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N Z Scoville

Min S. Yun, *University of Massachusetts - Amherst*

P M Bryant

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ARCSECOND IMAGING OF CO EMISSION IN THE NUCLEUS OF ARP 220

N. Z. SCOVILLE,¹ M. S. YUN,^{1,2} AND P. M. BRYANT¹

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ABSTRACT

We report high-resolution ($1''$) imaging of CO (2–1) and dust continuum emission in the ultraluminous galaxy Arp 220. The CO (1–0) line was also imaged at $2''$ resolution for comparison. Both data sets recover essentially all of the observed single-dish line emission. Our aperture synthesis maps reveal for the first time, multiple components in the dense gas: peaks corresponding to each of the double nuclei (separated by $0''.95$ at P.A. = 101°) seen in the near infrared and radio continuum and a more extended disklike structure at P.A. = 53° , similar to the dust lane seen in optical images. Approximately two-thirds of the total CO emission (and presumably the H_2 mass) coincides with the compact double nucleus region. The ISM associated with these nuclear sources is most apparent in the 1.3 mm dust continuum emission, but the brightest CO (2–1) emission is also correlated with the near infrared nuclei and exhibits a radial velocity difference of $250\text{--}300\text{ km s}^{-1}$ between the two nuclei. The latter is in excellent agreement with published near-infrared recombination line measurements. The observed velocity difference between the two nuclei is probably much less than their orbital velocity because the nuclei do not lie along the kinematic major axis of the inner disk. The elongated disk feature exhibits a monotonic velocity gradient parallel to the major axis of the CO intensity distribution with the highest receding velocities in the southwest and the highest approach velocities in the northeast. From the major/minor axis ratio (0.66), we infer that the disk is moderately inclined to the line of sight ($i = 40\text{--}50^\circ$).

Detailed modeling of the CO line profiles using a Doppler image-deconvolution technique, analogous to Doppler radar imaging, yields a best-fit CO emissivity distribution and rotation curve which are mutually consistent in the sense that if the total mass distribution follows the CO emissivity, then it yields the derived rotation curve. The implied CO-to- H_2 conversion ratio is 0.45 times the Galactic value if the bulk of the mass resides in the molecular gas, rather than stars. This value is also consistent with that expected based on the likely molecular density and temperature in the nuclear disk of Arp 220. The total molecular gas mass for Arp 220 is $\sim 9 \times 10^9 M_\odot$ with an uncertainty of $\sim 30\%$ based on the line profile modeling. The peak gas surface density is $\sim 5.8 \times 10^4 M_\odot \text{ pc}^{-2}$ at 130 pc radius, while the two stellar nuclei are at ~ 235 pc radius and at position angle midway between the major and minor axes of the gaseous disk. From the profile modeling we derive an intrinsic velocity dispersion in the disk of $90 \pm 20 \text{ km s}^{-1}$ and thus a disk thickness (FWHM) of only 16 pc, assuming the disk is in hydrostatic equilibrium. With $5.4 \times 10^9 M_\odot$ of molecular gas concentrated in the very thin disk associated with the twin nuclei, the mean density will be $n_{H_2} \simeq 2 \times 10^4 \text{ cm}^{-3}$ ($\pm 30\%$), a value which is consistent with the strong molecular emission from high dipole moment molecules such as HCN and HCO^+ . From the high brightness temperatures of the observed CO emission (17–21 K), we conclude that the area filling factor of the disk is very high ($\simeq 0.25$) and therefore the gas must fairly uniformly fill the disk, rather than being in discrete self-gravitating clouds. This thin central disk will have inward accretion at $\simeq 100 M_\odot \text{ yr}^{-1}$ due to viscous and spiral arm transfer of angular momentum. The line profiles at the positions of the double nuclei are double peaked suggesting that there may also be less massive accretion disks associated with each nucleus. The fact that the bulk of the molecular gas has relaxed into a disk with large masses of gas concentrated interior to the double nuclei is consistent with scenarios in which the gas in merging systems settles into the center faster than the two stellar/starburst nuclei. We suggest that dense central accretion disks like that in Arp 220 may be a common feature in the evolution of ultraluminous starburst/AGN galaxies since similar qualitative features are seen in the molecular line data for other systems (e.g., Mrk 231 and NGC 6240).

Subject headings: galaxies: individual (Arp 220) — galaxies: interactions — galaxies: ISM

1. INTRODUCTION

Arp 220 (IC 4553/4) is the prototypical ultraluminous infrared galaxy with an infrared luminosity at $\lambda = 8\text{--}1000 \mu\text{m}$ of $1.5 \times 10^{12} L_\odot$, placing it in the luminosity regime of quasars. In the visual, Arp 220 exhibits two faint tails, which are probably the result of a past tidal interaction (see Joseph & Wright 1985) and in the nucleus, high-resolution near-infrared imaging reveals a double nucleus with spatial

separation of $0''.95$ at position angle 92° , a morphology similar to that of the compact nonthermal double radio source observed at centimeter wavelengths (Norris 1988; Graham et al. 1990). The projected separation of the double nuclei corresponds to 330 pc; this together with the extended optical tails, suggests that the galaxy is in the final stages of galactic merging.

The sources proposed for the enormous luminosity in the ultraluminous galaxies like Arp 220 include a prodigious burst of high mass star formation (e.g., Joseph & Wright 1985) and a nonthermal, active nucleus (see Sanders et al. 1988). Virtually all of the ultraluminous *IRAS* galaxies have

¹ Owens Valley Radio Observatory, Caltech 105-24, Pasadena, CA 91125.

² National Radio Astronomy Observatory, Socorro, NM 87801.

been found to be extremely rich in interstellar gas with H_2 masses in the range 4×10^9 – $4 \times 10^{10} M_\odot$, 2–20 times that of the Galaxy (Sanders, Scoville, & Soifer 1991). The abundant ISM in these galaxies may play a critical role in the energy output since both the starburst and the central AGN might be fueled by the interstellar matter. High-resolution aperture-synthesis mapping of the molecular gas in the ultraluminous galaxies has revealed that in addition to being extraordinarily abundant, the molecular gas is also highly concentrated in the nuclei (Scoville et al. 1991; Sargent & Scoville 1991; Bryant & Scoville 1996; Bryant 1996). For example, previous high-resolution mapping of the CO (1–0) emission in Arp 220 revealed that approximately two-thirds of the CO emission was contained in a nuclear source with radius 315 pc (Scoville et al. 1991) and single-dish measurements of high dipole moment molecular lines such as HCN revealed an abnormally high fraction of the molecular gas with a density exceeding 10^4 cm^{-3} (Solomon, Downes, & Radford 1992).

In this article, we report the first high-resolution aperture-synthesis mapping of the CO (2–1) emission and the dust continuum in Arp 220. The new maps, having nearly twice the resolution of previous aperture synthesis, clearly show the central nuclear source to be elongated parallel to the prominent dust lane seen in optical images and to exhibit a linear velocity gradient.

2. OBSERVATIONS

Arp 220 was observed at $\lambda = 1.3$ and 2.6 mm using the Owens Valley millimeter array in four configurations in 1993 November–1994 December. For these observations, the array consisted of five to six 10.4 m telescopes, and the longest baseline observed was 240 m (see Table 1). The pointing center, central velocity and adopted distance for Arp 220 are given in Table 1.

At $\lambda = 1.3$ mm in the CO (2–1) transition, the synthesized beam was $0''.99 \times 1''.20$ (uniform weighted) at P.A. = 66° . Each of the five telescopes was equipped with an SIS receiver and measured SSB system temperatures were 450–700 K, corrected for antenna and atmospheric losses. Spectral resolution was provided by a digital correlator configured with four bands, each with 32×4 MHz channels (5.7 km s^{-1}). In order to cover the full velocity extent of the CO (2–1) emission in Arp 220 ($\Delta v = 925 \text{ km s}^{-1}$), the spectrometer sections were configured with two bands contiguously covering the center of the line and the two outlying bands positioned to cover the line wings. This configuration resulted in gaps of approximately 50 km s^{-1} at two points

within the CO line profile. The total integration time on source was 17.8 hr distributed over the four source transits. For the CO (1–0) observations a single six-telescope configuration was used with 5.3 hr of time on source ($T_{\text{SSB}} = 300$ –450 K); the resulting synthesized beam was $1''.51 \times 2''.34$ at P.A. = -76° . At 2.6 mm the spectrometer was configured with four contiguous bands spanning 1210 km s^{-1} . In addition to the spectral line correlator, the continuum was measured in a 1 GHz BW analog correlator. The continuum without line contributions was detected in the upper sideband at 229.4 GHz during the CO (2–1) observations and in the lower sideband at 110.2 GHz during the CO (1–0) observations.

The nearby quasar 1641+399 was used for phase calibration and amplitudes were calibrated using Uranus ($T_B = 125 \text{ K}$) and 3C 273 for absolute flux calibration. The positional accuracy of the resulting maps is $\sim 0''.15$. For 1641+399, the measured flux was 2.6 Jy at 230 GHz and 5.3 Jy at 112 GHz during the periods of the observations. The data were calibrated using the standard Owens Valley array program (Scoville et al. 1992) and mapped using DIFMAP (Shepherd, Pearson, & Taylor 1994) and the NRAO AIPS package.

