1. INTRODUCTION

Galaxy–galaxy mergers are phenomena violent enough to disturb the galactic potentials of both of the colliding galaxies. They create shocked gas at the merging region, make interstellar matter fall into the new galactic potential, and induce strong starbursts. This extreme starburst heats up the surrounding dust, which sometimes radiates $10^{12} \ L_\odot$ or more in infrared luminosity. These sources are often called ultra-luminous infrared galaxies (ULIRGs).

Since molecular gas and dust create stars, observations of these components toward ULIRGs are important for understanding the nature of extreme starbursts. Multiple molecular lines or multiple transition studies revealed that a large fraction of molecular gas in ULIRGs is dominated by dense and warm gas (e.g., Solomon et al. 1992; Gao & Solomon 2004; Papadopoulos et al. 2007). In addition, the efficiency of star formation is tightly correlated with the dense gas fraction in molecular gas (Solomon et al. 1992; Gao & Solomon 2004).

ULIRGs are also important for the study of high-$z$ submillimeter galaxies (SMGs). The Submillimetre Common-User Bolometer Array (SCUBA) on the James Clerk Maxwell Telescope (JCMT) has detected many high-$z$ SMGs (e.g., Hughes et al. 1998; Eales et al. 1999, 2000; Scott et al. 2002; Borys et al. 2003). Most of them have infrared luminosities of $10^{12} \ L_\odot$, and bright ones have $10^{13} \ L_\odot$. Local ULIRGs can be studied as nearby counterparts of high-$z$ SMGs or used as nearby templates to derive photometric redshifts. To compare redshifted emission lines or continuum emission in high-$z$ galaxies to those in local ULIRGs, we need to observe local ULIRGs at the same wavelengths as the rest wavelengths of the detected lines or continuum from the high-$z$ galaxies. Many of the high-$z$ galaxies were observed at millimeter-wave (around 1–3 mm; e.g., Greve et al. 2005; Tacconi et al. 2006). Therefore, the rest wavelengths of the detected lines or continuum are at submillimeter wavelengths. Our knowledge of submillimeter lines or continuum from local ULIRGs, especially from compact starburst regions or from nuclei, is very limited so far, because only recently have high-resolution submillimeter observations been possible.

Here we present the first interferometric $^{12}$CO($J = 6 – 5$) and $435 \ \mu m$ continuum observations of Arp 220 using the Submillimeter Array (SMA; Ho et al. 2004). The interferometric $^{12}$CO($2-1$), $^{13}$CO($2-1$), and $^{18}$O($2-1$) lines and $1.3 \ mm$ (226 GHz) continuum observations have also been made simultaneously with the $^{12}$CO($6-5$) and $435 \ \mu m$ observations. Neither the $^{12}$CO($6-5$) nor $^{18}$O($2-1$) line has ever been observed...
in this galaxy, No. 1, 2009 SMA 12CO(∼)

High gas mass concentration is similar also to numerical simulations (e.g., Hernquist 1992, 1993). The infrared luminosity at 8–1000 μm of this galaxy is 1.6 × 10^{12} L_{\odot} (Sanders et al. 2003), and high spatial resolution radio continuum (Norris 1988), near-infrared (Graham et al. 1990), and mid-infrared (Soifer et al. 1999) observations revealed two nuclei at the center with a separation of ∼ 0′.95 (∼ 370 pc). Molecular gas is very rich in this galaxy, ∼ 9 × 10^9 M_{\odot}, and two-thirds of this mass is concentrated within 400 pc in radius (Scevola et al. 1997). Such high gas mass concentration is similar also to numerical simulation results (e.g., Barnes & Hernquist 1991; Mihos & Hernquist 1996). These observations and numerical simulations indicate that Arp 220 is in the final stage of merging.

Previous high spatial resolution millimeter-wave interferometric observations show molecular gas concentrations at the two nuclei, and these are embedded in an extended (∼ 1 kpc) molecular structure, which seems to be a rotating disk coincident with a dust lane in optical images (Scevola et al. 1997; Downes & Solomon 1998). The molecular gas peak at each nucleus shows a steep velocity gradient with the direction of the gradient different from that of the large-scale molecular gas disk. This suggests that a small-scale molecular gas disk rotates around each nucleus, and both disks are embedded in the large-scale rotating disk (Sakamoto et al. 1999). Recent ∼ 0′.3 molecular gas images resolved the detailed nuclear gas distributions (Downes & Eckart 2007; Sakamoto et al. 2008), which are consistent with the Hubble Space Telescope (HST) NICMOS near-infrared imaging results that suggest an opaque disk around one of the nuclei (Scevola et al. 1998).

Dust emission also peaks at the two nuclei. Sakamoto et al. (1999) reported that most of the continuum flux at 1.3 mm comes from the two nuclei, while Downes & Solomon (1998) mentioned that half of the 1.3 mm continuum flux comes from the extended component. It is suggested that a few tenths of the 860 μm (Sakamoto et al. 2008) and 24.5 μm (Soifer et al. 1999) continuum flux comes from the extended component. Far-infrared observations with the Infrared Space Observatory (ISO) also suggest the existence of extended dust emission (González-Alfonso et al. 2004).

2. OBSERVATIONS AND DATA REDUCTION

We observed the center of Arp 220 with the SMA on 2005 March 2. The phase reference center was at α(2000) = 15°34′57″19 and δ(2000) = 23°30′11″3. The 225 GHz atmospheric opacity was between 0.03 and 0.04, which was measured at the nearby Caltech Submillimeter Observatory. Six of the eight 6 m antennas were used with projected antenna separations between 14 and 68 m. High-frequency receivers were tuned to observe the redshifted 12CO(6-5) line (679.13 GHz) in the lower side band (LSB) and the 689.13 GHz (∼ 435 μm) continuum emission in the upper side band (USB). Low-frequency receivers were tuned to observe the redshifted 13CO(2-1) line (216.47 GHz) and 13C\(^18\)O(2-1) line (215.64 GHz) in the LSB and the redshifted 12CO(2-1) line (226.42 GHz) in the USB. The double sideband system temperature for the high-frequency band ranged from 2000 to 2500 K for most of the time (i.e., at high elevation), and that for the low-frequency band from 140 to 180 K. The SMA correlator covers a 2 GHz bandwidth for each sideband of both high and low-frequency bands, which corresponds to the velocity range of ∼ 880 and ∼ 2700 km s\(^{-1}\) for each sideband of the high and low-frequency bands, respectively. The channel width was configured to have 3.25 MHz (∼ 1.4 km s\(^{-1}\)) and 0.8125 MHz (∼ 1.1 km s\(^{-1}\)) for the high- and low-frequency bands, respectively.

