MILLIMETER INTERFEROMETRIC HCN(1–0) AND HCO⁺(1–0) OBSERVATIONS OF LUMINOUS INFRARED GALAXIES

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Received 2007 July 5; accepted 2007 September 8

ABSTRACT

We present the results on millimeter interferometric observations of four luminous infrared galaxies (LIRGs), Arp 220, Mrk 231, IRAS 08572+3915, and VV 114, and one Wolf-Rayet galaxy, He 2–10, using the Nobeyama Millimeter Array (NMA). Both the HCN(1–0) and HCO⁺(1–0) molecular lines were observed simultaneously, and their brightness-temperature ratios were derived. High-quality infrared L-band (2.8–4.1 µm) spectra were also obtained for the four LIRGs to better constrain their energy sources deeply buried in dust and molecular gas. When combined with other LIRGs we have previously observed with NMA, the final sample comprised nine LIRGs (12 LIRG nuclei) with available interferometric HCN(1–0) and HCO⁺(1–0) data, sufficient to investigate the overall trend in comparison with known AGNs and starburst galaxies. We found that LIRGs with luminous buried AGN signatures at other wavelengths tend to show high HCN(1–0)/HCO⁺(1–0) brightness-temperature ratios as seen in AGN-dominated galaxies, while the Wolf-Rayet galaxy He 2–10 displays a small ratio. An enhanced HCN abundance in the interstellar gas surrounding a strongly X-ray-emitting AGN, as predicted by some chemical calculations, and/or infrared radiative pumping, are possible explanations of our results.

Keywords: galaxies: active — galaxies: individual (Arp 220, Markarian 231, IRAS 08572+3915, VV 114, He 2–10) — galaxies: ISM — galaxies: nuclei — radio lines: galaxies

1. INTRODUCTION

It has recently been found that supermassive black holes (SMBHs) with masses of $M_{\text{SMBH}} > 10^6 M_\odot$ are ubiquitously present at the centers of spheroidal components (bulges and elliptical galaxies) (Magorrian et al. 1998). When active mass accretion onto a SMBH occurs, it is observed as an active galactic nucleus (AGN). The current AGN picture postulates that dust is present in the torus geometry around the central SMBH (Antonucci 1993). The direction perpendicular to the torus is mostly transparent to the bulk of the AGN’s ionizing UV soft X-ray photons. Gas clouds at 10–1000 pc distances from the AGN along the torus axis, photoionized by the central AGN’s radiation, produce the so-called narrow-line regions (NLRs; Robson 1996). Since the spectral shapes of the ionizing photons differ between AGNs and stars, emission-line ratios from NLRs differ from gas clouds photoionized in star-forming galaxies. Thus, AGNs surrounded by torus-shaped dust with well-developed NLRs are distinguishable from star-forming galaxies relatively easily (Veilleux & Osterbrock 1987).

Because dust at the central <10 pc of galaxies has an angular momentum, the spatial distribution of the dust is likely to be axi-symmetric; dust column density is higher in one direction (the torus direction) and lower in another direction (the torus axis). When the nuclear concentration of dust becomes large, even the torus axis direction can be opaque to the bulk of the AGN’s UV soft X-ray radiation, and the radiation can be blocked at the inner part (<10 pc), producing virtually no NLRs. Such buried AGNs are no longer detectable as long as emission lines originating in the NLRs are sought. Because a simple interpretation of the cosmic X-ray background spectrum suggests that most AGNs in the universe are buried (Fabian & Iwasawa 1999), it is important to establish a technique for finding buried AGNs. In a buried AGN, almost all of the energetic UV soft X-ray radiation is absorbed by the surrounding dust and is re-emitted as infrared dust emission. For this reason, luminous buried AGNs are expected to be strong infrared emitters. Luminous infrared galaxies (LIRGs), which radiate strong infrared emission with $L_{\text{IR}} > 10^{11} L_\odot$, and contain highly concentrated nuclear dust (Sanders & Mirabel 1996), are objects in which it is probable that luminous buried AGNs reside.

Since star-forming activity can also produce infrared emission, it is necessary to distinguish the origin of the infrared luminosities of LIRGs if we are to study the luminous buried AGN population. An effective method is to search for the presence of strong X-ray emission because an AGN intrinsically produces much stronger X-ray emission compared to star-forming activity (Robson 1996).
Unfortunately, buried AGNs generally contain a large amount of nuclear dust (Imanishi et al. 2006a), and most of them may be Compton-thick ($N_H > 10^{24} \, \text{cm}^{-2}$) sources (Maiolino et al. 2003). X-ray observations at $E > 10$ keV are needed to directly detect Compton-thick X-ray emission from luminous buried AGNs with a small scattered/reflected component (Fabian et al. 2002); however, these are applicable to only a few very nearby bright LIRGs due to a current sensitivity limit.

Although a systematic buried AGN search through direct X-ray observations is difficult, we can investigate the presence of a luminous buried AGN through the chemical effects of the intrinsically strong X-ray emission on the surrounding interstellar medium. Around a strongly X-ray-emitting buried AGN surrounded by dense gas and dust, the so-called X-ray dissociation regions (XDRs; Maloney et al. 1996) should develop, in contrast to the photodissociation regions (PDRs) usually seen in strongly UV-emitting star-forming regions. Detection of XDR signatures can thus be a useful tool for locating a luminous buried AGN. Among the several proposed probes of XDRs (Usero et al. 2004; Aalto et al. 2007), we focus on the observationally derived method based on HCN(1–0) and HCO$^+$ (1–0) line ratios (Kohno et al. 2001; Kohno 2005; Imanishi et al. 2006b; Graciá-Carpio et al. 2006), because theoretical prediction of line fluxes from PDRs and XDRs requires many free parameters (Yamada et al. 2007) and could still be uncertain, given that the most important parameter—detailed properties of the clumpy structure of molecular gas (Solomon et al. 1987)—is totally unknown from observations.

Here we present the results of our millimeter interferometric HCN(1–0) and HCO$^+$ (1–0) observations using the Nobeyama Millimeter Array (NMA) of nearby LIRGs whose energy sources have previously been investigated at other wavelengths. Compared to previous HCN(1–0) and HCO$^+$ (1–0) observations of LIRGs using single-dish radio telescopes (Gao & Solomon 2004; Graciá-Carpio et al. 2006), our interferometric maps have the important advantage that spatially resolved HCN(1–0) and HCO$^+$ (1–0) data are obtainable in LIRGs, which often show disturbed, multiple-nucleus morphologies (Sanders & Mirabel 1996). New ground-based infrared $L$-band (2.8–4.1 $\mu$m) spectra of higher quality than the older data were also taken for the individual main nuclei of these millimeter-observed LIRGs to better constrain the nature of their obscured energy sources. We adopted $H_0 = 75 \, \text{km} \, \text{s}^{-1} \, \text{Mpc}^{-1}$, $\Omega_M = 0.3$, and $\Omega_{\Lambda} = 0.7$ throughout this paper.

### 2. TARGETS

The target LIRGs were selected on the basis of their proximity ($z < 0.06$) to cover the redshifted HCN(1–0) and HCO$^+$ (1–0) emission lines with the NMA receiving systems, and their expected high fluxes of HCN(1–0) and HCO$^+$ (1–0). The four LIRGs Arp 220, IRAS 08572+3915, Mrk 231, and VV 114 were observed. Table 1 summarizes the infrared emission properties of these LIRGs. An angular scale of $1''$ corresponds to a physical size of 0.3–1 kpc at redshifts of 0.018–0.058.

