018 April 1 | 41             | 15–704       | 11                | J1229+0203 |      |       |
| HNC J=2–1/183 GHz H2O (J21b) | 2018 September 6 | 43 | 15–784 | 6 | J1229+0203 |                      |      |       |
| IRAS 12127–1412 | HCN/HCO+ J=2–1 (J21a) | 2017 December 15 | 45             | 15–2517      | 20                | J1127–1857 |      |       |
| HNC J=2–1/183 GHz H2O (J21b) | 2017 December 14 | 49 | 15–3321 | 33 | J1127–1857 |                      |      |       |
| IRAS 13509+0442 | HCN/HCO+ J=2–1 (J21a) | 2017 December 17 | 46             | 15–3083      | 16                | J1256–0547 |      |       |
| HNC J=2–1/183 GHz H2O (J21b) | 2017 December 17 | 44 | 15–3083 | 22 | J1256–0547 |                      |      |       |
| IRAS 15250+3609 | HCN/HCO+ J=2–1 (J21a) | 2018 August 31 | 43             | 15–784       | 14                | J1550+0527 |      |       |
| HNC J=2–1/183 GHz H2O (J21b) | 2018 August 28 | 44 | 15–782 | 13 | J1550+0527 |                      |      |       |
| Superantennae | HCN/HCO+ J=2–1 (J21a) | 2018 September 20 | 43             | 15–1398      | 13                | J1550+0527 |      |       |
| HNC J=2–1/183 GHz H2O (J21b) | 2018 September 18 | 43 | 15–1398 | 6 | J1617–5848 |                      |      |       |
| IRAS 20551–4250 | HCN/HCO+ J=2–1 (J21a) | 2018 August 24 | 45             | 15–500       | 48                | J2056–4714 |      |       |
| HNC J=2–1/183 GHz H2O (J21b) | 2018 August 24 | 45 | 15–500 | 48 | J2056–4714 |                      |      |       |
| IRAS 22491–1808 | HCN/HCO+ J=2–1 (J21a) | 2018 September 20 | 46             | 15–1398      | 7                 | J2258–2758 |      |       |
| HNC J=2–1/183 GHz H2O (J21b) | 2018 September 20 | 46 | 15–1398 | 8 | J2258–2758 |                      |      |       |

Note—Col.(1): Object name. Col.(2): Observed molecular line. Col.(3): Observation date in UT. Col.(4): Number of antennas used for observations. Col.(5): Baseline length in meters. Minimum and maximum baseline lengths are shown. Col.(6): Net on source integration time in minutes.Cols.(7), (8), and (9): Bandpass, flux, and phase calibrator for the target source, respectively.

We started our analysis from pipeline-processed data by ALMA, using CASA (McMullin et al. 2007)¹. We determined the continuum level using channels that did not contain discernible emission lines, and subtracted it using the CASA task “uvcontsub”. We then applied the CASA task “clean” (Briggs weighting; robust = 0.5 and gain = 0.1) to create maps of the continuum-subtracted molecular line data, by binning 20 channels for all ULIRGs (velocity resolution ~ 35 km s⁻¹). For the LIRG NGC 1614, we applied 10 channels binning (~20 km s⁻¹), because molecular emission lines were

¹ https://casa.nrao.edu
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much narrower than those of other ULIRGs. In addition, we created cleaned continuum maps by integrating the line-free-channels’ data.

The pixel scales were set as 0\'025–0\'1 pixel$^{-1}$, which were less than one-fifth of the synthesized beam size of each data. We adopted $\lesssim$10\% absolute flux calibration uncertainty for our band 4–5 data, based on the ALMA Cycle 5 Proposer’s Guide.

4. RESULTS

Continuum emission at $\sim$2 mm is detected in all sources and is displayed in Figure 1 as contours. Table 3 summarizes detailed continuum emission properties. The achieved beam size is $\lesssim$1\" (i.e., sub-arcsecond) for all the obtained data. According to the ALMA Cycle 5 Technical Handbook (equation 7.6), the maximum recoverable scale (MRS) is $>$10\" at $\sim$2 mm for the minimum baseline of 15 m (Table 2), which corresponds to $>$8 kpc for all the ULIRGs and $>$3 kpc for the LIRG NGC 1614. Thus, our targeting dense molecular line emission in compact nuclei ($\lesssim$a few kpc) should be fully recovered.

In the LIRG NGC 1614, there are four bright continuum emission peaks, denoted as NGC 1614 W, N, S, and E (Figure 1). In IRAS 12112+0305, continuum emission is significantly ($>$3$\sigma$) detected not only in the north-eastern (NE) primary nucleus, but also in the south-western (SW) secondary nucleus (Figure 1). Continuum emission properties of these multiple positions are tabulated in Table 3. For other ULIRGs, continuum emission is clearly detected only in the primary nucleus. In the fields of IRAS 13509+0442 and the Superantennae, a bright continuum emitting source is serendipitously detected at $\sim$8\" north and $\sim$8\" south side of the primary ULIRG’s nucleus, respectively. These continuum sources are unlikely to be physically related to each ULIRG, and thus their observed properties are described in Appendix A. In short, the former and latter sources are likely to be an infrared luminous dusty galaxy at $z > 1$ and a blazar, respectively.

Integrated intensity (moment 0) maps of the HCN J=2–1, HCO$^+$ J=2–1, HNC J=2–1 and 183 GHz H$_2$O lines are created by integrating signals in channels with significant line detection, and the peak emission flux as well as detection significance is tabulated in Table 4. Figure 1 displays the moment 0 maps of these emission lines with significant ($\gtrsim$3$\sigma$) detection. The peak positions of these detected molecular emission lines spatially agree with the simultaneously obtained continuum data.

For the nearby LIRG NGC 1614 ($z = 0.0160$), the continuum and molecular line emission are spatially extended, and are substantially larger than the synthesized beam size (Figure 1). We create spectra from original beam data cubes (hereafter “original beam”) at four bright continuum emission peaks, which are shown in Figure 2. In Figure 3, we display original beam spectra at the primary continuum peak in each ULIRG, except for the double nuclei ULIRG IRAS 12112+0305 for which the spectra at both nuclei are shown separately.

Figure 4 shows the intensity-weighted mean velocity (moment 1) maps of the HCN J=2–1, HCO$^+$ J=2–1, HNC J=2–1, and 183 GHz H$_2$O emission lines whenever they are detected with significantly high S/N ratios to obtain meaningful velocity information (Table 4). Intensity-weighted velocity dispersion (moment 2) maps are also shown in Figure 5.


2 https://almascience.eso.org/documents-and-tools/cycle5/alma-proposers-guide
3 https://almascience.eso.org/documents-and-tools/cycle5/alma-technical-handbook
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Figure 1. Integrated intensity (moment 0) map of HCN J=2–1 (Left), HCO⁺ J=2–1 (Second left), HNC J=2–1 (Second right), and 183 GHz H₂O (Right) emission line. Continuum emission that is simultaneously obtained with individual lines is shown as contours. The contours start from 4σ and increase by a factor of 2 (i.e., 8σ, 16σ, and 32σ) for all sources except NGC 1614, for which contours are 4σ, 6σ, 8σ, and 10σ. Continuum peak position is shown as a cross. The length of the vertical white solid bar at the right side of HCN J=2–1 data (Left) corresponds to 1 kpc. Beam size for each moment 0 map is shown as a filled circle in the lower-left region. The beam size of HCN and HCO⁺ (HNC and H₂O) is comparable to that of continuum-J21a (continuum-J21b) data (Table 3, column 6).
| Object            | Frequency [GHz] | Flux [mJy/beam] | Peak Coordinate (RA,DEC)ICRS | rms [mJy/beam] | Synthesized beam ["] × ["] | ° |
|-------------------|-----------------|-----------------|------------------------------|---------------|-------------------------------|---|
| NGC 1614 W        | J21a (173.2−176.9, 185.4−189.1) | 0.88 (10σ) | (04h33m59.98s, −08°34'45.1") | 0.088 | 0.55×0.37 (−83°) |
|                   | J21b (177.4−181.2, 189.6−193.3) | 0.76 (8.1σ) | (04h33m59.99s, −08°34'45.3") | 0.093 | 0.58×0.33 (−79°) |
| NGC 1614 N        | J21a (173.2−176.9, 185.4−189.1) | 0.96 (11σ) | (04h34m00.01s, −08°34'44.6") | 0.088 | 0.55×0.37 (−83°) |
|                   | J21b (177.4−181.2, 189.6−193.3) | 0.36 (3.3σ) | (04h34m00.01s, −08°34'44.6") | 0.093 | 0.58×0.33 (−79°) |
| IRAS 06035−7102   | J21a (163.1−166.7, 175.0−178.7) | 1.0 (9.8σ) | (06h02m33.94s, −71°03'10.2") | 0.10 | 1.1×0.80 (−51°) |
|                   | J21b (166.9−170.7, 178.9−182.6) | 0.83 (13σ) | (06h02m34.94s, −71°03'10.2") | 0.064 | 0.48×0.34 (68°) |
| IRAS 08572+3915   | J21a (166.2−169.9) | 1.4 (18σ) | (09h00m25.37s, +39°03'54.1") | 0.080 | 0.71×0.35 (−61°) |
|                   | J21b (170.3−174.1) | 1.6 (22σ) | (09h00m25.37s, +39°03'54.1") | 0.073 | 0.68×0.33 (14°) |
| IRAS 12112+0305 NE| J21a (163.9−167.5, 175.7−179.4) | 3.4 (33σ) | (12h13m46.06s, +02°48'41.5") | 0.10 | 0.87×0.68 (29°) |
|                   | J21b (167.9−171.5) | 3.6 (18σ) | (12h13m46.06s, +02°48'41.4") | 0.20 | 0.83×0.57 (−61°) |
| IRAS 12112+0305 SW| J21a (163.9−167.5, 175.7−179.4) | 0.39 (3.9σ) | (12h13m45.95s, +02°48'39.1") | 0.10 | 0.87×0.68 (29°) |
|                   | J21b (167.9−171.7) | 0.39 (9.1σ) | (12h13m45.93s, +02°48'39.0") | 0.20 | 0.83×0.57 (−61°) |
| IRAS 15250+3609   | J21a (142.9−146.4, 155.1−158.7) | 0.84 (34σ) | (12h15m19.13s, −14°29'41.8") | 0.024 | 0.29×0.19 (−81°) |
|                   | J21b (159.0−162.7) | 0.85 (42σ) | (12h15m49.13s, −14°29'41.8") | 0.020 | 0.24×0.16 (−56°) |
| IRAS 13509+0442 A | J21a (142.5−146.0, 154.7−158.2) | 0.27 (10σ) | (13h53m31.57s, +04°28'04.8") | 0.027 | 0.27×0.19 (−68°) |
|                   | J21b (158.5−162.2) | 0.21 (7.2σ) | (13h53m31.57s, +04°28'04.8") | 0.029 | 0.29×0.18 (−63°) |
| Superantennae     | J21a (166.7−170.3) | 5.1 (22σ) | (15h26m59.42s, +35°58'37.4") | 0.23 | 1.1×0.68 (−22°) |
|                   | J21b (170.8−174.6) | 5.6 (47σ) | (15h26m59.42s, +35°58'37.4") | 0.12 | 0.70×0.39 (−10°) |
| IRAS 20551−4250   | J21a (166.8−172.3) | 2.5 (43σ) | (20h58m26.80s, −42°39'00.3") | 0.058 | 1.1×0.82 (−89°) |
|                   | J21b (172.8−176.5, 185.0−188.7) | 2.3 (63σ) | (20h58m26.80s, −42°39'00.3") | 0.036 | 0.61×0.41 (−84°) |
| IRAS 22491−1808   | J21a (163.2−166.8, 175.0−178.6) | 2.0 (23σ) | (22h51m49.35s, −17°52'24.1") | 0.088 | 0.50×0.33 (−76°) |
|                   | J21b (167.2−171.0) | 2.2 (20σ) | (22h51m49.35s, −17°52'24.1") | 0.11 | 0.41×0.34 (−89°) |

A Band 4 observation because the targeted molecular lines are redshifted into Band 4 (125−163 GHz).

Note—Col.(1): Object name. Col.(2): Frequency range in GHz used for continuum extraction. Frequencies of obvious emission lines were removed. When only one frequency range is shown, it means that data in another sideband were noisy owing to poor Earth’s atmospheric transmission, and were not used. Col.(3): Flux density (in mJy beam⁻¹) at the emission peak. Value at the highest flux pixel (0''025−0''1 pixel⁻¹) is extracted. The detection significance relative to the root mean square (rms) noise is shown in parentheses. Col.(4): Coordinate of the continuum emission peak in ICRS. Col.(5): The rms noise level (1σ) (in mJy beam⁻¹), derived from the standard deviation of sky signals in each continuum map. Col.(6): Synthesized beam (in arcsec × arcsec) and position angle (in degrees). The position angle is 0° along the north–south direction and increases in the counterclockwise direction.
Table 4. Peak Flux of Molecular Emission Line in Integrated Intensity (Moment 0) Map with Original Beam Size

