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MOLECULAR GAS IN THE TYPE 1 SEYFERT GALAXY NGC 7469: IMPLICATIONS FOR NUCLEAR ACTIVITY

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ABSTRACT

We report the results of a search for 2.12 μm H_2 1–0 $S(1)$ line emission from the nuclear (≤ 1 kpc) region in 11 active galaxies. The galaxies observed included type 1 and type 2 Seyferts, LINERs, and starburst nucleus galaxies. H_2 emission was detected in one galaxy, the classical type 1 Seyfert NGC 7469 ($L_{S(1)} \sim 3 \times 10^{40}$ ergs s^{-1} for $H_0 = 75$ km s^{-1} Mpc^{-1}). We also report the detection of very luminous ^{12}CO 2.6 mm emission from NGC 7469, and present optical narrow-band images and long-slit spectroscopy data concerning the ionized gas in this galaxy. These data imply that NGC 7469 not only contains a highly active compact nucleus but also is undergoing a luminous ($\sim 10^{11.5}$ $L_\odot$) circumnuclear (few kpc scale) starburst. Most of the other galaxies with known H_2 emission also seem to be composite "monster"/starburst systems and/or interacting galaxies. This result may arise because the molecular gas is associated with the starburst, while the primary form of the mechanical energy necessary to shock-excite the H_2 is either outflow (possibly a wind) driven by the compact active nucleus or noncircular motions of gravitational origin. In either case, high-velocity (>300 km s^{-1}) collisions between dense molecular clouds and a more ubiquitous, less dense gas phase can drive slow (10–30 km s^{-1}) shocks into the molecular clouds, exciting the observed H_2 emission.

Subject headings: galaxies: individual — galaxies: nuclei — galaxies: Seyfert — interstellar: molecules

I. INTRODUCTION

Most information concerning the physical condition of material in and around galactic nuclei has come from optical spectroscopic investigations of emission-line gas. Yet only gas within a rather narrow range of temperatures which is not heavily obscured by dust is readily accessible to an optical spectroscopist. The thermal infrared continuum emission, large Balmer decrements, strongly asymmetric emission-line profiles, and wavelength-dependent optical polarization seen in many active galactic nuclei imply that dust often distorts the optical spectra and significantly alters our view of the emitting regions (e.g., MacAlpine 1985). This result is not surprising, since the central interstellar medium in many disk galaxies (including Seyfert galaxies) appears to be largely molecular (Morris and Rickard 1982; Blitz, Mathieu, and Bally 1986). It is, therefore, of great interest to search for and to probe the molecular material in galactic nuclei, particularly those that are unusually active. Such material may serve as fuel for both "true" nuclear activity and nuclear starbursts, and may also provide a source for the hotter atomic material seen optically.

Study of the near-infrared emission lines of the H_2 molecule (Shull and Beckwith 1982) is particularly interesting in this regard, since these lines come from highly excited molecular gas (i.e., molecular clouds which are probably interacting with the energetic nuclear phenomena). Several galaxies emit strong H_2 lines from their central regions (Thompson, Lebofsky, and Rieke 1978; Hall *et al.* 1981; Fischer *et al.* 1983; Rieke *et al.* 1985; Joseph, Wright, and Wade 1984; Becklin, Depoy, and Wynn-Williams 1984). These lines might be energized by ultraviolet radiation or shocks produced in a nuclear starburst, by gas collisions induced in a galaxy merger, or by ultraviolet/X-ray radiation or shocks produced by a compact active nucleus, as discussed in the above references and by Black and Dalgarno (1976) and Lepp and McCray (1983). Indeed, many of the detected galaxies show signs of both an active nucleus and an exceptionally luminous circumnuclear starburst, and many have highly disturbed optical morphologies suggestive of violent galaxy collisions/mergers. Thus, further investigation of excited molecular gas in a variety of active galactic nuclei may offer valuable clues to the possible interrelationships between compact active nuclei, starburst nuclei, and galaxy interactions (e.g., Weedman 1983).

This paper reports the results from a search for 2.12 μm H_2 $v = 1$–0 $S(1)$ line emission in 11 bright active galactic nuclei of many types. One galaxy was detected, the classical type 1 Seyfert galaxy NGC 7469—an object which also appears on the basis of optical, radio, and infrared data to be undergoing a circumnuclear starburst. NGC 7469 has also been detected by us as one of the most luminous $J = 1$–0 ^{12}CO sources known.

II. OBSERVATIONS AND DATA REDUCTION

a) Infrared Spectroscopy

Observations were made on 1984 October 30 and 31 and November 1 using the Infrared Telescope Facility (IRTF) on Mauna Kea and the cooled grating spectrometer described by Beckwith *et al.* (1983) with an InSb photodiode. The entrance diaphragm defined a 7."5 diameter circular beam on the sky and a spectral resolving power $\lambda/\Delta\lambda \sim 840$ (360 km s^{-1}). The secondary mirror chopped 30" north-south at 4 Hz to provide background cancellation.

Observations of standard stars and Galactic sources of H_2 and H I emission calibrated the flux density and wavelength scales, respectively. The flux densities were accurate to better than 10%, based on variations in the standard-star observations. The wavelength scale shifted slightly during the observ-

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ing run, leading to a fractional uncertainty of 7×10^{-4} in the wavelengths, equivalent to 200 km s^{-1} in the line velocities or roughly one-half the resolution.