Arp 220 ($z = 0.018$) is one of the best-studied nearby ultra-luminous infrared galaxies (ULIRGs; $L_{IR} > 10^{12} \, L_{\odot}$; Sanders et al. 1988a). It consists of two nuclei, Arp 220E and 220W, with a separation of $\sim 1''$ (Scoville et al. 2000; Soifer et al. 2000), and the optical spectrum of the combined emission is classified as a LINER (i.e., non-Seyfert; no obvious AGN signatures in the optical spectrum; Veilleux et al. 1999). The presence of starburst activity (active star formation) is evident in various observational data (Genzel et al. 1998; Imanishi & Dudley 2000), but the detected starburst is energetically insufficient to fully account for the observed infrared luminosity of Arp 220 quantitatively (Imanishi et al. 2006a, 2007; Armus et al. 2007), requiring an energy source deeply buried in Arp 220’s nuclear core (Spoon et al. 2004; González-Alfonso et al. 2004). The presence of a luminous buried AGN at the core has long been unclear, even through detailed observations in the X-ray (Iwasawa et al. 2005), infrared (Genzel et al. 1998; Armus et al. 2007), and radio (Shioya et al. 2001; Parra et al. 2007) frequencies. However, the recent discovery of a compact energy source with a very high emission surface brightness has provided the first strong signatures of a luminous buried AGN in Arp 220 (Downes & Eckart 2007).

Mrk 231 ($z = 0.042$) is a well-studied, single-nucleus ULIRG and is the most luminous object ($L_{IR} \sim 10^{12.5} \, L_{\odot}$) in the local universe. It is an optically known AGN classified as a Seyfert 1 galaxy (Veilleux et al. 1999), but it displays absorption features in the infrared spectra (Roche et al. 1983; Armus et al. 2007) and X-rays (Braito et al. 2004) possibly originating in broad absorption line clouds (Boksenberg et al. 1977). The presence of a very luminous and probably energetically dominant AGN is revealed by various observations (e.g., Soifer et al. 2000; Imanishi & Dudley 2000; Braito et al. 2004; Imanishi et al. 2006a).

IRAS 08572+3915 ($z = 0.058$) is an ULIRG ($L_{IR} \sim 10^{12.1} \, L_{\odot}$) consisting of two nuclei (northwest and southeast) with a separation of $\sim 5''$ (Scoville et al. 2000; Kim et al. 2002). The northwest nucleus (IRAS 08572+3915N) is believed to be energetically dominant (Soifer et al. 2000) and is therefore our primary interest. It is classified optically as a LINER (Veilleux et al. 1999). It is one of the strong buried AGN candidates because (1) the energy source is suggested to be very compact and is more centrally concentrated than the nuclear dust, as expected for a buried AGN (Dudley & Wynn-Williams 1997; Soifer et al. 2000; Imanishi et al.)
2006a, 2007), and (2) the polycyclic aromatic hydrocarbon (PAH) emission (a starburst indicator) is extremely weak (Imanishi & Dudley 2000; Imanishi et al. 2006a, 2007; Spoon et al. 2006; Armus et al. 2007). It is thus a particularly interesting target for investigating whether the HCN(1–0) to HCO+(1–0) brightness-temperature ratio is similar to those found in AGN-dominated nuclei or starburst-dominated galaxies (Kohno 2005).

VV 114 (z = 0.020) is a double-nucleus LIRG (\(L_{\text{IR}} \sim 10^{11.6} L_{\odot}\)) with a separation of \(\sim 15''\) (Knop et al. 1994). Both nuclei are classified optically as H n regions (Veilleux et al. 1995). In short optical wavelengths, the western nucleus (VV 114W) is brighter than the eastern nucleus (VV 114E), but VV 114E becomes more important with increasing wavelength and is prominent in the infrared band (Knop et al. 1994; Le Floc’h et al. 2002), probably dominating the infrared luminosity of the VV 114 system. The VV 114E nucleus has a secondary peak \(\sim 1.5''\) southwest of the VV 114E peak (VV 114ESW; Soifer et al. 2001). The presence of a luminous buried AGN is suggested in VV 114E from the strong featureless mid-infrared 15 \(\mu\)m continuum emission (Le Floc’h et al. 2002).

In Kohno (2005), HCN(1–0) to HCO+(1–0) brightness-temperature ratios are studied in AGNs and typical starburst galaxies such as M82. In the nuclei of LIRGs, where molecular gas is very highly concentrated (Sanders & Mirabel 1996), putative star formation could be extreme in that young, massive, hot stars are more predominant than normal starbursts. To determine if such an extreme starburst shows a different HCN(1–0)/HCO+(1–0) brightness-temperature ratio from a normal starburst, a nearby well-studied Wolf-Rayet galaxy, He 2–10 (z = 0.003), dominated by massive, hot Wolf-Rayet stars (Allen et al. 1976) was also studied (Table 1).

### 3. OBSERVATIONS AND DATA REDUCTION

#### 3.1. Millimeter Interferometry

Interferometric observations of HCN(1–0) (\(\lambda_{\text{rest}} = 3.3848\) mm or \(v_{\text{rest}} = 88.632\) GHz) and HCO+(1–0) (\(\lambda_{\text{rest}} = 3.3637\) mm or \(v_{\text{rest}} = 89.188\) GHz) lines were undertaken with the NMA and the RAINBOW interferometer at the Nobeyama Radio Observatory (NRO) between 2005 January and 2007 April. Table 2 summarizes the detailed observation log. The NMA consists of six 10 m antennas, and observations were undertaken using the AB (with a longest baseline of 351 m), C (163 m), and D (82 m) configurations. The RAINBOW interferometer is a seven-element combined array that includes the NRO 45 m telescope in addition to the six 10 m antennas (NMA). The RAINBOW observations were scheduled when the NMA array was set at the AB configuration and the longest baseline was 410 m. In the 3 mm wavelength range, the sensitivity of the RAINBOW interferometer is about twice as good as that of the NMA array only because the total aperture size increases by a factor of 4 with the inclusion of the NRO 45 m telescope.

The back end was the Ultra-Wide-Band Correlator (Okumura et al. 2000) configured to cover 1024 MHz with 128 channels at 8 MHz resolution. The central frequency for each source (Table 2) was set to cover both the redshifted HCN(1–0) and HCO+(1–0) lines simultaneously. A bandwidth of 1024 MHz corresponds to \(\sim 3500\) km s\(^{-1}\) at \(\nu \approx 84–89\) GHz. The field of view at this frequency is \(\sim 26''\) (full width at half-maximum [FWHM]) and \(\sim 77''\) (FWHM) for the RAINBOW and the NMA array, respectively. The Hanning window function was applied to reduce sidelobes in the spectra; thus, the effective resolution was widened to 16 MHz or 55 km s\(^{-1}\) at \(\nu \approx 84–89\) GHz. Since the declinations of VV 114 and He 2–10 are low (<\(-15''\)), the observable time period (elevation >\(20''\)) for each day from the NMA site is short, requiring many observing days.

