

APERTURE SYNTHESIS MAPPING OF MOLECULAR GAS IN HIGH-LUMINOSITY IRAS GALAXIES

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ABSTRACT

The Owens Valley millimeter-wave interferometer has been used for high-resolution (6") mapping of the 2.6 mm CO emission from the high-luminosity infrared galaxies NGC 520 (Arp 157), NGC 7469 (Arp 298), and Arp 55. For these distant galaxies, the bolometric luminosities are in the range $1\text{--}5 \times 10^{11} L_{\odot}$. In all three cases, the interferometer observations revealed massive concentrations of gas centered on the optical/infrared nuclei. Assuming the same empirical relationship between CO brightness and molecular hydrogen surface mass density as has been found for giant molecular clouds in the Milky Way, we find that the masses of H_2 gas in these concentrations are $10^9\text{--}10^{10} M_{\odot}$, typically one-third of the total molecular gas content of these galaxies. The interferometric sizes correspond to radii of 0.8 kpc (NGC 520), 1.4 kpc (NGC 7469), and <2.8 kpc (Arp 55). For the same regions the dynamical masses estimated from the CO line width and size of the emission region are only a factor of 3–5 higher. The mean molecular gas surface densities averaged over these regions are in the range $610\text{--}825 M_{\odot} \text{ pc}^{-2}$, a factor of 10 brighter than those obtained for corresponding regions in the nucleus of the Milky Way. The high mass fractions obtained for the interstellar medium in the central regions of these three galaxies strongly suggest that large-scale gravitational instability in the gas may play an important role in the further concentration of the gas in the nucleus and in possibly precipitating a large-scale burst of star formation.

Subject headings: galaxies: interstellar matter — interferometry

I. INTRODUCTION

The source and nature of the energetic activity in the nuclei of galaxies remains one of the fundamental problems of galactic structure. Over the last two decades, optical and radio studies have highlighted quasars as the most luminous objects in the universe. However, recent studies have clearly shown that there exist galaxies which emit the bulk of their luminosity at far-infrared wavelengths which are, at least in the local universe ($z < 0.1$), more numerous than, and as luminous as, the optical quasars (Soifer *et al.* 1986). There is a strong possibility that these separate classes of objects, the optical quasars and infrared galaxies, may in fact represent two stages in a larger evolutionary sequence of starburst/active galactic nuclei (Sanders *et al.* 1988). A prime example suggesting a connection is provided by Mrk 231, an infrared galaxy rich in molecular gas (Sanders *et al.* 1987), with total bolometric luminosity of $4 \times 10^{12} L_{\odot}$ (Rieke and Low 1972) for which optical spectroscopy of the nucleus indicates broad emission lines with characteristics similar to those seen in quasars (Boksenberg *et al.* 1976).

The presence of strong thermal infrared emission clearly indicates copious amounts of interstellar material in the IR luminous galaxies. High spatial resolution observations of this gas are vital to understanding the genesis and evolution of the IR-luminous galaxies. Determination of the abundance and spatial distribution of the dense interstellar gas allows a quantitative evaluation of star formation rates, and by implication the evolutionary lifetime of the galactic nuclear region. Recent

aperture synthesis mapping of two high-luminosity IR galaxies, Arp 220 and NGC 3690/IC 694 = Arp 299 (Scoville *et al.* 1986; Sargent *et al.* 1987), have clearly demonstrated the feasibility of measuring the cold molecular gas distribution on the scale of 5" in galactic nuclei at distances out to 80 Mpc.

Over the last observing season, we have undertaken aperture synthesis mapping of three additional high-luminosity IR galaxies—NGC 520, NGC 7469, and Arp 55. All three galaxies have luminosities in excess of $10^{11} L_{\odot}$ and molecular gas contents, based on single-dish CO measurements, of $5\text{--}20 \times 10^9 M_{\odot}$ (Sanders and Mirabel 1985; Young *et al.* 1986; Sanders *et al.* 1986). Optical photographs show that NGC 520 and Arp 55 are clear mergers while NGC 7469 may have recently undergone a strong interaction with IC 5283 1:3 to the north. The optical spectra of these galaxies span the range from a typical H II region spectrum (NGC 520) and a narrow-line AGN spectrum (Arp 55) (Sanders *et al.* 1986) to a broad-line, classic Seyfert 1 spectrum (NGC 7469; Seyfert 1943).