Each spectrum consisted of observations at nine wavelengths spaced by one-half the instrumental resolution and centered on the redshifted $v = 1$–0 $S(1)$ line. Averaging several (typically six) spectra, each with a short integration time (40 s per point, 6 minutes in total for the 9-point spectrum) determined the statistical uncertainties and minimized the systematic effects of pointing drifts (see Table 1). For the one object where H_2 emission was detected, NGC 7469, we took a set of six spectra on each of two nights (72 minutes total integration).

A least-squares fit of the instrumental wavelength profile to the data established line strengths and upper limits for the nondetections. The measured flux far from the expected line center determined the continuum level. The line amplitude and peak wavelength were free parameters for the fit. In the case of the detected line in NGC 7469 (Fig. 1), separate fits to the data for the two nights showed statistically significant (4 σ) detections in both cases.

b) *Optical Long-Slit Spectroscopy*

The kinematics of the Hβ and [O III] $\lambda\lambda$4959, 5007 emission lines in the inner region of NGC 7469 have been mapped by means of long-slit spectroscopy with a SIT Vidicon detector on the CTIO[7] 4 m telescope. The data were obtained, reduced, and analyzed in the same manner as described in Wilson, Baldwin, and Ulvestad (1985). The data on NGC 7469 will be discussed elsewhere in detail (Wilson, Sun, and Baldwin 1986).

[7] The Cerro Tololo Inter-American Observatory of the National Optical Astronomy Observatory is operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

The data most relevant to the present paper are displayed in Figure 2.

c) *Optical Narrow-Band Imaging*

We have imaged NGC 7469 in the light of the [O III] λ5007 and Hα + [N II] $\lambda\lambda$6548, 6584 emission lines using the video camera on the 4 m telescope at KPNO.[8] The images shown in Figure 3 were produced by differencing on-band and off-band images, each of which was obtained with a narrow-band ($\Delta\lambda/\lambda \sim 0.01$) interference filter centered at the appropriate wavelength. For further details concerning the techniques and instrumentation see Balick and Heckman (1985).

d) *Millimeter-Wave Spectroscopy*

We have observed NGC 7469 with the new 80–120 GHz Schottky-barrier receiver on the NRAO 12 m telescope[9] as part of a survey for 2.6 mm $J = 1$–0 ^{12}CO emission from Seyfert galaxies. The angular resolution (beam size FWHM) is $\sim 1'.1$. A spectral resolution of 2 MHz ($\sim$5.3 km s^{-1}) over a bandwidth of 512 MHz (1360 km s^{-1}) was obtained, although the data displayed in Figure 4 have been smoothed to 8 MHz resolution. Reference positions for beam-switching were offset 15′ in azimuth from NGC 7469. The data were edited by removing scans with significant baseline curvature, and a linear baseline was removed from the sum of the good scans by means of a least-squares fit to the channels within 300 km s^{-1} from the ends of the bandpass. The data were calibrated to the

[8] The Kitt Peak National Observatory of the National Optical Astronomy Observatory is operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

[9] The 12 m telescope of the National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation.

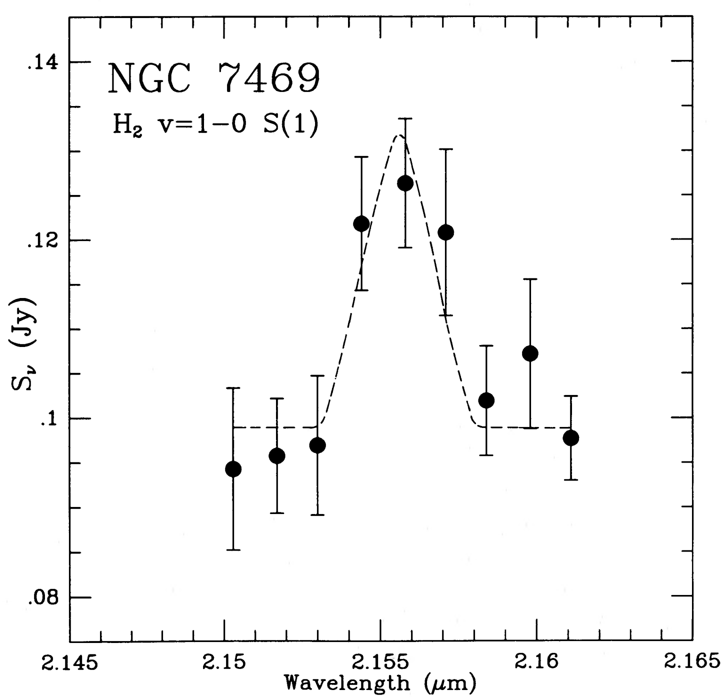

FIG. 1.—Sum of IRTF cooled grating spectrometer data centered at the wavelength of the redshifted H_2 2.12 μm $S(1)$ (–0 line in NGC 7469. The $\pm 1\ \sigma$ error bars associated with each data point have been directly calculated from the data. The dashed line shows a best fit of the instrumental profile. The total line flux is $(6.6 \pm 1.1) \times 10^{-14}$ ergs cm^{-2} s^{-1} (see Table 1).

T_R^* scale using the "chopper-wheel" method (cf. Kutner and Ulich 1981). The final unsmoothed (smoothed) data have an rms noise level of 14 (8) mK.