The UVPROC-II package developed at NRO (Tsutsui et al. 1997) and the AIPS package of the National Radio Astronomy Observatory were used for standard data reduction. Corrections for the antenna baselines, bandpass properties, and the time variation in the visibility amplitude and phase were applied to all of the data (Table 2). A fraction of the data with large phase scatter due to poor millimeter seeing were removed from our analysis. After clipping a small fraction of data of unusually high amplitude, the data were Fourier-transformed using a natural \(u\nu\) weighting. The flux calibration was made using observations of Uranus or appropriate quasars (Table 2) whose flux levels relative to Uranus or Neptune had been measured at least every month in the NMA observing seasons. A conventional CLEAN method was applied to deconvolve the synthesized beam pattern. The primary beam pattern of the NMA antenna was corrected for LIRGs with very extended spatial structures (VV 114 and He 2–10).

| Object Name | Array Configuration | Observing Date (UT) | Central Frequency (GHz) | Phase Calibrator | Bandpass Calibrator | Flux Calibrator |
|-------------|---------------------|---------------------|------------------------|-----------------|-------------------|----------------|
| Arp 220     | RAINBOW AB          | 2006 Jan 26, 28, 30 | 87.34                  | 1538+149        | 3C 273            | 1741–038       |
| Mrk 231     | RAINBOW AB          | 2006 Jan 22, 23, 24, 25 | 85.31                  | 1418+546        | 3C 273            | 1741–038       |
| IRAS 08572+3915 | RAINBOW AB       | 2006 Jan 25, 26, 28 | 84.04                  | 0923+392        | 3C 84, 3C 273    | 3C 84          |
| VV 114      | RAINBOW AB          | 2007 Jan 29, 30, Feb 6, 7, 8 | 87.16                  | 0048–097        | 3C 84, 3C 454.3 Uranus |       |
| He 2–10     | RAINBOW AB          | 2007 Feb 6          | 88.64                  | 0834–201        | 3C 84, 3C 279    | 3C 84          |

Notes.—Col. (1): Object name. Col. (2): NMA array configuration. Col. (3): Observing date in UT. Col. (4): Central frequency used for the observations. Col. (5): Object used as a phase calibrator. Col. (6): Object used as a bandpass calibrator. Col. (7): Object used as a flux calibrator.
Table 3 summarizes the total net on-source integration times and synthesized beam patterns. Absolute positional uncertainties of the NMA/RAINBOW maps were estimated to be much less than 1″.

### Table 3

| Object        | On-Source Integration (hr) | Beam Size (arcsec) | Beam Position Angle (deg) |
|---------------|----------------------------|--------------------|---------------------------|
| Arp 220       | 24                         | 1.8 × 1.5          | -55.1                     |
| Mrk 231       | 4                          | 2.1 × 1.8          | -34.8                     |
| IRAS 08572+3915 | 33                         | 4.7 × 3.5          | -50.7                     |
| VV 114        | 18                         | 7.5 × 5.5          | -13.2                     |
| He 2-10       | 13                         | 10.8 × 5.5         | -10.1                     |

Notes.—Col. (1): Object name. Col. (2): Net on-source integration time. Col. (3): Beam size. Col. (4): Position angle of the beam pattern. It is 0° for the north-south direction, and increases counterclockwise on the sky plane.

3.2. Infrared 2.8–4.1 μm (L-Band) Spectroscopy

We conducted ground-based infrared 2.8–4.1 μm (L-band) slit spectroscopy on the main nuclei of the four LIRGs (Arp 220, Mrk 231, IRAS 08572+3915, and VV 114) to better understand the nature of their obscured energy sources based on the equivalent width of the 3.3 μm PAH emission and the optical depths of absorption features at λ_{rest} ~ 3.05 μm (in the rest frame) from ice-covered dust grains and at λ_{rest} ~ 3.4 μm from bare carbonaceous dust grains (Imanishi & Dudley 2000; Imanishi & Maloney 2003). A normal starburst galaxy should always show large equivalent-width PAH emission, while a pure AGN produces a PAH-free continuum (Imanishi & Dudley 2000; Imanishi et al. 2006a). For absorption features, optical depths have upper limits in a normal starburst, in which stellar energy sources and dust are spatially well mixed, while they can be arbitrarily large in a buried AGN with a more centrally concentrated energy source geometry than the dust has (Imanishi & Maloney 2003; Imanishi et al. 2006a). For these reasons, PAH emission and dust-absorption features can be used to distinguish the dust-obscured energy sources of LIRGs.

Ground-based infrared spectra taken with large (>4 m) telescopes are superior in spatial resolution to those obtained by space satellites with small diameters (<1 m), thus enabling us to obtain spatially resolved spectra of double nuclei with a small separation (<2″). For example, Arp 220 and VV 114E have double nuclei with separations of 1″–1.5″, which can be resolved only with the ground-based spectra. For Mrk 231 and IRAS 08572+3915, although infrared L-band spectra taken with <4 m telescopes have been published (Imanishi et al. 1998, 2006a; Imanishi & Dudley 2000), a higher quality L-band spectrum obtained with a larger, 8 m class telescope may be able to provide new constraints on their energy sources. We thus obtained infrared L-band spectra of Arp 220, Mrk 231, IRAS 08572+3915, and VV 114E using the Subaru 8.2 m telescope (Iye et al. 2004) atop Mauna Kea, Hawaii.

We used the IRS an infrared spectrograph (Kobayashi et al. 2000) at the Nasmyth focus of the Subaru telescope to obtain the new infrared L-band spectra of these LIRGs. Table 4 tabulates the observation log. The sky was clear during the observations. The seeing in the K band measured in images taken before the L-band spectroscopy was 0.4″–0.8″ in FWHM. A 0.6″ or 0.9″ wide slit and the L grism were used with a 52 mas pixel^{-1} scale. The achievable spectral resolution is R ~ 140–200 at λ ~ 3.5 μm. When the seeing size was sufficiently small, we basically used the 0.6″ slit to search for AGN signatures at nuclear cores based on the PAH equivalent widths and the strengths of the dust absorption features (Imanishi & Dudley 2000; Imanishi & Maloney 2003; Imanishi et al. 2006a), with reduced contamination from extended starburst components. However, for IRAS 08572+3915 the 0.9″ slit was employed because the seeing in the K band worsened during the observation. Thus, PAH emission from an extended (>0.6″ or >0.9″) starburst component was not covered, and thus, the PAH flux or luminosity is not considered in our discussion. For Arp 220, Mrk 231, and IRAS 08572+3915, nuclear PAH fluxes (or luminosities) within the central 1″–2″ can be better investigated from previously obtained spectra using a wider slit (Imanishi & Dudley 2000). The precipitation was low, 1–2 mm for the 2006 July observing run and <1 mm for the 2007 January run. We employed a standard telescope nodding technique (ABBA pattern) with a throw of 5″–7″ along the slit to subtract background emission. We used the optical guider of the Subaru telescope to monitor the telescope tracking. Exposure time was 1.0–1.5 s, and 30–60 co-adds were made at each nod position.

For both observing runs, F- or G-type main-sequence stars (Table 4) were observed as standard stars, with a mean air-mass difference of <0.1 from the individual LIRG nuclei, to correct for the transmission of Earth’s atmosphere and to provide flux calibration. The L-band magnitudes of the standard stars were estimated from their V-band (λ = 0.6 μm) magnitudes, adopting the V−L colors appropriate to the stellar types of individual standard stars (Tokunaga 2000).