3. RESULTS

In Figure 1, the vector-average interferometric spectra on Arp 220 are shown for both the 2–1 and 1–0 lines, smoothed to velocity resolutions of 20.8 km s^{-1} . The spectrum shown here corresponds to the emission integrated over a $5''$ aperture centered at the phase center, since this spectrum was obtained by averaging only data with fringe spacing greater than $5''$ and the source is $\leq 5''$ in size (see below). The line profile shapes are similar for the two transitions and the peak fluxes are 2.3 and 0.88 Jy in the 2–1 and 1–0 lines, respectively. The measured emission-line parameters are summarized in Table 2. The integrated line fluxes, 1071 and 410 Jy km s^{-1} , respectively, are in excellent agreement with published single-dish spectra obtained with the IRAM 30 m telescope (1038 and 479 Jy km s^{-1} ; Radford, Solomon, & Downes 1991) and our previous OVRO interferometric

TABLE 1
OBSERVATIONAL PARAMETERS FOR

Pointing center ^a (B1950.0)	R.A. 15 32 46.92, Decl. 23 40 07.9
cz (center of passband)	5450 km s^{-1}
Adopted distance	77 Mpc
Bandwidth of spectrometer ...	464 MHz
Resolution	4 MHz
	5.3 km s^{-1} CO (2 → 1)
	2.7 km s^{-1} CO (1 → 0)
Dates of tracks	1994 Dec 30 CO (1 → 0) 6 telescopes
	1993 Nov 25 CO (2 → 1) 5 telescopes
	1993 Dec 21 CO (2 → 1) 5 telescopes
	1994 Feb 01 CO (2 → 1) 5 telescopes
	1994 Feb 02 CO (2 → 1) 5 telescopes

^a Right ascension is in hours, minutes, and seconds. Declination is in degrees, arcminutes, and arcseconds.

FIG. 1.—Vector-averaged spectrum of CO 1–0 and 2–1 emission in Arp 220, including all data with interferometric fringe spacing greater than $5''$. The gaps in the CO (2–1) interferometric spectra are due to positioning of the spectrometer bands such that the center two spectrometer bands span the line center and the outer two bands are positioned to cover the line wings. The 2–1 line fluxes were multiplied by 0.25 in order to fit in the display.

FIG. 2.—Channel maps for the CO (2–1) line emission are shown with velocity resolution of 21 km s^{-1} . In each panel, the number indicates the center velocity and the crosses show the locations of the near-infrared and radio continuum double nuclei (Norris 1988; Graham et al. 1990). The spatial box is $8''$ on a side, and the beam (HPBW) is shown in the upper left panel. The contours are at 2, 3, 4, 5, 6, ... $\times 50 \text{ mJy beam}^{-1}$.

TABLE 2
ARP 220 CO LINE EMISSION PARAMETERS^a

Parameter	CO (1 → 0)	CO (2 → 1)
Synthesized beam (arcsec).....	2.34×1.51 (P.A. -76°)	1.20×1.00 (P.A. 66°)
Source size (deconvolved) (arcsec).....	2.02×1.35 (P.A. 60°)	1.94×1.28 (P.A. 53°)
ΔV_{FWHM}	504 km s^{-1}	447 km s^{-1}
S_{CO}	410 Jy km s^{-1}	$1071 \text{ Jy km s}^{-1}$
T_{Bpeak}	14.3 K	15.8 K

^a The source size estimates are based on Gaussian fits to the integrated line flux; the line width is derived from the integrated emission spectrum (Fig. 1); and the peak Rayleigh-Jeans brightness temperatures are from the 4 MHz resolution channel maps. The line fluxes are uncertain by $\sim 10\%$, mostly due to absolute calibration uncertainties.

measurement (384 Jy km s^{-1} in the 1–0 line; Scoville et al. 1991). (Both the interferometric and single-dish fluxes probably have absolute calibration uncertainties of at least 10%.)

Based on the good agreement of the interferometric line flux with the single-dish CO line fluxes, it is clear that the aperture synthesis data is recovering virtually all of the molecular line emission in Arp 220. The observed ratio of integrated 2–1/1–0 fluxes is 2.61 ± 0.3 corresponding to a mean brightness temperature ratio of 0.65 ± 0.1 . Ratio maps for the 2–1 and 1–0 lines also show no evidence of large excitation variations but the comparison is crude, with only a few independent resolution elements available in the lower resolution 1–0 data. This ratio clearly rules out the possibility that the emission is dominated by high-excitation optically thin gas which would yield brightness temperatures ratios in the range 1–4.

Narrowband (21 km s^{-1} resolution) channel maps for the CO (2–1) emission are shown in Figure 2. The center velocity for each is indicated on the panels, and the crosses show the positions of the double infrared/radio continuum nuclei. Both transitions have emission peaks approximately midway between the nuclei and a clear velocity gradient is apparent. The redshifted emission appears northeast of the emission centroid, and the blueshift emission to the southwest. These displacements are clearest in the higher resolution CO (2–1) maps. The overall CO distribution is more extended than the separation of the double nuclei and exhibits a different major axis position angle (see below). The peak Rayleigh-Jeans brightness temperatures in the CO (2–1) and (1–0) channel maps are 15.8 and 14.3 K (see Table 2) which correspond to Planck brightness temperatures of 20.8 and 16.9 K, respectively. The ratio of CO (2–1)/(1–0) peak brightness temperatures, uncorrected for their different beam sizes, is ~ 1.1 which is approximately 50% greater than typically observed in Galactic GMCs (Sanders et al. 1991). Thus the peak CO excitation temperatures are apparently somewhat higher in the nucleus of Arp 220, but there is no strong evidence for substantial optically thin emission. Comparison of the observed CO line brightness temperatures with the far-infrared color temperature of the dust emission suggests that the molecular gas area filling factor is $\simeq 0.25$ at the peak.

In Figure 3, the continuum emission in the upper sideband is shown together with the $2 \mu\text{m}$ continuum (Graham et al. 1990). The upper sideband map contains no significant emission lines and the continuum at this wavelength is almost entirely from dust. (For the integrated 2–1 emission map shown in Figure 4, this continuum emission, measured in the upper sideband, was subtracted from the spatial-

frequency data, assuming the continuum flux was constant over the 2.8 GHz frequency difference between the two sidebands. Similar maps were also made for the CO (1–0) emission and the continuum at 110.2 GHz. These are not shown here because of their lower angular resolution; however, they are consistent in position and elongation with the 1.3 mm line and continuum images in Figures 3–4. Measured parameters for both the line and continuum emission at 1.3 and 2.6 mm are given in Tables 2–3. Comparing the 229 GHz continuum with the integrated line emission maps (Figs. 3 and 4), it is apparent that the dust continuum is more concentrated than the line emission. The deconvolved major axis radii for the dust and the molecular gas are 200 and 370 pc, respectively (see Tables 2–3). The orientations for the *total* emission in the line and continuum are different: the 1.3 mm CO emission is elongated at P.A. $\sim 53^\circ$, parallel to the dust lane which bifurcates the $\text{H}\alpha$ emission while the dust is elongated with major axis at P.A. $\sim 91^\circ$,

FIG. 3.—The 1.3 mm (*top*) and $2 \mu\text{m}$ (*bottom*; Graham et al. 1990) continuum emission are shown. The upper sideband at 232.96 GHz contains no line emission and is mostly emission from interstellar dust. The synthesized beam is $1''.0 \times 1''.2$, and the contours are spaced by 10% of the peak value of $0.143 \text{ Jy beam}^{-1}$.

FIG. 4.—CO (2–1) line emission integrated over all lower sideband spectrometer channels is shown superposed on a H α image of Arp 220 (Armus et al. 1995). This lower sideband map has had the upper sideband continuum subtracted from it and thus constitutes an image of just the integrated CO (2–1) line flux. The synthesized beam is $1\farcs0 \times 1\farcs2$ and the CO (2–1) contours are spaced by $20 \text{ Jy km s}^{-1} \text{ beam}^{-1}$.

approximately along the position angle of the double nuclei (Fig. 4; Tables 2–3). Most of these differences are apparently due to the low-level CO emission. If one looks at just the brightest core of line emission, its major axis is closer to that of the dust emission (see Figs. 3 and 4). From the ratio of deconvolved sizes for the major and minor axes in the integrated CO intensity distribution (0.66; Table 2), we find formal values for the inclination of 45° – 49° if the gas is modeled as an inclined disk. Throughout the following analysis we will adopt $i = 45^\circ$.

In Figure 5 the mean velocity of the CO (2–1) emission is shown as a function of position. The derived kinematic center is given in Table 4, and in Figure 6 position-velocity maps are shown for strips along the major axis (P.A. $\simeq 40^\circ$) and along the line of the double nuclei. Comparison of Figures 4 and 5 clearly shows that the kinematic major axis is approximately aligned with the major axis of the

extended CO emission distribution and not with the P.A. of the double nuclei. The alignment of the kinematic and CO isophotal axes suggests that the gas is confined in an inclined, rotating disk (rather than a more spherical distribution). The fact that this direction is different from that of the nuclei implies that the two nuclei must be well away from the major axis if they are in the same plane as the gas. The position angle (101°) of the second velocity strip map shown in Figure 4b corresponds roughly to that observed by Larkin et al. (1995) in Fe II, Pa β , Br γ , and H $_2$ at velocity and spatial resolutions of approximately 300 km s^{-1} and $0\farcs5$, respectively. Both the sense and the magnitude of the velocity gradients detected in the near-infrared lines and in the millimeter CO line are similar; that is, approximately 200 km s^{-1} velocity separation between the eastern and western nuclei. This velocity difference is considerably less than that measured along the major axis (see Fig. 6a).

TABLE 3
ARP 220 CONTINUUM EMISSION^a

Parameter	110.2 GHz	229.4 GHz
Synthesized beam (arcsec).....	2.29×1.50 (P.A. -82°)	1.18×0.99 (P.A. 66°)
Source size (deconvolved) (arcsec).....	$1.30 \times <0.29$ (P.A. 105°)	1.07×0.63 (P.A. 91°)
S_ν	$35 \pm 4 \text{ mJy}$	$192 \pm 20 \text{ mJy}$

^a The uncertainties include both map noise and absolute calibration uncertainties.

FIG. 5.—Mean velocity (first moment) of the CO (2–1) emission is shown as a function of displacement from the pointing center (Table 1). The contours are spaced by 50 km s^{-1} .