II. INTERFEROMETER OBSERVATIONS

The CO ($J = 1 \rightarrow 0$) observations of the three galaxies were made in 1986 November to 1987 February using the Owens Valley millimeter-wave interferometer. Each of the 10.4 m telescopes was equipped with a SIS receiver, cooled to 4.5 K. The measured receiver temperatures were approximately 250 K SSB. Spectral coverage was provided by a filterbank consisting of 32.5 MHz channels, giving it a velocity coverage of 416 km s^{-1} with a resolution of 13.6 km s^{-1} . For NGC 520 and NGC

7469, four configurations of the three telescopes resulted in synthesized beams of $6'' \times 5''$ at position angle 10° . For Arp 55, two configurations were used, resulting in a synthesized beam of $9'' \times 7''$ at position angle 4° .

Phase calibration was carried out by observing the standard sources 3C 454.3, 0202 + 149, and 0923 + 392, respectively for NGC 7469, NGC 520, and Arp 55 every half-hour; absolute flux calibration was based on measurements of Uranus (Ulich 1981) and W3(OH), for which a flux of 4 Jy was assumed. Data were then processed after initial calibration using the NRAO AIPS package. CLEAN maps of the CO emission were generated for single channels and for an average over all 32 channels. Since the shortest projected baseline possible with the interferometer is 10 m, the interferometer is insensitive to any emission extended over angular scales greater than $30''$.

III. RESULTS

In Figure 1 (Plates L5–L7), the integrated intensity maps of the CO emission from each of the galaxies are superposed on optical photographs. The phase centers of the maps are listed in Table 1, along with the mean heliocentric redshifts and adopted distances based upon the Virgocentric flow model of Aaronson *et al.* (1982). In all three galaxies, the observed emission in each individual 5 MHz channel is unresolved. On the other hand, for NGC 520 and NGC 7469, when the emission is integrated over the entire 416 km s^{-1} bandwidth of the filterbank, the velocity changes across the galactic nuclei result in an emission distribution which is extended over a region slightly larger than the synthesized beam. In NGC 520 and NGC 7469, the size of the emission region is approximately $12''$ (FWHM) and $9''$ (FWHM) respectively. In Arp 55, the total integrated intensity map indicates the presence of two unresolved components coincident with the optical nuclei of the two merging galaxies separated by approximately $7''$ east–west. The integrated fluxes and measured half-power sizes (based upon the integrated intensity maps) are listed in Table 1. In all three galaxies, approximately one-third of the total single-dish CO line flux is detected by the interferometer, indicating that

approximately 2/3 of the CO emission is distributed over regions between $15''$ and $60''$ in size.

IV. DISCUSSION

H_2 masses have been computed from the measured CO luminosity using a “standard” $\text{CO} \rightarrow \text{H}_2$ conversion factor of $3.6 \times 10^{20} \text{ H}_2 \text{ cm}^{-2} (\text{K km s}^{-1})^{-1}$ determined from the virial theorem (Scoville *et al.* 1987) and γ -ray measurements (Bloemen *et al.* 1986) of molecular clouds in the Milky Way. This is equivalent to the relation $M(\text{H}_2)[M_\odot] = 5.8 L_{\text{CO}} [\text{K km s}^{-1} \text{ pc}^2]$ (Sanders, Solomon, and Scoville 1984), or $M(\text{H}_2) = 0.13 L_{\text{CO}} [\text{Jy km s}^{-1} \text{ pc}^2]$. Nearly all empirical measures of the $\text{CO} \rightarrow \text{H}_2$ conversion factor in Galactic GMCs are within a factor of 2 of this value (cf. Scoville and Sanders 1987; Dame *et al.* 1987). In one instance, the nucleus of M82, there is a possibility that the conversion ratio is somewhat lower since the high observed ratio of $\text{CO}(2-1)/\text{CO}(1-0)$ and $^{13}\text{CO}(1-0)/\text{CO}(1-0)$ may indicate partial optical thinness (Knapp *et al.* 1980; Stark and Carlson 1982). However, this is not the only possible interpretation of the M82 line ratios (Young and Scoville 1984), and other galactic nuclei apparently have $^{13}\text{CO}(1-0)/\text{CO}(1-0)$ intensity ratios similar to those in the Galactic disk (Young and Sanders 1986). The CO conversion factor actually depends on both the average CO brightness temperature and the mean gas density, with $M(\text{H}_2)/L_{\text{CO}} \propto \rho^{0.5}/T_{\text{CO}}$ (Scoville and Sanders 1987; Solomon *et al.* 1987). Since hotter clouds (e.g., in galactic nuclei) tend to be denser (Bally *et al.* 1987), the temperature and density dependences will to some extent cancel.