| Object          | Peak [Jy beam\(^{-1}\) km s\(^{-1}\)] | \(\nu_{\text{rest}}\) | \(\nu_{\text{rest}}\) | \(\nu_{\text{rest}}\) | \(\nu_{\text{rest}}\) |
|-----------------|------------------------------------|------------------------|------------------------|------------------------|------------------------|
|                 | HCN J=2–1                         | HCO\(^+\) J=2–1        | HNC J=2–1              | 183 GHz H\(_2\)O      |
|                 | (1)                                | (2)                    | (3)                    | (4)                    | (5)                    |
| NGC 1614 W      | 0.40 (6.6\(\sigma\)) \(^{A}\)    | 0.79 (8.3\(\sigma\)) \(^{A}\) | <0.29 (<3\(\sigma\)) \(^{A}\) | <0.31 (<3\(\sigma\)) \(^{A}\) |
| NGC 1614 N      | 0.49 (8.1\(\sigma\)) \(^{A}\)    | 0.84 (8.8\(\sigma\)) \(^{A}\) | <0.29 (<3\(\sigma\)) \(^{A}\) | <0.31 (<3\(\sigma\)) \(^{A}\) |
| NGC 1614 S      | 0.34 (5.5\(\sigma\)) \(^{A}\)    | 0.56 (5.9\(\sigma\)) \(^{A}\) | 0.32 (3.0\(\sigma\)) \(^{A}\) | <0.31 (<3\(\sigma\)) \(^{A}\) |
| NGC 1614 E      | 0.29 (4.8\(\sigma\)) \(^{A}\)    | 0.54 (5.7\(\sigma\)) \(^{A}\) | <0.29 (<3\(\sigma\)) \(^{A}\) | <0.31 (<3\(\sigma\)) \(^{A}\) |
| IRAS 06035–7102 | 2.5 (19\(\sigma\))               | 3.1 (20\(\sigma\))     | 1.0 (14\(\sigma\))     | 0.45 (9.4\(\sigma\))  |
| IRAS 08572+3915 | 1.1 (13\(\sigma\))               | 1.4 (15\(\sigma\))     | 0.37 (8.3\(\sigma\))   | 0.57 (11\(\sigma\))   |
| IRAS 12112+0305 NE | 4.7 (26\(\sigma\))               | 2.6 (19\(\sigma\))     | 3.4 (15\(\sigma\))     | 1.9 (14\(\sigma\))    |
| IRAS 12112+0305 SW | 0.43 (4.2\(\sigma\)) \(^{B}\) | 0.88 (7.9\(\sigma\)) \(^{B}\) | <0.34 (<3\(\sigma\)) \(^{B}\) | <0.45 (<3\(\sigma\)) \(^{B}\) |
| IRAS 12127–1412 | 0.48 (8.2\(\sigma\))             | 0.33 (6.8\(\sigma\))   | 0.32 (7.6\(\sigma\))   | 0.22 (4.6\(\sigma\))  |
| IRAS 13509+0442 | 0.28 (5.7\(\sigma\))             | 0.28 (5.3\(\sigma\))   | 0.16 (5.5\(\sigma\))   | 0.15 (3.8\(\sigma\))  |
| IRAS 15250+3609 | 3.0 (20\(\sigma\))               | 1.3 (13\(\sigma\))     | 3.0 (19\(\sigma\))     | 2.7 (20\(\sigma\))    |
| Superantennae   | 2.9 (12\(\sigma\))               | 1.6 (11\(\sigma\))     | 1.1 (10\(\sigma\))     | 4.3 (21\(\sigma\))    |
| IRAS 20551–4250 | 4.4 (53\(\sigma\))               | 6.0 (59\(\sigma\))     | 1.8 (30\(\sigma\))     | 1.3 (27\(\sigma\))    |
| IRAS 22491–1808 | 3.9 (24\(\sigma\))               | 2.5 (20\(\sigma\))     | 2.4 (23\(\sigma\))     | 1.3 (17\(\sigma\))    |

\(^{A}\)For NGC 1614, integrated channels are determined to cover all of the nuclear (~1 kpc) emission components. Molecular emission at individual continuum peaks is narrower than the whole nuclear emission and has different peak velocity (Table 6 and Figure 2). Thus, the detection significance is apparently low, owing to increased noise originating from the integration of a large number of channels, even if narrow emission line signatures are clearly discernible in original beam spectra (Figure 2).

\(^{B}\)Integrated channels are optimized for the SW nucleus, because the molecular emission from the SW nucleus is faint and has a significantly different velocity profile from the brighter NE nucleus.

Notes—Col.(1): Object name. Cols.(2)–(4): Flux (in Jy beam\(^{-1}\) km s\(^{-1}\)) at the emission peak in the integrated intensity (moment 0) map with original synthesized beam. Detection significance relative to the rms noise (\(\sigma\)) in the moment 0 map is shown in parentheses. These moment 0 maps of the original beam are primarily used for (a) verification of significant detection at the peak position of the molecular line and (b) confirming its spatial coincidence with continuum peak within peak determination uncertainty (= beam-size/signal-to-noise [S/N] ratio). Col.(2): HCN J=2–1 \((\nu_{\text{rest}}=177.261\ GHz)\). Col.(3): HCO\(^+\) J=2–1 \((\nu_{\text{rest}}=178.375\ GHz)\). Col.(4): HNC J=2–1 \((\nu_{\text{rest}}=181.325\ GHz)\). Col.(5): Para-H\(_2\)O \(3_{1,3}–2_{2,0}\) \((\nu_{\text{rest}}=183.310\ GHz)\). In each object, the synthesized beam size of the HCN J=2–1 and HCO\(^+\) J=2–1 (HNC J=2–1 and H\(_2\)O) is virtually identical to that of continuum J21a (J21b) shown in Table 3, column 6.
Figure 2.  (a)–(h): Spectra at the W-, N-, S-, and E-continuum peak positions (Figure 1 top) within original elliptic beam (black solid line) and 200 pc circular beam (red dotted line).  (i)–(j): Spectra with 1 kpc circular beam. The abscissa represents the observed frequency in GHz and the ordinate represents flux density in mJy. Downward arrows are plotted at the redshifted frequency of certain emission lines, where $z = 0.0160$ (Table 1, column 2) is adopted for all positions. When the detection is not significant, the mark “(?)” is added. The horizontal black thin dotted line indicates the zero flux level.
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(i) IRAS 12127−1412 (z=0.1332)

(j) IRAS 12127−1412 (z=0.1332)

(k) IRAS 13509+0442 (z=0.1364)

(l) IRAS 13509+0442 (z=0.1364)

(m) IRAS 15250+3609 (z=0.0552)

(n) IRAS 15250+3609 (z=0.0552)

(o) Superantennae (z=0.0617)

(p) Superantennae (z=0.0617)
Figure 3. Spectra of the HCN J=2–1, HCO\(^+\) J=2–1, HNC J=2–1, and 183 GHz H\(_2\)O lines of ULIRGs. The abscissa represents the observed frequency in GHz and the ordinate is flux density in mJy. The black solid and red dotted lines represent the original elliptic beam and a \(\sim\)1kpc circular beam spectrum at the continuum peak, respectively. For IRAS 20551–4250, a spectrum is added to (u) to highlight faint emission lines. Other symbols are the same as in Figure 2.
\( \text{H}_2\text{O} \) AND DENSE MOLECULAR LINE EMISSION IN ULIRGS
Figure 4. Intensity-weighted mean velocity (moment 1) maps of the HCN J=2–1 (Left), HCO⁺ J=2–1 (Second left), HNC J=2–1 (Second right), and 183 GHz H₂O (Right) lines for sources with sufficiently bright emission. Continuum peak position is shown as a cross. The length of the vertical black solid bar at the right side of HCN J=2–1 data (Left) corresponds to 1 kpc. IRAS 12127−1412 and IRAS 13509+0442 are excluded because all the four molecular emission lines are not sufficiently bright to obtain meaningful velocity information. The maps of the 183 GHz H₂O line of NGC 1614, and HNC J=2–1 and 183 GHz H₂O lines of IRAS 12112+0305 SW, are not shown because these lines are faint. An appropriate cutoff (∼2σ) is applied when we make these moment 1 maps to prevent them from being dominated by noise.
$\text{H}_2\text{O}$ and dense molecular line emission in ULIRGs
Figure 5. Intensity-weighted velocity dispersion (moment 2) maps of the HCN J=2–1 (Left), HCO+ J=2–1 (Second left), HNC J=2–1 (Second right), and 183 GHz H2O (Right) lines for sources with sufficiently bright emission. Continuum peak position is shown as a cross. The length of the vertical black solid bar at the right side of HCN J=2–1 data (Left) corresponds to 1 kpc. IRAS 12127–1412 (all four lines), IRAS 13509+0442 (all four lines), NGC 1614 (183 GHz H2O), and IRAS 12112+0305 SW (HNC J=2–1 and 183 GHz H2O) are not included as in Figure 4. An appropriate cutoff (\(\sim 2\sigma\)) is applied when we make these moment 2 maps so that they are not dominated by noise.

Since probed physical scale in the original beam spectra is largely different among different (U)LIRGs (Table 3), we compare molecular emission line fluxes with the same physical scale for further discussion. We choose 1 kpc, because we can investigate dense molecular emission line properties at energetically dominant ULIRGs’ nuclei (e.g., Soifer et al. 2000; Diaz-Santos et al. 2010; Imanishi et al. 2011; Pereira-Santaella et al. 2021), with minimum contaminations from spatially extended (\(\gtrsim\) a few kpc) star-formation in the host galaxies. We modify the beam to 1 kpc for all molecular lines in ULIRGs if their beam sizes are smaller than 1 kpc, using the CASA task “imsmooth”, and then extract 1 kpc beam-sized spectra, which are overplotted as red dotted lines in Figure 3. This is the case for all ULIRGs except IRAS 06035–7102, IRAS 12112+0305, and IRAS 15250+3609, for which we set the beam size to 1.6 kpc, 1.2 kpc, and 1.2 kpc, respectively, because the beam size of some lines is larger than 1 kpc. Hereafter, we denote these spectra with 1–1.6 kpc beam sizes as
Table 5. Continuum Peak Flux in ∼1kpc-beam Data

| Object                  | Peak [mJy/beam] |
|-------------------------|-----------------|
|                         | J21a            | J21b            |
| NGC 1614 (1 kpc, 3′′1)  | 10 (7.5σ)       | 11 (5.1σ)       |
| IRAS 06035−7102 (1.6 kpc, 1′′1) | 1.1 (10σ) | 1.2 (10σ)       |
| IRAS 08572+3915 (1 kpc, 0′′90) | 1.8 (17σ) | 1.9 (17σ)       |
| IRAS 12112+0305 NE (1.2 kpc, 0′′87) | 3.4 (31σ) | 3.7 (17σ)       |
| IRAS 12112+0305 SW (1.2 kpc, 0′′87) | 0.39 (3.6σ) | 0.41 (1.9σ) |
| IRAS 12127−1412 (1 kpc, 0′′43) | 1.0 (27σ) | 1.1 (32σ)       |
| IRAS 13509+0442 (1 kpc, 0′′42) | 0.47 (12σ) | 0.40 (10σ)       |
| IRAS 15250+3609 (1.2 kpc, 1′′1) | 5.4 (21σ) | 6.6 (29σ)       |
| Superantennae (1 kpc, 0′′85) | 3.9 (14σ) | 4.3 (23σ)       |
| IRAS 20551−4250 (1 kpc, 1′′2) | 2.6 (45σ) | 2.8 (33σ)       |
| IRAS 22491−1808 (1 kpc, 0′′69) | 2.1 (20σ) | 2.6 (16σ)       |

Note— Col.(1): Object name. Beam size in kpc and arcsec is shown in parentheses. Col.(2) and (3): Flux density (in mJy beam−1) at the continuum peak position in ∼1kpc-beam data of J21a (taken with HCN J=2–1 and HCO+ J=2–1) and J21b (obtained with HNC J=2–1 and 183 GHz H2O), respectively. Detection significance relative to the noise level is shown in parentheses. The continuum peak position spatially agrees with that listed in Table 3 (column 4).

“∼1kpc-beam” spectra. For the LIRG NGC 1614, we modify the beam size of all molecular lines to 200 pc and extracted 200pc-beam spectra at four bright continuum peak positions, which are shown as red dotted lines in Figure 2a–h. We also create 1kpc-beam spectra for NGC 1614 (Figure 2i–j) for comparison with other ULIRGs.

As expected for the presence of spatially resolved components, emission line peak fluxes usually increase with increasing beam sizes for all (U)LIRGs. Flux density at the continuum peak position in ∼1kpc-beam data is tabulated in Table 5. The continuum flux density significantly increases from the original beam data (Table 3) in many sources.

Gaussian fits are applied to estimate the molecular emission line flux from nuclear ∼1 kpc regions in individual (U)LIRGs (and 200 pc regions for NGC 1614). We apply a single Gaussian fit as long as the observed emission line profile is approximated by a single peaked profile with small deviation. However, some molecular emission lines in certain ULIRGs display double-peaked profiles with central dips and clearly deviate from a single Gaussian profile (e.g., HCO+ J=2–1 line of IRAS 12112+0305 NE in Figure 3e). For these, we apply two Gaussian fits (two emission components). If the two Gaussian fits better trace the observed emission line profile than the single Gaussian fit, we adopt the former flux, which is slightly (≥ a few % to ∼10%) smaller than the latter. Adopted Gaussian fits of individual emission lines with possible detection signatures in the ∼1kpc-beam spectra for all (U)LIRGs (and 200pc-beam spectra for NGC 1614) are displayed in Appendix B. Table 6 summarizes the Gaussian-fit velocity-integrated fluxes, which will be used to discuss molecular line flux ratios,
unless otherwise stated for certain faint emission lines for which the peak values or 3σ upper limits in ~1kpc-beam moment 0 maps are used.