### Table 4

| Object        | Date (UT) | Integration (minutes) | Slit Width (arcsec) | P.A. (deg) | Name | L Mag. | Type | T_{eff} (K) |
|---------------|-----------|-----------------------|--------------------|------------|------|--------|------|-------------|
| Arp 220       | 2006 Jul 17 | 24                    | 0.6                | 87         | HR 5728 | 4.5    | G3 V   | 5800        |
| Mrk 231       | 2007 Jan 14 | 20                    | 0.6                | 87         | HR 5728 | 4.5    | G3 V   | 5800        |
| IRAS 08572+3915 | 2007 Jan 14 | 16                    | 0.6                | 90         | HR 4767 | 4.8    | F8–G0 V  | 6000        |
| VV 114        | 2006 Jul 19 | 24                    | 0.6                | 60         | HR 3451 | 5.0    | F7 V   | 6240        |

Notes.—Col. (1): Object name. Col. (2): Observing date in UT. Col. (3): Net on-source integration time. Col. (4): Slit width. Col. (5): Position angle of the slit; 0° corresponds to the north-south direction. Position angle increases counterclockwise on the sky plane. Col. (6): Standard star name. Col. (7): Adopted L-band magnitude. Col. (8): Stellar spectral type. Col. (9): Effective temperature.
4. RESULTS

4.1. Millimeter Interferometric Data

For Arp 220 and Mrk 231, millimeter spectra at HCN(1–0) or HCO⁺(1–0) emission peak positions show that the flux levels

between these lines are substantially above the zero level, indicating that continuum emission is clearly present. We combined data points that were unaffected by these lines and made interferometric maps of the continuum emission. Figure 1 presents the contours of the continuum emission. The continuum emission is clearly detected (>3σ) in Arp 220 and Mrk 231. We barely see the continuum emission signature for VV 114, IRAS 08572+3915, and He 2–10, but its detection significance is <3σ. Table 5 presents the estimated continuum levels.

Figure 2 shows the integrated intensity maps of the HCN(1–0) and HCO⁺(1–0) emission of the five observed sources (Arp 220, Mrk 231, IRAS 08572+3915, VV 114, and He 2–10). The continuum emission is subtracted for Arp 220, Mrk 231, and VV 114, but not for IRAS 08572+3915 and He 2–10 because of possible large ambiguities.

Since molecular gas is highly concentrated at the nuclei of LIRGs, the importance of high-density molecular gas (n_H > 10^4 cm⁻³) is expected to increase there (Gao & Solomon 2004). Such molecular gas is better probed with HCN(1–0) and HCO⁺(1–0) rather than the widely used CO(1–0) because the dipole moments of HCN and HCO⁺ (μ > 3 D) are much larger than CO (μ ~ 0.1 D; Botschwina et al. 1993; Millar et al. 1997). Hence, the maps in Figure 2 reflect the spatial distribution of this important dense molecular gas. A spatially unresolved emission peak is clearly seen for Mrk 231 at the nuclear position. For IRAS 08572+3915, the spatially unresolved HCN(1–0) emission peaks at the energetically

| Object            | Continuum Emission |
|-------------------|---------------------|
|                   | Flux (mJy)          | Frequency (GHz) |
| Arp 220           | 30                  | ~87             |
| Mrk 231           | 35                  | ~85             |
| IRAS 08572+3915NW | <3 (<3σ)           | ~84             |
| VV 114            | <4 (<3σ)           | ~87             |
| He 2–10           | <6 (<3σ)           | ~88.5           |
dominant northwest nucleus, as expected (see §2, paragraph 4). For He 2–10, HCO'\(^+(1\rightarrow0)\) emission displaying no significant spatial extent is found close to the CO\((1\rightarrow0)\) peak (Kobulnicky et al. 1995). A spatially extended emission component is detected for Arp 220 and VV 114. Figures 3 and 4 display the channel maps around the HCN\((1\rightarrow0)\) and HCO'\(^+(1\rightarrow0)\) lines of Arp 220 and VV 114, respectively.

For Arp 220, the HCN\((1\rightarrow0)\) and HCO'\(^+(1\rightarrow0)\) emission peaks reside in between the double nuclei in the integrated intensity maps of Figure 2. Nevertheless, the channel map in Figure 3 clearly
shows that Arp 220E becomes more prominent with increasing velocity (red component; upper left panels) and Arp 220W does with decreasing velocity (blue component; lower right panels). Our HCN(1–0) and HCO+(1–0) channel maps thus confirm that the Arp 220E nucleus is farther redshifted than Arp 220W, as was previously noted (Larkin et al. 1995; Downes & Solomon 1998; Taniguchi & Shioya 1998; Sakamoto et al. 1999).

In the case of VV 114, the HCN(1–0) emission peak is close to VV 114E, while that of HCO+(1–0) is strong between the VV 114E and 114W nuclei (Fig. 2), similar to the CO(1–0), (2–1), and (3–2) emission (Yun et al. 1994; Iono et al. 2004). The spatial distributions of HCN(1–0) and HCO+(1–0) are quite different, possibly because (1) HCN(1–0) and HCO+(1–0) probe molecular gas with different density (Greve et al. 2006) due to their slightly different critical densities* or (2) HCO+(1–0) may selectively trace shock regions due to enhanced HCO+ abundance from shocks (Dickinson et al. 1980). Further details will be discussed in a future paper (Y. Tamura et al., in preparation). No significant HCN(1–0) or HCO+(1–0) emission is recognizable in VV 114W.

* The critical density (\(n_c\)) is, by definition, proportional to Einstein’s \(A\)-coefficient divided by the collision rate (Schloier et al. 2005). The \(A\)-coefficient is \(\propto \mu^2\nu^3\), where \(\mu\) is the dipole moment and \(\nu\) is the frequency of the molecular line. The dipole moments (\(\mu\)) of HCN (\(\mu \approx 3\); Millar et al. 1997) and HCO+ (\(\mu \approx 4\); Botschwina et al. 1993) are similar to each other. The frequencies of HCN(1–0) (88.632 GHz) and HCO+(1–0) (89.188 GHz) are almost identical. Thus, the \(A\)-coefficient is similar between HCN(1–0) and HCO+(1–0). However, using the collision rates estimated by Schloier et al. (2005), the \(n_c\) value of HCN(1–0) is a factor of \(~5\) larger than that of HCO+(1–0) (see also Papadopoulos 2007).

Figure 5 shows spectra around the HCN(1–0) and HCO+(1–0) lines for Arp 220, Mrk 231, IRAS 08572+3915, and VV 114. For Mrk 231 and IRAS 08572+3915 spectra are extracted at the nuclear peak position. For Arp 220 the spectra are extracted at both the Arp 220E and 220W positions, and double-peaked HCN(1–0) and HCO+(1–0) emission is seen at both positions. Although the double-peaked profile suggests that emission from Arp 220E and 220W is not clearly spatially resolved in a map, the redshifted (lower frequency) component is stronger at the Arp 220E position than at Arp 220W, as expected from the channel map (Fig. 3). We can thus separate the emission from Arp 220E and 220W spectroscopically, with the redshifted and blueshifted components coming from Arp 220E and 220W, respectively. For VV 114, both the HCN(1–0) and HCO+(1–0) emission have spatial structure, and their peak positions are not the same. We thus extract spectra at four different positions: 114E-1, the HCN(1–0) peak at the eastern side of VV 114E in Figure 2; 114E-2, the HCN(1–0) peak at the western side of VV 114E in Figure 2; 114-3, the eastern HCO+(1–0) peak between VV 114E and 114W in Figure 2; and 114-4, the western HCO+(1–0) peak between VV 114E and 114W in Figure 2.