Despite the high far-infrared luminosity of the three galaxies studied here, their mean dust temperatures and ratios of total far-infrared luminosity to total CO luminosity are not extreme: the values of $\langle L_{\text{fir}}/L_{\text{CO}} \rangle$, 90, 150, and 77 for NGC 520, NGC 7469, and Arp 55, respectively, are much less than the 650 and 550 for the luminous infrared galaxies Arp 299 and Arp 220 (Young *et al.* 1984; Sanders and Mirabel 1985). The $\langle L_{\text{fir}}/L_{\text{CO}} \rangle$ ratios and dust temperatures are similar to those of massive galactic molecular clouds, such as W51 and M17 (Scoville and Good 1987; Solomon *et al.* 1987). The total H_2 masses, computed using our adopted conversion factor, are $4 \times 10^9 M_\odot$ for NGC 520, $9.3 \times 10^9 M_\odot$ for NGC 7469, and $2.9 \times 10^{10} M_\odot$ for Arp 55 (Sanders *et al.* 1986). The total CO luminosity for NGC 7469 reported here is similar to that found by Young *et al.* (1986), and Heckman *et al.* (1986), although the latter group derives an H_2 mass twice that adopted here.

The derived H_2 masses in the central sources detected by the interferometer and mean surface densities averaged uniformly over the synthesized beams are listed in Table 1. The derived surface densities for all three galaxies are approximately an order of magnitude higher than those obtained for comparable regions in the Milky Way (Sanders, Solomon, and Scoville 1984).

A plausible mechanism for triggering the extraordinary concentration of molecular gas in the nuclei of these three galaxies is the strong interaction of two spiral galaxies, one or both of which may have been rich in molecular gas. In the case of Arp 55 and NGC 520, the optical images indicate that the two original galaxies are near a complete merger; in NGC 7469, a possible collision partner approximately $1/3$ north suggests that an interaction may have occurred approximately 10^8 – 10^9 yr ago. During a collision, concentration of the molecular gas in the nucleus should occur when cloud orbits experience large perturbations away from circular motion, resulting in frequent cloud-cloud collisions. These collisions will tend to transfer

TABLE 1

MOLECULAR GAS PROPERTIES OF HIGH-LUMINOSITY IRAS GALAXIES

Parameter	NGC 520	NGC 7469	Arp 55
α_{1950}^a	01 ^h 21 ^m 59 ^s .6	23 ^h 00 ^m 44 ^s .0	09 ^h 12 ^m 37 ^s .6
δ_{1950}^a	03°31'53"	08°36'18"	44°32'20"
$\langle \text{CZ}(\text{CO}) \rangle (\text{km s}^{-1})^b$	2261	4963	11957
$\Delta \text{CZ}(\text{FWHM}) (\text{km s}^{-1})^b$	330	285	250
Distance (Mpc)	29	66	163
$L_{\text{fir}}(40\text{--}400 \mu\text{m})(10^{11} L_\odot)^c$	0.6	2.6	3.9
Integrated CO flux (Jy km s^{-1}):			
OVRO	325	144	83
FCRAO ^b	968	398	230
Source size _{OVRO} (kpc) ^d	0.8	1.4	<2.8
$M(\text{H}_2 + \text{He})_{\text{OVRO}} (10^9 M_\odot)$	1.9	4.5	14.4
$M_{\text{dyn}} (10^9 M_\odot)$	8.0	12.5	23.0
$\langle \sigma(\text{H}_2 + \text{He}) \rangle_{\text{OVRO}} (M_\odot \text{ pc}^{-2})$	825	690	610

^a Phase center of OVRO CO detection.