We calibrated the data using the Owens Valley Radio Observatory software package MIR, which is modified for the SMA. For the high-frequency band calibration, we used a partially resolved source, Callisto, as a gain (amplitude and phase) and flux calibrator,\(^{10}\) since quasars were too weak for gain calibration. Callisto was about 50″ away from Arp 220. The rms phase fluctuation was about 21°. We used a source model at the gain calibration to correct for the effect of the partially resolved structure. Bandpass calibration was done using three sources, Mars, Callisto, and Ganymede to gain the signal-to-noise ratio (S/N). Ceres was imaged after the calibrations, and its flux was 22% lower than the calculated flux (see footnote 10). Although the flux error for Ceres was about 20%, we conservatively adopt the flux error of 30% for the high-frequency band data throughout this paper. For the low-frequency band calibration, we used Ceres, which was about 40″ away, as the gain calibrator due to its closeness, and Mars, Callisto, and Ganymede were used as bandpass calibrators. Callisto was imaged after the calibrations, and showed 21% lower than the calculated flux. Hereafter, we adopt the flux error of 20% for the low-frequency band data.

Data from five antennas were used for the 12CO(6-5) line imaging because of a correlator problem. For 435 μm continuum imaging, we used the data from all six antennas after discarding the problematic data. We subtracted the continuum emission from the line emission data before line imaging. Since the 12CO(6-5) line width is comparable with the band width, we could not obtain the continuum emission from the same sideband. We therefore subtracted the continuum emission using the other sideband (i.e., USB) in the uv plane using the National Radio Astronomy Observatory software package AIPS. For the low-frequency (1 mm) data, we created the continuum image using the line-free channels in the same band. The line images for the low-frequency data were made after the subtraction of the continuum emission from the data in the uv plane.

The calibrated data were binned, and the final channel maps have velocity resolutions of about 30 km s\(^{-1}\) for the $^{12}$CO(6-5), $^{13}$CO(2-1), and $^{13}$C\(^18\)O(2-1) lines, and about 5 km s\(^{-1}\) for the $^{12}$CO(2-1) line. We use the radio definition for the local standard of rest (LSR) velocity in this paper, which is \(v_{\text{LSR}} = v_c(1 - \nu/\nu_{\text{rest}})\). The $^{13}$C\(^18\)O(2-1) line was observed up to the LSR velocity of 5550 km s\(^{-1}\), covering about 72% of the full velocity range, which was not an edge of the bandpass.

We CLEANed the images with natural weighting, and the resulting synthesized beam sizes were about 1″ for 690 GHz band images, and about 3″–4″ for 230 GHz band images. The beam sizes and the rms noise levels for all the images are summarized in Table 1. The half-power width of the primary beam at 690 and 230 GHz are 17″ (6.6 kpc) and 52″ (20.1 kpc), respectively. These sizes are much larger than the sizes of the line/continuum emitting regions (at most a few arcseconds), and we did not make any primary beam correction to our images.

Our $^{12}$CO(6-5) images show a systematic position shift of about 0′.7 from the peak positions of the double nucleus reported in the previous observations at longer wavelengths (e.g.,...
Table 1
Parameters for the Continuum and Molecular Line Images

| Wavelength (Frequency) or Line | Synthesized Beam Size and Position Angle (Linear scale) | Velocity Resolution (km s\(^{-1}\)) | RMS Noise (mJy beam\(^{-1}\) (mK)) |
|-------------------------------|---------------------------------------------------------|-------------------------------------|----------------------------------|
| 435 (689.13) µm | 1\(^{\prime\prime}\) × 0\(^{\prime\prime}\)9, 139°  
(470 pc × 350 pc) | ... | 190 (450) |
| 1320 (226.46)  
12CO(6-5) | 3\(^{\prime}\)8 × 3\(^{\prime}\)3, 28°  
(1.47 kpc × 1.28 kpc) | ... | 4.8 (9.1) |
| 1380 (216.46)  
13CO(2-1) | 3\(^{\prime}\)9 × 3\(^{\prime}\)5, 27°  
(1.51 kpc × 1.36 kpc) | ... | 5.7 (11) |
| 13CO(2-1), C\(^{18}\)O(2-1) | 3\(^{\prime}\)9 × 3\(^{\prime}\)5, 27°  
(1.51 kpc × 1.36 kpc) | 30.8 | 13.1 (25) |

3. RESULTS

3.1. 435 µm Continuum Emission

The 435 µm (689 GHz) continuum emission image is shown in Figure 1. The image clearly shows two peaks with a separation of about 1\(^{\prime\prime}\), consistent with the past continuum images in centimeter, millimeter, and infrared wavelengths. We therefore call these peaks eastern and western nuclei as in past studies. Intensities of the western and eastern nuclei are 1.28 ± 0.38 Jy beam\(^{-1}\) and 0.96 ± 0.29 Jy beam\(^{-1}\), respectively. The total flux density of the continuum emission is 2.5 ± 0.8 Jy. Since the flux distribution can be smeared by the phase fluctuation or baseline errors, we convolved the image to larger beam sizes (up to 10\(^{\prime\prime}\) with a Gaussian convolution) and measured the total flux density. It did not change from 2.5 Jy, indicating that the flux smearing effect due to the phase or baseline errors is small. The rms phase fluctuation at this wavelength was indeed only 21\(^{\prime\prime}\) (Section 2), which induces < 0.1\(^{\prime\prime}\) smearing, so it is consistent with this result.

The previously published 450 µm (670 GHz) single dish results show a very large variation in the detected flux densities; the United Kingdom Infrared Telescope (UKIRT) UKT14 result shows the flux density of 3.0±1.1 Jy (Eales et al. 1989), but that of the JCMT SCUBA result shows 6.286 ± 0.786 Jy (Dunne & Eales 2001). We plot the submillimeter (1.5 mm–300 µm or 200–1000 GHz) spectrum energy distribution (SED) using published single dish results in Figure 2. The large crosses in the plot are the data for the total flux densities at various frequencies, and the solid line shows the \(\chi^2\) fitting of the data (see Section 4.1 for details). As shown in the figure, the JCMT SCUBA data point is on the fit, but the UKIRT UKT14 data point is significantly lower than the fit. There is no report for the time variation of flux density at submillimeter wavelength in this galaxy so far. In addition, the measurements for the total flux density in the plot is distributed over three decades, but only 450 µm shows the large difference, which is unlikely to be caused by the time variation. We therefore assume that the JCMT SCUBA value is more accurate. Using the fit, we estimated the total flux density at 435 µm as 5.9 Jy. This suggests that our 435 µm continuum observations missed ~ 58% of the total flux density.

Since this missing flux is larger than our flux error of ~ 30%, and the effect of the flux smearing due to phase or baseline errors is small, this missing flux is probably due to the existence of an extended component. If the missing flux of 3.4 Jy is due to an extended component with a Gaussian distribution that has a...
The kinematics in the west nucleus displays a smaller velocity gradient in our data, probably due to poorer spatial resolution and lower S/N of our data. The detection of the large-scale kinematics feature suggests that our data detected some of the extended (a few arcsecond scale) component, but much less than that detected in $^{12}$CO(1-0), $^{12}$CO(2-1), or $^{12}$CO(3-2) observations (Scoville et al. 1997; Downes & Solomon 1998; Sakamoto et al. 1999, 2008).