Table 6. Gaussian Fit of Emission Lines

| Object          | Line     | Gaussian fit          | FWHM    | Integrated flux |
|-----------------|----------|-----------------------|---------|-----------------|
|                 |          | Velocity (km s⁻¹)     | Peak flux density (mJy) | |
|                 |          |                       | FWHM (km s⁻¹) | |
|                 |          |                       | |
| NGC 1614        | HCN J=2−1 | 4765±4                | 27±1    | 243±10          | 6.8±0.4 |
| (1 kpc, 3″)     | HCO⁺ J=2−1 | 4769±4                | 47±1    | 252±8           | 12±1   |
|                 | HNC J=2−1 | 4766±8                | 16±1    | 222±17          | 3.7±0.4 |
| NGC 1614 W      | HCN J=2−1 | 4763±3                | 6.1±0.3 | 112±7           | 0.72±0.06 |
| (200 pc, 0″62) | HCO⁺ J=2−1 | 4761±2                | 11±1    | 114±5           | 1.3±0.1 |
|                 | HNC J=2−1 | 4744±5                | 5.3±0.8 | 77±13           | 0.42±0.10 |
| NGC 1614 N      | HCN J=2−1 | 4833±2                | 7.3±0.4 | 93±6            | 0.72±0.05 |
| (200 pc, 0″62) | HCO⁺ J=2−1 | 4833±2                | 11±1    | 109±5           | 1.2±0.1 |
|                 | HNC J=2−1 | 4842±4                | 5.8±0.8 | 57±9            | 0.34±0.07 |
| NGC 1614 S      | HCN J=2−1 | 4643±5                | 5.1±0.4 | 109±13          | 0.58±0.08 |
| (200 pc, 0″62) | HCO⁺ J=2−1 | 4639±2                | 8.6±0.4 | 97±8            | 0.88±0.08 |
|                 | HNC J=2−1 | 4638±6                | 3.8±0.4 | 104±18          | 0.41±0.08 |
| NGC 1614 E      | HCN J=2−1 | 4708±5                | 3.8±0.3 | 124±15          | 0.49±0.07 |
| (200 pc, 0″62) | HCO⁺ J=2−1 | 4700±2                | 7.2±0.3 | 120±6           | 0.90±0.06 |
|                 | HNC J=2−1 | 4744±13               | 2.7±0.6 | 112±35          | 0.32±0.12 |
| IRAS 06035−7102 | HCN J=2−1 | 23857±5               | 7.8±0.2 | 371±11          | 2.9±0.1 |
| (1.6 kpc, 1″1) | HCO⁺ J=2−1 | 23867±5               | 8.9±0.2 | 404±13          | 3.6±0.1 |
|                 | HNC J=2−1 | 23832±11              | 4.6±0.3 | 356±25          | 1.6±0.1 |
|                 | 183 GHz H₂O | 23898±20              | 2.0±0.2 | 424±77          | 0.83±0.18 |
| IRAS 08572+3915 | HCN J=2−1 | 17485±11              | 3.6±0.2 | 383±27          | 1.4±0.1 |
| (1 kpc, 0″90)  | HCO⁺ J=2−1 | 17388±27, 17563±31     | 4.9, 4.7 (fix) ^A | 162±23, 185±15 | 1.7±0.2 |
|                 | HNC J=2−1 | 17481±16              | 1.9±0.2 | 315±33          | 0.61±0.09 |
|                 | 183 GHz H₂O | 17551±18, 17558±15     | 2.2±0.3, 2.6±0.3 | 133±44, 174±36 | 0.75±0.15 |
| IRAS 12112+0305 NE | HCN J=2−1 | 21684±20, 21942±13     | 9.2±0.6, 10±1 | 289±35, 243±22 | 5.1±0.5 |
| (1.2 kpc, 0″87) | HCO⁺ J=2−1 | 21659±7, 21957±7       | 6.8±0.4, 7.6±0.4 | 198±17, 233±22 | 3.1±0.2 |
|                 | HNC J=2−1 | 21804±5               | 12±1    | 349±13          | 4.0±0.2 |
|                 | 183 GHz H₂O | 21807±5               | 7.8±0.3 | 268±14          | 2.1±0.1 |
| IRAS 12112+0305 SW | HCN J=2−1 | 21987±18              | 1.7±0.2 | 267±44          | 0.45±0.10 |
| (1.2 kpc, 0″87) | HCO⁺ J=2−1 | 21975±15              | 2.9±0.3 | 338±42          | 0.97±0.15 |
|                 | HNC J=2−1 | 21917±15, 22077±16     | 1.8±0.5, 1.9±0.5 | 104±41, 73±48 | 0.32±0.13 |
| IRAS 12127−1412 | HCN J=2−1 | 39966±25              | 1.5±0.2 | 483±63          | 0.70±0.12 |
| (1 kpc, 0″43)  | HCO⁺ J=2−1 | 39867±38, 40146±16     | 1.4±0.2, 1.4±0.5 | 360±111, 93 (fix) | 0.60±0.17 |
|                 | HNC J=2−1 | 39871±55, 40141±33     | 1.2±0.2, 1.5±0.4 | 376±89, 132±75 | 0.61±0.17 |
|                 | 183 GHz H₂O | 40036±74              | 0.75±0.55 | 500±193           | 0.35±0.29 |
| IRAS 13509+0442 | HCN J=2−1 | 40935±15              | 2.2±0.2 | 286±40          | 0.59±0.11 |

Table 6 continued on next page
recover the bulk of ULIRGs’ nuclear dense molecular and 183 GHz H\textsubscript{2} IRAS 13509+0442, but significantly smaller in the remaining ULIRGs (Appendix B). Namely, we
\[ \text{Thus, we adopt quantities derived from} \]
\[ \text{emission line signals, but increases noise a lot, making the detection of faint emission lines difficult.} \]

beam data. A further increase of the beam size does not significantly increase dense molecular
\[ \text{of a few (U)LIRGs in Figures 2 and 3. We apply Gaussian fits in the} \sim \text{1kpc-beam spectra (and} \]

\begin{table}[h]
\centering
\caption{(continued)\label{tab:6}}
\begin{tabular}{llllll}
\hline
Object & Line & Gaussian fit & & & \\
& & Velocity & Peak flux density & FWHM & Integrated flux \\
& & [km s\textsuperscript{-1}] & [mJy] & [km s\textsuperscript{-1}] & [Jy km s\textsuperscript{-1}] \\
\hline
(1 kpc, 0\textdegree42) & HCO\textsuperscript{+} J=2–1 & 40914±20 & 2.0±0.2 & 307±52 & 0.57±0.12 \\
& HNC J=2–1 & 40957±16 & 1.5±0.2 & 221±40 & 0.32±0.07 \\
& 183 GHz H\textsubscript{2}O & 41047±134 & 0.45±0.12 & 799±482 & 0.33±0.22 \\
IRAS 15250+3609 & HCN J=2–1 & 16582±4 & 12±1 & 274±10 & 3.4±0.2 \\
(1.2 kpc, 1\arcsec1) & HCO\textsuperscript{+} J=2–1 & 16564±7 & 7.1±0.5 & 216±17 & 1.6±0.2 \\
& HNC J=2–1 & 16591±7 & 13±1 & 295±18 & 3.7±0.3 \\
& 183 GHz H\textsubscript{2}O & 16581±5 & 11±1 & 313±12 & 3.4±0.2 \\
Superantennae & HCN J=2–1 & 18539±19 & 5.5±0.3 & 878±54 & 4.9±0.4 \\
(1 kpc, 0\textdegree85) & HCO\textsuperscript{+} J=2–1 & 18505±21 & 4.3±0.3 & 665±52 & 2.9±0.3 \\
& HNC J=2–1 & 18504±22 & 2.9±0.2 & 661±57 & 1.9±0.2 \\
& 183 GHz H\textsubscript{2}O & 18215±15 & 5.8±0.3 & 391±33 & 5.1±0.3 \\
IRAS 20551−4250 & HCN J=2–1 & 12890±1 & 23±1 & 202±2 & 4.8±0.1 \\
(1 kpc, 1\arcsec2) & HCO\textsuperscript{+} J=2–1 & 12887±1 & 34±1 & 214±3 & 7.4±0.1 \\
& HNC J=2–1 & 12892±2 & 12±1 & 182±5 & 2.3±0.1 \\
& 183 GHz H\textsubscript{2}O & 12887±2 & 7.9±0.2 & 175±5 & 1.4±0.1 \\
IRAS 22491−1808 & HCN J=2–1 & 23317±5 & 12±1 & 434±11 & 5.1±0.2 \\
(1 kpc, 0\textdegree69) & HCO\textsuperscript{+} J=2–1 & 23285±7 & 7.2±0.2 & 466±16 & 3.3±0.2 \\
& HNC J=2–1 & 23315±9 & 9.3±0.5 & 349±20 & 3.2±0.2 \\
& 183 GHz H\textsubscript{2}O & 23323±9 & 4.7±0.3 & 354±23 & 1.6±0.1 \\
\hline
\end{tabular}
\end{table}

\textsuperscript{a}Fixed to the best fit value.

\textbf{Note—}Col.(1): Object name. Beam size in kpc and arcsec is shown in parentheses. Col.(2): Line. Cols.(3)–(6): Gaussian fit of emission line in a \sim 1kpc-beam spectrum at the continuum peak position. For NGC 1614, that in a 200pc-beam spectrum is also shown. Col.(3): Optical local standard of rest (LSR) velocity (v\textsubscript{opt}) of emission line peak (in km s\textsuperscript{-1}). Col.(4): Peak flux density (in mJy). Col.(5): Observed full width at half maximum (FWHM) (in km s\textsuperscript{-1}). Col.(6): Gaussian-fit velocity-integrated flux (in Jy km s\textsuperscript{-1}). The Gaussian fit for the 183 GHz H\textsubscript{2}O line is not attempted for NGC 1614 and IRAS 12112+0305 SW, because there is no emission signature in each spectrum (Figures 2 and 3).

We also attempt to estimate the fluxes of dense molecular (HCN, HCO\textsuperscript{+}, and HNC J=2–1) and 183 GHz H\textsubscript{2}O emission lines, based on Gaussian fits in 2kpc-beam spectra (Appendix B). We find that the flux increase from \sim 1 kpc to 2kpc-beam data, is as high as \sim 80% in the starburst-dominated ULIRG IRAS 13509+0442, but significantly smaller in the remaining ULIRGs (Appendix B). Namely, we recover the bulk of ULIRGs’ nuclear dense molecular and 183 GHz H\textsubscript{2}O line emission in the \sim 1kpc-beam data. A further increase of the beam size does not significantly increase dense molecular emission line signals, but increases noise a lot, making the detection of faint emission lines difficult. Thus, we adopt quantities derived from \sim 1kpc-beam data for our discussion of (U)LIRGs’ nuclei.

There are serendipitously detected emission lines. The HC\textsubscript{3}N J=20–19 line at \nu\textsubscript{rest} = 181.945 GHz was covered in the J21b spectra of all ten (U)LIRGs and was clearly detected in four ULIRGs (IRAS 12112+0305 NE, IRAS 15250+3609, IRAS 20551−4250, and IRAS 22491−1808 in Figure 3f, 3n, 3r, and 3t, respectively).

Signatures of the HCN-VIB and HNC-VIB J=2–1 emission lines are recognizable in the spectra of a few (U)LIRGs in Figures 2 and 3. We apply Gaussian fits in the \sim 1kpc-beam spectra (and
200pc-beam spectra for NGC 1614) as well as create moment 0 maps with original beam. We claim significant (>3σ) detection as an isolated emission peak, of the HCN-VIB J=2–1 line in two ULIRGs (IRAS 15250+3609 and IRAS 20551–4250 in Figure 3m and 3u, respectively) and of the HNC-VIB J=2–1 line in three (U)LIRGs (NGC 1614 S, IRAS 15250+3609, and IRAS 22491–1808 in Figure 2f, 3n, and 3t, respectively). Table 7 summarizes the observed properties of these detected HC$_3$N J=20–19 and VIB emission lines. The HCO$^+$-VIB J=2–1 emission line is not detected in any spectra (Figures 2 and 3).

In the spectrum of IRAS 20551–4250 (Figures 3q and 3u), at the high frequency side of the HCO$^+$ J=2–1 line, an emission line signature exists, which we identify as SO 5(4)–4(3) ($\nu_{\text{rest}} = 178.605$ GHz). Moreover, the HOC$^+$ J=2–1 emission line ($\nu_{\text{rest}} = 178.972$ GHz) is detected (Figure 3u). We create moment 0 maps (with original beam) of both the lines and confirmed clear signals at the continuum peak position of IRAS 20551–4250. Gaussian fitting results in the 1kpc-beam spectrum as well as peak flux values in the moment 0 maps of these lines are presented in Table 7. Our Gaussian fits of other possible emission-like features provide no significant detection (<3σ).

In spectral windows other than J21a and J21b, the CS J=4–3 ($\nu_{\text{rest}} = 195.954$ GHz) and HC$_3$N J=21–20 ($\nu_{\text{rest}} = 191.040$ GHz) lines are included in certain fraction of (U)LIRGs and are detected in a few (U)LIRGs. Figure 6 displays these spectra. The observed properties of these detected emission lines are also summarized in Table 7. Both CS J=4–3 and HC$_3$N J $> 10$ lines have high critical densities of $>10^5$ cm$^{-3}$ (Shirley 2015), and thus can be regarded as additional dense molecular gas tracers.

5. DISCUSSION

5.1. HCN to HCO$^+$ J=2–1 Flux Ratios

From Table 6, we find that the observed HCN J=2–1 flux is significantly higher than the HCO$^+$ J=2–1 flux in several ULIRGs classified as AGN important (§2; IRAS 12112+0305 NE, IRAS 15250+3609, the Superantennae, and IRAS 22491–1808), while no such trend is seen in the three starburst-classified galaxy nuclei, NGC 1614, IRAS 12112+0305 SW, and IRAS 13509+0442 (§2), where the observed HCO$^+$ flux is higher than or at least comparable to the observed HCN J=2–1 flux. Elevated HCN emission, relative to HCO$^+$ emission, has been observed in a high fraction of, if not all, luminous AGNs at J=1–0 (e.g., Kohno 2005; Imanishi et al. 2007b; Krips et al. 2008; Imanishi et al. 2009; Privon et al. 2015), J=3–2 (e.g., Imanishi et al. 2016a,c, 2018a, 2019), and J=4–3 (e.g., Garcia-Burillo et al. 2014; Imanishi & Nakanishi 2014; Viti et al. 2014; Izumi et al. 2015, 2016; Imanishi et al. 2018b). A similar trend is seen also at J=2–1. However, not all AGN-important ULIRGs clearly show elevated HCN J=2–1 emission, relative to HCO$^+$ J=2–1 (e.g., IRAS 06035–7102, IRAS 08572+3915, IRAS 12127–1412, and IRAS 20551–4250 in Table 6), as previously seen at other J-transition lines (e.g., Imanishi et al. 2019; Privon et al. 2020). Further detailed discussion about how the observed HCN to HCO$^+$ flux ratios change among J=2–1, J=3–2, and J=4–3, will be presented by Imanishi et al. (2021; in preparation), to better understand the properties of nuclear dense molecular gas in nearby (U)LIRGs with and without luminous AGN signatures.