^b Mean heliocentric redshift ($\pm 20 \text{ km s}^{-1}$), velocity width (FWHM), and integrated CO flux determined from single-dish $\text{CO}(1 \rightarrow 0)$ line profiles (Sanders and Mirabel 1985; Sanders *et al.* 1986) obtained with the 14 m telescope of the Five College Radio Astronomy Observatory (FCRAO).

^c IRAS far-infrared luminosity (Sanders *et al.* 1986).

^d HWHM measured from the OVRO total integrated intensity maps.

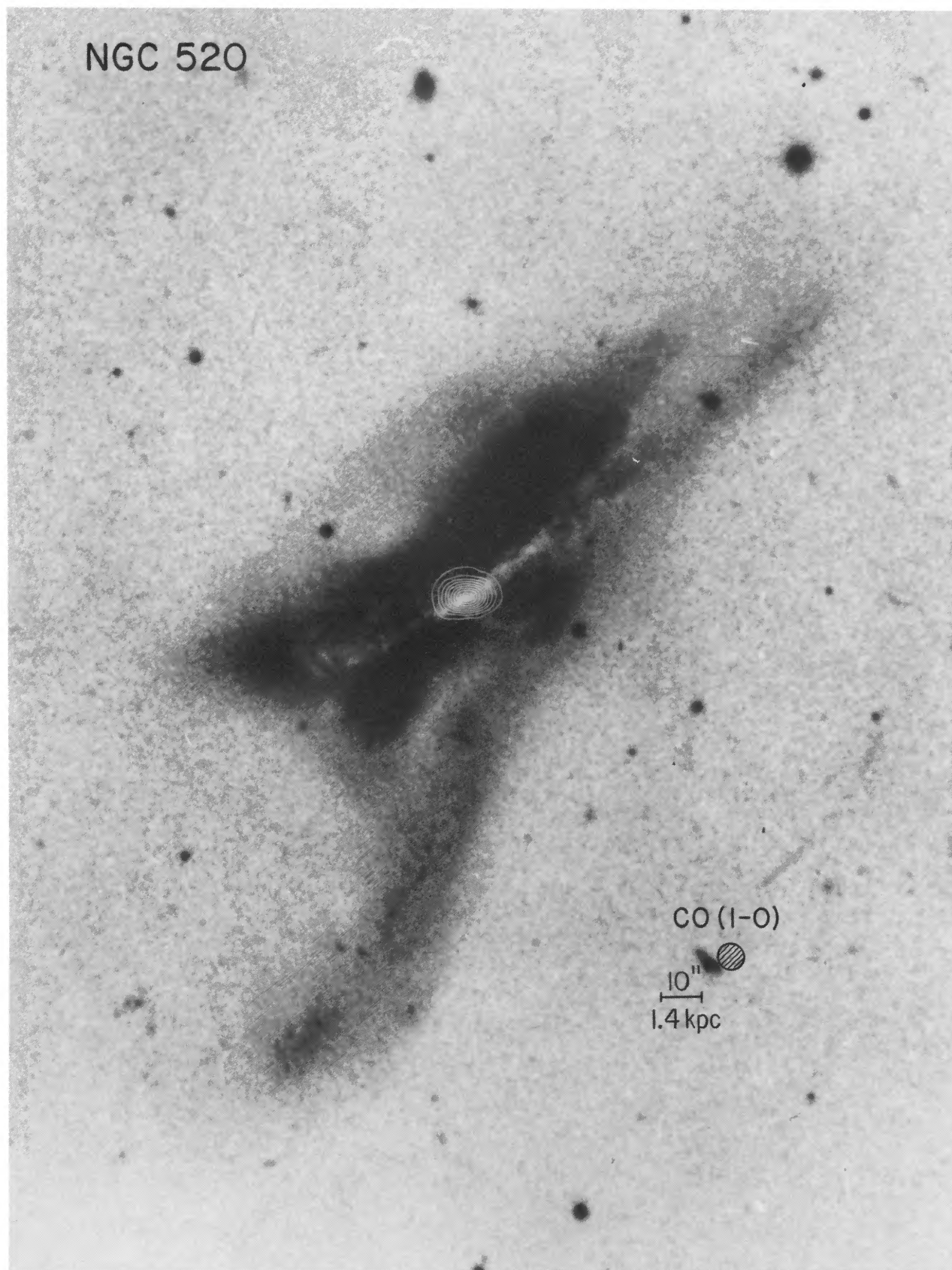


FIG. 1a

FIG. 1.—Integrated intensity maps of CO emission in (a) NGC 520, (b) NGC 7469, and (c) Arp 55 superposed on optical photographs from the Arp atlas (Arp 1966). Contour levels are 10% of peak. The hatched beam symbol indicates both the position angle and size of the synthesized beam for each object.