TABLE 4
DERIVED PARAMETERS FOR ARP 220^a

Kinematic center (B1950.0) ^b	R.A. $15^{\text{h}}32^{\text{m}}46^{\text{s}}.94$, Decl. $23^{\circ}40'08''.4$
cz (systemic velocity) ^b	5511 km s^{-1}
Kinematic major axis	40°
Inclination	45°
Nuclear Disk:	
Mass ($M_{\text{dyn}} = M_{\text{H}_2}$)	$5.4 \times 10^9 M_{\odot}$
Radius	250 pc
α/α_G	0.45
σ_v	90 km s^{-1}
Σ_{H_2} : peak at 220 pc	$5.8 \times 10^4 M_{\odot} \text{ pc}^{-2}$
mean at 250 pc	$2.75 \times 10^4 M_{\odot} \text{ pc}^{-2}$
2H (full width)	32 pc
$\langle n_{\text{H}_2} \rangle$	$2 \times 10^4 \text{ cm}^{-3}$
Stellar Nuclei:	
Radius	235 pc
V_{rot}	310 km s^{-1}
τ_{rot}	$4.6 \times 10^6 \text{ yr}$
Outer Galactic Disk:	
M_{H_2}	$3 \times 10^9 M_{\odot}$
Radius	0.25–1.5 kpc
$\langle n_{\text{H}_2} \rangle$	$\approx 10^3 \text{ cm}^{-3}$

^a Derived from the CO (1–0) data with spectral line profile modeling using the Doppler imaging technique of Scoville, Young, & Lucy (1983).

^b Derived from the CO (1–0) first moment map (centroid velocities, Fig. 5) using the AIPS task GAL.

The fact that the locations and velocities of the nuclei are mutually consistent with their being situated in the molecular disk is suggestive that the nuclei are indeed orbiting within the disk plane. If they were above or below the disk and simply seen in projection against the disk, the positions and velocities would be unlikely to match those of the gas.

In the following analysis, we adopt the kinematic major axis (P.A. = 40°) for the gas spatial distribution and kinematics in the nuclear disk of Arp 220. Assuming that the nuclei share the same orbital motion of the CO gas (as measured along the major axis), we find that the two nuclei must be rotated 69° from the major axis within the disk of the galaxy (assuming an inclination of 45°).

4. MOLECULAR AND DYNAMICAL MASSES

The results presented in the previous section are consistent with a geometry for the central region of Arp 220 in which both the molecular gas and the double nuclei are situated in an inclined, rotationally supported disk. In this section we analyze quantitatively the mass distribution which is inferred from this geometry and the observed kinematics. This geometry is shown schematically in Figure 7.

We first estimate the total H_2 mass from the integrated CO (1–0) line flux using a standard Galactic CO-to- H_2 conversion ratio of $3 \times 10^{20} \text{ H}_2 \text{ cm}^{-2} (\text{K km s}^{-1})^{-1}$. Using

FIG. 6.—Position-velocity maps for P.A. = 40° (the kinematic major axis) and P.A. = 101° (the position angle of the double nuclei). The last strip corresponds approximately to that measured for P α by Larkin et al. (1995).

equation (A15) in Sanders et al. (1991), we obtain a total H₂ mass of $2.9 \times 10^{10} M_{\odot}$.

To first order, the velocities near the major axis (e.g., at P.A. = 53° as shown in Fig. 6a) increase monotonically with radius out to $\sim 1''$, that is about twice the radii of the double nuclei. This indicates that if the material is undergoing circular rotation in the nuclear disk, the enclosed mass must increase significantly at radii well beyond the two nuclei. The mass distribution is therefore not dominated by the nuclei (stellar or AGN in origin). This is consistent with the large amount of CO emission seen in the interferometer maps beyond the separation of the two near-infrared nuclei and the notion that the gas mass dominates the stellar mass in the central regions of Arp 220. In the context of a disk model, the total dynamical mass enclosed in the same region can therefore be estimated by taking the rotation velocity at the outer radius of the CO to be half of the full line width (925 km s^{-1}). When corrected for inclination 45°, this yields a rotation velocity of 613 km s^{-1} at 362 pc radius and a dynamical mass, assuming a spherical potential, of $3.2 \times 10^{10} M_{\odot}$. For a thin disk potential the dynamical mass could increase by a factor 1.5–2 (see below).

The mean kinematics of the CO emission were determined by the AIPS task “GAL” from the CO (1–0) data. This routine determines a best-fit rotation curve, kinematic major axis P.A., and inclination, systemic velocity, and center position from the CO centroid velocities (Fig. 5). The kinematic center from the CO (1–0) data (given in Table 4) is within 0.5 of the CO (2–1) intensity centroid and the inclination and the P.A. of the major axis are within 10° and 20° of the parameters found from the 2–1 intensity distribution.

4.1. Mass Distribution

In order to derive both the CO emissivity distribution and the overall mass distribution in the central disk of Arp 220, we have employed the kinematic deconvolution schemes presented by Scoville, Young, & Lucy (1983) to self-consistently model the CO emission line profiles. This technique was developed by them and applied to the CO single-dish observations of NGC 1068. In that galaxy, the velocity field was known from optical spectroscopy at high spatial resolution and, by modeling the CO line profiles, they were able to deduce the spatial distribution of the CO

FIG. 6—Continued

emissivity on a scale much finer than the diffraction beam of the CO single dish data. We call this technique Doppler image-deconvolution since it is similar to Doppler radar imaging, which is used to provide high-resolution imaging in planetary astronomy.

In Arp 220, the heavy obscuration by dust precludes an optical determination of the velocity field, and near-infrared spectroscopy (Larkin et al. 1995) has been limited to a single slit along the position angle of the two infrared nuclei. Since the velocity field is not a priori known in Arp 220, we have therefore taken the approach of testing whether the hypothesis that the mass distribution is dominated by the molecular gas (i.e., is proportional to the CO emissivity) is self-consistent. For this model, it is assumed that the molecular gas is confined to a disk and is in purely circular motion about the interior mass. Thus, the rotation velocities in this model at any radius are determined by the integral of the model CO emissivity at interior radii. The constant of proportionality between the CO emissivity and the mass (i.e., the CO conversion ratio) is taken to be constant with radius but having a value which can be varied in order to obtain the best global fit to the emission line profiles. Based on the integrated CO emission and centroid velocity maps (Figs. 4 and 5), we adopt an inclination of 45° for the disk and take the position angle of the major axis to be 40° . Model fitting was performed with both the axisym-

metric and nonaxisymmetric schemes given in Scoville et al. (1983).

4.1.1. Axisymmetric Model

The CO (2–1) and (1–0) data cubes were sampled at $0''.5$ spacing and for the axisymmetric modeling the spectra on the approaching side of the galaxy were inverted about the systemic velocity and averaged with the spectra at equivalent positions on the receding side of the galaxy. In the axisymmetric modeling, the two free parameters are the assumed velocity dispersion of the gas and the CO-to- H_2 conversion ratio, both of which were taken to be independent of radius. For the instrumental response function we used the two-dimensional Gaussian fits to the synthesized beams of the (2–1) and (1–0) data. The model galaxy was fitted out to 1.5 kpc radius ($4''$), with bins every 20 pc in radius.

An excellent fit to the observed line profiles was obtained with a velocity dispersion $\sigma_v = 90 \text{ km s}^{-1}$ and a CO-to- H_2 conversion ratio of 0.45 times the Galactic ratio [$\alpha_G = 3 \times 10^{20} \text{ cm}^{-2} (\text{K km s}^{-1})^{-1}$]. The derived CO emissivities, the gas surface densities, the rotation curve, and the dynamical mass as function of radius are shown in Figures 8a–8d. In Figure 9 the model line profiles are compared with the observed CO (1–0) line profiles at nine representative positions, labeled by offset x and y parallel and perpen-

FIG. 7.—Schematic of the nucleus of Arp 220 showing the central molecular gas disk with the double infrared/radio nuclei orbiting at the outer edge of the nuclear gas disk. Based on the elongation of the molecular disk, the adopted major axis is at P.A. = 45°, and the disk is inclined at approximately 40° to the line of sight. The infrared nuclei then lie along a line between the major and minor axes of the gas disk (69° from the major axis in the disk plane). Approximately two-thirds of the total molecular emission arises from this disk, the remaining from a more extended disk with approximately 10 times lower surface density.

FIG. 8.—CO emissivity (a), the H_2 mass surface density (b), the rotation curve (c), and interior dynamical mass (d) derived from axisymmetric modeling of the observed CO (1-0) line profiles as a function of position using the deconvolution scheme of Scoville, Young, & Lucy (1983). As explained in the text, the model was made with $i = 45^\circ$, major axis P.A. = 40°, $\sigma_v = 90$ km s $^{-1}$, and a CO-to- H_2 conversion ratio of 0.45 times the Galactic ratio.

FIG. 9.—Observed (*thick line*) and model (*thin line*) CO (1–0) line profiles are shown for a sample of positions using the model parameters given in Fig. 8. The coordinates at the top of each frame indicate the offsets parallel (x) and perpendicular (y) to the major axis (P.A. = 40°) in parsecs (100 pc corresponds to $0''.27$) from the adopted center position (taken as the “pointing center” given in Table 1). The observed line profiles shown here have been averaged at equivalent positive and negative x with the velocities flipped about the systemic velocity for the negative x spectra.

pendicular to the major axis. The model and observed line profiles are in excellent agreement in peak velocity, shape, and intensity. One exception to this is that in the outer disk the model emission is at slightly lower velocity than the observed emission, indicating a higher value of the CO-to- H_2 conversion ratio there, a significant stellar mass contribution or the effect of a nonspherical mass distribution (see below).

Models with velocity dispersion differing by more than 20 km s^{-1} or conversion factor 25% different from that given above gave significantly poorer fits. Thus, based on this modeling we find that a CO-to- H_2 conversion ratio of $0.45 \alpha_G$ is applicable to the nucleus of Arp 220, despite the very different physical conditions there than are found in Galactic GMCs. However, in relating the circular velocities to the mass, we employed a simple spherical approximation (i.e., $v^2 = GM_r/r^2$) rather than the much more complex integral expressions appropriate to a disk potential. For a disk with the same circular velocities, the implied interior masses in the inner disk can be up to a factor of 2 higher than those for a spherical mass distribution (see Nordsieck 1973). therefore, if the disk formulae had been used, a factor of 2 more molecular gas could have still been consistent with the observed kinematics. In the other direction, we note that a massive stellar component distributed similarly in radius to the CO emissivity would allow less molecular gas and therefore a lower CO-to- H_2 conversion ratio, but still be consistent with the CO kinematics.