The integrated intensity image, on the other hand, displays a single peak that is elongated along the two nuclei, which looks different from our 435 μm continuum image or the previously published high-resolution $^{12}$CO(2-1) and $^{12}$CO(3-2) images (Downes & Solomon 1998; Sakamoto et al. 1999, 2008) at first glance. Our image is rather similar to the low resolution maps of $^{12}$CO(2-1) line (Sakamoto et al. 1999; Scoville et al. 1997) without diffuse and extended (larger than a few arcsecond) emission from their maps. The total integrated $^{12}$CO(6-5) intensity is $1250 \pm 250$ Jy km s$^{-1}$ in our data. Since there is no published result for the $^{12}$CO(6-5) line emission, we could not estimate the missing flux of our $^{12}$CO(6-5) data.

Figure 5 shows the $^{12}$CO(6-5) line spectrum at each nucleus. The peak brightness temperature of the western nucleus is $8.7 \pm 2.6$ K ($3.4 \pm 1.0$ Jy beam$^{-1}$) around the LSR velocity of $\sim 5500$ km s$^{-1}$, and that of the eastern nucleus $6.1 \pm 1.8$ K ($2.4 \pm 0.7$ Jy beam$^{-1}$) around $\sim 5500$ km s$^{-1}$. The overall velocity ranges for the two nuclei are similar to those in the high-resolution $^{12}$CO(2-1) and $^{12}$CO(3-2) observations (Sakamoto et al. 1999, 2008).

3.3. 1.32 and 1.38 mm Continuum Emission

Both 1.32 mm (226.46 GHz) and 1.38 mm (216.46 GHz) continuum emissions are detected at a significant signal level ($\sim 30\sigma$), and the emission is unresolved at both wavelengths at our resolution of 3″-4″ (the 1.32 mm image is shown in Figure 6(a); the 1.38 mm image is almost the same as the 1.32 mm image, and not shown here). The total flux densities for 1.32 and 1.38 mm are $167 \pm 33$ mJy and $160 \pm 32$ mJy, respectively. From the dust continuum fitting (Section 3.1), we estimate the total flux densities at 1.32 and 1.38 mm as 153 ± 3 and 178 mJy (including the non-thermal flux contribution). The observed total flux density therefore agrees with that from the SED fitting within our calibration error. We therefore conclude that our 1.32 and 1.38 mm continuum data have no missing flux.

3.4. $^{12}$CO, $^{13}$CO, and C$^{18}$O J = 2 − 1 Line Emissions

The $^{12}$CO(2-1) line image exhibits an extended structure along northeast and southwest direction even with our low resolution image (Figure 6(b)), which is consistent with the past interferometric maps (Scoville et al. 1997; Downes & Solomon 1998; Sakamoto et al. 1999). On the other hand, the $^{13}$CO(2-1) and C$^{18}$O(2-1) line images (Figures 6(c), (d)) are unresolved at our resolution.

The integrated intensities of the $^{12}$CO, $^{13}$CO, and C$^{18}$O J = 2 − 1 lines are $1430 \pm 290$ Jy km s$^{-1}$, $45.7 \pm 9.1$ Jy km s$^{-1}$, and $31.5 \pm 6.3$ Jy km s$^{-1}$, respectively. Our observation covers only $\sim 72\%$ of the line width of the C$^{18}$O(2-1) line (Section 2), so the derived value should be a lower limit (see also Section 3.5).

We compared the integrated intensities with the single dish results for the $^{12}$CO(2-1) and $^{13}$CO(2-1) lines. The JCMT observations of the $^{12}$CO(2-1) line (21″−22″ resolution) indicate $1730 \pm 350$ Jy km s$^{-1}$ (Wiedner et al. 2002) and $1549 \pm 311$ Jy km s$^{-1}$.
Figure 3. Channel maps of the $^{12}$CO(6-5) line emission. Continuum emission is already subtracted. The LSR velocity (radio definition) in km s$^{-1}$ is shown at the upper left corner of each channel map, and the synthesized beam (1$''$3 × 0$''$.8 or 500 pc × 310 pc) with the P.A. of 129$^\circ$ is shown at the lower left corner of the first channel map. The position offsets are measured from $\alpha$(2000) = 15$^h$34$^m$57$^s$.25 and $\delta$(2000) = 23$^\circ$30$'$11$''$.4. The two crosses in each channel map indicate the 1.3 mm continuum peaks (Sakamoto et al. 1999). The contour levels are $-3$, $3$, $4$, $5$, and $6\sigma$, where $1\sigma = 535$ mJy beam$^{-1}$ ($=1.4$ K).

Figure 4. (a) Integrated intensity (moment 0) and (b) intensity-weighted mean velocity (moment 1) maps of the $^{12}$CO(6-5) line emission. Continuum emission is already subtracted. The position offsets, the synthesized beam, and the crosses are the same as in Figure 3. The contour levels for the moment 0 map are (2, 4, 6, 8, 10, 12 and 14) × 68 Jy beam$^{-1}$ km s$^{-1}$ ($=175$ K km s$^{-1}$). The contour levels for the moment 1 map are $-90$, $-60$, $-30$, $0$, $30$, $60$, $90$, $120$, $150$, and $180$ km s$^{-1}$, where 0 km s$^{-1}$ corresponds to the LSR velocity of 5351 km s$^{-1}$. Zero velocity is shown in thick solid contour, and negative and positive velocities are shown in dashed and solid contours, respectively.

(Greve et al. 2009). The flux differences between our and these observations are within the calibration errors. The $^{13}$CO(2-1) line was observed with the Institut de Radio Astronomie Millimétrique (IRAM) 30 m telescope (11$''$ resolution) and JCMT...
Figure 5. Spectra of the $^{12}$CO(6-5) line at the two nuclei. Continuum emission is already subtracted.

Figure 6. Continuum and line images taken in the low-frequency band. Continuum is already subtracted from the line images. Synthesized beams are shown at the lower left corner of each image, and their sizes are in Table 1. The crosses are the same as in Figure 3. The position offsets are measured from $\alpha(2000) = 15^h34^m57^s24$ and $\delta(2000) = 23^\circ30'11''3$. (a) 1.32 mm continuum. Contour levels are $-3, 3, 5, 10, 20, \text{ and } 30\sigma$, where $1\sigma = 4.8$ mJy. (b) $^{12}$CO(2-1) integrated intensity. The contour levels are 5, 10, 20, 50, 100, 150, \ldots, 350 $\times$ 2.5 Jy beam$^{-1}$ km s$^{-1}$ ($= 4.8$ K km s$^{-1}$). (c) $^{13}$CO(2-1) integrated intensity. The contour levels are 3, 5, 10, 15, 20, and 25 $\times$ 2.1 Jy beam$^{-1}$ km s$^{-1}$ ($= 4.0$ K km s$^{-1}$). (d) C$^{18}$O(2-1) integrated intensity. The contour levels are the same as in the $^{13}$CO(2-1) map.

(21" resolution) (Greve et al. 2009), and they obtained the integrated intensities of $60 \pm 13$ Jy km s$^{-1}$ and $70 \pm 16$ Jy km s$^{-1}$, respectively. The differences between our and these observations are again explained by the calibration errors. We therefore conclude that our $^{12}$CO(2-1) and $^{13}$CO(2-1) line data have no missing flux.