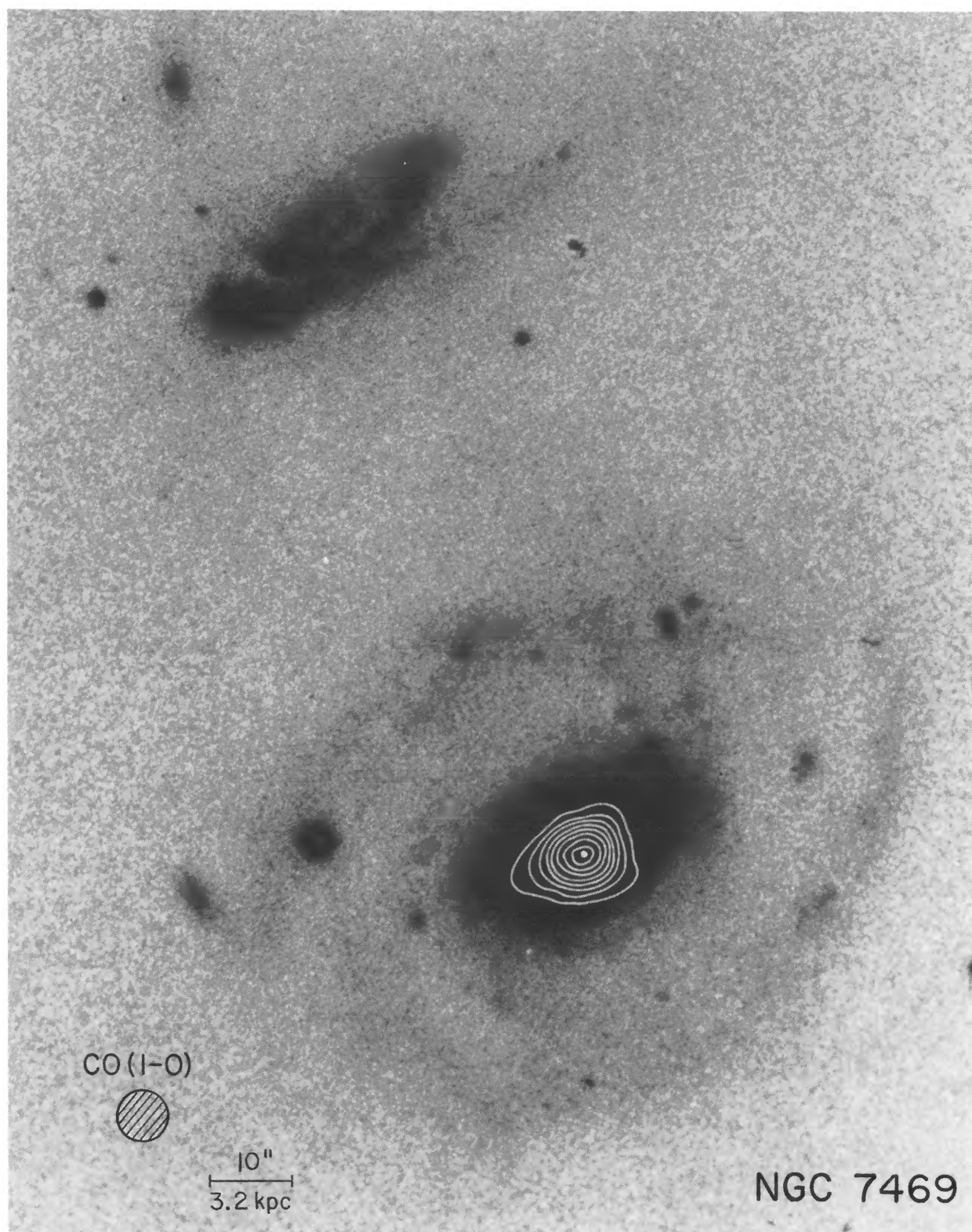


FIG. 1b

SANDERS *et al.* (see 324, L56).