III. RESULTS

a) Infrared Spectroscopy

We list the results of our infrared observations in Table 1, together with relevant results from the literature on other galaxies. The most interesting result is the detection of strong H_2 2.12 μm emission from the region within ~ 1 kpc of the nucleus of the classical type 1 Seyfert galaxy NGC 7469 (Fig. 1). The detection of the line has a formal statistical significance of $\sim 6\ \sigma$. The deconvolved line width is < 500 km s^{-1}, with a heliocentric velocity of 4750 ± 200 km s^{-1}. As can be seen in Table 1, the luminosity of the 2.12 μm line in NGC 7469 is similar to other published examples of extragalactic H_2 emission (both in absolute terms and relative to the 60 μm continuum luminosity). Assuming LTE and an excitation temperature of 2000 K (cf. Shull and Beckwith 1982), we derive a mass of radiating $H_2 \sim 10^4\ M_\odot$. In the remainder of this section we present our results concerning the optical emission-line gas, millimeter-wave CO, and nonthermal radio continuum emission in NGC 7469. These data are pertinent to the origin of the H_2 emission, as we discuss in § IV.

b) Optical Long-Slit Spectroscopy

The full results of this work will be published elsewhere, but we summarize here some preliminary results of particular relevance to the interpretation of the infrared and millimeter-wave spectroscopy.

1. The velocity field of the [O III] (high-excitation) and Hβ (low-excitation) gases are quite different. For example, the systemic velocity defined by the low-excitation gas is $\sim 4917 \pm 7$ km s^{-1}, in excellent agreement with the single-dish 21 cm H I

TABLE 1

H_2 IN GALAXIES

Name (1)	cz (km s^{-1}) (2)	τ (minutes) (3)	$F_{S(1)}$ (10^{-14} ergs cm^{-2} s^{-1}) (4)	D_{AP} (kpc) (5)	S_{60} (Jy) (6)	$L_{S(1)}$ (10^{39} ergs s^{-1}) (7)	$R_{S(1)}/60$ (10^{-5}) (8)	Nuclear Type (9)
Present Survey								
Mrk 348/NGC 262	4536	36	<5.4	2.2	1.4	<22	<77	S2
NGC 1068/NE[a]	1153	24	<7.1	0.6	...	<1.9	...	S2
NGC 1275	5268	48	<5.1	2.6	7.1	<28	<14	S2
Mrk 609	10250	24	<6.3	5.0	2.5	<133	<50	S1
NGC 1614	4763	102	<4.2	2.3	33	<19	<2.6	H
NGC 2110	2311	24	<5.8	1.1	4.4	<6.2	<26	S2
MCG 8-11-11	6009	36	<5.3	2.9	2.8	<3.8	<39	S1
NGC 2273	1863	30	<6.9	0.9	7.6	<4.8	<18	S2
NGC 2623	5335	42	<4.9	2.6	24	<28	<4.1	L
NGC 2992	2305	18	<13.1	1.1	6.8	<14	<39	S2
NGC 3079[b]	1114	24	<7.9	0.5	49	<2	<3.2	L
NGC 7469	4917	72	6.6 ± 1.1	2.3	27	31	4.9	S1
Observations by Others								
NGC 1068/NUC[c]	1153	...	16.5	0.3	186	4.4	1.8	S2
NGC 3034/M82[d]	322	...	<4	?	1140	<0.04	<0.07	H
NGC 3690/IC 694[e]	3300	...	<3; 6.4; 29	1.8; 4.5; 7.2	105	<6.5; 14; 63	<0.6; 1.2; 5.5	H
Arp 220/IC 4553[f]	5420	...	2.5; 7.2	1.7; 3.1	104	15; 42	0.5; 1.4	S2
NGC 6240	7362	...	15; 43	2.4; 4.1	23	164; 470	13; 37	L

Col. (1).—Galaxy name(s) in order of right ascension.
Col. (2).—Galaxy heliocentric velocity (km s^{-1}).
Col. (3).—Total integration time in the present observations.
Col. (4).—The flux or flux upper limit for the H_2 $S(1)$ 1–0 2.12 μm line (in 10^{-14} ergs cm^{-2} s^{-1}). The upper limits are at the 3 σ level, while the uncertainty in the NGC 7469 flux represents $\pm 1\ \sigma$ (σ determined in all cases from the data).
Col. (5).—Projected spectroscopic aperture size (in kpc).
Col. (6).—Total 60 μm flux density (in Jy) as measured by *IRAS*.
Col. (7).—Luminosity (or luminosity upper limit) in the $S(1)$ line with no extinction correction (in 10^{39} ergs s^{-1}).
Col. (8).—Ratio of the $S(1)$ line to *IRAS* 60 μm continuum flux in units of 10^{-5}. We take the 60 μm continuum flux to be $F_{\nu,60} \equiv \nu_{60} S_{\nu,60}$, where $\nu_{60} = 5 \times 10^{12}$ Hz and $S_{\nu,60}$ is the flux density at 60 μm in ergs cm^{-2} s^{-1} Hz^{-1}.
Col. (9).—Nuclear optical spectroscopic type (H = H II region; L = LINER; S1, S2 = Seyfert type 1 or type 2). For details concerning the classification see Baldwin, Phillips, and Terlevich 1981, Heckman *et al.* 1983*b*, and Rieke *et al.* 1985.