Since there is no single dish C$^{18}$O(2-1) line observation, we cannot estimate the missing flux for this line. On the other hand, since we did not see any significant missing flux in the 1.32 and 1.38 mm continuum data and the $^{12}$CO(2-1) and $^{13}$CO(2-1) line data, we expect no significant missing flux in the C$^{18}$O(2-1) line data.
3.5. Line Spectra and Ratios

To compare the line spectra and intensities of all the four obtained lines, we convolved the data into the largest synthesized beam size of $3.9\times3.5$ resolution with the P.A. of $27^\circ$, which is the beam size of the $^{13}$CO(2-1) and C$^{18}$O(2-1) lines. Figure 7 shows the spectra of all these four lines. Note that the $uv$ coverage is different between $J = 2\rightarrow 1$ lines and the $J = 6\rightarrow 5$ line in this figure.

The $^{12}$CO(2-1) line shows a double peak profile with stronger intensity at lower velocity, which is consistent with the past single dish measurements (Wiedner et al. 2002; Solomon et al. 1990). The line width of the $^{12}$CO(2-1) line reaches 900 km s$^{-1}$ (4900–5800 km s$^{-1}$). The $^{13}$CO(2-1) and C$^{18}$O(2-1) lines exhibit very similar line profiles and intensities. The $^{12}$CO(6-5) line is mostly emitted at higher velocities and is weak at lower velocities. This asymmetry is similar to that of the HCN(4-3) line (Wiedner et al. 2002).

We matched the shortest $uv$ distance between the $^{12}$CO(6-5) and $^{13}$CO(2-1) data to match the spatial structures between these two lines, and measured the $^{12}$CO(6-5)/(2-1) intensity ratio to be 0.34 ± 0.12. This value is much lower than the lower-J ratios, such as $^{12}$CO(3-2)/(2-1) of 0.85±0.24 (Wiedner et al. 2002) or $^{12}$CO(2-1)/(1-0) of 0.65±0.1 (Scoville et al. 1997). This is mostly due to the different line profile of the $^{12}$CO(6-5) line from the lower-J CO lines. This indicates that the lower velocity is dominated by lower-J CO lines, but the higher velocity is rich in higher-J lines. This trend is consistent with the observations of Wiedner et al. (2002) that the $^{12}$CO(3-2) line intensity decreased relative to the $^{12}$CO(2-1) line in the lower velocity part, but stay almost constant at higher velocities.

The relation between the spatial distribution and the velocities of the molecular gas in this galaxy is, however, not simple; all the molecular gas components in this galaxy, namely the two nuclei and the extended component, have low and high velocities (Figure 5; see also Sakamoto et al. 1999, 2008). It is therefore difficult to tell which component contributes to high or low excitation condition only from the large-scale line spectra. The $^{12}$CO transition ratios for each nucleus is derived in Section 4.3.

The $^{12}$CO(2-1)/$^{13}$CO(2-1) line ratio is 13.0 ± 3.7 at our resolution of $3.9\times3.5$. We also convolved our data to 13$^\circ$ resolution ($\approx$ single dish resolution), and the ratio was 16.2 ± 4.6. These values are similar or slightly lower than the values observed in U/LIRGs, and similar or somewhat higher than starburst or Seyfert galaxies; the $^{12}$CO(2-1)/$^{13}$CO(2-1) line ratios in U/LIRGs observed with single dish telescopes are 23.5 ± 4 (Casoli et al. 1992) and 16 ± 8 (Glenn & Hunter 2001), and those in starburst and Seyfert galaxies are 13 ± 5 (Aalto et al. 1995) and 13 ± 1 (Papadopoulos & Seaguest 1998), respectively.

The line profiles and the line intensities of the $^{13}$CO(2-1) and C$^{18}$O(2-1) are almost identical (Figure 7), and the $^{13}$CO(2-1)/C$^{18}$O(2-1) line intensity ratio is 1.0 ± 0.3 between the velocity range of 4800 and 5550 km s$^{-1}$, which is the velocity range we observed the C$^{18}$O(2-1) line (Section 2). The $^{13}$CO(2-1) line has 92% of its total integrated intensity in this velocity range, so the result with the full line width will not change significantly. This very low $^{13}$CO(2-1)/C$^{18}$O(2-1) intensity ratio matches very well with $^{13}$CO(1-0)/C$^{18}$O(1-0) = 1.0 ± 0.3 (Greve et al. 2009). We discuss this ratio in Section 4.4.

4. DISCUSSION

4.1. Dust Emissivity Index and Dust Opacity of the Two Nuclei

We plot in Figure 8 the flux ratios between the two nuclei as a function of frequency. Although our continuum data have ~30% of calibration errors and a large amount (~60%) of missing flux, the flux density ratio between the two nuclei is accurate, since it depends on the noise level of the map. Hence, this flux ratio diagram has higher accuracy than the SED diagrams shown in Figure 2. The flux ratio in our data is 0.75 ± 0.19. If we assume that the missing flux of our data is due to the extended emission (see Section 3.1), the size of the extended emission is larger than the separation of the two nuclei. Therefore, the correction of the missing flux will increase both the fluxes of the two nuclei with almost the same amount, and the flux ratio increases toward unity, namely the ratio derived...
above is the lower limit. Contamination of the flux from one
nucleus to the other due to the large beam size is small; this
effect lowers the ratio by ~ 6%, which is smaller than the
calibration errors. As frequency goes down to ~ 200 GHz, the
flux ratio also goes down, and the flux of the eastern nucleus is
about half or less of that of the western nucleus. Since the data
for the two lower frequencies may not have significant missing
flux (e.g., Sakamoto et al. 1999, 2008), the difference between
the ratio at 689 GHz and those at lower frequencies will be
more pronounced if we correct for the missing flux of the 689
GHz data. Since the emission at these frequencies is dominated
by dust emission, this result suggests that the dust SEDs are
different between the two nuclei.

We then made continuum SEDs for the two nuclei at submilli-
meter wavelength (Figure 2) as well as that for the total flux
density to discuss the dust property differences more quantita-
tively. The crosses, filled squares, and filled diamonds in the
plot are the data for the total flux density, east nucleus, and west
nucleus, respectively. The crosses, filled squares, and filled diamonds in the
plot are the data for the total flux density, east nucleus, and west
nucleus, respectively. The solid, dashed, and dotted lines are the χ² fitting of the data with a function ϵB(Td), where B(Td)
is the Planck function for temperature Td and ϵ is the emissivity
function. We adopted a form ϵ = 1 - exp(-[ν/νc]β); νc is the critical frequency where the opacity is unity, and β is the emissivity index. We adopted the source sizes of 0.′′13 for the eastern nucleus and 0.′′16 × 0.′′13 for the western nucleus
(Sakamoto et al. 2008), since their images have the highest spa-
tial resolution at the highest frequency around submillimeter wavelengths. For the source size of the total flux density, we
adopted the deconvolved size of the extended 12CO(2-1) emis-
sion of 1.′94 × 1.′28 (Scoville et al. 1997). The flux density for the non-thermal component is subtracted from all the fluxes in the plots before the fitting, following the method explained in
Scoville et al. (1991), although it is not significant especially at high frequencies; about several milli-Jy or several percent of the
flux around 200–300 GHz, and even smaller at 600–700 GHz.
We also estimated the CO flux contamination into the total flux, but most of the data are affected for only a few percent, and the
fitting result did not change. The fitting results are summarized
in Table 2.