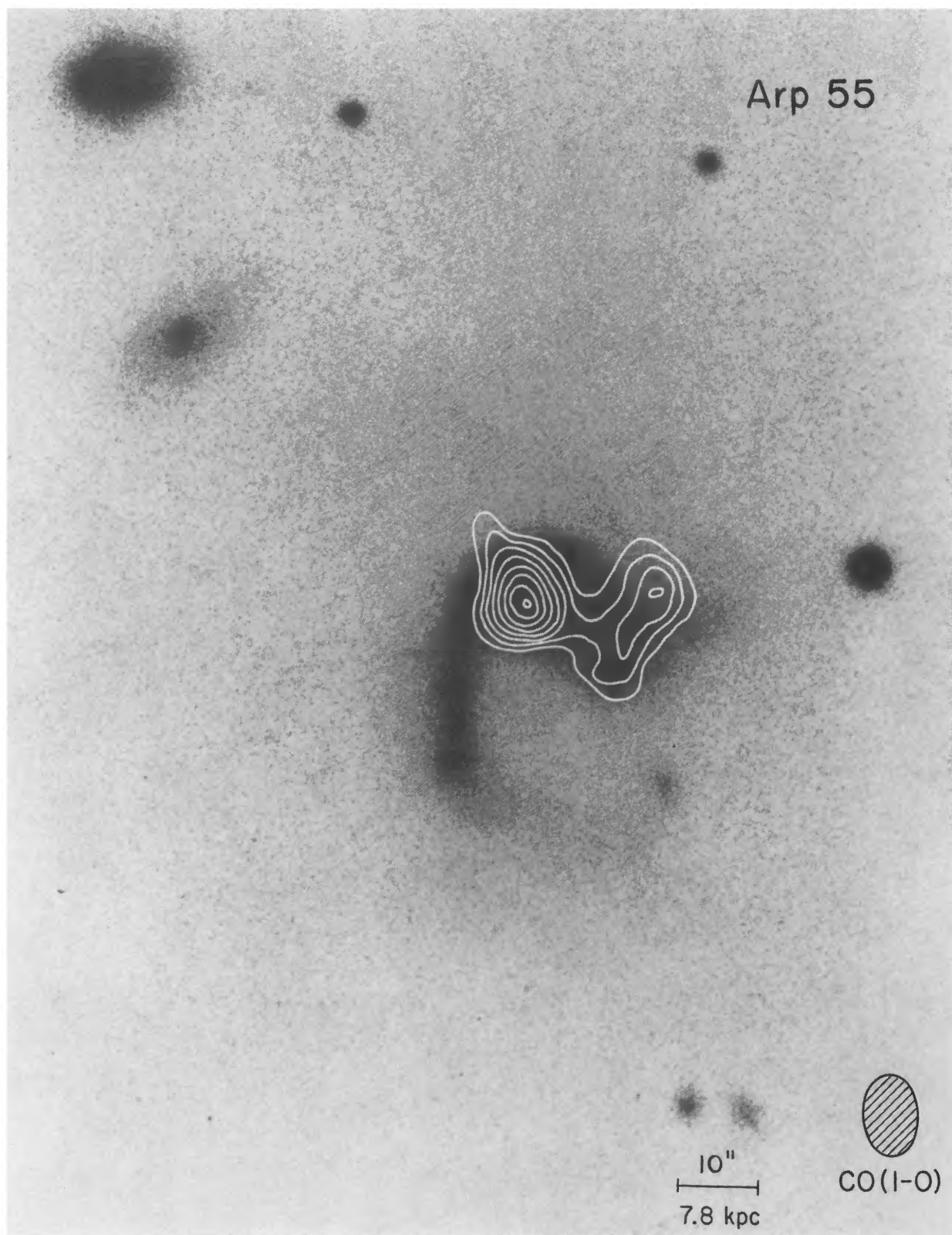


FIG. 1c

SANDERS *et al.* (see 324, L56).

angular momentum outward and result in a gas flow inward toward the nuclei. The unusually high nuclear gas densities derived from the interferometer observations provide the first *direct* evidence that in colliding/merging galaxies the gas is much more centrally concentrated than in normal spirals.

The concentration of molecular gas in the central regions of these galaxies can have two effects: an increased star formation efficiency as a result of the frequent cloud-cloud collisions (Scoville, Sanders, and Clemens 1986) and the creation of a site for the formation of a dense, central star cluster, possibly a precursor of the AGN phase. If the far-infrared luminosity is simply due to star formation, a reasonable minimum estimate of the time scale for consumption of the molecular gas can be made by assuming the $L_{\text{fir}}/M(\text{H}_2)$ ratio of the central gas concentration is the same as that for the entire galaxy. Assuming that all of the far-infrared luminosity originates from early-type O, B, and A stars, yielding $8 \times 10^{-11} M_{\odot} \text{ yr}^{-1}$ per $L_{\odot}$ of luminosity in a steady state (cf. Scoville and Young 1983), implies rates of massive star formation of 3, 7, and $12 M_{\odot} \text{ yr}^{-1}$ for NGC 520, NGC 7469, and Arp 55, respectively, compared to a rate of $\sim 1 M_{\odot} \text{ yr}^{-1}$ for the entire Milky Way. Allowing for a minimum of a factor of 3 more mass in lower mass stars implies that the central molecular