5.2. 183 GHz H$_2$O Emission

5.2.1. Flux Comparison

In the moment 0 maps in Figure 1, the 183 GHz H$_2$O emission line is not clearly detected (<4σ) in the three starburst-classified galaxy nuclei (NGC 1614, IRAS 12112+0305 SW, and IRAS
Table 7. Observed Properties of Other Possibly Detected Faint Emission Lines

| Object        | Line            | Moment 0 peak | Gaussian fit (≈1 kpc beam) A |
|---------------|-----------------|---------------|-----------------------------|
|               | (original beam) | Velocity      | Peak Flux                   |
|               |                 | [km s\(^{-1}\)] | [mJy]                       | [km s\(^{-1}\)] | [Jy km s\(^{-1}\)] |
| (1)           | (2)             | (3)           | (4)                         | (5)              | (6)              | (7)              |
| NGC 1614 S (200 pc) A | HNC-VIB J=2–1 | 0.14 (3.6σ) | 4699±23                     | 1.7±0.5          | 123 (fix) B      | 0.22±0.06        |
| IRAS 12112+0305 NE (1.2 kpc) A | HC\(_3\)N J=20–19 | 0.28 (5.9σ) | 21806±22                    | 1.6±0.3          | 278±71           | 0.44±0.14        |
| IRAS 15250+3609 (1.2 kpc) A | HCN-VIB J=2–1 | 0.24 (4.9σ) C | —                           | —                | —                | —                |
| IRAS 20551–4250 E | HC\(_3\)N J=20–19 | 0.62 (12σ) | 16615±10                    | 3.2±0.2          | 272±25           | 0.89±0.11        |
| IRAS 22491–1808 | SO 5(4)–4(3) | 0.40 (18σ) | 12892±4                     | 2.5±0.1          | 174±11           | 0.44±0.04        |
| IRAS 22491–1808 | HOC\(^+\) J=2–1 | 0.072 (5.3σ) D | —                           | —                | —                | —                |
| NGC 1614          | CS J=4–3        | 1.9 (5.1σ)   | 4774±20                     | 6.5±1.0          | 249±38           | 1.7±0.4          |
| IRAS 06035–7102   | CS J=4–3        | 0.72 (6.9σ)  | 23850±26                    | 2.4±0.3          | 417±72           | 1.0±0.2          |
| IRAS 12112+0305 NE (1.2 kpc) A | HC\(_3\)N J=21–20 | 0.55 (3.8σ) | 21608±60                    | 1.7±0.5          | 299 (fix) B      | 0.50±0.16        |
| IRAS 20551–4250   | CS J=4–3        | 1.5 (24σ)    | 12894±2                     | 12±1             | 175±5            | 2.1±0.1          |
| IRAS 22491–1808   | HC\(_3\)N J=21–20 | 0.52 (7.1σ) | 23297±29                    | 2±0.4            | 318±60           | 0.63±0.18        |

\(^A\)200 pc beam for NGC 1614 S, and 1.2 kpc beam for IRAS 12112+0305 and IRAS 15250+3609. For the remaining sources, 1 kpc beam size is adopted, including IRAS 06035–7102 (see also Figure 6b).

\(^B\)Fixed to the best fit value.

\(^C\)Signals of the emission tail at the lower frequency side of the HCO\(^+\) J=2–1 line (a horizontal solid bar in Figures 3e and 3s) are integrated. These values are only approximate for the HCN-VIB J=2–1 emission line flux, because we choose the integrated frequency range to minimize the contaminations from the nearby bright HCO\(^+\) J=2–1 emission line, and thus not all velocity components are likely to be covered, particularly for IRAS 22491–1808.

\(^D\)Only signals marked with the horizontal solid bar in Figure 3m are integrated. Other possible emission components at \(v_{\text{obs}} = 168.6–168.75\) GHz at even lower frequencies are not included, because they may originate from other components (e.g., redshifted HCO\(^+\) J=2–1 emission in the P Cygni profile of outflow (Imanishi et al. 2018b)).

\(^E\)There may be some emission signature at the expected frequency of the HCN-VIB J=2–1 line in Figure 3r, but its velocity profile is largely different from other detected bright emission lines. We do not argue that the HNC-VIB J=2–1 emission line is clearly detected in our data, because certain unidentified faint emission line may also contribute to the observed emission signature.

**Note.**—Col.(1): Object name. Col.(2): Line. Data listed above the horizontal solid line are molecular lines detected in Figures 2 and 3 within the spectral windows that cover the primarily targeted molecular lines, and those below the line are molecular lines detected in other spectral windows in Figure 6. Only lines with significant detection (>3σ), either with the Gaussian fit with all parameters set as free and/or moment 0 map, are listed. Col.(3): Peak flux (in Jy beam\(^{-1}\) km s\(^{-1}\)) in the moment 0 map of original beam. Detection significance relative to the rms noise (1σ) in the moment 0 map is shown in parentheses. The peak position spatially agrees with simultaneously obtained continuum peak position within peak determination uncertainty. For the CS J=4–3 and HC\(_3\)N J=21–20 lines below the horizontal solid line, data of IRAS 12112+0305 NE and IRAS 22491–1808 were obtained during J21a observations, while the remaining data were obtained during J21b observations. Synthesized beam sizes are comparable to those of individual J21a or J21b data listed in Table 3 (column 6). Col.(4)–(7): Gaussian fit of emission line in ~1kpc-beam spectrum at the continuum peak position. For NGC 1614 S, the beam size is 200 pc. Col.(4): Optical LSR velocity (\(v_{\text{opt}}\)) of emission line peak (in km s\(^{-1}\)). Col.(5): Peak flux density (in mJy). Col.(6): Observed FWHM (in km s\(^{-1}\)). Col.(7): Gaussian-fit velocity-integrated flux (in Jy km s\(^{-1}\)).
Figure 6. Serendipitously detected emission lines in spectral windows other than those covering the primarily targeted lines (HCN, HCO$^+$, HNC, and H$_2$O). The black solid and red dotted line is an original-beam and a $\sim$1kpc-beam spectrum at the continuum peak, respectively. (a): CS J=4–3 emission line ($\nu_{\text{rest}} = 195.954$ GHz) in the 189.6–193.3 GHz spectrum of NGC 1614. (b): CS J=4–3 emission line in the 179.0–182.5 GHz spectrum of IRAS 06035–7102. (c): HC$_3$N J=21–20 emission line ($\nu_{\text{rest}} = 191.040$ GHz) in the 175.7–179.1 GHz spectrum of IRAS 12112+0305 NE. (d): CS J=4–3 emission line in the 185.0–188.7 GHz spectrum of IRAS 20551–4250. (e): HC$_3$N J=21–20 emission line in the 175.0–178.6 GHz spectrum of IRAS 22491–1908. For (b) IRAS 06035–7102, the beam size of the CS J=4–3 line in the J21b data is smaller than 1 kpc (Table 3); therefore, the red dotted line spectrum is extracted from 1kpc-beam data (not 1.6 kpc, as shown in Figure 3), in order not to decrease the detection significance of this faint CS J=4–3 emission line. (Gaussian-fit velocity-integrated flux of CS J=4–3 emission line agrees within 4% between 1 kpc and 1.6 kpc beam.)

13509+0442), whereas it is detected with higher significance ($>4.5\sigma$) in the AGN-important ULIRGs’ nuclei (Table 4, column 5). Gaussian fits of the $\sim$1kpc-beam spectra also provide significant ($>3\sigma$) H$_2$O detection in all AGN-important ULIRGs except IRAS 12127–1412, but do not ($<3\sigma$) for the three starburst nuclei (Table 6, column 6). As briefly described in §1, theoretically, the 183 GHz H$_2$O emission line can be extremely luminous in warm and dense molecular gas in the immediate vicinity of a luminous AGN, if maser amplification caused by population inversion occurs (e.g., Deguchi 1977; Neufeld & Melnick 1991; Yates et al. 1997; Maloney et al. 2002). The strong 183 GHz H$_2$O megamasr ($>10L_\odot$) emission was detected in a few very nearby ($<20$ Mpc) AGNs (Humphreys et al. 2005, 2016). In the AGN-hosting ULIRG, the Superantennae at $z = 0.0617$ ($\sim$270 Mpc), the detected bright 183 GHz H$_2$O emission line was argued to primarily originate from the megamasr phenomena in AGN-illuminated gas at the very center of galaxy nucleus ($<1$ kpc), based on substantially elevated flux (luminosity) relative to, and spatially more compact distribution than, other dense molecular gas tracers (HCN, HCO$^+$, and HNC J=2–1 emission lines) (Imanishi et al. 2021).
Furthermore, in such gas near an AGN, it is predicted that the H$_2$O abundance can be enhanced by X-ray radiation (e.g., Neufeld et al. 1994; Meijerink et al. 2012) and/or H$_2$O evaporation from dust grain mantles into gas phase (e.g., Gonzalez-Alfonso et al. 2010). In fact, high H$_2$O abundance in AGNs has been observationally supported (e.g., Gonzalez-Alfonso et al. 2010, 2012; Liu et al. 2017). Hence, even if the maser amplification does not work as effectively as in the Superantennae, the 183 GHz H$_2$O emission in AGN-important ULIRGs can be elevated because of the enhanced H$_2$O abundance.

We investigate the 183 GHz H$_2$O emission line flux, in comparison with other dense molecular gas tracers, to determine whether the elevated 183 GHz H$_2$O emission, previously found in the Superantennae, is also observed in other (U)LIRGs. Figures 7a and 7b compare, respectively, the 183 GHz H$_2$O to HCO$^+$ J=2–1 and the 183 GHz H$_2$O to HNC J=2–1 flux ratio (abscissa), with HCN to HCO$^+$ J=2–1 flux ratio (ordinate). In Figure 7a, two sources with distinctly high 183 GHz H$_2$O to HCO$^+$ J=2–1 flux ratios show high HCN to HCO$^+$ J=2–1 flux ratios with >1.6. In Figure 7c, the 183 GHz H$_2$O to HCN J=2–1 flux ratio is compared with the HNC to HCN J=2–1 flux ratio. The Superantennae is distinguishable as the 183 GHz H$_2$O emission is elevated relative to all the HCO$^+$, HNC, and HCN J=2–1 emission lines. IRAS 15250+3609 also shows elevated 183 GHz H$_2$O emission, with respect to the HCO$^+$ and HCN J=2–1 lines, but not relative to the HNC J=2–1. The signatures of the elevated 183 GHz H$_2$O emission are much weaker in the remaining (U)LIRGs.

5.2.2. Compactness

We search for the presence of spatially unresolved (<<1 kpc), compact H$_2$O emission and measure how its fraction, relative to the total nuclear (~1 kpc) emission, is higher than the other three dense molecular lines, using several indicators. In Figure 3, it is clear that the peak flux increase from the original beam to the ~1 kpc beam, is much smaller for the 183 GHz H$_2$O line than the HNC J=2–1 line in the spectra of (e.g.,) IRAS 20551−4250 and IRAS 22491−1808 (Figures 3r and 3t), suggesting that the fraction of spatially unresolved components is higher for the 183 GHz H$_2$O in some ULIRGs. We (1) quantitatively compare the flux increase of the H$_2$O and HNC J=2–1 emission lines from original beam to ~1kpc-beam, based on Gaussian fit in the spectra. We find that the flux increase of the H$_2$O is significantly smaller than that of HNC J=2–1 in two ULIRGs (the Superantennae and IRAS 20551−4250) (Appendix B, columns 3 and 4 of Table 11). The presence of spatially unresolved compact H$_2$O emission can explain the observed trend in these ULIRGs. However, as HNC abundance can be low in AGN-illuminated warm molecular gas at the center of a galaxy nucleus (Imanishi et al. 2020), it may be possible that the observed higher HNC J=2–1 flux increase is simply due to the suppression of HNC J=2–1 emission at the innermost region, rather than the presence of compact H$_2$O emission. To overcome this ambiguity, we combine the H$_2$O data with the HCN and HCO$^+$ J=2–1 line data as well (different synthesized beams from H$_2$O) and (2) check whether the flux increase from ~1kpc-beam to 2kpc-beam is substantially smaller for the H$_2$O emission line than that of the HCN and HCO$^+$ J=2–1 emission lines. This trend is found in three ULIRGs (IRAS 12112+0305 NE, the Superantennae, and IRAS 20551−4250) (Appendix B, columns 4 and 5 of Table 11).

We also (3) compare the measured emission size of the H$_2$O with those of other dense molecular gas tracers, by applying the CASA task “imfit” to the original beam moment 0 maps (Figure 1). These results are summarized in Table 8. Because the beam sizes are not the same between J21a and J21b data, we first compare the deconvolved intrinsic size of H$_2$O and HNC J=2–1.
Figure 7. Emission line flux ratio in ∼1kpc-beam data and 200pc-beam data for NGC 1614. (a) 183 GHz H$_2$O to HCO$^+$ J=2–1 (abscissa) vs. HCN J=2–1 to HCO$^+$ J=2–1 flux ratio (ordinate). (b) 183 GHz H$_2$O to HNC J=2–1 (abscissa) vs. HCN J=2–1 to HCN J=2–1 flux ratio (ordinate). (c) 183 GHz H$_2$O to HCO$^+$ J=2–1 (abscissa) vs. HNC J=2–1 to HCN J=2–1 flux ratio (ordinate). Our data are shown as circles. Filled circles are AGN-important ULIRGs and open circles are three starburst-dominated (U)LIRGs (NGC 1614, IRAS 12112+0305 SW, and IRAS 13509+0442). NGC 1614 has five data points (200pc-beam data at four positions and 1kpc-beam data). Data of the nearby ULIRG, Arp 220 (z = 0.018), measured with ∼13 kpc beam (Galametz et al. 2016), are displayed as filled triangles for reference. The Super antennae and IRAS 15250+3609 (two sources exhibiting distinct 183 GHz H$_2$O emission excess in certain plots) are indicated as Superantennae and IR15250, respectively. The Gaussian-fit velocity-integrated fluxes in Table 6 are used for bright emission lines with significant (>3σ) detection. For IRAS 12127−1412 and IRAS 13509+0442, although some emission signature of the 183 GHz H$_2$O line in the spectra (Figure 3) is observed, the Gaussian fit detection significance is <3σ (Table 6). We adopt peak flux values of ∼1kpc-beam moment 0 maps with 0.34 (3.2σ) and 0.26 (3.2σ) [Jy km s$^{-1}$] (Appendix C) as the 183 GHz H$_2$O emission line flux for IRAS 12127−1412 and IRAS 13509+0442, respectively. For NGC 1614 (four continuum positions) and IRAS 12112+0305 SW, we adopt 3σ upper limits in 200pc-beam and ∼1kpc-beam moment 0 maps (<0.36 and <0.76 Jy km s$^{-1}$, respectively) as the 183 GHz H$_2$O emission line flux. The HNC J=2–1 emission line of IRAS 12112+0305 SW is also <3σ detection in the Gaussian fit in the ∼1kpc-beam spectrum (Table 6), as well as in a ∼1kpc-beam moment 0 map (<0.47 Jy km s$^{-1}$). In (b) and (c), IRAS 12112+0305 SW is not plotted because both the HNC J=2–1 and 183 GHz H$_2$O emission line fluxes are upper limits. and IRAS 20551−4250 show substantially smaller size for the H$_2$O than the HNC J=2–1. For these two ULIRGs, the intrinsic size of H$_2$O is also much smaller than those of HCN and HCO$^+$ J=2–1.

We (4) create H$_2$O to HCO$^+$ J=2–1 flux ratio maps, after matching beam size, and find that four ULIRGs (IRAS 12112+0305 NE, the Superantennae, IRAS 20551−4250, and IRAS 22491−1808) show a higher ratio at the continuum peak (putative AGN position) than in spatially extended regions. These maps are shown in Figure 8. However, compared to the Superantennae, the central-concentrations of the elevated H$_2$O emission regions are weaker in the remaining three ULIRGs.