The effective radial spatial resolution for the models is dependent on the velocity dispersion relative to the rotational gradient (see Scoville et al. 1983). For the adopted velocity dispersion we estimate the spatial resolution to be approximately 100 pc in the region where most of the CO emission originates. This represents a factor of 3–6 better

spatial resolution than is obtained directly from the observationally synthesized beams.

The derived emissivity distribution shown in Figure 8a has a peak in the CO emissivity at ~ 130 pc radius with a steep descent to a factor of 9 lower surface density at 400 pc. Outside 400 pc radius, the CO emissivity falls slowly with increasing radius. Approximately two-thirds of the total CO emission is contained inside 400 pc and one-third is in the more extended component. The core component has the same extent as the region containing the two stellar nuclei seen in the near infrared which are separated by $0''.95$ or a projected distance of 354 pc. This is very similar to the relative distributions found by Bryant (1996) and Bryant & Scoville (1997) in the double nuclei merger galaxies NGC 6090 and NGC 6240.

As a check on the model, we can compare the derived rotation law with the observed kinematics of the infrared nuclei. The actual separation of the double nuclei is probably larger than their apparent separation since their position angle (P.A. = 101°) is 61° from the major axis in the CO model. For an inclination of 45° , this translates into 69° from the major axis in the plane of the Galaxy, and the true separation of the two nuclei is 470 pc, assuming as discussed earlier that they are in the same plane as the gas. From the CO rotation curve (Fig. 8c), the circular velocity at the radius (235 pc) of each nucleus is 310 km s^{-1} . Correcting for the fact that the nuclei are 69° off the major axis and for the inclination of the Galaxy, the line-of-sight component of the orbital speed is expected to be 80 km s^{-1} , implying an apparent separation between the two nuclei of 160 km s^{-1} . This is in reasonable agreement with the value of 200 km s^{-1} measured by Larkin et al. (1995).

The calculated angular frequencies for circular motion (Ω) and for epicyclic motion $\Omega \pm \kappa/2$ (where κ is the epi-

FIG. 10.—Orbital frequencies for the rotation curve shown in Fig. 8c. The solid curve is the circular angular frequency (Ω), and the dashed curves are $\Omega \pm \kappa/2$, where κ is the epicyclic frequency. The horizontal dotted line is at the angular frequency of the stellar nuclei, possibly corresponding to a pattern speed for the inner disk.

cyclic frequency) are shown in Figure 10. An appropriate frequency for any possible spiral or bar in the inner disk might be that of the two stellar nuclei (i.e., $\Omega_p = 310 \text{ km s}^{-1}/0.235 \text{ kpc}$) and the horizontal line in Figure 10 indicates this pattern frequency. If this pattern frequency is correct, the inner Lindblad resonance (where $\Omega - \kappa/2 = \Omega_p$) would occur near the center of the disk, if at all. An outer resonance would be at $R \simeq 400 \text{ pc}$.

4.1.2. Nonaxisymmetry

Although the axisymmetric modeling provides generally good agreement with the observed line profiles, there are significant departures from axisymmetry. Specifically, the CO emission is extended further to the southwest (blueshifted emission) than to the northeast (redshifted emission) and in the core region the CO contours are oriented along the position angle of the two infrared nuclei rather than the major axis determined from the outer CO isophotes. We have therefore also tried a nonaxisymmetric modeling in which the CO emissivity is allowed to freely vary on a rectangular grid in the disk plane (see Scoville et al. 1983). Adopting a slightly different position angle for the kinematic major axis (P.A. = 20°), we have obtained a best-fit CO emissivity distribution in which the major peaks in the CO emissivity are separated by $\sim 1''$ and lie along the position angle of the infrared nuclei. Although the separation of the two peaks in this model is reasonably well determined ± 0.1 , their position angle is entirely determined by the adopted kinematic major axis position angle. We therefore do not think this model is well-determined and do not show it here. Future infrared observations which map the entire two-dimensional velocity field within the inner few arcsec might critically constrain the P.A. of the kinematic major axis. In any case, the nonaxisymmetric modeling implies that a CO emissivity distribution with strong peaks coinciding with the two galactic nuclei *could* be made consistent with the observed line profiles.

In order to more directly test for the presence of CO associated with the double nuclei, we have made maps which include just the brightest clean components from the CO (2–1) channel maps (Fig. 11). This procedure suppresses the lower level background emission, and these bright clean components were restored with a $0.5''$ beam to enhance the resolution. The resulting integrated intensities are shown in Figure 11, and it is clear that bright peaks in the CO emiss-

ivity occur at the positions of the near-infrared nuclei. CO (2–1) profiles at the two nuclei are also shown in Figure 11. The mean velocities derived from the same clean component data are approximately 5300 and 5600 km s^{-1} at the western and eastern nuclei. The level of CO (2–1) emission between the nuclei is at least 50% below that associated with each nucleus. It should be noted that the 2–1 line is more susceptible than the 1–0 line to enhancement where the gas is hotter and therefore this distribution may not reflect quantitatively the density distribution. That is, the present data do not constrain whether these are simply maxima in the temperature of the molecular gas near the luminous nuclei or whether they are density peaks.

It is very interesting to note that the clean component line-profiles of the CO (2–1) emission on each of the nuclei appear double peaked (within the limitations of the missing spectrometer coverage between correlator bands). These line profiles appear both double peaked and much broader than the line of sight velocity dispersion. They are therefore suggestive that each of the nuclei may be embedded in its own, local accretion disk since the profile shapes are readily produced by disk structures. The velocity widths of each profile are $\sim 250 \text{ km s}^{-1}$ implying a rotational velocity of 200 km s^{-1} if the inclination is the same as the larger disk. If the diameter of each disk is $0.25''$ (50 pc radius), so that they cover a small fraction of the disk between the IR nuclei, then the dynamical mass within each disk is $4 \times 10^8 M_\odot$.

5. DUST CONTINUUM

The map of the 1.3 mm continuum emission from Arp 220 is shown together with the $2 \mu\text{m}$ contour map of Graham et al. (1990) in Figure 3. At $\lambda = 1.3 \text{ mm}$, most of the flux is due to interstellar dust, and this dust clearly exhibits a morphology similar to the double nuclei seen at $2 \mu\text{m}$. Measurements of the integrated continuum fluxes (35 and 192 mJy) and source sizes at both 110.2 and 229.4 GHz are summarized in Table 3. The measured fluxes are in excellent agreement with our earlier results (Scoville et al. 1991; Woody et al. 1989). The radio nonthermal flux at $\lambda = 1.3 \text{ cm}$ is $\sim 36 \text{ mJy}$ with a measured spectral index of -0.75 (Norris et al. 1985; Norris 1988). Extrapolating this continuum to 110.2 and 229.4 GHz implies nonthermal contributions of 11 and 7 mJy , respectively. The residual emission (24 and 185 mJy at 110.2 and 229.4 GHz) is probably dominated by the long wavelength tail of the far-infrared dust emission, with a small contribution from free-free emission.

As discussed by Scoville et al. (1991), the spectral energy distribution at $\lambda = 60 \mu\text{m}$ – 2.7 mm can be fitted well with a blackbody temperature of 42.2 K and an emissivity law $\epsilon \sim \lambda^{-1.3}$ with $\tau \sim 1$ at $\lambda = 200 \mu\text{m}$. The observed fluxes then imply an effective diameter for the emission region of 1.13 . For a mass-opacity coefficient of $12 \text{ cm}^2 \text{ g}^{-1}$ at $200 \mu\text{m}$ (Hildebrand 1983; Draine & Lee 1984), the dust mass is $5 \times 10^7 M_\odot$. A standard gas-to-dust mass ratio of 100 – 200 , then implies a gas mass of 5 – $10 \times 10^9 M_\odot$, in good agreement with the $6 \times 10^9 M_\odot$ of molecular gas obtained from the CO (1–0) emission in the same region (integrating the curve in Fig. 8b out to the 235 pc radius of the nuclei) with a CO-to- H_2 conversion ratio equal to 45% of the standard Galactic value. Scoville et al. (1991) also note that the residual continuum flux at 2.6 mm provides a strong constraint on the free-free emission and hence on the production rate of ionizing photons (Q). Since the continuum fluxes in the previous and present observations are virtually

FIG. 11.—Integrated intensity map (*top*) for the brightest CO (2-1) "clean" components peaks at the positions of the near-infrared nuclei which are indicated by the "+" symbols. In the bottom panels the CO (2-1) spectra at each of the peaks are shown. The gaps in the spectra correspond to the missing frequencies not covered by the four spectrometers. The mean velocities derived from the "clean" components at the western and eastern peaks are ~ 5300 and 5600 km s^{-1} , respectively.

identical, this constraint is unchanged and corresponds to $Q = 7.5 \times 10^{54} \text{ s}^{-1}$ after removing the nonthermal contribution to the flux.

6. DISCUSSION

In the previous section, we found that a self-consistent fit for the molecular mass distribution and the observed kinematics as reflected in the CO line profiles could be obtained.