gas concentrations will be consumed in approximately 10^8 yr. The actual time scale may be even shorter given that the $L_{\text{fir}}/M(\text{H}_2)$ ratio may increase in the Galactic center and that all of the gas does not end up in stars. Thus, if the current far-infrared luminosity is to be maintained for periods longer than 10^8 yr an additional source of energy is required.

Also included in Table 1 are estimates of the dynamical masses within the regions defined by the CO interferometer sources. The dynamical masses were computed using the measured CO linewidths ($\times \sqrt{3}$) and radii of the emitting regions provided in Table 1. The CO linewidth is assumed to be a good measure of the galactic rotation curve as illustrated for NGC 520 in Figure 2. In NGC 520, the emission in the individual channel maps is marginally resolved and the centroid of the emission shifts from channel to channel across the spectrum in a systematic fashion. In the upper panel of Figure 2, the spectrum of flux observed by the interferometer is compared with that obtained in single-dish measurements (Sanders and Mirabel 1985); the centroid position is plotted as a function of velocity in the lower panel. The velocity gradient seen in Figure 2 corresponds to a change of 300 km s^{-1} across approximately $6''$ or 700 pc. For NGC 7469 the data are much more noisy, but the position of the emission centroid also appears to vary systematically with velocity in both R.A. and decl., with a velocity gradient of $\sim 200 \text{ km s}^{-1}$ across approximately $4''$.