We obtained from the fit to the total flux density Td of 51 K
and β of 1.4, which are consistent with the past estimates of
Td ~ 40–60 K with β ~ 1.2–2.0 (Scoville et al. 1991; Downes
& Solomon 1998; Dunne & Eales 2001; Klass et al. 2001).
The critical frequency is estimated to be 2200 GHz (~ 140 μm),
which is also consistent with the estimation that dust is already
optically thick at ~ 100 μm (Scoville et al. 1991; Klass et al.
2001). If we adopt a smaller source size for the total flux of
1.′13 (Scoville et al. 1997), Td, β, and νc would be 66 K, 1.3,
and 2000 GHz (~ 0.15 μm), respectively. The temperature is
slightly higher, but the critical frequency and the emissivity
index are still consistent with the past estimates.

The fitting for the two nuclei gives high temperatures of 83
and 180 K for the east and west nuclei, respectively. These high
temperatures are due to the small source sizes. The emissivity
indices are different between the two nuclei, 2.1 for the eastern
class and 1.2 for the western nucleus. The critical frequencies
are estimated to be 370 GHz (~ 810 μm) for the eastern nucleus
and 190 GHz (~ 1.6 mm) for the western nucleus.

The large uncertainties in our fitting for the two nuclei are
the source flux density and the adopted source size. If we increase the 689 GHz flux density of each nucleus by 30%,
which corresponds to the calibration error of our data may have
(Section 2), the fitting results would be Td = 120 K and 310 K,
β = 1.8 and 0.7, and νc = 520 GHz (~ 580 μm) and 610 GHz
(~ 490 μm) for the eastern and western nuclei, respectively. We adopted the source size derived at 860 μm (Sakamoto et al.
2008), but the effective source size at 435 μm may be different from that at 860 μm. This is because the opacity is
wavelength dependent, and therefore the effective source size is
also wavelength dependent. Ideally we need to determine the source size at each wavelength, but our spatial resolution at
435 μm is too low for this. Since opacity is higher at shorter
wavelength, the effective source size at 435 μm may be larger
than what we adopted. If we increase the source size (area)
of each nucleus by 50%, which roughly corresponds to the
deconvolved size of the double nucleus in our data, the fitting
results would be Td = 49 K and 97 K, β = 2.1 and 1.1, and νc = 400 GHz (~ 750 μm) and 210 GHz (~ 1.4 mm) for the
eastern and western nuclei, respectively.

The fitting results, with the uncertainties, indicate that the dust
temperature, the emissivity index, and the critical frequency
for the eastern nucleus are better constrained than the past
observations, because of our high-frequency observations with
high spatial resolution. The eastern nucleus seems to have a
warm temperature of 49–120 K, a steep emissivity index of
~ 2, and becomes optically thick at frequencies above ~ 400 GHz. Sakamoto et al. (2008) derived a dust temperature
of 30–160 K, so our estimate narrows the range. They also
estimated the 350 GHz opacity of 2.8 for β = 2 (and 0.8 for
β = 1), hence our result is somewhat lower, but still both results
indicate a high opacity condition at submillimeter wavelengths
in the eastern nucleus.

The emissivity index and the critical frequency for the western
nucleus are less constrained than those for the eastern nucleus,
but are better constrained than the past observations. Our fitting
results indicate a shallow emissivity index of about unity and a
low critical frequency of < 600 GHz. Downes & Eckart (2007)
estimated the 230 GHz opacity as ≥ 0.7 and Sakamoto et al.
(2008) estimated the 350 GHz opacity as 0.8–5.3 for β = 2 (the
estimated ranges depend on the source size and the flux errors).
Both of these observations and our results indicate the western
nucleus is optically thick at submillimeter wavelengths.

The fitted temperature for the western nucleus, on the other
hand, has a large range, and therefore it does not set a tighter limit
than the past estimations. It appears that the western nucleus is
warmer than the eastern nucleus, with dust temperatures of a

| Source          | Dust Temperature Td (K) | Emissivity Index β | Critical Frequency (Wavelength) νc (GHz (μm)) |
|-----------------|-------------------------|--------------------|-----------------------------------------------|
| Arp 220 (total) | 51–66                   | 1.3–1.4            | 2000–2200 (~ 140–150)                         |
| East nucleus    | 49–120                  | 1.8–2.1            | 370–520 (~ 580–810)                           |
| West nucleus    | 97–310                  | 0.7–1.2            | 190–610 (~ 0.90–1600)                         |
| Extended component | ~ 38                   | ~ 2.4              | ~ 1500 (~ 200)                                |
few hundred Kelvin. Downes & Eckart (2007) suggested a dust temperature of 170 K, and Sakamoto et al. (2008) derived a temperature of 90–180 K, hence our estimate is consistent.

Our results indicate that the derived properties, especially the emissivity, indices are different between the two nuclei, suggesting that the dust properties, such as dust size distributions or dust compositions, are different. This difference may reflect the dust properties of the original host galaxies of each nucleus, or the difference in activities, such as star formation or AGN.

### 4.2. Extended Component in the Dust Emission

Our 435 μm (689 GHz) continuum data missed a significant amount (≈ 61%) of the total flux. Here, we discuss whether this missing flux can be attributed to an extended component in the dust emission. The molecular gas clearly has an extended component with a size of ∼ 1 kpc, which is interpreted as a molecular gas disk from the gas kinematics (Scoville et al. 1997; Downes & Solomon 1998; Sakamoto et al. 1999). In dust emission, on the other hand, the extended component is weakly detected or not detected at a significant signal level. At 1.3 mm, Downes & Solomon (1998) suggested that the flux of 55 ± 11 mJy can be attributed to the flux from the extended component, but Sakamoto et al. (1999) did not detect any significant emission from the extended component. At 860 μm, Sakamoto et al. (2008) attributed about 25% of the total flux density emission from outside the two nuclei.

Assuming that all of the missing flux of our 435 μm continuum data is from the extended component, we derived the dust properties of this extended component using the χ² fitting mentioned above using the data between 1.3 mm and 435 μm. We adopt for the size of this component the same size as Tₐ ∼ 38 K, β ∼ 2.4, and the νₑ ∼ 1500 GHz (∼ 200 μm). These values are roughly consistent with the values derived by González-Alfonso et al. (2004) using ISO LWS data; they derived for the extended component Tₐ ∼ 50 K, νₑ ∼ 3000 GHz (∼ 100 μm), and a source size of ∼ 1.8–1.9′ (these values vary depending on their models) assuming β = 2.0. These results suggest that a significant amount (> 50%) of 435 μm flux is in the extended component as mentioned in Section 3.1, contrary to the longer wavelengths where continuum is dominantly from the two nuclei.