Figure 6 presents Gaussian fits to the detected HCN(1–0) and HCO+(1–0) lines. The central velocity and line width of the Gaussian fit are determined independently for the HCN(1–0) and HCO+(1–0) lines. For IRAS 08572+3915, a double-Gaussian fit was attempted because the lines seemed to be double-peaked. Table 6 summarizes the Gaussian-fitting results. For Mrk 231 and IRAS 08572+3915 (the LIRGs dominated by a single primary nucleus), the HCN(1–0) peak velocity is similar to that of CO(1–0) in previous reports (Downes & Solomon 1998; Bryant 2007).
For the Arp 220E and 220W nuclei, the peak velocities of HCN(1–0) and HCO+(1–0) agree with that of CO(2–1) within 50 km s\(^{-1}\) (Downes & Solomon 1998).

For Arp 220, Mrk 231, IRAS 08572+3915, and VV 114, the integrated fluxes of HCN(1–0) and HCO+(1–0) at each peak position estimated from the Gaussian fits in the spectra are summarized in Table 7. For He 2–10 the fluxes are derived from the peak contours of the integrated intensity maps (Fig. 2) because the spectrum is noisy. The HCN(1–0)/HCO+(1–0) brightness-temperature ratios (\(\alpha T_b\), flux density) are also shown in Table 7.

In Mrk 231 and IRAS 08572+3915 both the HCN(1–0) and HCO+(1–0) emission show a spatially unresolved single peak at the main nuclear position. The integrated HCN(1–0) and HCO+(1–0) fluxes are also estimated from the peak contours of the integrated intensity maps in Figure 2. The estimated values are consistent with those based on the Gaussian fits for both HCN(1–0) and HCO+(1–0) emission within 15% in Mrk 231 and 30% in IRAS 08572+3915 if the continuum in Figure 6 is assumed.

Arp 220, VV 114, and He 2–10 display spatially extended HCN(1–0) and HCO+(1–0) emission. Their total fluxes are shown.

![Fig. 3.—Channel maps of HCN(1–0) and HCO+(1–0) emission for Arp 220. Left: HCN(1–0) emission. The contours are 4 \(\times\) (3, 5, 7, 9, and 11) mJy beam\(^{-1}\). The rms noise level is ~4 mJy beam\(^{-1}\). Right: HCO+(1–0) emission. The contours are 4 \(\times\) (3, 4, 5, and 6) mJy beam\(^{-1}\). The rms noise level is ~4 mJy beam\(^{-1}\).](image1)

![Fig. 4.—Channel maps of HCN(1–0) and HCO+(1–0) emission for VV 114. Left: HCN(1–0) emission. The contours are 3 \(\times\) (3, 4, and 5) mJy beam\(^{-1}\). The rms noise level is ~3 mJy beam\(^{-1}\). Right: HCO+(1–0) emission. The contours are 3 \(\times\) (3, 4, 5, 6, and 7) mJy beam\(^{-1}\). The rms noise level is ~3 mJy beam\(^{-1}\).](image2)
in Table 8. For Arp 220 and Mrk 231, the HCN(1−0) and HCO+(1−0) fluxes have previously been measured using single-dish radio telescopes. Table 9 compares their fluxes with our measurements, which are similar, suggesting that our interferometric data recover the bulk of HCN(1−0) and HCO+(1−0) emission.

4.2. Infrared Spectra

4.2.1. PAH Emission

Figure 7 presents the flux-calibrated infrared 2.8−4.1 μm (L-band) spectra of Arp 220, Mrk 231, IRAS 08572+3915NW, and VV 114E. For Arp 220 and VV 114E, our ground-based spectra provide spatially resolved spectra of double nuclei with small (1′′−2′′) separation, which is not possible for space-based infrared spectra (see § 3.2). Thus, our L-band spectra make it possible to discuss the energy sources of individual nuclei separately for Arp 220E and 220W (Scoville et al. 2000; Soifer et al. 2000), and VV 114E and 114ESW (Soifer et al. 2001).

The 3.3 μm PAH emission is clearly seen in the spectra of the observed LIRGs, except for IRAS 08572+3915NW, indicating that a detectable amount of starburst activity is surely present. Table 10 summarizes the strength of the 3.3 μm PAH emission feature. The observed 3.3 μm PAH luminosities (L_{3.3 \text{PAH}}) roughly trace the absolute magnitudes of modestly obscured (A_V < 15 mag) starburst activities covered inside our slit spectra (the L_{IR} of such a starburst is ∼10^3 L_{3.3 \text{PAH}}; Mouri et al. 1990; Imanishi 2002).

For Arp 220E and 220W, Mrk 231, and IRAS 08572+3915NW, the equivalent widths of the 3.3 μm PAH emission (EW_{3.3 \text{PAH}}) are similar to previous estimates based on old, lower quality spectra (Imanishi & Dudley 2000; Imanishi et al. 2006a). The EW_{3.3 \text{PAH}} values of Mrk 231, IRAS 08572+3915NW, and VV 114E are more than a factor of ~5 smaller than the typical value found in starburst-dominated galaxies (EW_{3.3 \text{PAH}}: ~100 nm; Imanishi & Dudley 2000), indicating that PAH-free continua from the putative luminous AGNs make important contributions to their observed L-band fluxes (Imanishi & Dudley 2000; Imanishi et al. 2006a; Imanishi 2006). For Arp 220E, Arp 220W, and VV 114E, the EW_{3.3 \text{PAH}} values are as large as seen in normal starburst galaxies, so no explicit signs of PAH-free continua from buried AGNs are detected in this wavelength range.

For Mrk 231 and IRAS 08572+3915, the ULIRGs dominated by compact nuclear emission, the L-band continuum flux levels in our slit spectra are similar, within 0.1 mag, to the photometric measurements using a 2.5′′ aperture (Zhou et al. 1993). For Arp 220E and 220W, the L-band continuum flux level is a factor of
~2 smaller than in previously obtained spectra using a 1.2" aperture (Imanishi & Dudley 2000) and photometric data using a 2.5" aperture (Zhou et al. 1993). The small flux is possibly due to the small slit width (0.6") in the new spectra and/or possible $L$-band flux ambiguity in the adopted standard star, HR 5728 (Table 4).

4.2.2. Absorption Features

IRAS 08572+3915NW (Fig. 7) shows a strong absorption feature at $\lambda_{\text{obs}} = 3.6\mu$m in the observed frame or $\lambda_{\text{rest}} = 3.4\mu$m in the rest frame due to bare carbonaceous dust grains. Its optical depth is estimated to be $\tau_{3.4} \sim 0.8$, which is similar to previous estimates (Imanishi & Dudley 2000; Imanishi et al. 2006a). The optical depth is larger than the upper limit produced with the natural geometry of a normal starburst (with stellar energy sources and dust spatially well mixed; $\tau_{3.4} < 0.2$) but requires buried AGN-type geometry in which the energy source is more centrally concentrated than the dust (Imanishi & Maloney 2003; Imanishi et al. 2006a), supporting the buried-AGN classification as previously indicated from the low $\text{EW}_{3.3\text{PAH}}$ value ($\lesssim$3 nm; Table 10).