[a] Observations centered 6".8 north and 4".0 east of the nucleus near the position of the northeast radio lobe in NGC 1068 (Wilson and Ulvestad 1983).
[b] Observations obtained at the position of the peak in the radio and 10 μm surface brightness which is $\sim 5''$ north of the peak in the optical brightness (see Lawrence *et al.* 1985 for details).
[c] Data on the NGC 1068 nucleus from Hall *et al.* 1981. Roughly the same flux in the H_2 2.12 μm line was observed by Thompson, Lebofsky, and Rieke 1978 through a 0.4 kpc projected aperture.
[d] Data on M82 from Rieke *et al.* 1985. Aperture size not given.
[e] For NGC 3690/IC 694, cols. (4), (5), (7), and (8) each have three entries referring respectively to measurements made by Rieke *et al.* 1985 through an 8".7 aperture, by Fischer *et al.* 1983 through a 21".4 aperture, and by Fischer *et al.* 1983 through a 34" aperture. The H_2 line-emitting region is evidently highly extended spatially in this galaxy (see original references for details).
[f] For Arp 220/IC 4553 and NGC 6240, cols. (4), (5), (7), and (8) each have two entries corresponding respectively to measurements made by Joseph, Wright, and Wade (1984) through a 5" aperture and by Rieke *et al.* 1985 through an 8".7 aperture. See original references for details.

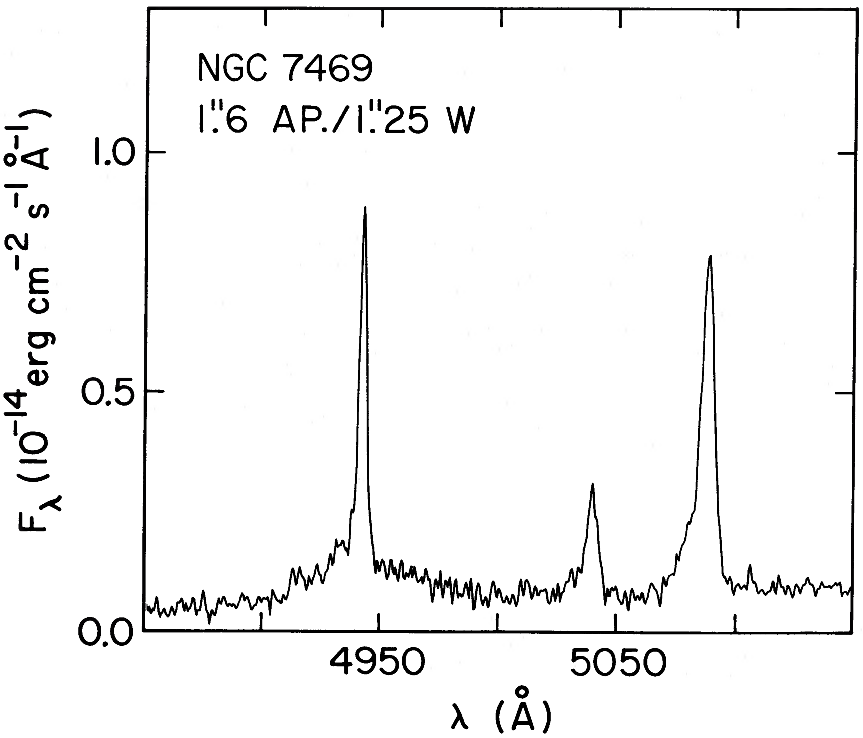

FIG. 2*a*

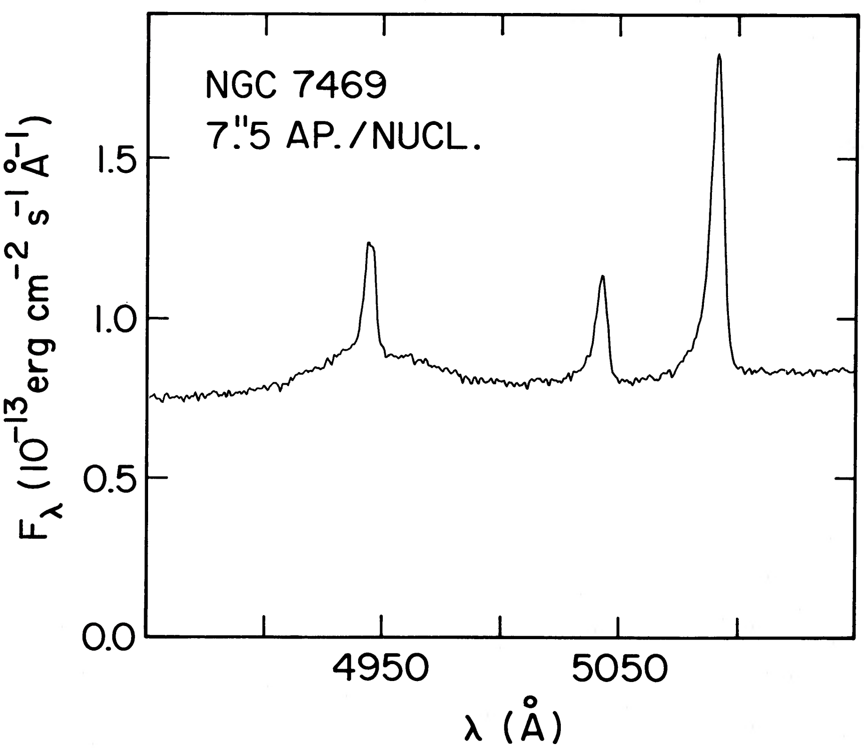

FIG. 2*b*

FIG. 2.—Spectra of the Hβ and [O III] λλ4959, 5007 lines in NGC 7469 (from Wilson, Sun, and Baldwin 1986). (*a*) Region of size 1".5 × 1".65 centered 1".25 west of the nucleus. Three different emission regions are evident in this spectrum. The very broad base to Hβ represents scattered light from the broad-line region. The broad [O III] lines originate in the conventional "narrow-line region," while the narrow Hβ may arise in circumnuclear H II regions, ionized by young stars. (*b*) Result of summing 20 individual spectra at different locations around the nucleus, to simulate observation with the same aperture used in the infrared spectroscopy (7".5 circular diameter).