5.2.3. Dynamics

We also try to use dynamical information to constrain the presence of compact H$_2$O emission. We (5) compare the properties of the H$_2$O emission with those of the other dense molecular tracers in the moment 1 maps because spatially unresolved (<1 kpc) H$_2$O emission may be dynamically decoupled from nuclear (∼1 kpc) dense molecular gas, as observed in the Superantennae (Imanishi et al. 2021). Besides the Superantennae, in IRAS 08572+3915, IRAS 12112+0305 NE, and IRAS 22491−1808, blueshifted and redshifted motions identified in the HCN, HCO$^+$, and HNC J=2–1 lines along similar directions, are not clearly seen in the H$_2$O line (Figure 4). However, since H$_2$O emission is fainter
Table 8. Emission Size

| Object               | HCN J=2–1 mas | HCO+ J=2–1 mas | J21a continuum mas | HNC J=2–1 mas | 183 GHz H2O mas | J21b continuum mas |
|----------------------|---------------|----------------|-------------------|---------------|----------------|-------------------|
| IRAS 06035−7102      | 587±107, 540±140 | 703±72, 523±50 | 705±188, 613±236 | 352±77, 248±184 | 420±174, 194±90 | 312±75, 296±86  |
| IRAS 08572+3915      | 397±114, 213±180 | 478±106, 360±62 | 318±65, 287±124 | —             | —              | 238±86, 208±155  |
| IRAS 12112+0305 NE   | 552±57, 337±101 | 687±80, 462±135 | 283±72, 186±156 | 479±105, 428±122 | —              | 380±94, 228±90   |
| IRAS 12127−1412      | 290±88, 46±69   | 333±96, 172±53  | 151±22, 96±68   | 357±116, 185±104 | 759±349, 239±150 | 162±40, 97±92    |
| IRAS 13509+0442      | 491±130, 392±119 | 659±164, 356±104 | 481±75, 367±57  | 695±184, 376±118 | 655±276, 327±155 | 580±97, 473±82   |
| IRAS 15250+3609      | 338±114, 339±145 | 597±183, 432±341 | 445±85, 375±80  | 467±85, 234±72  | 357±85, 220±52  | 388±71, 226±30   |
| Superantennae        | 838±123, 446±65  | 1040±141, 466±61 | 348±71, 284±61  | 563±132, 483±137 | 171±61, 134±46  | 260±30, 245±30   |
| IRAS 20551−4250      | 479±59, 373±58   | 552±80, 417±95  | 367±56, 346±74  | 382±28, 264±16  | 203±45, 135±40  | 304±32, 236±20   |
| IRAS 22401−1808      | 277±36, 231±28   | 433±80, 337±64  | 217±49, 131±41  | 285±34, 223±29  | 251±78, 157±92  | 363±41, 160±37   |

Note—Col.(1): Object name. Cols.(2)–(7): Deconvolved size in milli-arcsecond (mas) in the original beam moment 0 map (Figure 1) derived from the CASA task “imfit”. Value in the major and minor axis is shown as first and second, respectively. Because it is very difficult to constrain the deconvolved intrinsic size to be considerably (a factor of >2−3) smaller than the beam size (Table 3, column 6), in the case of extremely compact emission, the derived value can still be larger than the actual value. The mark “±” is added when the size is not sufficiently constrained owing to limited S/N ratios. The position angle (PA) is not shown because its uncertainty is large, except in the case of the Superantennae whose PA is ∼150° (east of north) with <10° uncertainty for HCN, HCO+, and HNC J=2–1 (roughly aligned to the blueshifted and redshifted direction in Figure 4), and 70±80° (large uncertainty) for the 183 GHz H2O line. Col.(2): HCN J=2–1. Col.(3): HCO+ J=2–1. Col.(4): J21a continuum. Col.(5): HNC J=2–1. Col.(6): 183 GHz H2O. Col.(7): J21b continuum.

than the other dense molecular lines and outer regions are not sufficiently probed in the moment 1 maps (Figure 4), further discussion of the possible dynamical difference is difficult. In the moment 2 maps (Figure 5), dynamically distinct features of the H2O, compared to the other three dense molecular gas tracers, are not clearly observed, except the Superantennae (Imanishi et al. 2021).

5.2.4. Summary of the 183 GHz H2O Emission

In summary, based on any of the above methods (1)–(5), besides the Superantennae, it is suggested that spatially more compact H2O emission is higher than the nuclear (∼1 kpc) HCN, HCO+, and HNC J=2–1 emission, may be present in three ULIRGs (IRAS 12112+0305 NE, IRAS 20551−4250, and IRAS 22401−1808). Interestingly, despite the very high 183 GHz H2O to HCO+ J=2−1 and 183 GHz H2O to HCN J=2–1 flux ratios (Figure 7), IRAS 15250+3609 has no obvious signature of compact H2O emission in the above methods. The compact H2O emission in the three ULIRGs can be of AGN-megamaser origin and/or thermal (non-maser) emission from the H2O-abundant AGN vicinity. Even if AGN megamaser emission is present, its contribution to the observed nuclear (∼1 kpc) H2O flux is much smaller than that of the Superantennae, because of much weaker signatures of the compact H2O emission. Except the Superantennae, the bulk of the observed 183 GHz H2O luminosity comes from entire nuclear regions (∼1 kpc), most likely thermal emission or possibly ensemble of stellar maser emission (Konig et al. 2017).

Among ten observed (U)LIRGs, eight ULIRGs are diagnosed to contain luminous obscured AGNs (§2). The detection rate of very luminous AGN-origin megamaser 183 GHz H2O emission is low (1/8 = 12.5%). The detection rates of 22 GHz H2O 61,6−52,3 megamaser emission in previously conducted ex-
Figure 8. Ratio of 183 GHz H₂O to HCO⁺ J=2–1 flux measured in Jy km s⁻¹ of (a) IRAS 12112+0305 NE, (b) the Superantennae, (c) IRAS 20551−4250, and (d) IRAS 22491−1808, with matched circular beam of 0′′.91, 0′′.57, 1′′.1 and 0′′.53, respectively. Continuum peak position is shown as a cross. An appropriate cutoff (∼2σ) for HCO⁺ J=2–1 (denominator) is applied to prevent the ratio map being dominated by noise.

Extensive surveys are also low (≲10%) for active galaxies (e.g., Braatz et al. 1997; Hagiwara et al. 2002; Greenhill et al. 2003; Braatz et al. 2004; Henkel et al. 2005), but can increase (10–50%) if only highly obscured AGNs are observed (e.g., Kondratko et al. 2006; Yamauchi et al. 2017; Castangia et al. 2019; Kuo et al. 2020; Panessa et al. 2020). Observations of a larger number of nearby (U)LIRGs that are diagnosed to host luminous obscured AGNs, are needed to better constrain how the detection rates of very luminous 183 GHz H₂O megamaser emission differ from those of 22 GHz H₂O magamaser emission.

5.3. Emission Line Luminosity and Nuclear Dense Molecular Gas Mass

We use the following formulas to convert molecular emission line flux to luminosity (Solomon & Vanden Bout 2005),

\[
\left( \frac{L_{\text{line}}}{L_\odot} \right) = 1.04 \times 10^{-3} \left( \frac{\nu_{\text{rest}}}{\text{GHz}} \right) (1 + z)^{-1} \left( \frac{D_L}{\text{Mpc}} \right)^2 \left( \frac{S\Delta V}{\text{Jy km s}^{-1}} \right),
\]

and

\[
\left( \frac{L_{\text{line}}'}{\text{K km s}^{-1} \text{pc}^2} \right) = 3.25 \times 10^7 \left( \frac{\nu_{\text{rest}}}{\text{GHz}} \right)^{-2} (1 + z)^{-1} \left( \frac{D_L}{\text{Mpc}} \right)^2 \left( \frac{S\Delta V}{\text{Jy km s}^{-1}} \right),
\]

where SΔV is Gaussian-fit velocity-integrated emission line flux and D_L is luminosity distance. The derived luminosity of the HCN, HCO⁺, HNC J=2–1, and 183 GHz H₂O emission lines from the
Table 9. Nuclear Molecular Emission Line Luminosity and Derived Dense Molecular Gas Mass

| Object                  | HCN J=2–1 | HCO\(^+\) J=2–1 | HNC J=2–1 | 183 GHz H\(_2\)O | M\(_{\text{dense}-\text{HCO}^+}\) |
|-------------------------|-----------|-----------------|-----------|-----------------|-----------------|
|                         | 10\(^4\) \(L_\odot\) | \((10^7 \text{ K km s}^{-1} \text{ pc}^2)\) | 10\(^8\) \([M_\odot]\) |
| NGC 1614                | 0.58±0.03 (3.3±0.2) | 1.1±0.1 (5.8±0.2) | 0.32±0.03 (1.7±0.2) | <0.084 (<0.43) | 1–3 |
| IRAS 06035−7102         | 6.2±0.2 (35±1) | 7.8±0.3 (43±2) | 3.6±0.3 (19±2) | 1.9±0.4 (9.4±2.1) | 8–22 |
| IRAS 08572+3915         | 1.6±0.1 (9.0±0.8) | 2.0±0.2 (11±1) | 0.71±0.11 (3.7±0.6) | 0.88±0.18 (4.5±0.9) | 2–6 |
| IRAS 12112+0305 NE      | 9.5±2.0 (53±11) | 5.7±0.4 (31±2) | 7.5±0.4 (39±2) | 3.9±0.3 (20±1) | 6–16 |
| IRAS 12112+0305 SW      | 0.83±0.17 (4.7±1.0) | 1.8±0.3 (9.9±1.5) | <0.088 (<4.6) | <1.5 (<7.3) | 2–5 |
| IRAS 12127−1412         | 4.4±0.7 (24±4) | 3.8±1.1 (21±6) | 3.9±1.1 (20±6) | 2.2±0.7 (11±3) | 4–11 |
| IRAS 13509+0442         | 3.9±0.7 (22±4) | 3.8±0.8 (21±4) | 2.1±0.5 (11±3) | 1.8±0.6 (8.9±2.8) | 4–11 |
| IRAS 15250+3609         | 3.5±0.2 (20±6) | 1.6±0.2 (8.9±0.9) | 4.0±0.3 (21±2) | 3.6±0.2 (18±1) | 2–4 |
| Superantennae           | 6.3±0.5 (35±3) | 3.7±0.1 (21±2) | 2.6±0.3 (13±1) | 6.9±0.5 (35±2) | 4–11 |
| IRAS 20551−4250         | 3.0±0.1 (17±1) | 4.6±0.1 (25±1) | 1.4±0.1 (7.5±0.3) | 0.91±0.03 (4.6±0.2) | 5–13 |
| IRAS 22491−1808         | 10±1 (59±2) | 6.9±0.3 (38±2) | 6.8±0.5 (36±3) | 3.5±0.3 (18±1) | 8–19 |

Note—Col.(1): Object name. Cols.(2)–(5): Molecular emission line luminosity in units of \((10^4 \text{ L}_\odot)\), derived from \(\sim 1\text{kpc}\)-beam data. That in units of \((10^7 \text{ K km s}^{-1} \text{ pc}^2)\) is shown in parentheses. Col.(2): HCN J=2–1. Col.(3): HCO\(^+\) J=2–1. Col.(4): HNC J=2–1. Col.(5): 183 GHz H\(_2\)O. Col.(6): Dense molecular gas mass derived from the HCO\(^+\) J=2–1 luminosity, assuming that the HCO\(^+\) emission is thermalized and optically thick at J=2–1 and J=1–0, and using the conversion factor of 2–5 \((\text{M}_\odot [\text{K km s}^{-1} \text{ pc}^2]^{-1})\) from HCO\(^+\) J=1–0 luminosity to dense H\(_2\) mass (Leroy et al. 2017).

(U)LIRGs’ nuclear regions, based on the \(\sim 1\text{kpc}\)-beam flux data (Table 6), is summarized in Table 9 (columns 2–5).

Figure 9 shows the comparison of nuclear (\(\sim 1\) kpc) dense molecular line luminosity with infrared (8–1000 \(\mu\)m) luminosity from the entire (U)LIRG regions measured with IRAS’s large (>30\(^\circ\)) apertures. In Figures 9a and 9b, the infrared luminosity positively correlates with the nuclear HCN J=2–1 and HCO\(^+\) J=2–1 emission line luminosity. The previously derived relations at J=4–3 (Zhang et al. 2014; Tan et al. 2018) are overplotted for reference. These relations were derived by observing galaxies with a wide (six orders of magnitude) infrared luminosity range (Zhang et al. 2014; Tan et al. 2018) and were largely determined by nearby ULIRGs which dominate the high luminosity part. Although the HCN and HCO\(^+\) J=4–3 line data of nearby ULIRGs (Zhang et al. 2014; Tan et al. 2018) were taken with large apertures of single dish telescopes, we regard that the bulk of the observed J=4–3 luminosities come from nuclear regions, because (1) nearby ULIRGs are usually energetically dominated by compact (\(\sim 1\) kpc) nuclear regions, with small contributions from spatially extended (\(\gtrsim a\) few kpc) star-forming regions in the host galaxies (e.g., Soifer et al. 2000; Diaz-Santos et al. 2010; Imanishi et al. 2011; Pereira-Santaella et al. 2021), and (2) when ALMA high-spatial-resolution data are available, the HCN and HCO\(^+\) J=4–3 emission of nearby (U)LIRGs are confirmed to be spatially compact (Imanishi et al. 2018b). Our J=2–1 data roughly follow the updated J=4–3 relation by Tan et al. (2018). If the HCN and HCO\(^+\) are almost thermally excited at up to J=4 and optically thick, the ratio of molecular line luminosity (in units of K km s\(^{-1}\) pc\(^2\)) to infrared luminosity (in units of \(L_\odot\)) is expected to be comparable for J=4–3 and J=2–1. Our data suggest that this is the case for
Figure 9. Comparison of molecular emission line and infrared (8–1000 µm) luminosity. The abscissa is (a) HCN J=2–1, (b) HCO$^+$ J=2–1, (c) HNC J=2–1, and (d) 183 GHz H$_2$O emission line luminosity in units of (K km s$^{-1}$ pc$^2$) measured with ∼1kpc-beam ALMA data. The ordinate is infrared luminosity measured with the IRAS’s large (>30″) apertures. The solid lines in (a) and (b) are the latest best-fit lines derived for the HCN J=4–3 ($\log L_{\mathrm{IR}}^\prime = 1.00\log L_{\mathrm{HCN}(4\rightarrow3)}^\prime + 3.80$) and HCO$^+$ J=4–3 ($\log L_{\mathrm{IR}}^\prime = 1.13\log L_{\mathrm{HCO}^+(4\rightarrow3)}^\prime + 2.83$) for various types of sources with wide (six orders of magnitude) infrared luminosity range (Tan et al. 2018). The best-fit lines derived by Zhang et al. (2014) for HCN J=4–3 ($\log L_{\mathrm{IR}}^\prime = 1.00\log L_{\mathrm{HCN}(4\rightarrow3)}^\prime + 3.67$) and HCO$^+$ J=4–3 ($\log L_{\mathrm{IR}}^\prime = 1.10\log L_{\mathrm{HCO}^+(4\rightarrow3)}^\prime + 2.48$) are also shown as dotted lines in (a) and (b) for reference. For IRAS 12112+0305 in (c) and (d), molecular line luminosity detected at the primary NE nucleus is adopted, excluding the upper limit at the fainter SW nucleus.