In the high-quality IRAS 08572+3915NW spectrum in Figure 7, the broad absorption feature centered at $\lambda_{\text{obs}} = 3.2\mu$m or $\lambda_{\text{rest}} = 3.0-3.05\mu$m is seen for the first time. In a buried AGN and starburst composite galaxy, the buried AGN emission is more highly obscured, because the central compact buried AGN should be geometrically surrounded by the starburst. Hence, the contribution from buried AGN emission to an observed flux becomes higher with increasing wavelength, from the $K$ band ($2-2.5\mu$m) to the $L$ band ($2.8-4.1\mu$m), due to smaller dust extinction. In addition, blackbody radiation from stars ($T > 4000$ K) generally shows a steeply decreasing flux from the $K$ to the $L$ band. For these reasons, it could happen that an observed $K$-band continuum emission largely comes from foreground stellar emission, in addition to buried AGN emission, while an $L$-band continuum, particularly at a longer wavelength, is dominated by buried AGN emission. If this is the case for IRAS 08572+3915NW and if the stellar emission’s tail extends from the $K$ band to the shorter part of the $L$ band ($\lambda_{\text{obs}} < 3.0\mu$m), then an absorption-like feature at $\lambda_{\text{rest}} \sim 3.05\mu$m could be reproduced. However, the $K$-band spectrum of IRAS 08572+3915 comes mostly from buried-AGN-heated hot dust emission, because of the extremely red $K$-band continuum and no stellar CO absorption features at $\lambda_{\text{rest}} \sim 2.3\mu$m (Goldader et al. 1995; Imanishi et al. 2006a). Thus, this scenario seems implausible. We ascribe the absorption-like feature to the 3.05$\mu$m absorption by ice-covered dust grains and estimate its optical depth to be $\tau_{3.4} \sim 0.3$.

The spectrum of VV 114E also displays a 3.05$\mu$m ice absorption feature with an optical depth of $\tau_{3.4} \sim 0.5$. Its optical depth is again larger than the threshold explained by the mixed dust/source geometry of a normal starburst ($\tau_{3.4} < 0.3$; Imanishi &
Fig. 6.—Gaussian fits to the detected HCN(1–0) and HCO+(1–0) emission lines. The abscissa is the LSR velocity \(v_{\text{opt}} \equiv (v/\beta - 1)c\) in \(\text{km} \, \text{s}^{-1}\), and the ordinate is flux in mJy beam\(^{-1}\). Single-Gaussian fits are used as defaults and are shown as dashed lines. The spectrum of IRAS 08572+3915 is only for the northwest nucleus. For this source, since evidence for double peaks exists, we attempted a double-Gaussian fit, shown as dashed lines. A constant continuum is assumed and is set as a free parameter because the continuum emission was not subtracted from the spectrum of IRAS 08572+3915. For other sources the continuum level is set as the zero value. The adopted continuum levels are shown as the horizontal solid straight lines for all sources.
Fig. 6—Continued
TABLE 6
GAUSSIAN-FITTING PARAMETERS OF HCN(1–0) AND HCO+(1–0) EMISSION LINES

| OBJECT                  | LSR VELOCITY (km s⁻¹) | FWHM (km s⁻¹) |
|-------------------------|-----------------------|---------------|
|                         | HCN(1–0) (2) | HCO+(1–0) (3) | CO(1–0) or CO(2–1) (4) | HCN(1–0) (5) | HCO+(1–0) (6) |
| Arp 220E                | 5640 | 5680 | 5650 | 240 | 190 |
| Arp 220W                | 5510 | 5290 | 5340 | 320 | 270 |
| Mrk 231                 | 12660, 12690 | 12650 | 260 | 290 |
| IRAS 08572+3915NW       | 17110, 17540 | 17250, 17900 | 17490 | 420, 300 | 320, 180 |
| VV 114E-1               | 6090 | ... | ... | 170 | ... |
| VV 114E-2               | 6070 | 6060 | ... | 190 | 260 |
| VV 114-3                | 6060 | 6030 | ... | 290 | 360 |
| VV 114-4                | 5910 | 5950 | ... | 250 | 310 |

Notes.—Col. (1): Object name. Col. (2): LSR velocity [v_{opt} ≡ (ν_{opt} - 1)c] of the HCN(1–0) emission peak. Col. (3): LSR velocity of the HCO+(1–0) emission peak. Col. (4): LSR velocity of the CO(1–0) or CO(2–1) emission peak, taken from the literature (Bryant & Scoville 1996; Downes & Solomon 1998; Evans et al. 2002). Col. (5): Line width of the HCN(1–0) emission at FWHM. Col. (6): Line width of the HCO+(1–0) emission at FWHM.

° A double-Gaussian fit.
Maloney 2003), suggesting the presence of a luminous buried AGN, as inferred from the low EW3.3_PAH value (~20 nm; Table 10).

For the infrared L-band spectra of the remaining LIRG nuclei (Arp 220E, Arp 220W, Mrk 231, and VV 114ESW), no clear absorption features are recognizable. The absence of absorption features in Mrk 231 (the low EW3.3_PAH object; Table 10) implies that the AGN is only weakly obscured, while those for Arp 220E, Arp 220W, and VV 114ESW are explained by the predominant contribution from starburst emission to the observed L-band fluxes. For Arp 220W, the nucleus with luminous buried AGN signatures (Downes & Eckart 2007), we see no explicit AGN sign in the infrared L-band spectrum. The emission from the putative buried AGN may be so highly flux-attenuated that its contribution to the observed L-band flux is insignificant compared to foreground weakly obscured starburst emission.

5. DISCUSSION

5.1. Comparison of HCN(1−0)/HCO+(1−0)

Brightness-Temperature Ratios with Those of Other Galaxies

Figure 8 shows the HCN(1−0)/HCO+(1−0) and HCN(1−0)/CO(1−0) brightness-temperature ratios for Arp 220, Mrk 231, IRAS 08572−3915W, VV 114, and He 2−10. Previously obtained data points of nearby LIRGs (Imanishi et al. 2004, 2006b; Imanishi & Nakanoishi 2006), starbursts, and Seyfert galaxies (Kohno 2005) are also plotted. As stated by Imanishi et al. (2006b) we mainly use the HCN(1−0)/HCO+(1−0) ratios (ordinate) in our discussions for the following reasons. First, since the HCN(1−0) and HCO+(1−0) lines are observed simultaneously with the same array configuration of NMA/RAINBOW, their beam patterns are virtually identical. We can thus be confident that the same regions are probed with both lines. Second, both HCN(1−0) and HCO+(1−0) fluxes are measured at the same time with the same receiver and same correlator unit, so that the possible absolute flux calibration uncertainty of the interferometric data does not propagate into the uncertainty in the ratio, which is dominated by statistical noise and fitting errors (see Fig. 6). Therefore, the derivation of the HCN(1−0)/HCO+(1−0) brightness-temperature ratio is straightforward. Neither of the first or second arguments hold for the HCN(1−0)/CO(1−0) brightness-temperature ratios in the abscissa of Figure 8, which complicates their interpretation.