The adopted model consisted of a nuclear disk at intermediate inclination (45°) to the line of sight with a CO-to- H_2 conversion ratio equal to 45% of the standard Galactic value and with the overall mass dominated by the molecular gas (or a similarly distributed mass component). This conclusion is contrary to recent results of Shier, Rieke, & Rieke (1994) who analyzed the stellar velocity dispersion measurements ($125 \pm 30 \text{ km s}^{-1}$) of Doyon et al. (1994) in

the 2.3 μm CO bands. Based on their derived dynamical mass of $1.8 \times 10^9 M_\odot$ at $r \leq 350$ pc and correcting for the expected stellar mass contribution, Shier et al. concluded that the CO-to- H_2 ratio must be $\leq 10\%$ of the Galactic value. However, their analysis of the CO band velocity dispersion is inconsistent with the observed kinematics in the nucleus of Arp 220. They also assumed a spherical (rather than disklike geometry) and an isotropic velocity dispersion with no allowance for rotation or other systematic gradients. In contrast with these assumptions, the near-infrared clearly shows a double nucleus, the gas distribution is elongated parallel to the optical dust lane and both the mm CO lines (our work) and the near-infrared H II ($\text{Br}\gamma$ and $\text{Pa}\beta$) and H_2 lines (Larkin et al. 1995) clearly show systematic velocity gradients. Subsequent analysis by Shier, Rieke, & Rieke (1996) has taken into account the velocity gradient between the nuclei in a disk-like geometry, leading them to increase the original mass estimate by a factor of 2. In our analysis we have interpreted the relatively low gradients seen in the near-infrared lines as being due to the fact that the two infrared nuclei observed by Larkin et al. are located well off both the CO isophotal and kinematic major axis (P.A. $\simeq 45^\circ$). The radial scale length ($2''$) adopted by Shier et al. (1994) also suggests that the majority of the stars responsible for the CO bands are red supergiants well outside the H_2 disk. The stars within the smaller nuclear region containing the millimeter CO emission are likely to be underrepresented in large beam, near-infrared measurements due to higher extinction in the nucleus since the mean extinctions through the dust disk correspond to $A_V = 2000$ mag (see § 6.5).

6.1. Mass Densities and Stability in Nuclear Disk

The deconvolved CO emission distribution in the central disk of Arp 220 indicates that approximately one-half of the molecular gas is concentrated near the double nuclei within radii ≤ 250 pc. From the derived rotation curve (Fig. 8d), the velocity is 305 km s^{-1} at $r = 250$ pc, and the enclosed mass is therefore $5.4 \times 10^9 M_\odot$. If essentially all of this mass is molecular gas, then the mean interior surface density is $2.7 \times 10^4 M_\odot \text{ pc}^{-2}$. At the peak deconvolved surface density ($r = 130$ pc; see Fig. 8a), the CO emissivity is $830 \text{ Jy km s}^{-1} \text{ kpc}^{-2}$. Using a CO-to- H_2 conversion factor 45% of the Galactic value, we find a peak H_2 surface density of $5.8 \times 10^4 M_\odot \text{ pc}^{-2}$ or $3.8 \times 10^{24} \text{ cm}^{-2}$ at $r = 220$ pc. This corresponds to $A_V = 3800$ mag for a standard gas-to-dust abundance ratio if the line of sight passes directly through the disk.

For a self-gravitating disk, the effective thickness (H) of the gas can be obtained from the mass surface density using the standard condition of hydrostatic equilibrium (Spitzer 1942):

$$H = \left[\frac{4 \tanh^{-1} (1/2) \sigma_v^2}{12\pi G \mu m_{\text{H}_2} n^{-\text{H}_2}} \right]^{1/2}, \quad (1)$$

where σ_v is the vertical velocity dispersion and n_{H_2} is the H_2 volume density. This thickness is such that $2H\rho_0 = \Sigma$. In terms of the mass surface density of the disk, $\Sigma (= M_d/A_d)$,

$$H = \left(\frac{0.233 \sigma_v^2}{G \Sigma} \right). \quad (2)$$

For $\sigma_v = 90 \text{ km s}^{-1}$ and $M_d = 5.4 \times 10^9 M_\odot$ within $R = 250$ pc, the average surface density is $2.75 \times 10^4 M_\odot \text{ pc}^{-2}$ (as noted above), and the thickness of the disk, within which half the surface density is contained, is only $H = 16$

pc. This is approximately a factor of 10 thinner than the gas disk in the Galactic center (see Scoville & Sanders 1987). The mean gas density in the Arp 220 central disk (full thickness 32 pc and 250 pc in radius) is $n_{\text{H}_2} = 1.3 \times 10^4 \text{ cm}^{-3}$.

The stability of the gas disk to axisymmetric perturbations can be estimated using the Toomre (1964) stability criterion:

$$Q = \frac{\sigma_v \kappa}{\pi G \Sigma}, \quad (3)$$

where κ is the epicyclic frequency (derived from the rotation curve in Fig. 8c) and Q must be greater than unity for stability. Shown in Figure 12 is the Toomre Q -parameter as a function of radius in the Arp 220 disk. Outside the central region, the velocity dispersion is high enough and the mass surface density low enough that stability can occur. On the other hand, within 400 pc radius, Q is ≤ 1 , and one expects that the gas will develop large density enhancements, ultimately leading to the formation of massive star clusters in the disk.

6.2. Starburst

The upper limit to the Ly continuum photon production rate obtained in § 5, combined with upper limits to the stellar mass from the rotation curve provide strong constraints on scenarios in which the luminosity in the nucleus of Arp 220 arises from a starburst. The limit on Q ($7.5 \times 10^{54} \text{ s}^{-1}$) is clearly inconsistent with simple models in which the far-infrared luminosity arises entirely from a population of O-type stars (e.g., Solomon et al. 1992) since the ratio of bolometric luminosity-to-Lyman-continuum would be a factor of 10 lower in that case. To avoid too high a Lyman continuum production rate, starburst models require that a large fraction of the luminosity arise from lower mass stars which produce proportionally less ionizing UV emission.

Higher luminosity-to-Ly-continuum ratios can also be obtained in an aging starburst since a significant fraction of the OB stars will have evolved off the main sequence but the lower mass stars live longer. An additional constraint on the models is provided by the dynamical mass of the region, i.e., there cannot be so many low-mass stars that their mass exceeds limits on the total mass. Relevant models are discussed by Scoville & Soifer (1991), and we summarize their results here in the context of Arp 220. We adopt an overall rate of star formation which is constant for a burst timescale

FIG. 12.—Toomre Q stability parameter for the rotation curve and gas surface density distribution shown in Figs. 8b and 8c. The velocity dispersion is $\sigma_v = 90 \text{ km s}^{-1}$ based on the line profile modeling. $Q \leq 1$ corresponds to the regions ($R \leq 400$ pc) where the gas is unstable to axisymmetric perturbations.

(t_B). At the radius of 235 pc, corresponding to nuclei, the orbital velocity is 310 km s^{-1} (see Fig. 8c) and the orbital time is therefore $\tau \sim 4.6 \times 10^6 \text{ yr}$. Since the starburst is probably triggered dynamically as a result of the galactic merging, we adopt a characteristic timescale $\sim 5 \times 10^7 \text{ yr}$, i.e., approximately 10 orbits at the present radius. During this time, stars are assumed to form with a modified Miller-Scalo initial mass function. The ZAMS mass-luminosity relations and main-sequence lifetimes were taken from Renzini & Buzzoni (1986) and Maeder (1987) for $\leq 10 M_\odot$ and $\geq 10 M_\odot$ respectively. The ionizing photon production rates (Q) are from Panagia (1973). Given these constraints, then the total luminosity (L), Ly continuum production (Q), and accumulated stellar mass (M_*) can be approximated as power laws of the lower and upper mass cutoffs for stars (m_l and m_u), the constant rate of star formation ($\dot{M}$) and the burst timescale (t_B). To normalize the relations given in Scoville & Soifer (1991) with parameters more appropriate to Arp 220, we adopt $L = 1.5 \times 10^{12} L_\odot$, $Q \leq 7.5 \times 10^{54} \text{ s}^{-1}$ (see § 5), and a burst timescale $t_B = 5 \times 10^7 \text{ yr}$. The starburst luminosity is then given by

$$L = 2.1 \times 10^{12} \left(\frac{m_l}{5 M_\odot} \right)^{0.40} \left(\frac{m_u}{45 M_\odot} \right)^{0.27} \left(\frac{\dot{M}}{100 M_\odot \text{ yr}^{-1}} \right) \times \left(\frac{t_B}{5 \times 10^7 \text{ yr}} \right)^{0.37} L_\odot. \quad (4)$$

(The exponent for m_l increases to ~ 0.58 if m_l is decreased to $1 M_\odot$.) The rate of production of Ly continuum is

$$Q = 2.9 \times 10^{55} \left(\frac{m_l}{5 M_\odot} \right)^{0.77} \left(\frac{m_u}{45 M_\odot} \right)^{1.23} \times \left(\frac{\dot{M}}{100 M_\odot \text{ yr}^{-1}} \right) \text{ s}^{-1}. \quad (5)$$

(The exponent for m_l decreases to ~ 0.59 if m_l is decreased to $1 M_\odot$ and that for m_u increases to ~ 1.67 if m_u is lowered to $35 M_\odot$.) Thus, the ratio L/Q is given by

$$\frac{L}{Q} = 7.2 \times 10^{-44} \left(\frac{m_l}{5 M_\odot} \right)^{-0.37} \left(\frac{m_u}{45 M_\odot} \right)^{-0.96} \times \left(\frac{t_B}{5 \times 10^7 \text{ yr}} \right)^{0.37} L_\odot \text{ s}. \quad (6)$$

The total mass still in stars (main-sequence and stellar remnants) at time t_B is

$$M_* = 2.4 \times 10^9 \left(\frac{m_l}{5 M_\odot} \right)^{-0.94} \left(\frac{m_u}{45 M_\odot} \right)^{-0.17} \times \left(\frac{\dot{M}}{100 M_\odot \text{ yr}^{-1}} \right) \left(\frac{t_B}{5 \times 10^7 \text{ yr}} \right)^{0.31} M_\odot. \quad (7)$$

(For $m_l = 1 M_\odot$, the leading constant in eq. [7] increases to 4.1×10^9 and the exponent of m_l increases to ~ -0.14 .) The stellar mass included in equation (7) is only that remaining in present epoch stars; i.e., it excludes the matter lost from the earliest high-mass stars during their post-main-sequence evolution. For this mass function with $m_l = 5 M_\odot$, the mass in dead stellar remnants is only 1.5%, 4%, and 5% after 2, 5, and $10 \times 10^7 \text{ yr}$. For the same times, 23%, 52%, and 72% of the stellar mass has been recycled back into the ISM, enriched in heavy elements. The ratio

L/M_* is given by

$$\frac{L}{M_*} = 875 \left(\frac{m_l}{5 M_\odot} \right)^{1.34} \left(\frac{m_u}{45 M_\odot} \right)^{0.44} \times \left(\frac{t_B}{5 \times 10^7 \text{ yr}} \right)^{0.06} \frac{L_\odot}{M_\odot}, \quad (8)$$

In order to avoid violating the dynamical mass constraint, a high value is required for the lower mass cutoff. Adopting $M_* \leq 2.5 \times 10^9 M_\odot$ (i.e., 50% of the dynamical mass at $r \leq 235 \text{ pc}$; the remaining 50% in gas and preburst stars) as an upper limit to the mass of burst stars, the luminosity-to-stellar-mass ratio is $600 L_\odot/M_\odot^{-1}$.