We derive nuclear dense molecular gas mass from HCO$^+$ J=2–1 luminosity, because (1) the slope of infrared and HCO$^+$ J=2–1 luminosity relation is the closest to unity among the four lines (Figure 9), and (2) HCO$^+$ can be a less biased dense molecular gas mass tracer than HCN and HNC, particularly in the vicinity of a luminous AGN (Imanishi et al. 2020). Table 9 (column 6) summarizes the derived dense molecular gas mass in the observed (U)LIRGs’ nuclei, where we adopt the conversion factor
of 2–5 (M⊙ [K km s$^{-1}$ pc$^{2}$]$^{-1}$) from optically thick HCO$^+$ J=1–0 line luminosity to dense H$_2$ mass (Leroy et al. 2017), and the above validated assumption that HCO$^+$ emission is thermalized and optically thick at J=2–1 and J=1–0. All the (U)LIRGs are estimated to contain nuclear ($\sim$1 kpc) dense molecular gas with mass of M$_{dense} \gtrsim$ a few × 10$^8$M$_\odot$.

We can estimate a lower limit of the depletion time ($t_{dep}$) of the nuclear dense molecular gas by star-formation, by assuming (1) lower side of the derived mass in Table 9 (column 6) and (2) the nuclear star formation rate (SFR) of SFR (M$_\odot$ yr$^{-1}$) = 4.5 × 10^{-4} L$_{IR}$ (ergs s$^{-1}$) (Kennicutt 1998), where infrared (8–1000 µm) and far-infrared (40–500 µm) luminosities are considered comparable for (U)LIRGs. This is a stringent lower limit because AGN activity can contribute significantly to the observed infrared luminosity with IRAS. The estimated lower limit of the depletion time ($t_{dep} \equiv M_{dense}/SFR$) is $\sim$1–3 × 10$^6$ yr, which is shorter than that derived in dense molecular clouds in our Galaxy and nearby star-forming galaxies, $\sim$10$^7$–8 yr (e.g., Lada et al. 2010; Zhang et al. 2014; Liu et al. 2016; Tan et al. 2018; Jiang et al. 2020), but it is longer than the free-fall time of dense (>10$^4$ cm$^{-3}$) molecular gas, $t_{ff} \equiv \sqrt{\frac{3\pi}{32G\rho}} \lesssim 5 \times 10^5$ yr (G is the gravitational constant and $\rho$ is the mass volume density). Thus, even considering only for (U)LIRGs’ nuclei where dense molecular gas highly concentrates through galaxy mergers, it is suggested that the bulk (≥50%) of dense molecular gas is not forming stars with a free-fall time scale (Krumholz & Tan 2007), possibly because of various feedback processes from AGN and starburst activities (e.g., Hopkins et al. 2011, 2013; Chevance et al. 2020).

5.4. Vibrationally Excited Emission Lines

The rotational J=3–2 and J=4–3 emission lines at the vibrationally excited v$_2$=1f levels of HCN and HNC (HCN-VIB and HNC-VIB, respectively) were detected in active galaxies, mostly those diagnosed as containing luminous obscured AGNs (e.g., Sakamoto et al. 2010; Imanishi & Nakanishi 2013b; Aalto et al. 2015a,b; Costagliola et al. 2015; Martin et al. 2016; Imanishi et al. 2016b,c, 2018b; Falstad et al. 2019, 2021; Sakamoto et al. 2021). It is widely believed that infrared radiative pumping is responsible for vibrationally exciting HCN and HNC, by absorbing mid-infrared $\sim$14 µm and $\sim$21.5 µm photons, respectively, because the excitation energy level (>650 K) is too high to collisionally excite (e.g., Aalto et al. 1995, 2007b; Sakamoto et al. 2010). Because a luminous AGN usually emits a strong 3–15 µm continuum originating from hot (>100 K) dust in the AGN vicinity, the HCN-VIB line can be emitted efficiently and its luminosity, relative to vibrational ground emission line and/or total infrared (8–1000 µm) luminosity, can be higher in AGNs than in starbursts. Because HNC can be vibrationally excited by longer wavelength infrared photons ($\sim$21.5 µm), the HNC-VIB emission lines can be moderately strong in starbursts as well, where the dust temperature is usually lower than in the AGN’s vicinity (e.g., Ando et al. 2017; Martin et al. 2021). HCN-VIB emission lines with intrinsically low absolute luminosity can also be detected in very nearby starbursts if sensitivity is sufficient (Krieger et al. 2020; Martin et al. 2021).

As explained in §4 and summarized in Table 7, the HCN-VIB J=2–1 emission line is significantly detected ($>3\sigma$) as an isolated peak in IRAS 15250+3609 and IRAS 20551–4250. In addition to these two ULIRGs, both IRAS 12112+0305 NE and IRAS 22491–1808 display excess emission at the lower frequency side of the HCO$^+$ J=2–1 line, close to the expected frequency of the HCN-VIB J=2–1 line (Figures 3e and 3s). For both IRAS 12112+0305 NE and IRAS 22491–1808, a similar excess was found at the lower frequency part of the HCO$^+$ J=3–2 and J=4–3 lines, which was interpreted as
HCN-VIB J=3–2 and J=4–3 emission line contributions, respectively (Imanishi et al. 2016c, 2018b). Thus, the excess components of IRAS 12112+0305 NE and IRAS 22491–1808 in Figure 3e and 3s, respectively, may originate from the HCN-VIB J=2–1 emission line. We create moment 0 maps of the excess components (with original beam) and confirm detection with >3.5σ (Table 7). The HNC-VIB J=2–1 emission line is also significantly detected (>3σ) in an original beam moment 0 map for NGC 1614 S, IRAS 15250+3609, and IRAS 22491–1808 (Table 7).

As the number of ∼21.5 μm photons is typically much larger than that of ∼14 μm (rest-frame) in (U)LIRGs (e.g., Armus et al. 2007; Imanishi et al. 2007a; Veilleux et al. 2009; Imanishi 2009; Imanishi et al. 2010a; Hernan-Caballero & Hatziminaoglou 2011), HNC can be vibrationally excited with a higher infrared radiative pumping rate than HCN. The emission line luminosity of HNC-VIB is expected to be nearly an order of magnitude higher than that of HCN-VIB, if the number of molecules illuminated by the mid-infrared radiation in the close proximity to energy sources (AGN and/or young stars) is comparable (Imanishi et al. 2016b). However, the HNC-VIB emission lines are not as bright as expected even in the case of detection in Figure 3 for J=2–1, as well as for J=3–2 and J=4–3 (Imanishi et al. 2018b). A plausible scenario is that HNC abundance is low at the innermost (<1 kpc) obscuring material exposed to strong mid-infrared radiation, even if the emission line luminosity from, and abundance in, the entire nuclear region (∼1 kpc) is roughly comparable between HCN and HNC. In fact, it is well known from observations of Galactic sources that HNC abundance is very low in high radiation density environments around luminous energy sources (e.g., Schilke et al. 1992; Hirota et al. 1998; Graninger et al. 2014; Bublitz et al. 2019). In the recent ALMA observations of the very nearby (∼14 Mpc) galaxy NGC 1068, it has been clearly demonstrated that HNC abundance is much lower than HCN in the vicinity of a luminous AGN (Imanishi et al. 2020). A plausible explanation for the observed weaker-than-expected HNC-VIB emission is that an HNC abundance is depressed substantially in the mid-infrared-radiation-illuminated, innermost high-temperature molecular gas around the luminous energy sources in (U)LIRGs.

HCO⁺ can also be vibrationally excited by absorbing mid-infrared ∼12 μm photons, and the vibrational excitation rate was estimated to be roughly comparable to HCN in typical infrared spectra of (U)LIRGs (Imanishi et al. 2016b). However, the HCO⁺-VIB line detection was never reported in emission in any (U)LIRGs, and only very recently, Kameno et al. (2020) have reported the first detection of the HCO⁺-VIB J=4–3 line in absorption against strong background continuum emission in the very nearby (∼17 Mpc) radio-loud AGN NGC 1052, with its absorption peak and equivalent width ∼2.5 times smaller than those of the HCN-VIB J=4–3 line. Considering that the HCO⁺ J=2–1 flux at the vibrational ground level (v=0) is comparable within a factor of ∼2 to, or sometimes higher than, the HCN J=2–1 flux in nearby (U)LIRGs’ nuclei (Figure 7a,b), if the same fraction of HCO⁺ and HCN are exposed to mid-infrared radiation, the HCO⁺-VIB J=2–1 emission line should have been detected at least in certain (U)LIRGs with clearly detected HCN-VIB emission. The considerably weaker HCO⁺-VIB emission than HCN-VIB in (U)LIRGs is also very difficult to explain unless the HCO⁺ abundance is substantially lower than HCN at the innermost mid-infrared-radiation-illuminated region around the luminous AGNs at the very center of galaxy nuclei (e.g., Maloney et al. 1996; Papadopoulos 2007; Harada et al. 2010).

5.5. Other Fainter Dense Molecular Gas Tracers

5.5.1. HC₃N
Figure 10. (a): Flux ratio of HC$_3$N, relative to HCN J=2–1 (blue open circle), HCO$^+$ J=2–1 (green open star) and HNC J=2–1 (red filled square) in the ordinate. ID=1–5 (the left side of the vertical dashed line) are meant for the HC$_3$N J=20–19 line, and ID=6–7 (the right side) are meant for the HC$_3$N J=21–20 line. 1: IRAS 12112+0305 NE, 2: IRAS 15250+3609, 3: IRAS 20551–4250, 4: IRAS 22491–1808, 5: Arp 220 (Galametz et al. 2016), 6: IRAS 12112+0305 NE, and 7: IRAS 22491–1808. Each flux is measured in [Jy km s$^{-1}$] with $\sim$1 kpc beam for all ULIRGs, except Arp 220 (ID=5) whose flux measurement was made with $\sim$13 kpc beam (Galametz et al. 2016). (b): Comparison of HNC J=2–1 to HCN J=2–1 flux ratio (abscissa) and HC$_3$N J=20–19 to HCN J=2–1 flux ratio (ordinate), measured with $\sim$1 kpc beam, for four ULIRGs with significant detection of the faint HC$_3$N J=20–19 emission line in Table 10 (open circle). We also plot Arp 220 whose flux measurement was made with $\sim$13 kpc beam (Galametz et al. 2016), for reference (open triangle). The horizontal dashed line indicates the flux ratio of 0.15 in the ordinate (see §5.5.1). (c): Flux ratio of CS J=4–3, relative to HCN J=2–1 (blue open circle), HCO$^+$ J=2–1 (green open star) and HNC J=2–1 (red filled square) in the ordinate. Each flux is measured in [Jy km s$^{-1}$] with $\sim$1 kpc beam. In the abscissa, “N1614”, “IR06035”, and “IR20551” means NGC 1614, IRAS 06035–7102, and IRAS 20551–4250, respectively. In the abscissa of (a) and (c), the horizontal positions of HCN, HCO$^+$, and HNC data for each object are slightly displaced for presentation.

The HC$_3$N J=20–19 line was covered in the spectra of all the ten observed (U)LIRGs, and was clearly detected in four ULIRGs (IRAS 12112+0305 NE, IRAS 15250+3609, IRAS 20551–4250, and IRAS 22491–1808), as explained in §4 and summarized in Table 7. HC$_3$N J=21–20 data were also obtained in some sources and were detected in two ULIRGs (IRAS 12112+0305 NE and IRAS 22491–1808) in Figure 6 and Table 7.

Various rotational J-transition emission lines of HC$_3$N were detected in active galaxies (e.g., Aalto et al. 2002; Wang et al. 2004; Aalto et al. 2007a; Aladro et al. 2011; Lindberg et al. 2011; Meier et al. 2011; Aladro et al. 2015; Costagliola et al. 2015; Jiang et al. 2017; Rico-Villas et al. 2021). HC$_3$N lines are considered dense ($>10^4$ cm$^{-3}$) molecular gas tracers with fainter flux than HCN, HCO$^+$, and HNC (e.g., Wang et al. 2004; Aladro et al. 2011; Meier et al. 2011). Figure 10a plots HC$_3$N J=20–19 and J=21–20 to HCN, HCO$^+$, and HNC J=2–1 flux ratios, which are $\lesssim$0.6 (i.e., HC$_3$N lines are fainter) for all the HC$_3$N-detected sources.