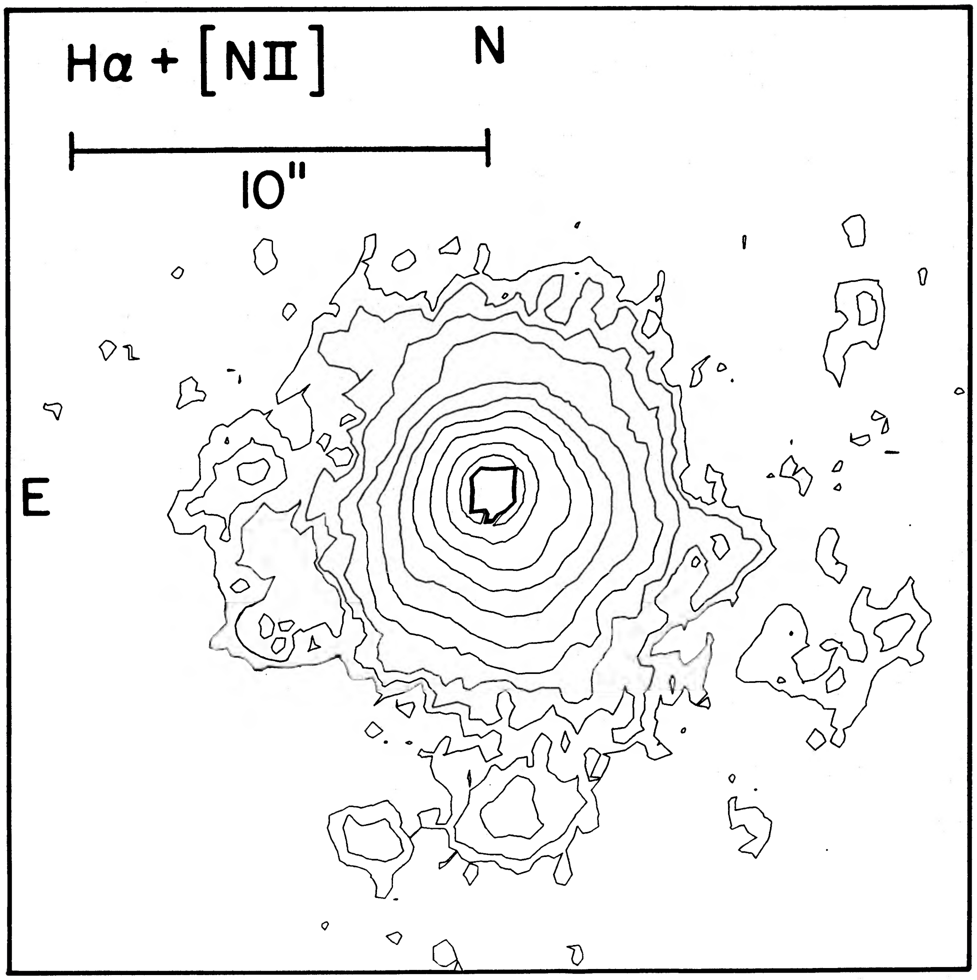

FIG. 3a

FIG. 3.—Contour plots of narrow-band ($\Delta\lambda/\lambda \sim 0.01$) images obtained with the video camera at KPNO. (*a*) Hα + [N II] lines (continuum light subtracted using an "off-band" image). Contour levels are logarithmic at 20, 40, 80, 160, 320, ... (arbitrary units of surface brightness). The innermost ~1" of the image is saturated. North is at the top, and east is to the left, and the tick marks along the axes are spaced every 20 pixels (5."8 = 1.8 kpc for $H_0 = 75$ km s^{-1} Mpc^{-1}). (*b*) The [O III] λ5007 line (otherwise as in Fig. 3*a*).

velocity of 4916 km s^{-1} (Mirabel and Wilson 1984). However, the central [O III] velocity is more than 100 km s^{-1} below this value.

2. The widths of the off-nuclear Hβ lines tend to be considerably less than those of the [O III] emission (e.g., Fig. 2*a*). Even after summation of the optical spectra over the 7."5 aperture used in the infrared observation (which tends to broaden Hβ because of rapid rotation of the low-excitation gas), the Hβ line is still somewhat narrower than the [O III] λ5007 line (305 km s^{-1} vs. 350 km s^{-1}; see Fig. 2*b*).