For a burst timescale of $t_B = 5 \times 10^7 \text{ yr}$, simultaneous solution of equations (4), (6), and (7) to match the observed luminosity and upper limits to the ratios L/Q and M_* yields $m_l = 5.6 M_\odot$, $m_u = 16 M_\odot$, and $\dot{M} = 91 M_\odot \text{ yr}^{-1}$. That is, in order to satisfy the upper limits on the free-free flux, the upper mass limit must be very low and in order to satisfy the limit on the dynamical mass the lower limit must be high. Numerical solution to avoid the approximations involved in the power-law extrapolations of equations (4)–(8), yields $m_l = 5 M_\odot$, $m_u = 23 M_\odot$, and $\dot{M} = 90 M_\odot \text{ yr}^{-1}$. (For a longer burst timescale, $t_B = 10^8 \text{ yr}$, the upper mass limit can be increased to $m_u = 28 M_\odot$, and $\dot{M} = 70 M_\odot \text{ yr}^{-1}$.) The narrow range of permissible stellar masses suggests that a starburst origin for a major fraction of the stellar luminosity in Arp 220 is unlikely, although not ruled out. Starbursts with low-mass stars ($m_l = 0.1 M_\odot$) are categorically ruled out since they violate the L/M_* constraint by more than an order of magnitude; similarly starbursts with only high-mass OB stars are easily ruled out since they violate the L/Q constraint.

Our conclusion that a starburst is unlikely to power the luminosity of Arp 220 is similar to that of Armus et al. (1995). From the small equivalent width of Br γ in their near infrared spectra, they find that no more than 10% of the total luminosity in Arp 220 could arise from a starburst. Their conclusion is subject to that caveat that high extinction in the near-infrared might hide a significant starburst component. Our upper limit on the free-free emission at millimeter-wavelengths avoids this uncertainty since the dust is optically thin at millimeter-wavelengths. From the variations in the Br γ and stellar CO bands across Arp 220, Armus et al. suggest different burst timescales for the double nuclei (at ≤ 0.5 radius) and the surrounding region (at $2''$ – $2.5''$ radius), lasting 7–8 Myr and $\sim 10^8 \text{ yr}$, respectively. An alternative means of satisfying the requirement of a low Lyman continuum emission rate in the context of starburst models is with a steeply decaying rate of star formation and a burst age since first turn-on significantly longer than the $2 \times 10^7 \text{ yr}$ lifetime of OB stars (see Genzel et al. 1995). We do not favor this solution simply because a significant fraction of the mass in the nucleus is still in the ISM and it is probably more concentrated than in the past. There is therefore no obvious explanation for why the present epoch star formation would be significantly less than at earlier times.

6.3. Radial Accretion

The extreme gas densities in the central disk of Arp 220 will result in high accretion rates, both on to the double nuclei and toward the center of the system, between the

nuclei. In this section we estimate the viscous and spiral-arm-induced accretion rates for comparison with the required star formation rates.

To estimate the rate of gas accretion due to viscous transport of angular momentum, we use the treatment of Pringle (1981). With the assumption of conservation of angular momentum in an axisymmetric disk, he obtained an expression for the time derivative of the mass surface density and this can be integrated over annular rings to obtain

$$\dot{M}_{\text{viscous}} = 2\pi \frac{d}{dr} \left(-\nu \Sigma r^3 \frac{d\Omega}{dr} \right) \frac{1}{(d/dr)(r^2\Omega)} \Big|_{R_0}^{R_1}, \quad (9)$$

where ν is the kinematic coefficient of viscosity, Σ is the gas disk surface density, and Ω is the angular rotation speed. If the disk is made up of a single population of clouds with cloud-cloud velocity dispersion σ_v and collisional mean free path l , the kinematic coefficient of viscosity, $\nu = vl/3$, can be evaluated from the molecular cloud area filling factor and the disk scale height (see Canzian 1990). Within the disk, the mean free path is given by

$$l = \frac{1}{\sqrt{2}\bar{n}_{\text{cl}}a} = \frac{\sqrt{2}}{n_{\text{cl}0}a}, \quad (10)$$

where $\bar{n}_{\text{cl}}$ is the cloud number-density averaged over the disk height, $n_{\text{cl}0}$ is the number-density at the disk midplane, and a is the cloud cross section. The product $n_{\text{cl}0}a$ may be estimated from the observed brightness temperature and the molecular gas kinetic temperature assuming the emission is thermalized and optically thick:

$$n_{\text{cl}0}a = \frac{T_B \sigma_v}{T_K \sigma_{\text{vcl}} 2H}, \quad (11)$$

where T_B is the observed CO brightness temperature, σ_v is the velocity dispersion in the z direction, T_K is the gas kinetic temperature, σ_{vcl} is the cloud internal velocity dispersion, and $2H$ is the effective thickness of the gas layer (i.e., $n_{\text{cl}0}M_{\text{cl}}2H = \Sigma$). The effective thickness of the gas layer ($2H$) in hydrostatic equilibrium is given by equation (2). We then obtain

$$\nu = \frac{32 \tanh^{-1}(1/2) \sigma_v^2 \sigma_{\text{vcl}} T_K}{9\pi^{3/2} G \Sigma T_B}, \quad (12a)$$

$$\nu = \frac{0.3507 \sigma_v^3 T_K}{G \Sigma T_B}, \quad (12b)$$

where we have adopted $\sigma_{\text{vcl}} = \sigma_v$ (this is equivalent to assuming that the layer really consists of a smooth gas distribution rather than clouds). Using $\sigma_v = 90 \text{ km s}^{-1}$, a gas surface density $\Sigma = 2.75 \times 10^4 M_{\odot} \text{ pc}^{-2}$ (corresponding to the average within $R = 250 \text{ pc}$) and the ratio $T_K/T_B \sim 4$, we obtain $\nu = 2.9 \times 10^{27} \text{ cm}^2 \text{ s}^{-1}$.

We have evaluated the viscous gas accretion rates for annuli 100 pc in width using equation (9) with the derived rotation curve (Fig. 8). The results are shown in Figure 13 for a gas surface density distribution which is constant out to 1.5 kpc (with total mass equal to the observed total). The expected variations in T_B which enter equation (12a) were taken to vary inversely with radius as $\Sigma/\Sigma_{\text{pk}}$, i.e., normalized to the present epoch peak at 130 pc radius. This gas distribution is meant as a zeroth-order approximation to the gas distribution at an earlier epoch before the gas had fully concentrated in the nucleus. Typical accretion rates in the

FIG. 13.—Viscous accretion rates for the rotation curve and a constant gas surface density distribution. The velocity dispersion is $\sigma_v = 90 \text{ km s}^{-1}$. The viscous accretion rate is shown for a constant surface density out to $R = 1.5 \text{ kpc}$ and total mass equal to that derived from the total CO emission. As discussed in the text, this density distribution might be representative of the prior state of Arp 220 before the gas was strongly concentrated in the nucleus and the expected radial accretion rates would have been $\sim 100 M_{\odot} \text{ yr}^{-1}$.

uniform surface density disk are in the range $100\text{--}200 M_{\odot} \text{ yr}^{-1}$ with the maximum occurring at $R \sim 250 \text{ pc}$. The implication is then that simply as a result of viscous accretion (neglecting torques provided by bars), the present distribution could arise in $\sim 10^8 \text{ yr}$. Similarly derived accretion rates based on the present epoch density distribution are extremely large in a small range of radii near 400 pc; however, these very high rates are due entirely to the steep gradients in the model surface density distribution, and we do not consider the derived density distribution to be that reliable in view of the simplifying axisymmetry assumption. The important point remains that the prior inflow of molecular gas can lead to the present configuration in a few dynamical timescales.

Angular momentum can also be removed from the central by spiral density waves. A timescale for this can be estimated from the torque of the spiral wave (see Lynden-Bell & Kalnajs 1972), assuming that the maximum amplitude of the spiral wave is that which yields a phase velocity just greater than the stellar velocities generated by the passage of the wave. The timescale for removing significant angular momentum by this spiral wave is given by

$$\tau_{\text{spiral}} = \frac{M_D R \Omega \kappa^4}{4\pi^4 G^3 \Sigma^4 \delta^2 (1 - \delta^2)^2}, \quad (13)$$

where κ is the epicyclic frequency, M_D is the mass of the disk, and $\delta = (\Omega_p + \Omega)/\kappa$ (see Canzian 1990). The spiral wave would most likely be excited by the orbiting stellar nuclei, and in this case the pattern speed would equal the angular velocity of the double nuclei ($\Omega_p = 310 \text{ km s}^{-1}/0.235 \text{ kpc} = 1320 \text{ km s}^{-1} \text{ kpc}^{-1}$). The spiral density wave removes angular momentum from inside the corotation radius (235 pc); the calculated gas infall rate is therefore only applicable at radii inside corotation. Using $M_D = 5.4 \times 10^9 M_{\odot}$ (within 250 pc radius) and $\Omega = 2000 \text{ km s}^{-1} \text{ kpc}^{-1}$ and $\kappa \simeq 2\Omega$ which are appropriate to $R = 125 \text{ pc}$, we find a timescale, $\tau = 5.6 \times 10^8 \text{ yr}$. This estimate yields an effective mean accretion rate of $\sim 10 M_{\odot} \text{ yr}^{-1}$. The timescale obtained from equation (13) depends on $(1 - \delta^2)^{-2}$ and is thus very sensitive to the relative magnitudes of Ω , Ω_p , and κ . Since the pattern speed is poorly constrained, the

numerical estimate given above should be viewed with caution.