HC$_3$N can be easily destroyed by UV radiation, and thus can be emitted strongly in UV-shielded regions at certain distance from the central energy sources (Lindberg et al. 2011; Meier et al. 2011). Luminous HC$_3$N emission lines, relative to other dense molecular tracers, were detected in galaxies with high column density of obscuring material around energy sources (Aalto et al. 2007a; Lindberg et al. 2011). Lindberg et al. (2011) defined HC$_3$N-luminous galaxies as those with HC$_3$N J=10–9 to HCN J=1–0 flux ratio of >0.15, which constitutes less than one-third of the observed galaxies. We compare the HC$_3$N J=20–19 and HCN J=2–1 fluxes (Tables 6 and 7), and find that IRAS 15250+3609
Table 10. Flux Ratio of HC₃N to HCN, HCO⁺, and HNC Lines

| Object          | HC₃N J=20–19 | HCN J=2–1 | HCO⁺ J=20–19 | HNC J=2–1 | HCN J=21–20 | HCO⁺ J=21–20 | HNC J=21–20 |
|-----------------|---------------|-----------|--------------|-----------|-------------|--------------|-------------|
| IRAS 12112+0305 NE | 0.085±0.033  | 0.14±0.05 | 0.11±0.04  | 0.095±0.036 | 0.16±0.05  | 0.12±0.04  |
| IRAS 15250+3609  | 0.26±0.03    | 0.57±0.09 | 0.24±0.03  | —         | —           | —            | —           |
| IRAS 20551−4250  | 0.052±0.009  | 0.034±0.006 | 0.11±0.02 | —         | —           | —            | —           |
| IRAS 22491−1808  | 0.21±0.02    | 0.32±0.04 | 0.33±0.04  | 0.12±0.04  | 0.19±0.06  | 0.20±0.06  |

Arp 220 (~13 kpc) | 0.11±0.03    | 0.23±0.05 | 0.16±0.04  | —         | —           | —            | —           |

Note— Col.(1): Object name. Cols.(2)–(7): Ratio of Gaussian-fit velocity-integrated emission line flux in (Jy km s⁻¹) derived from ~1kpc-beam spectra. Arp 220 data measured with ~13 kpc beam (Galametz et al. 2016) are also added. Col.(2): HC₃N J=20–19 to HCN J=2–1 flux ratio. Col.(3): HC₃N J=20–19 to HCO⁺ J=2–1 flux ratio. Col.(4): HC₃N J=20–19 to HNC J=2–1 flux ratio. Col.(5): HC₃N J=21–20 to HCN J=2–1 flux ratio. Col.(6): HC₃N J=21–20 to HCO⁺ J=2–1 flux ratio. Col.(7): HC₃N J=21–20 to HNC J=2–1 flux ratio.

Table 10. Flux Ratio of HC₃N to HCN, HCO⁺, and HNC Lines

and IRAS 22491−1808 show HC₃N J=20–19 to HCN J=2–1 flux ratios of >0.15, whereas IRAS 12112+0305 NE and IRAS 20551−4250 do not (Table 10, column 2). The upper excitation energy level is $E_u \sim 92$ K for HC₃N J=20–19 and $E_u \sim 13$ K for HCN J=2–1. If both lines are thermalized and optically thick, the HC₃N J=20–19 to HCN J=2–1 flux ratios are expected to be comparable to the HC₃N J=10–9 to HCN J=1–0 flux ratios, because the rest frequency ($\nu_{rest}$) of HC₃N J=20–19 and HCN J=2–1 is approximately twice that of HC₃N J=10–9 and HCN J=1–0, respectively, and the emission flux (in Jy km s⁻¹) increases with $\nu_{rest}^2$. However, given the much higher excitation energy of HC₃N J=20–19 ($E_u \sim 92$ K) than HC₃N J=10–9 ($E_u \sim 24$ K), HCN J=2–1 ($E_u \sim 13$ K), and HCN J=1–0 ($E_u \sim 4$ K), if HC₃N is only sub-thermally excited at J=20, HC₃N J=20–19 to HCN J=2–1 flux ratio can be smaller than that of HC₃N J=10–9 to HCN J=1–0 flux ratio. Thus, IRAS 15250+3609 and IRAS 22491−1808 are safely classified as HC₃N-luminous galaxies (Lindberg et al. 2011), and even IRAS 12112+0305 NE and IRAS 20551−4250 could be in this classification. Because ULIRGs’ nuclear energy sources are usually highly obscured and UV-shielded regions are expected to develop, the HC₃N emission can be bright in ULIRGs.

Not only HC₃N, but also HNC emission can be strong in UV-shielded regions (§5.4). In regions which are UV shielded, but are strongly exposed to infrared 20–45 μm radiation, HC₃N can be vibrationally excited by infrared radiative pumping, and thus rotational J-level excitation at vibrational ground level (v=0) can be largely affected through back decay (Costagliola & Aalto 2010; Rico-Villas et al. 2021). Because this is also the case for HNC (§5.4), certain flux correlation between HC₃N and HNC may be expected. In Figure 10a and Table 10, while the HC₃N J=20–19 to HNC J=2–1 flux ratio is 0.11–0.33 (a factor of ~3), the distribution of the HC₃N J=20–19 to HCN J=2–1 and HC₃N J=20–19 to HCO⁺ J=2–1 flux ratio is much wider (a factor of >5 and >15, respectively.) Lindberg et al. (2011) argued that HNC to HCN flux ratio and HC₃N to HCN flux ratio are correlated. Figure 10b compares the flux ratios for four ULIRGs with significant HC₃N J=20–19 line detection and Arp 220 (Table 10). For this limited ULIRG sample, HC₃N-luminous galaxies tend to be HNC-luminous, when normalized by HCN. Both Figures 10a and 10b support the above expected flux correlation between HC₃N and HNC emission.

5.5.2. CS
The CS J=4–3 line was covered in certain sources, and it was clearly detected in NGC 1614, IRAS 06035–7102, and IRAS 20551–4250 (Figure 6). The derived fluxes based on the Gaussian fits of ∼1kpc-beam spectra are shown in Table 7. CS lines are considered as moderately bright, dense (>10^4 cm^{-3}) molecular gas tracers (Shirley 2015), but usually fainter than HCN, HCO^+, and HNC (e.g., Helfer & Blitz 1993; Paglione et al. 1995; Wang et al. 2004; Aladro et al. 2015; Meier et al. 2015; Krieger et al. 2020; Martin et al. 2021; Sakamoto et al. 2021). The CS J=4–3 to HCN, HCO^+, and HNC J=2–1 flux ratios are plotted in Figure 10c. The ratios are 0.1–1 (i.e., CS lines are fainter), and slightly higher in two AGN-hosting ULIRGs (IRAS 06035–7102 and IRAS 20551–4250) than in the starburst-classified LIRG NGC 1614. In the literature, Izumi et al. (2016) argued that AGNs tend to show lower CS J=7–6 to HCN J=4–3 flux ratios than starbursts, while no systematic difference of the CS to HCN, HCO^+, and HNC flux ratios was reported between AGNs and starbursts (Aladro et al. 2015). Possible AGN effects to CS emission are not clear with currently available data.

6. SUMMARY

We conducted ALMA band 4–5 (∼2 mm) observations of nine ultraluminous infrared galaxies (ULIRGs; L_{IR} > 10^{12}L_⊙) at z = 0.04–0.14, and one starburst-dominated luminous infrared galaxy, NGC 1614 (LIRG; L_{IR} = 10^{11.7}L_⊙) at z = 0.016, with the aim of investigating the properties of dense molecular gas tracers (HCN, HCO^+, and HNC J=2–1) and 183 GHz H_2O 3_1,3–2_2,0 lines. The following main results were obtained.

1. Continuum at ∼2 mm, HCN J=2–1, HCO^+ J=2–1, and HNC J=2–1 emission lines were clearly detected in all sources in our sub-arcsec-resolution (<1") data. The 183 GHz H_2O emission lines were also clearly detected in almost all ULIRGs that were classified as AGN important, but not in the three starburst-classified (U)LIRGs’ nuclei (NGC 1614, IRAS 12112+0305 SW, and IRAS 13509+0442).

2. We found significantly higher HCN to HCO^+ J=2–1 flux ratios in a high fraction of, but not all, AGN-important ULIRGs than in starburst-classified sources.

3. We compared the molecular emission line flux ratios and found that two ULIRGs with elevated 183 GHz H_2O emission, relative to HCO^+ J=2–1, tend to show elevated HCN J=2–1 emission. However, for the remaining (U)LIRGs, the observed 183 GHz H_2O to HCO^+ J=2–1 flux ratios are not strongly correlated with the observed HCN J=2–1 to HCO^+ J=2–1 flux ratios.

4. Besides the Superantennae that was reported to display strong signatures of compact, extremely luminous 183 GHz H_2O megamaser emission in AGN-illuminated molecular gas at the very center (<1 kpc) of the galaxy nucleus (Imanishi et al. 2021), data of four other ULIRGs (IRAS 12112+0305 NE, IRAS 15250+3609, IRAS 20551–4250, and IRAS 22491–1808) suggested an elevated flux or the presence of a spatially unresolved compact component of the 183 GHz H_2O emission. However, the bulk of the observed H_2O emission in the four ULIRGs originates from the entire nuclear regions (∼1 kpc), with limited contributions from possible AGN-origin megamaser phenomena.

5. The infrared (8–1000 μm) luminosity positively correlates with nuclear (∼1 kpc) HCN J=2–1 and HCO^+ J=2–1 luminosity. The correlation roughly follows the previously established luminosity ratios between infrared and J=4–3 lines of HCN and HCO^+. Using HCO^+ J=2–1
luminosity as the least biased tracer of dense molecular gas mass ($M_{\text{dense}}$) at nuclear ($\sim 1$ kpc) regions, we derived the mass to be $M_{\text{dense}} \gtrsim a \times 10^8 M_\odot$ for all (U)LIRGs. In addition, we estimated that the depletion time of the nuclear dense molecular gas by star-formation is $\gtrsim 1 \times 10^6$ yr, significantly longer than the free-fall time of dense molecular gas even considering the (U)LIRGs' nuclear regions only.

6. Signatures of vibrationally excited $v_2=1f$ HCN and HNC emission lines (HCN-VIB and HNC-VIB) were detected in four and three (U)LIRGs, respectively. However, those of HCO$^+$-VIB were not found in any (U)LIRGs. The detection rate and estimated flux of HCO$^+$-VIB and HNC-VIB were much smaller than those expected from (1) the comparable observed fluxes of HCN, HCO$^+$, and HNC at the vibrational ground level ($v=0$), and (2) calculated rate of vibrational excitation by infrared radiative pumping, if the same proportion of these molecules are exposed to mid-infrared photons. We suggested that at the innermost strongly-mid-infrared-exposed obscuring material around the luminous AGNs, the abundance of HCO$^+$ and HNC is considerably smaller than that of HCN.

7. Another fainter dense molecular gas tracer, HC$_3$N J=20–19 line, was detected in four ULIRGs with bright HCN, HCO$^+$, and HNC J=2–1 emission lines. CS J=4–3 and HC$_3$N J=21–20 lines were included in the spectra of certain fraction of (U)LIRGs and their emission signatures were identified in three and two (U)LIRGs, respectively. We found that HC$_3$N J=20–19 luminous sources tend to be HNC J=2–1 luminous, when normalized by HCN J=2–1 emission. This conforms to our expectations because both HC$_3$N and HNC emission lines are thought to largely originate from UV-shielded regions at certain distance from central energy sources.

8. Two continuum emission sources were serendipitously detected from our ALMA band 4–5 ($\sim 2$ mm) observations of ten (U)LIRGs. One is at $\sim 8''$ north of IRAS 13509+0442 and after combining with previously obtained ALMA data at 0.9–1.3 mm, we interpreted it as an infrared luminous dusty galaxy at $z > 1$, based on the increasing flux with decreasing wavelength from 2 mm to 0.9 mm and detection of one emission line signature. The other is at $\sim 8''$ south of the Superantennae and regarded as a blazar, based on a flat continuum spectrum at 0.8–2 mm and no emission line signatures. Detecting two serendipitous 1–2 mm continuum sources with flux of $\gtrsim 0.8$ mJy in two out of ten observed (U)LIRG fields appears to be many, compared to the surface density of such sources ($\lesssim 0.03$ expected for each ALMA field at 1–2 mm within $\sim 10''$ from the center).

We have now J=4–3, 3–2, and 2–1 data of HCN, HCO$^+$, and HNC for the observed ten (U)LIRGs. The combination of these line data and non-LTE modeling will better constrain the properties of dense molecular gas and further elucidate the nature of these (U)LIRGs’ nuclei (M. Imanishi 2021; in preparation).

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H$_2$O and dense molecular line emission in ULIRGs

Figure 11. Continuum image of serendipitously detected object at $\sim$8$''$ north of IRAS 13509+0442 (Left) and at $\sim$8$''$ south of the Superantennae (Right). In the former and latter images, continuum J21a and J21b data with original beam are displayed, respectively, because the detection significance is higher than the other continuum data. Contours are 3$\sigma$, 6$\sigma$, and 9$\sigma$ for continuum emission in both the images. The continuum image of the left panel was created after excluding a possible emission line detected in this object in Figure 12.

APPENDIX

A. SERENDIPITOUSLY DETECTED CONTINUUM SOURCES

A serendipitously detected continuum emitting source was identified in the fields of view of IRAS 13509+0442 and the Superantennae data. Figure 11 displays the continuum image of the source at $\sim$8$''$ north of IRAS 13509+0442 ($\sim$20 kpc at the distance of this ULIRG) (Left) and at $\sim$8$''$ south of the Superantennae ($\sim$10 kpc at the distance of this ULIRG) (Right), whose peak ICRS coordinate is (13$^h$53$^m$31.7$^s$, +04$^\circ$28$'$13$''$) and (19$^h$31$^m$21.1$^s$, −72$^\circ$39$'$29$''$), respectively.

For the northern source of IRAS 13509+0442, continuum detection ($>$25$\sigma$) was reported in ALMA band 6 (211–275 GHz) and 7 (275–373 GHz) data (Imanishi et al. 2016c, 2018b), but no emission line signature was found in the obtained spectra. We extracted the spectra at the continuum peak position in our newly obtained band 4 data. An emission line signature with a peak flux of $>$1 mJy was detected at $\nu_{\text{obs}} \sim$ 156.34 GHz in the 154.7–158.2 GHz original beam spectrum in J21a data (Figure 12a). This emission line is located close to the edge of the two overlapped spectral windows and was detected similarly in the spectra of both spectral windows (Figure 12b), suggesting that...
Figure 12. (a): Original beam (0′′.27 × 0′′.19) spectrum at 154.7–158.2 GHz of the northern continuum source detected within IRAS 13509+0442 field of view. An emission line signature is detected at the observed frequency $\nu_{\text{obs}} \sim 156.34$ GHz, indicated by a downward arrow with the note of “Emission line (?).” (b): Magnified view of the possible emission line features. Spectrum in one spectral window is shown as a black solid line and that in another spectral window is shown as a red dotted line. In (a) and (b), the abscissa is the observed frequency in GHz, and the ordinate is flux density in mJy. The horizontal black thin dotted line indicates the zero-flux level.

this emission line is real. If we assume that this emission line signature originates from a bright CO J=2–1 ($\nu_{\text{rest}} = 230.538$ GHz) line, then the redshift of this source becomes $z \sim 0.47$. In this case, CO J=3–2 ($\nu_{\text{rest}} = 345.796$ GHz) and CO J=4–3 ($\nu_{\text{rest}} = 461.041$ GHz) lines are redshifted to the observed frequency of $\nu_{\text{obs}} \sim 235.2$ and 313.6 GHz, respectively, both of which were covered in the previously taken ALMA band 6 and 7 spectra (Imanishi et al. 2016c, 2018b). However, no clear emission lines were observed at these frequencies. Previous observations have shown that the majority of 1–2 mm continuum sources with flux of a few mJy are at $z > 0.5$ (Brisbin et al. 2017). The non-detection of optical and near-infrared counterparts at the position of this northern continuum source (Kim et al. 2002; Imanishi et al. 2018b) also makes it unlikely that this source is only at $z \sim 0.47$.