These kinematic differences probably indicate that the low-excitation emission originates in "normal" H II regions, while the high-excitation gas is associated with the Seyfert activity proper (cf. Wilson and Heckman 1985). The present data on the width and velocity of the H_2 line are not accurate enough to associate the excited molecular gas conclusively with one or the other of the two components of ionized gas.

c) Optical Narrow-Band Imaging

The Hα + [N II] image (Fig. 3*a*) shows structure, consisting of several discrete "lumps" at radii of ~8"–10" and noticeably asymmetric isophotes at the smaller radii included in the 7."5 diameter infrared diaphragm. In contrast, the [O III] image (Fig. 3*b*) is less structured, although resolved spatially (note that the centers of both images are saturated). We identify the Hα lumps and other structure with the low-excitation gas seen in the long-slit data described above. A similar dichotomy between the high- and low-excitation gas is seen on kpc scales in the Seyfert galaxy NGC 1068 (cf. Balick and Heckman 1985) and is interpreted as evidence for two distinct components—one comprising gas photoionized by a nuclear nonthermal source, the other being H II regions photoionized by hot, young stars.

d) Millimeter-Wave Spectroscopy

We have detected strong 2.6 mm $J = 1$–0 ^{12}CO line emission from the inner arcminute (~20 kpc) of NGC 7469 (Fig. 4). The measured line strength ($\int T_R^* \, dv$) is 11.1 ± 0.8 K km s^{-1}, in agreement with a recent measurement by Sanders and Mirabel (1985). Here the quoted uncertainty is a formal error only; the actual uncertainty due to possible nonlinearity in the spectral baseline is several times larger. The implied CO luminosity

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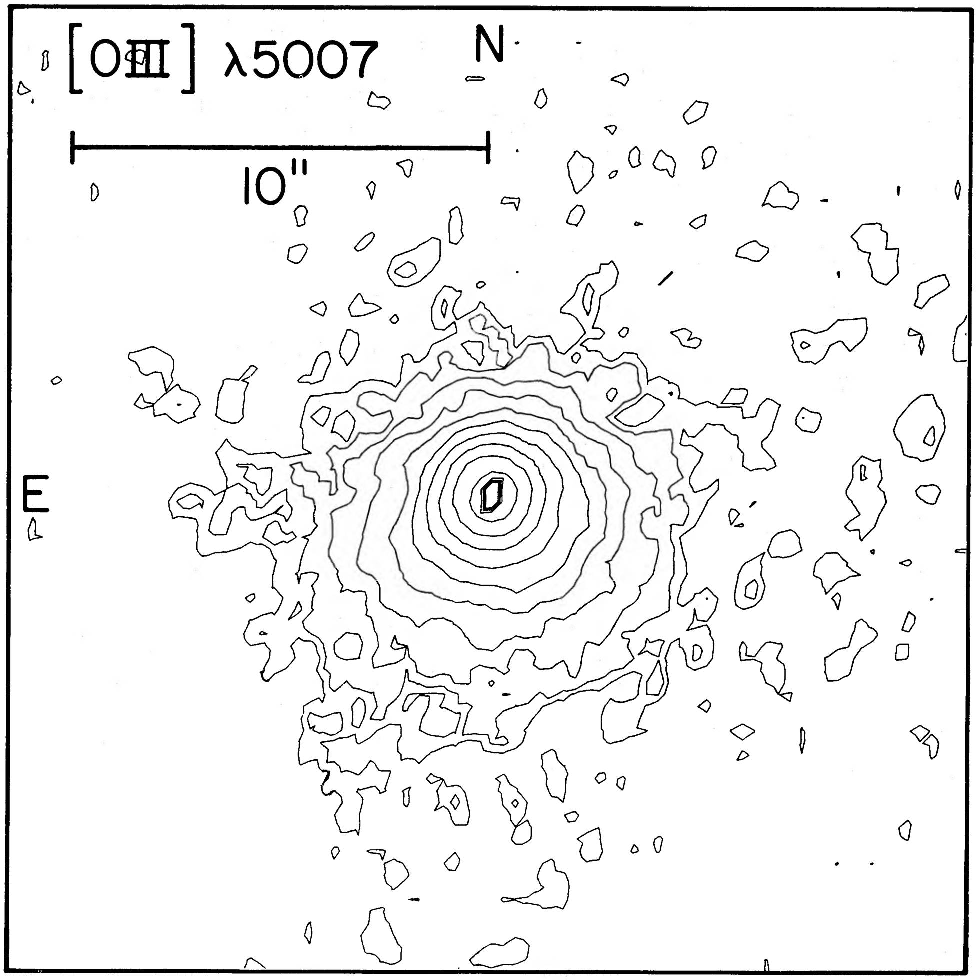

FIG. 3b

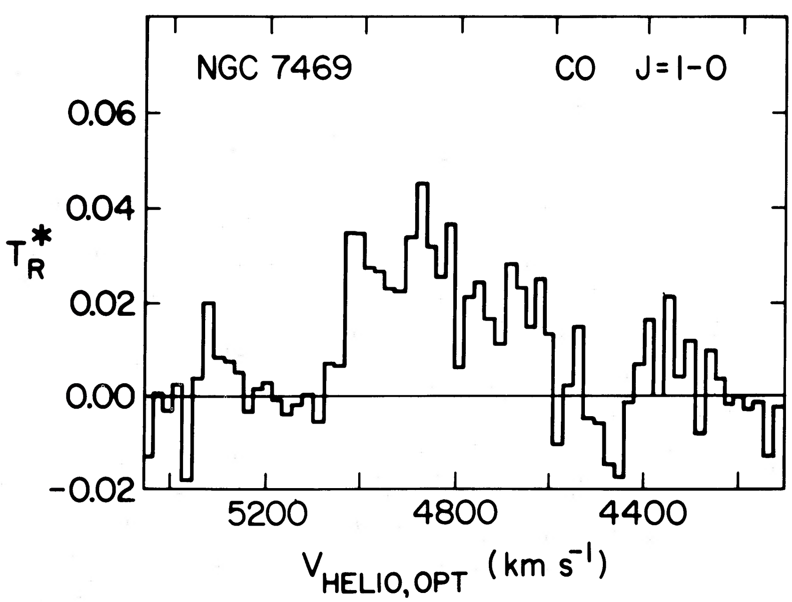

FIG. 4.—The 2.6 mm $J = 1$–0 ^{12}CO line from NGC 7469 obtained with the 80–120 GHz receiver on the NRAO 12 m telescope