### Table 7

Flux of HCN(1−0), HCO+(1−0), and CO(1−0) Emission at Each Peak Position

| Nucleus (1) | HCN(1−0) | HCO+(1−0) | CO(1−0) |
|-------------|----------|----------|--------|
|             | (Jy km s⁻¹) | (Jy km s⁻¹) | (Jy km s⁻¹) |
| Arp 220E    | 11.9     | 5.3      | 2.3    |
| Arp 220W    | 17.8     | 6.6      | 2.7    |
| Mrk 231     | 10.7     | 6.3      | 1.7    |
| IRAS 08572−3915W | 2.3 (1.4 ± 0.9) | 1.3 (0.7 ± 0.6) | 1.8 |
| VV 114E-1   | 2.7      | <1.7     | >1.6   |
| VV 114E     | 1.9      | 4.0      | 0.5    |
| VV 114W     | 3.2      | 5.5      | 0.6    |
| VV 114-4    | 1.3      | 6.0      | 0.2    |
| He 2−10     | 6.1      | 11.4     | <0.6   |

* CO(2−1) emission is detected at individual cores, but CO(1−0) emission is not (Downes & Solomon 1998). We estimate the CO(1−0) flux at the core from the CO(2−1) flux (Sakamoto et al. 1999), using the ν² scaling (Riechers et al. 2006), based on the assumption that emission is thermalized and that both CO(1−0) and CO(2−1) have the same brightness temperatures.

### Table 8

Total Flux of HCN(1−0) and HCO+(1−0) Emission for Sources that Show Spatially Extended Components

| Nucleus (1) | HCN(1−0) | HCO+(1−0) |
|-------------|----------|----------|
|             | (Jy km s⁻¹) | (Jy km s⁻¹) |
| Arp 220     | 34        | 18       |
| VV 114      | 7         | 19       |
| He 2−10     | 6.5       | 11       |

### Table 9

Comparison of HCN(1−0) and HCO+(1−0) Fluxes between Our Measurements and Those in the Literature

| Nucleus (1) | Line (2) | Flux (3) | Reference (4) |
|-------------|----------|----------|---------------|
| Arp 220     | HCN(1−0) | 34*      | This work     |
|             |          | 45       | Evans et al. (2006) |
|             |          | 37       | Solomon et al. (1992) |
|             |          | 35*      | Radford et al. (1991) |
|             | HCO+(1−0)| 18*      | This work     |
|             |          | 23       | Graciá-Carpio et al. (2006) |
| Mrk 231     | HCN(1−0) | 11*      | This work     |
|             |          | 14       | Solomon et al. (1992) |
|             | HCO+(1−0)| 6*       | This work     |
|             |          | 8        | Graciá-Carpio et al. (2006) |

* Measurements are made based on interferometric data.
LIRGs with luminous AGN signatures at other wavelengths (Arp 220W, Mrk 231, and IRAS 08572+3915) tend to show high HCN(1–0)/HCO+(1–0) brightness-temperature ratios, as seen in AGN-dominated galaxies. The ratio is also high in VV 114E-1, which is close to the putative AGN location at VV 114E, despite a slight positional deviation. The Wolf-Rayet galaxy He 2 shows a very low HCN(1–0)/HCO+(1–0) brightness-temperature ratio. Some individual examples of nearby Galactic high-mass-star-forming H\textsc{ii} region cores show high HCN(1–0)/HCO+(1–0) brightness-temperature ratios (Turner & Thaddeus 1977; Pirogov 1999). However, for external galaxies, the ensemble of H\textsc{ii} regions, molecular gas, and PDRs are observed as a whole. The low HCN(1–0)/HCO+(1–0) brightness-temperature ratio in He 2–10 suggests that even an extreme starburst dominated by young hot stars cannot easily produce a high HCN(1–0)/HCO+(1–0) brightness-temperature ratio when observed at a large physical scale. The high ratios observed in LIRGs are likely to have another cause than the extreme starburst scenario.

5.2. Interpretations of HCN(1–0)/HCO+(1–0) Brightness-Temperature Ratios

A natural explanation for the high HCN(1–0)/HCO+(1–0) brightness-temperature ratios in buried AGN candidates is the increasing abundance of HCN due to strong X-ray radiation from the AGN, as predicted by some simple chemical calculations (Lintott & Viti 2006; see also the high-$F_x$ range of Table 3 in Meijerink et al. 2006). When both the HCN(1–0) and HCO+(1–0) emission are optically thin, the HCN(1–0)/HCO+(1–0) brightness-temperature ratio will increase linearly with increasing HCN abundance relative to HCO+. Imanishi et al. (2006b) and Figure 9 show that even if the emission is moderately optically thick, the increasing HCN abundance results in a larger HCN(1–0)/HCO+(1–0) brightness-temperature ratio (see also Knudsen et al. 2007). Since the HCN(1–0)/HCO+(1–0) brightness-temperature ratios in Figure 8 derived from our NMA/RAINBOW data are only toward the cores where putative AGNs are expected to be present, with a minimum contamination from extended starburst emission outside the beam size, the potential AGN X-ray chemistry, if any, may be better reflected in this way than in single-dish telescope measurements.

The critical density ($n_c$) of HCN(1–0) is a factor of ~5 larger than that of HCO+(1–0) (§ 4.1). When the fraction of high-density gas, above the HCN(1–0) critical density, increases, the HCN(1–0)/HCO+(1–0) brightness-temperature ratio could be high compared to that for low-density gas. Since LIRGs have highly concentrated molecular gas in their nuclei (Sanders & Mirabel...
1996) and the density may be larger than in the normal starburst galaxies studied by Kohno (2005), the large HCN(1–0)/HCO⁺(1–0) brightness-temperature ratios could originate simply from the increased molecular gas density. However, in this scenario the HCN(1–0)/CO(1–0) brightness-temperature ratios should be correspondingly high (see § 4.1). Although the HCN(1–0)/CO(1–0) brightness-temperature ratios in the abscissa of Figure 8 exhibit some ambiguities (§ 5.1), no such expected trend is observed in Figure 8 (LIRGs are not distributed on the right side), which does not support this high-density gas scenario. The expected high gas density and not high HCN(1–0)/CO(1–0) brightness-temperature ratios in the nuclei of LIRGs can be reconciled if the

![Graphs of F.7—Continued](image)

**TABLE 10**

| Object               | \( f_{3.3\text{PAH}} \) (\( \times 10^{-18} \text{ ergs s}^{-1} \text{ cm}^{-2} \)) | \( L_{3.3\text{PAH}} \) (\( \times 10^{40} \text{ ergs s}^{-1} \)) | \( L_{3.3\text{PAH}}/L_{\text{IR}} \) (\( \times 10^{-3} \)) | Rest EW(3.3 PAH) (nm) |
|----------------------|---------------------------------------------|-----------------------------|---------------------------------------------|----------------------|
| Arp 220E             | 3.5                                         | 2.2                         | ...                                        | 85                   |
| Arp 220W             | 7.5                                         | 4.8                         | ...                                        | 95                   |
| Arp 220E+W           | 11.0                                        | 6.9                         | 0.01                                        | 95                   |
| Mrk 231              | 9.5                                         | 33.5                        | 0.03                                        | 1.5                  |
| IRAS 08572+3915NW    | <4.0                                        | <30.0                       | <0.05                                       | <3                   |
| VV 114E              | 3.0                                         | 2.5                         | ...                                        | 20                   |
| VV 114E_SW           | 2.5                                         | 2.0                         | ...                                        | 110                  |

**Notes.**—Col. (1): Object name. Col. (2): Observed flux of the 3.3 \( \mu \text{m} \) PAH emission. Col. (3): Observed luminosity of the 3.3 \( \mu \text{m} \) PAH emission. Col. (4): Observed 3.3 \( \mu \text{m} \) PAH-to-infrared luminosity ratio in units of \( 10^{-3} \), a typical value for a modestly obscured (\( A_V < 15 \) mag) normal starburst (Mouri et al. 1990; Imanishi 2002). For Arp 220E, Arp 220W, VV 114E, and VV 114E_SW, no values are shown, because the fraction of IRAS-measured infrared fluxes coming from individual nuclei is unknown. Col. (5): Rest-frame equivalent width of the 3.3 \( \mu \text{m} \) PAH emission. Normal starbursts have EW(3.3 PAH) \( \sim 100 \) nm (Imanishi & Dudley 2000).
higher average gas density in certain areas results from a larger volume-filling factor of the clump (Fig. 9) rather than the higher density of each clump.