We thus consider other possibilities in which the emission line signature at $\nu_{\text{obs}} \sim 156.34$ GHz originates from CO J=3–2 ($\nu_{\text{rest}} = 345.796$ GHz) at $z \sim 1.21$, or CO J=4–3 ($\nu_{\text{rest}} = 461.041$ GHz) at $z \sim 1.94$, or CO J=5–4 ($\nu_{\text{rest}} = 576.268$ GHz) at $z \sim 2.69$, or CO J=6–5 ($\nu_{\text{rest}} = 691.473$ GHz) at $z \sim 3.42$. In either case, one or two higher-J CO lines fall into the spectral coverages of the previously obtained ALMA band 6 and 7 data (Imanishi et al. 2016c, 2018b), but no clear emission line signatures were observed at the expected frequencies. This is not surprising if higher-J CO emission lines are faint due to sub-thermal excitation (Carilli & Walter 2013). We consider that identification of the emission line signature as an even higher-J CO line from a source at higher redshift is less likely because the bulk of 1–2 mm continuum sources with flux of a few mJy are at $z < 4$ (e.g., Brisbin et al. 2017).

This source appears spatially extended (Figure 11). In fact, the continuum flux increases by a factor of $\sim 2.5$ from the original beam ($\sim 0′′.3 \times \sim 0′′.2$) to $\sim 0′′.9$ beam in both J21a and J21b data, suggesting that the continuum emission is spatially extended with $\gtrsim 0′′.3$ or $\gtrsim \text{a few kpc}$ at $z = 1–4$. The CASA task “imfit” also confirms a factor of $\gtrsim 1.5$ larger deconvolved image size in both major and minor axis than the beam size. We measure the total continuum flux using the CASA
task “imfit” and display the flux at 0.9–2 mm (150–330 GHz) in Figure 13a. The continuum flux increases with decreasing wavelength, which is expected for the Rayleigh–Jeans part of dust thermal radiation. An infrared luminous dusty galaxy at $z = 1–4$ can satisfy this. Detection of other emission lines, particularly lower-J CO lines which are less affected by sub-thermal excitation (Carilli & Walter 2013), is necessary to securely identify the redshift.

For the southern source of the Superantennae, continuum emission was detected with 4–8σ in our previously obtained ALMA band 6 data at $\nu_{\text{obs}} \sim 250$ GHz ($\sim 1.2$ mm), but was not discussed (Imanishi et al. 2016c, 2018b), because band 7 continuum detection at $\nu_{\text{obs}} \sim 330$ GHz ($\sim 0.9$ mm) was only marginal ($\sim 3.5\sigma$ in $\sim$0′′7 $\times$ $\sim$0′′5 beam data). Now that band 5 continuum emission at $\nu_{\text{obs}} \sim 170$ GHz is detected ($\sim 9\sigma$; Figure 11), we can investigate the nature of this source in more detail. No emission line signature was observed in any of the ALMA band 5, 6, and 7 spectra. No spatial extension was detected using the CASA task “imfit”. The 0.8–2 mm continuum flux of this source is shown in Figure 13b. It is relatively flat or slightly decreasing with decreasing wavelength. This can be produced by an AGN core, whose emission is beamed toward our line of sight (i.e, blazar). X-ray detection as a hard source by Chandra observations (Wang et al. 2016) and the non-detection of any emission line in ALMA spectra can naturally be explained by this blazar scenario.

In summary, we serendipitously detected two continuum sources with flux of $\gtrsim 0.8$ mJy at 1–2 mm from our ALMA band 4, 5, and 6 observations of ten (U)LIRGs. The surface density of such continuum sources is $\sim 10^3$ deg$^{-2}$ (e.g., Hatsukade et al. 2018; Gonzalez-Lopez et al. 2020) or $\lesssim 0.03$ per each ALMA observing field at 1–2 mm within $\sim 10''$ radius from the center. Our detection rate of two such sources in ten ALMA observing fields is very high.
B. GAUSSIAN FITS OF EMISSION LINES

Figures 14 and 15 show Gaussian fits of individual emission lines listed in Table 6 and serendipitously detected faint emission lines in Table 7 (column 4–7), respectively. Table 11 tabulates Gaussian-fit velocity-integrated fluxes of dense molecular (HCN, HCO$^+$, and HNC J=2–1) and 183 GHz H$_2$O emission lines, measured with original, ~1 kpc, and 2 kpc beam, for the nine observed ULIRGs.

C. MOMENT 0 MAPS OF THE 183 GHZ H$_2$O EMISSION LINE FOR IRAS 12127--1412 AND IRAS 13509+0442.

Figure 16 displays moment 0 maps of the 183 GHz H$_2$O emission line, with 1kpc circular beam, for IRAS 12127--1412 and IRAS 13509+0442. Detection significance of this H$_2$O line in these two sources is $<3\sigma$ in the Gaussian fit in the 1kpc-beam spectra (Table 6), but $>3\sigma$ in the moment 0 maps. The peak values in the moment 0 maps are used in Figure 7.
Figure 14. Adopted Gaussian fits (solid curved lines) of the emission lines in the ∼1kpc-beam spectra (and 200pc-beam spectra for NGC 1614), tabulated in Table 6. The abscissa is optical LSR velocity in km s$^{-1}$ and the ordinate is flux density in mJy. The horizontal black thin dotted line indicates the zero flux level.
Figure 15. Adopted Gaussian fits (solid curved lines) of the serendipitously detected faint emission lines in the $\sim 1$ kpc-beam spectra (and 200 pc-beam spectrum for NGC 1614), tabulated in Table 7 (columns 4–7). The abscissa is optical LSR velocity in km s$^{-1}$ and the ordinate is flux density in mJy. The horizontal black thin dotted line indicates the zero flux level.
Table 11. Gaussian Fit Flux of Molecular Emission Lines with Various Beam Sizes for ULIRGs

| Object          | Line      | Integrated Flux [Jy km s\(^{-1}\)] | Original Beam | ~1 kpc | 2 kpc |
|-----------------|-----------|-----------------------------------|---------------|--------|-------|
|                 |           |                                   | (3)           | (4)    | (5)   |
| IRAS 06035−7102 | HCN J=2−1 | 2.7±0.1 (−5%)                     | 2.9±0.1 (1.6 kpc) | 3.0±0.1 (+5.4%) |
|                 | HCO\(^+\) J=2−1 | 3.4±0.1 (−4%)                   | 3.6±0.1 (1.6 kpc) | 3.8±0.2 (+6.3%) |
|                 | HNC J=2−1  | 1.1±0.1 (−32%)                    | 1.6±0.1 (1.6 kpc) | 1.7±0.2 (+4%)   |
|                 | 183 GHz H\(_2\)O | 0.54±0.09 (−35%)              | 0.83±0.18 (1.6 kpc) | 0.92±0.24 (+10%) |
| IRAS 08572+3915 | HCN J=2−1 | 1.2±0.1 (−18%)                    | 1.4±0.1         | 1.7±0.2 (+23%)  |
|                 | HCO\(^+\) J=2−1 | 1.4±0.1 (−15%)                   | 1.7±0.2         | 1.9±0.3 (+12%)  |
|                 | HNC J=2−1  | 0.41±0.07 (−33%)                   | 0.61±0.09       | 0.75±0.13 (+24%) |
|                 | 183 GHz H\(_2\)O | 0.62±0.08 (−17%)              | 0.75±0.15       | 0.82±0.30 (+10%) |
| IRAS 12112+0305 NE | HCN J=2−1 | 5.2±0.2 (−0%)                      | 5.1±0.5 (1.2 kpc) | 6.1±0.3 (+19%)  |
|                 | HCO\(^+\) J=2−1 | 2.8±0.2 (−9%)                       | 3.1±0.2 (1.2 kpc) | 3.7±0.3 (+20%)  |
|                 | HNC J=2−1  | 3.7±0.2 (−8%)                      | 4.0±0.2 (1.2 kpc) | 4.8±0.3 (+19%)  |
|                 | 183 GHz H\(_2\)O | 2.0±0.1 (−4%)                     | 2.1±0.1 (1.2 kpc) | 2.1±0.2 (+4%)   |
| IRAS 12112+0305 SW | HCN J=2−1 | 0.41±0.10 (−10%)                   | 0.45±0.10 (1.2 kpc) | 0.50±0.13 (+9%)  |
|                 | HCO\(^+\) J=2−1 | 0.81±0.11 (−16%)                  | 0.97±0.15 (1.2 kpc) | 0.97±0.17 (+6%)  |
|                 | HNC J=2−1  | 0.28±0.12 (−14%)                    | 0.32±0.13 (1.2 kpc) | — ^A |
| IRAS 12127−1412 | HCN J=2−1 | 0.48±0.09 (−31%)                   | 0.70±0.12       | 0.94±0.21 (+34%) |
|                 | HCO\(^+\) J=2−1 | 0.37±0.11 (−39%)                   | 0.60±0.17       | 0.90±0.27 (+49%) |
|                 | HNC J=2−1  | 0.36±0.08 (−40%)                    | 0.61±0.17       | 0.93±0.35 (+54%) |
|                 | 183 GHz H\(_2\)O | 0.22±0.10 (−39%)              | 0.35±0.29       | — ^A |
| IRAS 13509+0442 | HCN J=2−1 | 0.32±0.07 (−46%)                   | 0.59±0.11       | 1.0±0.2 (+77%)  |
|                 | HCO\(^+\) J=2−1 | 0.29±0.10 (−50%)                   | 0.57±0.12       | 1.0±0.2 (+77%)  |
|                 | HNC J=2−1  | 0.17±0.05 (−47%)                    | 0.32±0.07       | 0.57±0.14 (+78%) |
|                 | 183 GHz H\(_2\)O | — ^A                     | 0.33±0.22       | — ^A |
| IRAS 15250+3609 | HCN J=2−1 | 3.3±0.2 (−4%)                      | 3.4±0.2 (1.2 kpc) | 3.6±0.2 (+7%)   |
|                 | HCO\(^+\) J=2−1 | 1.4±0.1 (−12%)                     | 1.6±0.2 (1.2 kpc) | 1.8±0.2 (+18%)  |
|                 | HNC J=2−1  | 2.9±0.1 (−21%)                      | 3.7±0.3 (1.2 kpc) | 4.5±0.4 (+19%)  |
|                 | 183 GHz H\(_2\)O | 2.9±0.1 (−16%)                    | 3.4±0.2 (1.2 kpc) | 3.9±0.3 (+15%)  |
| Superantennae   | HCN J=2−1 | 3.1±0.2 (−36%)                      | 4.9±0.4         | 7.7±0.7 (+58%)  |
|                 | HCO\(^+\) J=2−1 | 2.0±0.2 (−31%)                     | 2.9±0.3         | 4.7±0.6 (+63%)  |
|                 | HNC J=2−1  | 1.2±0.2 (−40%)                      | 1.9±0.2         | 2.7±0.4 (+42%)  |
|                 | 183 GHz H\(_2\)O | 4.6±0.3 (−10%)                     | 5.1±0.3         | 5.5±0.7 (+88%)  |
| IRAS 20551−4250 | HCN J=2−1 | 4.6±0.1 (−5%)                      | 4.8±0.1         | 5.4±0.1 (+11%)  |
|                 | HCO\(^+\) J=2−1 | 6.9±0.1 (−6%)                      | 7.4±0.1         | 8.5±0.2 (+16%)  |
|                 | HNC J=2−1  | 1.8±0.1 (−21%)                      | 2.3±0.1         | 2.5±0.1 (+10%)  |
|                 | 183 GHz H\(_2\)O | 1.3±0.1 (−7%)                       | 1.4±0.1         | 1.5±0.1 (+3%)   |
| IRAS 22491−1808 | HCN J=2−1 | 4.3±0.1 (−14%)                      | 5.1±0.2         | 5.8±0.3 (+14%)  |
|                 | HCO\(^+\) J=2−1 | 3.1±0.4 (−8%)                      | 3.3±0.2         | 4.3±0.3 (+29%)  |
|                 | HNC J=2−1  | 2.7±0.1 (−17%)                      | 3.2±0.2         | 3.9±0.4 (+20%)  |
|                 | 183 GHz H\(_2\)O | 1.5±0.1 (−9%)                       | 1.6±0.1         | 2.0±0.3 (+22%)  |

\(^A\)Detection is not significant for meaningful estimate.

Note— Col.(1): Object name. Col.(2): Line. Cols.(3)–(5): Gaussian-fit velocity-integrated flux (in Jy km s\(^{-1}\)). For each line of each object, we adopt the same Gaussian (one or two components). Col.(3): Original beam size (Table 3, column 6). Col.(4): ~1 kpc beam. 1 kpc beam for all ULIRGs, except IRAS 06035−7102, IRAS 12112+0305, and IRAS 15250+3609, for which 1.6 kpc, 1.2 kpc, and 1.2 kpc beam is used, respectively. Col.(5): 2 kpc beam. In Col.(3) and (5), flux increase, relative to the ~1 kpc beam measurement, is shown in parentheses. Negative value means flux decrease.
Figure 16. Moment 0 map of the 183 GHz H$_2$O emission line created from 1kpc-beam data. (Left): IRAS 12127$-$1412. (Right): IRAS 13509+0442. Peak flux of the H$_2$O emission is 0.34 and 0.26 [Jy beam$^{-1}$ km s$^{-1}$] for IRAS 12127$-$1412 and IRAS 13509+0442, respectively. Contours are 2.5σ and 3σ, where the rms noise is 0.10 and 0.082 [Jy beam$^{-1}$ km s$^{-1}$] for IRAS 12127$-$1412 and IRAS 13509+0442, respectively. The detection significance at the H$_2$O emission peak is 3.2σ for both sources. Continuum peak position is shown as a cross. Circular 1 kpc beam is shown as a filled circle in the lower-left part.
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