A recent SMA U/LIRG survey shows that many of the sample galaxies (nine out of 14) have large missing fluxes (typically 50–80%) in 880 μm continuum emission, even though many of the galaxies also show compact distributions. This result suggests that many of ULIRGs have extended continuum emission with very luminous compact cores (Wilson et al. 2008), similar to the results of Arp 220.

### 4.3. Excitation Conditions of Molecular Gas in the Two Nuclei

We made 12CO SEDs of the two nuclei using our 12CO(6-5) data with the interferometric 12CO(2-1) and 12CO(3-2) data (Sakamoto et al. 1999, 2008) to study the 12CO excitation conditions. We first matched the shortest ν distance for all three data sets, and imaged at the same synthesized beam size of 1.3 x 0.8′ with PA of 129°., which is the same spatial resolution as our 12CO(6-5) image. The integrated intensities and line ratios of these three lines for each nucleus are listed in Table 3, and the relative 12CO intensities of various transitions are shown in Figure 9 for each nucleus.

The decrease of 12CO intensities toward higher-J in the western nucleus is smaller than that in the eastern nucleus, and indeed the intensity ratios are higher for the western nucleus than those for the eastern nucleus. These differences are, however, within observational errors. Thus the difference in the excitation conditions of molecular gas between the two nuclei is not significant.

To discuss the excitation conditions more quantitatively, we estimated the excitation conditions of the molecular gas using the large-velocity-gradient (LVG) approximation (Goldreich & Kwan 1974). The collision rates for CO of < 100 K were taken from Flower & Launay (1985) and of ≥ 250 K were from McKee et al. (1982). In these calculations, we assume that all the 12CO emission comes from the same region (i.e., one-zone model), and assume the 12CO relative abundance over velocity gradient, Z_(12CO)/(dv/dr), of 5 × 10⁻³ (km s⁻¹ pc⁻¹)⁻¹. In Figure 9(a), we overplotted two kinds of curves, one (dashed lines) is to see the temperature dependence (we fixed n_H₂ of 10³.6 cm⁻³), and another (dotted lines) is to see the number density dependence (we fixed Tₖ of 50 K). We only plotted the curves close to upper or lower limits to show the possible ranges of the excitation conditions and the goodness of the fitting. Under the above LVG assumptions, it is estimated that the eastern nucleus has a molecular gas temperature of 30–250 K, or a density of 10³.5–⁷.2 cm⁻³. For the western nucleus, we could only derive the lower limits, which are ≥ 40 K for temperature and ≥ 10³.5 cm⁻³ for density. As mentioned above, the estimated molecular gas conditions for the two nuclei overlap, but the western nucleus tends to have higher temperature or density than the eastern nucleus. This tendency is similar to that derived from the dust SED fitting (Section 4.1). Indeed, the derived molecular gas and dust temperatures for both nuclei match well. This suggests that both the molecular gas and dust reside at similar regions and in thermal equilibrium.

We also calculated the dependence of our results on Z_(12CO)/(dv/dr). If we decrease Z_(12CO)/(dv/dr) by an order of magnitude (i.e., decrease the 12CO relative abundance or increase the velocity gradient or both; we fixed n_H₂ of 10³.0 cm⁻³ or Tₖ of 100 K), the temperature or the density increases by about a factor of a few in both nuclei. If we increase Z_(12CO)/(dv/dr) by an order of magnitude (we fixed n_H₂ of 10³.4 cm⁻³ or Tₖ of...
the center to the outer region (Petitpas & Wilson 2000), and the a few hundred pc, and that in BR 1202–0725 is averaged over two nuclei of Arp 220 and in M82 are averaged over the central active star formation inside. The excitation conditions in the physical conditions derived above is more similar to those of the Galactic center (normal and quiescent galaxy), M82 (nearby starburst galaxy), Mrk 231 (evolved ULIRG with an AGN at the nucleus), and BR 1202–0725 (radio-quiet and CO bright high-z quasar at z of 4.69) together with the $^{12}$CO SEDs for the Arp 220 nuclei. The brightness temperatures of the Galactic center quickly decrease with the increase of rotational transitions, but those of BR 1202–0725, M82, and Mrk 231 stay almost constant even at high-J transitions. We overplotted the best fit temperature curves on each source for comparison (as shown in Figure 9(a), higher temperature can be replaced with higher density). The Galactic center can be modeled well with low temperature (or low density) conditions, but other galaxies are explained with higher temperatures (or higher densities). The two nuclei of Arp 220 are similar to these higher temperature (density) galaxies, and different from the Galactic center. This suggests that the molecular gas excitation condition in the double nucleus of Arp 220 is similar to these galaxies. Note that the $^{12}$CO SED up to $J = 6 − 5$ or $7 − 6$ data with the current accuracy are not enough to distinguish the excitation conditions between these high temperature (density) galaxies, including the two nuclei of Arp 220. Higher accuracy or higher-J observations are needed to differentiate the excitation conditions of these galaxies.

It is known that Arp 220, M82, and BR 1202–0725 have active star formation inside. The excitation conditions in the two nuclei of Arp 220 and in M82 are averaged over the central a few hundred pc, and that in BR 1202–0725 is averaged over several kpc. M82 has a gradient in the physical conditions from the center to the outer region (Petitpas & Wilson 2000), and the physical conditions derived above is more similar to those of the center, where the starburst region exist. BR 1202–0725 has two sources, north and south, and the southern source may consist of two sources (Carilli et al. 2002), probably interacting with each other. The similar excitation conditions of molecular gas regardless of the observed regions suggests that the observed molecular gas is biased toward the gas closely related to the star forming regions, and the effect of star forming activities to the exciting conditions of surrounding molecular gas is similar.

Our $^{12}$CO SEDs are compared with those of other galaxies in Figure 9(b). We plotted the multi-J $^{12}$CO intensities of the Galactic center (normal and quiescent galaxy), M82 (nearby starburst galaxy), Mrk 231 (evolved ULIRG with an AGN at the nucleus), and BR 1202–0725 (radio-quiet and CO bright high-z quasar at z of 4.69) together with the $^{12}$CO SEDs for the Arp 220 nuclei. The temperature or the density decreases by about a factor of a few. Therefore, a small (within an order of magnitude) change in $Z(^{12}$CO)/($dv/dr$) does not change the result significantly.

The $^{12}$CO SED study can also be a useful tool to search for AGN(s), since the nearby Seyfert galaxies exhibit strong enhancement of higher-J $^{12}$CO lines toward AGNs (e.g., Matsushita et al. 2004; Hsieh et al. 2008). Figure 9(b) exhibits, however, that the $^{12}$CO SED of the AGN hosting ULIRG Mrk 231 does not display any higher-J enhancement, and $^{12}$CO SED comparison between Mrk 231 and the two nuclei of Arp 220 shows no clear difference. In addition, the comparison between Mrk 231, starburst dominated galaxies M82 and BR 1202–0725 also show no clear difference. We therefore could not find any evidence of an AGN in Arp 220 from this $^{12}$CO SED study. These results suggest that the AGN contribution to the surrounding molecular gas (at least for Mrk 231) is much smaller than the nearby Seyferts, possibly due to the smoothing effect by a larger (linear scale) beam or to a larger opacity effect toward the AGN.