In all three galaxy nuclei, the measured molecular masses (assuming the standard CO to H_2 conversion ratio) are in the range 20%–35% of the derived dynamical masses.¹ In contrast, the typical molecular gas densities in the inner disk of the Milky Way corresponds to 5%–10% of the dynamical masses. The high mass fraction obtained for the molecular gas in the nuclei of these three galaxies suggests that self-gravity in the interstellar matter will play an important role. Theoretical work (e.g., Toomre 1964) has shown that large-scale gravitational instabilities in disk galaxies will set in when approximately 10% of the total mass is contained in the highly

¹ The total luminosity detected by the interferometer from Arp 55 is split nearly equally between the two components shown in Fig. 1.

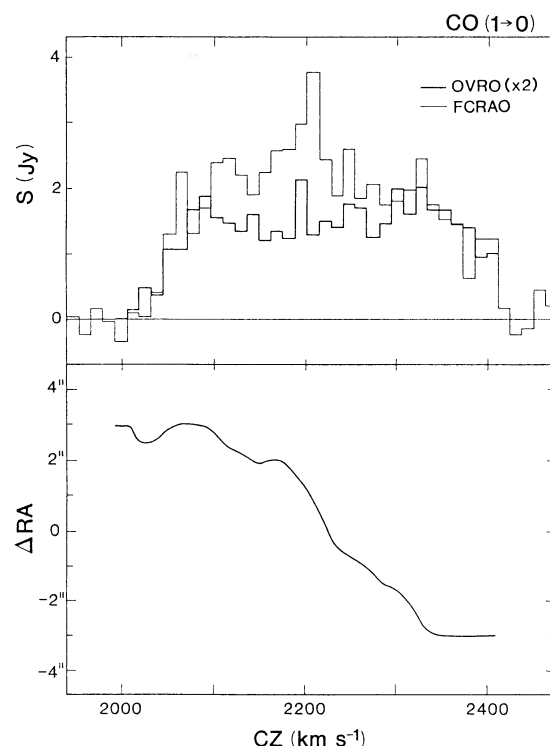


FIG. 2.—(upper panel) Comparison of interferometer and single-dish CO emission profiles for NGC 520. (lower panel) Position of phase center of CO emission in NGC 520 as a function of the center velocity in each filterbank channel.

dissipative interstellar matter. Such large-scale gravitational instabilities in galactic nuclei like those observed here are discussed in more detail by Norman (1987) and Scoville and Norman (1987).

It is clear from the disturbed morphology seen in the optical photographs, and by the presence in one case of a double nucleus, that the galaxies observed in this *Letter* could not have been in their present state for a significant fraction of a Hubble time. The implied high rate of star formation in the concentrated interstellar gas strongly suggests an upper limit of order 10^8 yr. Qualitatively, the optical and near-infrared spectra of NGC 7469 at least confirm the high rate of star formation (Cutri *et al.* 1984; Heckman *et al.* 1986). However, a more quantitative estimate is precluded by the high obscuration in all three nuclei.

The high rate of star formation in the condensed gas distribution in the nuclei of these three galaxies will probably result in the formation of a massive central star cluster. The evolution of such a cluster (Scoville and Norman 1987) can be followed theoretically. Due to the deep potential well of such a concentrated mass distribution and the high density of interstellar gas, virtually all of the gas loss during late stellar evolution will sink to the center of the cluster, probably building up a central massive black hole. For a coeval star cluster of mass $4 \times 10^9 M_{\odot}$, a central mass of approximately $1.5 \times 10^9 M_{\odot}$ can accumulate within approximately 10^8 yr. Accretion at an average rate of $2 M_{\odot} \text{ yr}^{-1}$ will result in a mean accretion luminosity (assuming $L_{\text{accr}} \approx 0.1 \dot{M} c^2$) in excess of $10^{12} L_{\odot}$. It is therefore plausible that the starbursts in gas-rich merging galaxies may be linked in a direct evolutionary scenario to the formation of an active galactic nucleus.

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Note added in proof.—P. Solomon and L. Sage (1987, private communication) have detected CO emission from NGC 520 outside the central 45" region. They compute a total CO luminosity for NGC 520 approximately twice that given by the single-beam (45") measurement of Sanders and Mirabel (1985). The larger total CO luminosity would imply that the central source detected at OVRO represents 17% of the total CO luminosity in NGC 520 rather than 33% as given in Table 1 of this *Letter*.

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