In summary, it appears that viscous accretion will dominate the accretion due to spiral arm torques. The very large viscous accretion rates and the limited, albeit massive reservoir of molecular gas, imply a timescale $\tau \sim M_{\text{H}_2}/\dot{M}_{\text{acc}} \leq 5 \times 10^7$ yr for significant evolution of the Arp 220 nucleus.

6.4. Dynamical Friction on the Double Nuclei

Synchronization of the orbits of two stellar nuclei with the rotation of the gas disk will occur due to dynamical friction. The decay time for a drift velocity of the nuclei relative to the gas is

$$\tau_{\text{df}} = \frac{v_d^2 \sigma_v}{\sqrt{32\pi G^2 M_{\text{nuc}} \rho \ln(\Lambda)} \left(\frac{1}{f_D}\right)}, \quad (14)$$

where v_d is the drift velocity of the nuclei relative to the rotating disk, M_{nuc} is the mass of each nucleus, ρ is the mass density in the disk, f_D is the fraction of time which the nuclear star clusters spend within the gas disk, and

$$\ln \Lambda = \ln \left[\frac{b_{\text{max}} v_{\text{rot}}^2}{G(M_{\text{nuc}} + m)} \right], \quad (15)$$

where b_{max} is the distance of the farthest encounter to be included and m is the individual stellar mass (see Binney & Tremaine 1987). For parameters, we adopt $b_{\text{max}} = 235$ pc ($=R_{\text{nuc}}$), $v_d = 30$ km s⁻¹, $M_{\text{nuc}} = 5 \times 10^8 M_{\odot}$, $\sigma_v = 90$ km s⁻¹, and $\rho = 5 \times 10^{-20}$ g cm⁻³ (corresponding to a uniform density disk of radius 250 pc, thickness 32 pc, and total mass $5 \times 10^9 M_{\odot}$). If the orbital plane of the stellar cluster is not coplanar with the gas disk, f_D , the fraction of time spent within the gas disk, will be less than unity. However, given the thickness of the disk and the radius of the cluster orbit, $f_D \geq 0.04$ (the extreme limit requires that the clusters orbit perpendicular to the disk). We then find

$$\tau_{\text{df}} \leq 9 \times 10^3 \left(\frac{0.04}{f_D}\right) \left(\frac{v_d}{30 \text{ km s}^{-1}}\right)^2 \text{ yr}, \quad (16)$$

for decay time of any relative drift. Thus, any initial drift of the stellar clusters relative to the gas will be rapidly damped with the clusters undergoing orbital decay down to a radius at which they are almost precisely corotating with the gas disk. For the same reason, vertical motion of the stellar nuclei out of the disk will be damped on a somewhat longer timescale and one expects the nuclei to orbit within the gas disk. It is also likely that the clusters will clear gaps in the disks and thus reduce the dynamical friction; however, these gaps would have to be larger than the cluster diameter (i.e., ≥ 150 kpc) to significantly change the decay rate.

6.5. Physical Conditions within the Molecular Disk

The characteristics of the molecular gas in the nuclear disk of Arp 220 are extraordinarily different from those in the centers of nearby lower luminosity galaxies. In the Galactic center, the molecular gas ($\leq 10^8 M_{\odot}$) is mostly contained in very massive, presumably self-gravitating, molecular clouds (e.g., Sgr B2 or the Sgr A complexes) with relatively little intercloud molecular gas and a half-thickness for the cloud distribution of 60–120 pc. (Liszt & Burton 1978 have proposed that both the atomic and molecular gas in our Galactic center are distributed in a fairly uniform [noncloudy] disk of thickness ~ 100 pc, total

mass $\sim 1.5 \times 10^9 M_{\odot}$, and radius 1 kpc. Superficially this resembles an extended version of the Arp 220 disk; however, there is not general acceptance of this uniform density medium for our Galactic center and the high mass estimates which it requires are difficult to reconcile with the weakness of the γ -ray emission there.) In Arp 220, the total gas mass is a factor ≥ 100 larger within a comparable radius, and it appears inescapable that this gas is much more uniformly distributed (i.e., less cloudlike) and confined to an extremely thin disk (16 pc half-thickness or one-tenth the thickness of that in the Galactic center). The thinness of the disk is implied by the measured velocity dispersion (90 km s⁻¹) combined with the very high-mass surface density (derived from both the rotation curve and the CO line luminosity). Uniformity of the gas in this disk is suggested by the high area filling factor ($\simeq 0.25$) of the molecular gas derived from the observed CO line brightness temperatures. And given the high area filling factor and small scale height, the mean free path of clouds within this layer should be only a few disk scale heights. If we conservatively estimate the cloud-cloud collisional mean free path as ≤ 50 pc, then the mean collision time is only 5×10^5 yr. With such short cloud-cloud collision times and high velocities, most preexisting clouds would be rapidly disrupted and their matter spread uniformly in the disk. These conditions, with the mean free path comparable with the disk thickness imply that the disk is an α -type accretion disk, similar in some respects to the disks seen around young stellar objects.

On the other hand, the existence of molecular gas in an environment where the velocity dispersion is ~ 90 km s⁻¹ does require some clumping of the gas. Maintenance of most of the gas as molecular rather than ionized can occur if the cooling and recombination timescales in the dense shock fronts are much shorter than the mean time between shocking of each parcel of gas. This can be accomplished by modest clumping of the gas; a similar problem (and solution) arises in Galactic GMCs which have line widths indicative of Mach number $M = 10$ –20 motions yet a majority of the gas is obviously molecular.

The mean density of the nuclear gas disk is $n_{\text{H}_2} \simeq 1.5 \times 10^4$ cm⁻³, and the density at the peak at $R = 200$ pc radius at the disk midplane is 8×10^4 cm⁻³. The far-infrared data at $\lambda = 25$ –100 μm can be fitted by a blackbody of temperature 65 K while that at $\lambda = 60$ μm –2.7 mm by a 42 K blackbody plus an emissivity $\epsilon \simeq \lambda^{-1.3}$. The temperature of the gas is not strongly constrained by our data, but given the high densities it is reasonable to assume thermal equilibrium between the dust and the gas. We therefore adopt $T_K = 50$ K. The densities and temperature are in fact similar to those in GMC core regions with high rates of star formation, although in Arp 220 these conditions extend fairly continuously over a region 450 pc in extent! A major difference in the state of the gas is the factor of 10–20 higher velocity dispersion. This implies much greater kinetic energy dissipation in shocks and a larger resupply of turbulent energy in order to maintain the disk for longer than the dissipation time. The latter timescale should be comparable to the mean collision time estimated above. The total nonrotational kinetic energy in the gas is $\simeq 4 \times 10^{56}$ ergs ($=M_D \sigma_v^2/2$), and the dissipation rate should be equivalent to $\simeq 7 \times 10^9 L_{\odot}$ ($=0.3\% L_{\text{bol}}$). This energy will be radiated mostly in shock excited lines of ionized gas, but $\simeq 10\%$ will also be carried in the 2 μm vibrational lines of H₂. In fact, the total observed H₂ line

emission amounts to $\simeq 1 \times 10^8 L_\odot$ when corrected for extinction. The accretion rate $33 M_\odot \text{ yr}^{-1}$ estimated by van der Werf (1996) from the $2 \mu\text{m}$ H_2 lines is in fact similar to that required to maintain the present star formation rate in the center of Arp 220.

The high volume densities estimated above for the disk gas are consistent with observations of higher dipole moment molecules such as HCN and CS which exhibit much higher intensities relative to CO in Arp 220 (and other ultraluminous IR galaxies) than in the Galactic disk or our Galactic center region. Solomon et al. (1992), Aalto et al. (1994), and Bryant & Scoville (1996) find HCN(1–0)/CO(1–0) ratios elevated by a factor of $\simeq 10$ –20 relative to the Galactic plane GMCs, implying that a significant fraction ($\simeq 0.5$) of the gas is at densities $\geq 2 \times 10^4 \text{ cm}^{-3}$. Interpretation of the strong HCN emission has in the past gone in the direction of changing the internal characteristics of the clouds (e.g., larger cloud core regions); here we suggest that concentrating the molecular gas in a thin disk will naturally increase the volume density to the level at which the higher dipole molecules have relatively stronger emission because of their higher critical density. The CO (2–1)/(1–0) line ratios, being less than unity, suggest a lower density molecular component. This lower density gas might reside at several scale heights above the disk where the pressure has decreased, in the envelopes of disk clouds or in an intercloud medium. Here we make no attempt to model such multicomponent ISMs. It is interesting to note that the GMCs in our Galactic center also exhibit high HCN/CO line ratios (similar to Arp 220) yet the $L_{\text{IR}}/L_{\text{CO}}$ ratios there are more similar to Galactic plane GMCs. Solomon et al. (1992) argued that the high HCN/CO ratio in Arp 220 (and other ultraluminous IR galaxies) indicated that the luminosity was probably produced by high-mass star formation, yet our Galactic center provides a counterexample to this argument since there the HCN/CO line ratio is high but the star formation efficiency is low.