4.4. Molecular Gas Abundance Anomaly in the Central Region of Arp 220?

As mentioned in Section 3.5, we obtained a very low $^{13}$CO(2-1)/$^{13}$O(2-1) line intensity ratio of about unity. Recent SMA observations toward nearby active star forming galaxies (NGC 253, NGC 1365, and NGC 3256) show $^{13}$CO(2-1)/$^{15}$O(2-1) ratios of ~ 4 (Sakamoto et al. 2006a, 2006b, 2007). The $^{13}$CO(1-0)/$^{13}$O(1-0) line ratios in nearby galaxies are ~ 4 (Sage et al. 1991), similar to the $J = 2 − 1$ ratios. If both the $^{13}$CO and the $^{18}$O lines are optically thin, the $^{13}$CO/$^{18}$O line ratios for $J = 2 − 1$ and $J = 1 − 0$ are expected to have almost the same values. Some of interferometric $^{13}$CO and $^{18}$O observations of nearby galaxies show $^{13}$CO/$^{18}$O ratio of about 2 (Meier & Turner 2004; Chou et al. 2007), but not unity as in Arp 220 (note that some regions observed by Meier & Turner show the $^{13}$CO/$^{18}$O ratios of about unity, but the S/Ns are low). The intensity ratio of about unity in Arp 220 is therefore unusual compared with those in other galaxies.

The intensity ratio may be closely related to the abundance ratio; the intensity ratio is expected to be similar to the abundance ratio, if both lines are optically thin. The abundance ratio

![Figure 9. Rotational transition dependence of the $^{12}$CO brightness temperatures (SEDs) of the double nucleus in Arp 220 and those of other galaxies. The horizontal axis is the upper rotational transition levels of the $^{12}$CO lines and the vertical axis is the brightness temperatures of the $^{12}$CO lines on an arbitrary scale. We fixed the $Z(^{12}$CO)/($dv/dr$) of 5 x $10^{-4}$ (km s$^{-1}$ pc$^{-1}$)$^{-1}$. (a) Arp 220 $^{12}$CO SED of each nucleus overplotted with the LVG calculation results. Dashed lines are for two temperatures at a density of 10$^{3.6}$ cm$^{-3}$. Dotted lines are for two densities at a temperature of 50 K. (b) $^{12}$CO SED of Arp 220 and other galaxies. The multi-J $^{12}$CO data of the Galactic center (7| < 2.5') are taken from Fixsen et al. (1999), and those of M82 and Mrk 231 are compiled by Weiß et al. (2005) and Papadopoulos et al. (2007), respectively. The $^{12}$CO data of BR 1202–0725 are taken from the following papers: $J = 1 − 0$: Riechers et al. (2006), $J = 2 − 1$: Carilli et al. (2002), $J = 4 − 3$, $J = 7 − 6$: Omont et al. (1996), and $J = 5 − 4$: Ohta et al. (1996). The best fitted molecular gas temperature curves, made from LVG calculations for a density of 10$^{3.8}$ cm$^{-3}$, are also overplotted for reference.

![Figure 9(a)](image1)

![Figure 9(b)](image2)
between $^{13}$CO and C$^{18}$O in our Galaxy is 5.5 for the solar system and 12.5 for the Galactic center, and that in external galaxies is 3–5 (Henkel & Mauersberger 1993), assuming $[^{13}\text{CO}]/[^{18}\text{O}] = [^{13}\text{C}]/[^{12}\text{C}] \times [^{18}\text{O}]/[^{18}\text{O}]$. Indeed, the abundance ratios and the aforementioned intensity ratios for external galaxies are similar. The intensity ratio of about unity is unusual also from the abundance viewpoint.

Here, we discuss possible reasons for this low intensity ratio using the LVG calculations. We assume both $^{13}$CO and C$^{18}$O molecules are located at the same region (one-zone model). Note that since the brightness temperatures are different between these two lines and the $^{12}$CO(2-1) line (see Figure 7), it is evident that these two lines and the $^{12}$CO(2-1) line emanate from different regions. We also assume that the $[^{13}\text{CO}]/[^{18}\text{O}]$ relative abundance ratio of 4 (Wang et al. 2004). Under this relative abundance ratio, both lines have to be optically thick for the line ratio to be unity. We calculated assuming $Z(^{13}\text{CO})/(dv/dr)$ of $1 \times 10^{-5}$, $1 \times 10^{-6}$, and $1 \times 10^{-7}$ (km s$^{-1}$ pc$^{-1}$)$^{-1}$, $Z(^{13}\text{CO})/(dv/dr)$ of $1 \times 10^{-6}$ (km s$^{-1}$ pc$^{-1}$)$^{-1}$ can be explained as the Galactic abundances of $[^{13}\text{CO}]/[^{18}\text{O}] = 1 \times 10^{-6}$ (Solomon et al. 1979) with the velocity gradient of 1 km s$^{-1}$ pc$^{-1}$. Other parameters are the same as in Section 4.3.

The calculation results are shown in Figure 10. In the case of $Z(^{13}\text{CO})/(dv/dr)$ of $1 \times 10^{-6}$ (km s$^{-1}$ pc$^{-1}$)$^{-1}$, a high density of $n_{\text{H}_2} > 1 \times 10^4$ cm$^{-3}$ is needed even for $T_\text{K}$ of 10 K, and about an order higher density is needed for 100 K to realize the $^{13}$CO(2-1)/C$^{18}$O(2-1) ratio of 1.0 ± 0.3. This is because both the $^{13}$CO and C$^{18}$O lines easily become optically thin at lower-$J$ with the increase of temperature, since the population moves to higher-$J$. To compensate this, the density, and therefore the column density per unit velocity, $N(^{13}\text{CO} \text{or C}^{18}\text{O})/dv = Z(^{13}\text{CO} \text{or C}^{18}\text{O})/(dv/dr) \times n_{\text{H}_2}$, also has to be high for both lines to be optically thick. If we increase $Z(^{13}\text{CO})/(dv/dr)$ by an order of magnitude, the density decreases by about a factor of several at a certain temperature. This is because the increase of $Z(^{13}\text{CO})/(dv/dr)$ makes the line easier to be optically thick. The response will be opposite if we decrease $Z(^{13}\text{CO})/(dv/dr)$ by an order of magnitude.

In the case of a lower $[^{13}\text{CO}]/[^{18}\text{O}]$ relative abundance ratio of 2 (half the abundance ratio used above with increasing [C$^{18}$O]), the required density for the ratio of 1.0 ± 0.3 is about an order of magnitude lower at a certain temperature (Figure 10). This is because the C$^{18}$O abundance increased from the above condition, the opacity and therefore the intensity of the C$^{18}$O line become similar to that of the $^{13}$CO line.