García-Burillo et al. (2006) found a very large HCN(5–4)/HCO+(5–4) brightness-temperature ratio in a luminous AGN with strong mid-infrared 12 μm continuum emission (APM 08279+5255), and suggested that infrared radiative pumping, rather than collisional excitation, can produce a high HCN/HCO+ brightness-temperature ratio. In general, an AGN is a more luminous mid-infrared 12 μm continuum emitter than a starburst, because 12 μm hot dust emission is stronger in the former. Hence, the infrared pumping may work more effectively in LIRGs with luminous buried AGNs than in those without, which could also explain the high HCN(1–0)/HCO+(1–0) brightness-temperature ratios seen in luminous buried AGN candidates.

Papadopoulos (2007) proposed that the HCN(1–0)/HCO+(1–0) brightness-temperature ratio could increase with increasing turbulence of molecular gas. In this model it is expected that the ratio will be higher with larger line widths of HCN(1–0) and HCO+(1–0). Figure 10 compares the line width with the ratio, but we see no clear positive trend.

Graciá-Carpio et al. (2006) measured the HCN(1–0) and HCO+(1–0) fluxes of LIRGs using a single-dish telescope with >25″ beam size, and found a positive correlation between the HCN(1–0)/HCO+(1–0) brightness-temperature ratio and the infrared luminosity. Figure 11 shows the HCN(1–0)/HCO+(1–0) brightness-temperature ratio only for the core emission inside
We presented the results of millimeter interferometric HCN(1–0) and HCO+(1–0) observations of nearby LIRGs using the NMA/RAINBOW array. When combined with other LIRGs we have previously observed, ours is the largest interferometric HCN(1–0) and HCO+(1–0) survey of LIRGs. Most of the observed LIRGs were selected based on the presence of luminous AGN signatures at other wavelengths. From the interferometric data, we extracted the HCN(1–0) and HCO+(1–0) flux at the core positions, where the putative AGNs are expected to be present. For observationally investigating the possible chemical effects of the putative strongly X-ray-emitting AGNs on the surrounding interstellar gas, our data set is much more advantageous than single-dish telescope data because the contamination from extended starburst emission can be reduced. We derived the HCN(1–0)/HCO+(1–0) brightness-temperature ratios of LIRGs and compared them to the ratios found in AGNs and starburst galaxies.

We reached the following main conclusions:

1. LIRGs with detected luminous AGN signatures through observations at other wavelengths generally show high HCN(1–0)/HCO+(1–0) brightness-temperature ratios and are distributed in the region occupied by AGNs.

2. When combined with the line widths of HCN(1–0) and HCO+(1–0), the high HCN(1–0)/HCO+(1–0) brightness-temperature ratios observed in these LIRGs could be explained by an HCN abundance enhancement, as suggested by some simple theoretical models, and/or by infrared radiative pumping.

3. We found a positive correlation between the HCN(1–0)/HCO+(1–0) brightness-temperature ratios toward only the LIRGs’ cores and the infrared luminosities of LIRGs, suggesting that AGN activity is more important in galaxies with higher infrared luminosities.

We are grateful to the NRO staff for their support during our NMA/RAINBOW observing runs, and T. Pyo, R. Potter, and S. Harasawa for their assistance during our Subaru observing runs. We thank J. Graciá-Carpio, S. Ishizuki, and M. Yamada for valuable discussions about molecular gas, and the anonymous referee for his or her useful comments. M. I. is supported by Grants-in-Aid for Scientific Research (16740117 and 19740109). Y. T. is financially supported by the Japan Society for the Promotion of Science for Young Scientists. K. K. is supported by Grants-in-Aid for Scientific Research on Priority Areas (15071202). NRO is a branch of the National Astronomical Observatory of Japan. This study utilized the SIMBAD database, operated at CDS, Strasbourg, France, and the NASA/IPAC Extragalactic Database (NED) operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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6. SUMMARY

We presented the results of millimeter interferometric HCN(1–0) and HCO+(1–0) observations of nearby LIRGs using the NMA/RAINBOW array. When combined with other LIRGs we have previously observed, ours is the largest interferometric HCN(1–0) and HCO+(1–0) survey of LIRGs. Most of the observed LIRGs were selected based on the presence of luminous AGN signatures at other wavelengths. From the interferometric data, we extracted the HCN(1–0) and HCO+(1–0) flux at the core positions, where the putative AGNs are expected to be present. For observationally investigating the possible chemical effects of the putative strongly X-ray-emitting AGNs on the surrounding interstellar gas, our data set is much more advantageous than single-dish telescope data because the contamination from extended starburst emission can be reduced. We derived the HCN(1–0)/HCO+(1–0) brightness-temperature ratios of LIRGs and compared them to the ratios found in AGNs and starburst galaxies.

We reached the following main conclusions:

1. LIRGs with detected luminous AGN signatures through observations at other wavelengths generally show high HCN(1–0)/HCO+(1–0) brightness-temperature ratios and are distributed in the region occupied by AGNs.

2. When combined with the line widths of HCN(1–0) and HCO+(1–0), the high HCN(1–0)/HCO+(1–0) brightness-temperature ratios observed in these LIRGs could be explained by an HCN abundance enhancement, as suggested by some simple theoretical models, and/or by infrared radiative pumping.

3. We found a positive correlation between the HCN(1–0)/HCO+(1–0) brightness-temperature ratios toward only the LIRGs’ cores and the infrared luminosities of LIRGs, suggesting that AGN activity is more important in galaxies with higher infrared luminosities.

We are grateful to the NRO staff for their support during our NMA/RAINBOW observing runs, and T. Pyo, R. Potter, and S. Harasawa for their assistance during our Subaru observing runs. We thank J. Graciá-Carpio, S. Ishizuki, and M. Yamada for valuable discussions about molecular gas, and the anonymous referee for his or her useful comments. M. I. is supported by Grants-in-Aid for Scientific Research (16740117 and 19740109). Y. T. is financially supported by the Japan Society for the Promotion of Science for Young Scientists. K. K. is supported by the MEXT Grant-in-Aid for Scientific Research on Priority Areas (15071202). NRO is a branch of the National Astronomical Observatory, National Institute of Natural Sciences, Japan. This study utilized the SIMBAD database, operated at CDS, Strasbourg, France, and the NASA/IPAC Extragalactic Database (NED) operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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