The conversion factor between CO emission line luminosity and molecular gas mass will vary depending on the physical conditions in the gas and its dynamical state (see Solomon et al. 1992; Bryant & Scoville 1996). Since the CO (1–0) line is optically thick and thermalized at these densities, the total line luminosity depends simply on the surface area of optically thick molecular gas, its line width (i.e., σ_v), and the gas kinetic temperature. In the simple situation relevant to Galactic disk GMCs which are self-gravitating, it can be shown that the conversion factor, α_G , from CO to H_2 should vary as $n_{\text{H}_2}^{1/2}/T_K$. For the Galactic GMCs, typical densities and temperatures are 300 cm^{-3} and 10 K. Comparison with the mean values given above ($1.5 \times 10^4 \text{ cm}^{-3}$ and 50 K) suggests that $\alpha_{\text{Arp 220}} = 1.4\alpha_G$, i.e., the gas mass is, in fact, higher than that estimated using the Galactic conversion factor. Bryant & Scoville (1996) analyzed the expected variation of the conversion factor for a thin self-gravitating disk and find

$$\alpha = 0.15\text{--}0.44 \text{ sec } i \left(\frac{n_{\text{H}_2}}{300 \text{ cm}^{-3}} \right)^{1/2} \left(\frac{10 \text{ K}}{T_K} \right) \alpha_G \quad (17)$$

for reasonable disk parameters (see eq. A22 in Bryant & Scoville 1996). With our adopted inclination angle of 45° for Arp 220, one therefore expects $\alpha_{\text{Arp 220}} = (0.3\text{--}0.88)\alpha_G$, and the value obtained from the profile fitting, $0.45\alpha_G$, is in the middle of this range. In conclusion, we believe that on the

basis of both the line profile analysis and the general considerations which led to equation (17) that a CO-to- H_2 conversion factor $\simeq 0.5\alpha_G$ is appropriate to the nuclear disk of Arp 220. Since the total molecular gas mass for the entire galaxy is $\simeq 10^{10} M_\odot$ and the dust mass is $5 \times 10^7 M_\odot$ (§ 5, estimated from the 1.3 mm continuum emission), the implied dust-to-gas mass-ratio is approximately 200. This value is entirely consistent with that obtained in the Galactic ISM.

In view of the extraordinarily high column densities of gas and dust in the Arp 220 disk, it is worthwhile to ask if these are consistent with the fact that the double nuclei can be seen at all in the near-infrared and with the extinctions derived from near-infrared recombination lines. Larkin et al. (1995) find $A_V = 10$ and 13 mag for the individual nuclei based on the recombination lines and Roche et al. (1991) estimate $A_V = 70$ mag from the $10 \mu\text{m}$ silicate feature. The latter may not be appropriate to the double nuclei since a substantial fraction of the $10 \mu\text{m}$ emission probably arises from dust in the disk rather than that associated with the stellar nuclei. The average surface density $\Sigma = 2.75 \times 10^4 M_\odot \text{ pc}^{-2}$ implies an extinction $A_V = 2000$ mag, perpendicular to the disk and approximately 10 times larger in the plane of the disk. Clearly, these numbers can only be reconciled if the nucleus is not completely covered by the gas and dust: either the gas is in very small clumps or the gas is narrowly confined to a disk inclined to the nuclear line of sight. On the basis of observed high CO brightness temperatures and the resulting high area covering factor, we believe that the latter explanation provides the most reasonable reconciliation. In fact, the size of the individual nuclear star clusters is probably large enough that the entire cluster would not be covered by the disk even if the disk were viewed edge-on and the cluster were situated in the disk. Graham et al. (1990) resolve the individual nuclei with a size $\simeq 0.5$ or 175 pc (FWHM).

Given the fact that $\sim 95\%$ of the bolometric luminosity from Arp 220 emerges in the far-infrared, it is required that there be a minimum extinction of at least 2 mag in front of virtually all of the luminosity sources in Arp 220 (both AGNs and the starburst clusters). Despite the thinness of the derived molecular disk, this does not appear to be a problem since the extinction within the disk is so high (2000 mag) that one would have to go many scale heights to get line-of-sight extinctions less than 2 mag. In addition, there may be a residual, more spherically distributed, component which provides a few magnitudes of extinction in front of the entire luminosity source.

7. CONCLUDING REMARKS

Analysis of these high-resolution CO observations has led us to a remarkable, new picture of the massive molecular gas concentration at the center of the ultraluminous infrared galaxy Arp 220 (as shown schematically in Fig. 7 and summarized quantitatively in Table 4). Approximately $\frac{2}{3}$ of the total molecular gas is concentrated inside 250 pc (at and inside the radii of the twin infrared/radio nuclei) where it is confined to a thin (16 pc, full width containing half the mass) accretion disk. The gas in the disk is at high density ($\langle n_{\text{H}_2} \rangle \simeq 2 \times 10^4 \text{ cm}^{-3}$), but distributed fairly uniformly, i.e., there is no clear need that this gas be in self-gravitating clouds like those in nearer low luminosity galactic nuclei. This morphology may be a common feature of the neutral gas in the nuclei of ultraluminous galaxies which are the

result of galactic merging. Several other systems imaged at high spatial resolution in the molecular gas (e.g., Mrk 231 and NGC 6240) bear striking similarities to Arp 220 (Bryant & Scoville 1996, 1997). Several exhibit CO peaks between double infrared/radio nuclei, clear rotational velocity gradients suggestive of a centrifugally supported disk, and relatively strong high critical-density molecular line emission (indicating a preponderance of dense gas). In Mrk 231, the small line width is consistent with there being a very thin disk (Bryant & Scoville 1996).

These dense molecular-gas accretion disks may play a critical role in the evolution of ultraluminous galaxy nuclei and in their energy release. The high density of the gas will undoubtedly promote extremely high rates of massive star formation since the conditions are very similar to those of GMC core regions in the Galaxy (see Solomon et al. 1992). However, initial compression of the gas to high density may result from shock compression (rather than gravitational collapse) since the velocity dispersion in the disk is much

higher than the thermal speed of sound ($\text{Mach} \sim 100\text{--}1000$). The resulting high effective temperature in these shocks should strongly favor high rather than low-mass star formation. The dense gas disks are also an efficient mechanism for removing angular momentum and thus feeding and building up a central active nucleus at rates up to $100 M_{\odot} \text{ yr}^{-1}$. This latter process is probably most important in the most evolved and highest luminosity systems such as Mrk 231. In Arp 220 the nonthermal AGN may also dominate, given the low upper limit on the free-free flux obtained from millimeter-continuum measurements.

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REFERENCES

- Aalto, S., Booth, R. S., Black, J. H., Koribalski, B., & Wielebinski, R. 1994, *A&A*, 286, 365
- Armus, L., Neugebauer, G., Soifer, B. T., & Matthews, K. 1995, *AJ*, 110, 610
- Armus, L., Shupe, D. L., Matthews, K., Soifer, B. T., & Neugebauer, G. 1995, *ApJ*, 440, 200
- Binney, J., & Tremaine, S. 1987, *Galactic Dynamics* (Princeton: Princeton Univ. Press)
- Bryant, P. M. 1996, Ph.D. thesis, California Inst. Tech.
- Bryant, P. M., & Scoville, N. Z. 1996, *ApJ*, 457, 678
- . 1997, in preparation
- Canzian, B. 1990, Ph.D. thesis, California Inst. Tech.
- Doyon, R., Wells, M., Wright, G. S., Joseph, R., & Nadeau, N. 1994, *ApJ*, 437, L23
- Draine, B., & Lee, H. M. 1984, *ApJ*, 285, 89
- Genzel, R., et al. 1995, *ApJ*, 444, 129
- Graham, J. R., Carico, D. P., Matthews, K., Neugebauer, G., Soifer, B. T., & Wilson, T. D. 1990, *ApJ*, 354, L5
- Hildebrand, R. H. 1983, *QJRAS*, 24, 267
- Joseph, R. D., & Wright, G. S. 1985, *MNRAS*, 214, 87
- Larkin, J. E., Armus, L., Knop, R. A., Matthews, K., & Soifer, B. T. 1995, *ApJ*, 452, 599
- Liszt, H. S., & Burton, W. B. 1978, *ApJ*, 226, 790
- Lynden-Bell, D., & Kalnajs, A. 1972, *MNRAS*, 157, 1
- Maeder, A. 1987, *A&A*, 173, 247
- Nordsieck, K. H. 1973, *AJ*, 184, 719
- Norris, R. P. 1988, *MNRAS*, 230, 345
- Panagia, N. 1973, *AJ*, 78, 929
- Pringle, J. E. 1981, *ARA&A*, 19, 137
- Radford, S. J. E., Solomon, P. M., & Downes, D. 1991, *ApJ*, 368, L15
- Renzini, A., & Buzzoni, A. 1986, in *Spectral Evolution of Galaxies*, ed. C. Chiosi & A. Renzini (Dordrecht: Reidel), 195
- Roche, P. F., Aitken, D. K., Smith, C. H., & Ward, M. J. 1991, *MNRAS*, 248, 606
- Sanders, D. B., Scoville, N. Z., & Soifer, B. T. 1991, *ApJ*, 370, 158
- Sanders, D. B., Soifer, B. T., Elias, J. H., Madore, B. F., Matthews, K., Neugebauer, G., & Scoville, N. Z. 1988, *ApJ*, 325, 74
- Sargent, A. I., & Scoville, N. Z. 1991, *ApJ*, 366, L1
- Scoville, N. Z., Carlstrom, J. C., Chandler, C. J., Phillips, J. A., Scott, S. L., Tilanne, R. P., & Wang, Z. 1992, *PASP*, 105, 1482
- Scoville, N. Z., Sargent, A. I., Sanders, D. B., & Soifer, B. T. 1991, *ApJ*, 366, L5
- Scoville, N. Z., & Sanders, D. B. 1987, in *Interstellar Processes*, ed. D. Hollenbach & H. A. Thronson (Dordrecht: Reidel), 21
- Scoville, N. Z., & Soifer, B. T. 1991, in *Massive Stars in Starbursts*, ed. C. Leitherer, N. R. Walborn, T. M. Heckman, & C. A. Norman (New York: Cambridge Univ. Press), 233
- Scoville, N. Z., Young, J. S., & Lucy, L. B. 1983, *ApJ*, 270, 443
- Shepherd, M. C., Pearson, T. J., & Taylor, G. B. 1994, *BAAS*, 26, 287
- Shier, L. M., Rieke, M. J., & Rieke, G. H. 1994, *ApJ*, 433, L9
- . 1996, *ApJ*, 470, 222
- Solomon, P. M., Downes, D., & Radford, S. J. E. 1992, *ApJ*, 387, L55
- Spitzer, L. 1942, *ApJ*, 95, 329
- Toomre, A. 1964, *ApJ*, 139, 1217
- van der Werf, P. P. 1996, in *Cold Gas at High Redshift*, ed. M. M. Bremer et al. (Kluwer: Dordrecht), 37
- Woody, D. P., Scott, S. L., Scoville, N. Z., Mundy, L. G., & Sargent, A. I. 1989, *ApJ*, 337, L41