(3200 ± 500 K km s^{-1} kpc^2) is comparable to that of the most luminous previously detected galaxies (Arp 220 and NGC 6240) observed by Young *et al.* (1984). Using the "standard" conversions from CO brightness to H_2 surface density (Bloemen *et al.* 1984) or from CO luminosity to H_2 mass (e.g., Israel and Rowan-Robinson 1984) yields an H_2 mass of $\sim 2 \times 10^{10}$ $M_\odot$ within our beam. The uncertainty in the CO-to-H_2 conversion for galactic centers is large (e.g., Blitz *et al.* 1985). Nevertheless, the hot H_2 observed in the $S(1)$ line represents only a tiny fraction of the total H_2 (see § III*a*). The CO line is also broad (450 ± 100 km s^{-1}), and its centroid (heliocentric optical velocity convention) is near the galaxy systemic velocity ($V_{CO} = 4850 \pm 100$ km s^{-1}).

e) Radio Imaging

Figure 5 shows a VLA radio continuum map at 4885 MHz and $\sim 1''$ resolution (see Ulvestad, Wilson, and Sramek 1981). Compared with most Seyfert galaxies with resolved radio structure, NGC 7469 is unusual in exhibiting strong, diffuse extended emission ($\sim 10'' \approx 3.2$ kpc in total size). There is also a compact, unresolved radio core ($\leq 0\farcs3$; ≤ 100 pc in size). The extended radio morphology is similar to that seen in many spiral galaxies with bright nuclear radio emission (see, e.g., Condon *et al.* 1982). Such diffuse radio emission has been widely interpreted as arising from a circumnuclear starburst, particularly when accompanied by an emission-line spectrum resembling that seen in H II regions (e.g., Weedman *et al.* 1981).

IV. DISCUSSION

a) Introduction

Early interpretations of H_2 line emission in galactic nuclei posited a large ensemble of star-forming regions like the Orion complex, all located within the inner few hundred pc of the nucleus (Thompson, Lebofsky, and Rieke 1978; Hall *et al.* 1981; Fischer *et al.* 1983). More recently, the discoverties of the extremely luminous H_2 sources in Arp 220 and especially NGC 6240 have led to the alternative suggestions that some type of global mechanism (such as the collision of the interstellar media of two merging galaxies) may be the excitation source (Rieke *et al.* 1985). Indeed, these last authors maintain that composite "mega-Orion" type models fail to account for the H_2 emission in NGC 6240 by a substantial factor (~ 20). There are at present at least two potentially important empirical clues to the nature of any such global mechanism for exciting the luminous H_2 emission in galactic nuclei. The first is that three of the five detected galaxies have highly disturbed optical morphologies strongly suggestive of galaxy collision/mergers in progress (Rieke *et al.* 1985; Joseph, Wright, and Wade 1984; Fischer *et al.* 1983). The second clue discussed below in more detail is that at least three, and possibly all five, detected galaxies contain both a luminous circumnuclear starburst and a compact active nucleus.

b) Composite Starburst/Active Nuclei

The origin of the H_2 line emission in NGC 7469 (and the other detected galaxies listed in Table 1) is intimately bound up with the question of whether galactic nuclei with strong radio and/or infrared continuum emission are powered by bursts of star formation or by compact active nuclei. We believe it may be significant that most (all?) of the galaxies with published detections of H_2 infrared emission exhibit signs of both compact nuclear activity *and* starbursts. This is especially clear in the case of NGC 7469.

1. NGC 7469 is a type 1 Seyfert galaxy with a pc-scale broad-line region and a powerful, nonstellar, nuclear optical and X-ray source ($L_{opt} \sim L_x \sim 10^{10}$ $L_\odot$). The kpc-scale gas in the narrow-line region (NLR) probably also requires a nonstellar ionizing source (e.g., Ferland and Netzer 1983). Finally, the compact nuclear radio source (Fig. 5) is likely to be powered by the active nucleus. At least two other galaxies with H_2 line emission also have highly active compact nuclei. NGC 1068 has a compact optical and infrared continuum source