As shown above, the important parameters for the low $^{13}$CO(2-1)/C$^{18}$O(2-1) ratio are (1) the molecular gas density and hence the column density per unit velocity, and (2) the molecular abundance. First, we discuss the gas density. The molecular gas density needs to be high ($\gtrsim 10^5$ cm$^{-3}$) for the ratio to be around unity. The molecular gas in Arp 220 indeed contains high density gas, which is supported by the observations of high critical density molecules, such as HCN, HCO$^+$, or CS (e.g., Solomon et al. 1990, 1992; Greve et al. 2009). On the other hand, there are many galaxies with the detections of these high critical density molecular lines, but almost no report of a $^{13}$CO(2-1)/C$^{18}$O(2-1) $\sim$ 1 so far. One possibility of the difference between Arp 220 and other galaxies may be due to the large fraction of dense molecular gas. Our $^{13}$CO(2-1) and C$^{18}$O(2-1) images exhibit compact distribution around the double nucleus, and the molecular gas in Arp 220 is dominated by dense gas (e.g., Greve et al. 2009). If the dense gas is concentrated toward the double nucleus, most of the molecular gas toward the double nucleus can be dominated by dense gas, and this makes the column density high enough to result in the $^{13}$CO(2-1)/C$^{18}$O(2-1) of unity.

Second, we discuss the molecular abundance. To realize the $^{13}$CO(2-1)/C$^{18}$O(2-1) intensity ratio of about unity with changing the abundance, two possibilities can be considered; one is the underabundance of the $^{13}$CO molecule, and another is the overabundance of C$^{18}$O. Deficiency of $^{13}$CO abundance is often suggested in merging galaxies based on their larger $^{12}$CO(2-1)/$^{13}$CO(2-1) ratios than those in starburst or Seyfert galaxies (e.g., Aalto et al. 1991; Casoli et al. 1992). But as is mentioned in Section 3.5, the observed $^{12}$CO(2-1)/$^{13}$CO(2-1) ratio of Arp 220 is not as extreme as those in the other merging galaxies, and not significantly different from those in starburst or Seyfert galaxies. In addition, the possible reason for the $^{13}$CO deficiency is the selective photodissociation of the $^{13}$CO molecules (e.g., Casoli et al. 1992). In this case, however, C$^{18}$O molecules will be more affected by the selective photodissociation (van Dishoeck & Black 1988; Casoli et al. 1992), hence this cannot be the cause. We therefore think that the underabundance of $^{13}$CO is possible, but less likely.

The overabundance of the C$^{18}$O molecule may be possible to achieve under the circumstance of Arp 220. Massive stars synthesize a large amount of the primary element, $^{12}$C, at helium burning phase, and it goes into interstellar medium via supernova (SN) explosions (Casoli et al. 1992). The $^{18}$O enrichment occurs also in massive stars (Sage et al. 1991; Henkel & Mauersberger 1993), either Wolf–Rayet stars or Type II SN explosions by partial helium burning (Amari et al. 1995). Since Arp 220 is very active in star formation (Section 1), both the $^{12}$C and $^{18}$O enrichment due to the above mechanism can be realized. This can lead to the enrichment of the C$^{18}$O molecule. This possibility still needs to be studied quantitatively. Note that a recent molecular gas abundance study toward a young (several Gyr old) galaxy at $z = 0.89$ show low $[^{13}\text{CO}]/[^{18}\text{O}]$ of 1.9 ± 0.2 (Muller et al. 2006). This result also suggests that the low intensity ratio is related to an abundance anomaly during the young star formation epoch.

Figure 10. The LVG calculation results for the $^{13}$CO(2-1)/C$^{18}$O(2-1) ratio as a function of $N_2$ number density and kinetic temperature. Solid, dashed, and dotted lines are the $^{13}$CO(2-1)/C$^{18}$O(2-1) ratios with $Z(^{13}\text{CO})/(dv/dr)$ of $1 \times 10^{-6}$, $1 \times 10^{-5}$, and $1 \times 10^{-5}$ (km s$^{-1}$ pc$^{-1}$)$^{-1}$, respectively, under the $[^{13}\text{CO}]/[^{18}\text{O}]$ relative abundance ratio of 4. Dot-dashed lines are the $^{13}$CO(2-1)/C$^{18}$O(2-1) ratios with the $[^{13}\text{CO}]/[^{18}\text{O}]$ relative abundance ratio of 2 under $Z(^{13}\text{CO})/(dv/dr)$ of $1 \times 10^{-6}$ (km s$^{-1}$ pc$^{-1}$)$^{-1}$.
5. CONCLUSIONS

We observed the central region of Arp 220 in the $^{12}$CO(6-5), $^{12}$CO(2-1), $^{13}$CO(2-1), and C$^{18}$O(2-1) lines, and 435 $\mu$m and 1.3 mm continuum simultaneously with the SMA. The two nuclei are clearly resolved in the 435 $\mu$m image, and kinematically resolved in the $^{12}$CO(6-5) image.

For the double nucleus, we concluded as follows:

1. The difference of the peak intensities in our 435 $\mu$m image between the two nuclei is smaller than at longer wavelengths. From the dust SED fitting, the dust in the two nuclei is estimated to be optically thick at 435 $\mu$m. The emissivity indices are estimated to be $\sim 2.0$ for the eastern nucleus and $\sim 1.0$ for the western nucleus. This suggests that the dust properties, such as dust size distributions or dust compositions, are different between the two nuclei.

2. The $^{12}$CO SEDs are similar between the two nuclei with the western nucleus having higher upper limits in the excitation conditions than those in the eastern nucleus. The $^{12}$CO SEDs for both nuclei and that of M82 or BR 1202–0725 are similar, characterized with small intensity decreases up to $J = 6 - 5$ ($^{12}$CO(6-5)/2-1) ratio of about 0.5. This suggests that the molecular gas in the two nuclei of Arp 220 has the similar excitation conditions as that in M82 or BR 1202–0725, which have a density of $\gtrsim 10^{3.3}$ cm$^{-3}$ or a temperature of $\gtrsim 30$ K.

3. We could not find any evidence of an AGN in Arp 220 with the $^{12}$CO SED study. There is no clear difference in the $^{12}$CO SEDs between the AGN hosting ULIRG Mrk 231 and the double nucleus of Arp 220 (and therefore M82 and BR 1202–0725). This suggests that the AGN heating is not important for molecular gas excitation conditions in the large scale (a few hundred to a few kpc scale).

For the global characteristics of the molecular gas and dust in Arp 220, we concluded as follows:

1. Based on the large amount of missing flux in our data and other previously published evidence in molecular gas and dust, we suggest the existence of an extended component in the dust emission with its dust properties, such as dust size distributions or dust compositions, are different between the two nuclei.

2. The $^{12}$CO(2-1) line spectrum shows stronger line intensity at the lower velocities than the higher velocities, but the spectra of the higher-J lines show the opposite, indicating that the higher velocity gas has higher density, higher temperature, or both, than the lower velocity component.

3. The intensities of the $^{13}$CO(2-1) and C$^{18}$O(2-1) lines are similar. This suggests that the molecular gas in Arp 220 is dense enough to be optically thick in both lines, or the abundance of either line deviates from the values in other nearby galaxies. To explain the ratio with the density effect, Arp 220 should have molecular gas largely dominated by dense gas, more than in other nearby galaxies. Underabundance of $^{13}$CO is possible, but it is less likely. Overabundance of C$^{18}$O is also possible, considering the $^{12}$C and $^{18}$O enrichment by high mass stars.

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