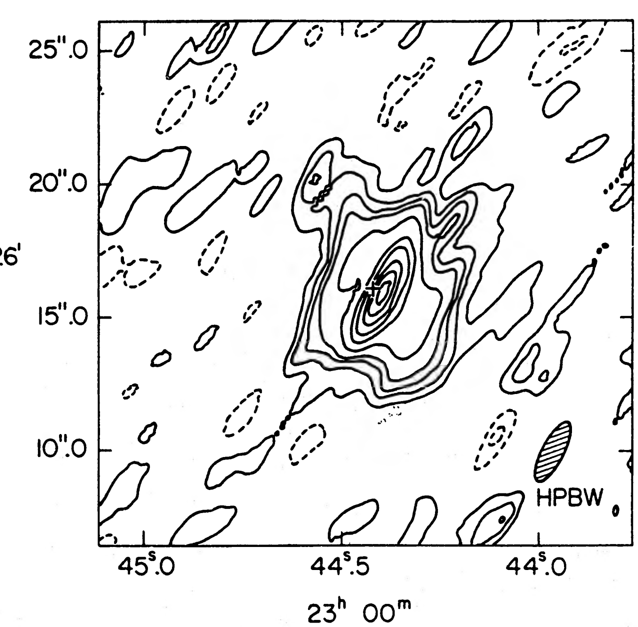

FIG. 5.—VLA map of NGC 7469 at 4885 MHz taken from Ulvestad, Wilson, and Sramek (1981). Contour values are −0.7, −0.35, 0.7, 1.05, 1.4, 2.3, 4.6, 6.9, 11.5, 16.1, and 20.7 mJy per beam area (beam shown at lower right).

(e.g., Telesco *et al.* 1984; Meaburn *et al.* 1982), an obscured broad-line region (Antonucci and Miller 1985), a classic Seyfert emission-line spectrum (e.g., Koski 1978), and radio jets (Wilson and Ulvestad 1983). Arp 220 = IC 4553 has a compact "triple" radio source and a Seyfert nucleus (see discussion in Rieke *et al.* 1985; Norris *et al.* 1985). For the other two galaxies with detected H_2 emission, the evidence for a compact active nucleus is suggestive but controvertible. NGC 3690 has a compact radio source which Gehrz, Sramek, and Weedman (1983) argue is a symptom of an active nucleus. NGC 6240 exhibits very broad optical emission lines of the low-ionization nuclear emission line region (LINER) variety, interpreted by many (e.g., Ferland and Netzer 1983; Filippenko and Halpern 1984; Keel 1985) as indicative of an active nucleus, but by others (e.g., Rieke 1985; Terlevich and Melnick 1985) as indicative of a starburst.

2. NGC 7469 is apparently undergoing a vigorous burst of star formation in its kpc-scale circumnuclear region. The diffuse radio emission, the narrow-lined low-excitation gas distributed in a clumpy fashion, the off-nuclear 3.3 μm dust emission feature (Cutri *et al.* 1984), the strong CO emission, and the luminous ($\sim 2.5 \times 10^{11}$ $L_\odot$), steep-spectrum, far-infrared emission seen by *IRAS* all support this idea. The other published examples of H_2 line-emitting galaxies also seem to be undergoing circumnuclear starbursts (see Telesco *et al.* 1984; Balick and Heckman 1985; Gehrz, Sramek, and Weedman 1983; Rieke *et al.* 1985) and are strong CO sources (Young *et al.* 1984).

c) The H_2 *Excitation Mechanism*

We believe that the infrared H_2 line emission in galactic nuclei is most likely shock-excited, as it is in most galactic objects (see Shull and Beckwith 1982 and references therein). In particular, the weakness of the $v = 2$–1 $S(1)$ line in NGC 1068 and NGC 6240 (Hall *et al.* 1981; Joseph, Wright, and Wade 1984) rules out UV fluorescence (Black and Dalgarno 1976). Heating of molecular clouds by X-rays (Lepp and McCray 1983) is unlikely to be *generally* important in the five detected nuclei, since NGC 7469 is the only strong X-ray source among them.

Since all the detected galaxies are undergoing nuclear starbursts, copious amounts of molecular gas are almost certainly present in the nuclei. The presence of such gas in abundance is strongly indicated by the exceptionally luminous CO emission observed from all the known H_2-emitting galaxies (Verter 1985; Sanders and Mirabel 1985; Young *et al.* 1984). For the H_2 to be shock-excited, a source of mechanical energy is required (the shock models of Kwan (1977) and Draine, Roberge, and Dalgarno (1983) require that the rate of this energy supply be *at least* $\sim 30 \times L_{S(1)}$, or $\geq 10^{41}$–10^{43} ergs s^{-1} for the detected galaxies in Table 1). It is important to emphasize that high-velocity noncircular gas motions—indicative of substantial amounts of mechanical energy—are present in all the galactic nuclei with known H_2 emission. The relevant data are summarized in Table 2 and are interpreted below.

The association of luminous H_2 emission with compact active nuclei and with galaxy collisions discussed above then suggests two plausible forms for this mechanical energy; outflow driven by the compact active nucleus and noncircular motions of gravitational origin. Strong evidence supporting both of these ideas has been provided by recent observations.

1. Data from optical spectroscopic surveys of galactic nuclei suggest that a compact active nucleus is a more important source of mechanical energy than is a nuclear starburst, in that large-amplitude noncircular motions in the optically emitting gas are ubiquitous in compact active nuclei (i.e., Seyfert nuclei) but are rare in classical starburst nuclei. Feldman *et al.* (1982) showed that the emission lines produced by gas on approximately kpc scales are generally far broader in Seyfert than in starburst nuclei (the most recent and complete compilations by Whittle 1985 and Wilson and Heckman 1985 show median line widths of 370 and 140 km s^{-1} for Seyfert galaxies and starbursts, respectively). LINERs have line widths which are similar, on average, to those in Seyfert galaxies (Heckman 1980; Whittle 1985). Not only are the gas velocities much higher in active nuclei, but the kinematics of the gas in Seyferts

TABLE 2

GAS VELOCITIES (km s^{-1}) IN GALAXY NUCLEI WITH DETECTED H_2 EMISSION

Name (1)	*W*([O III]) (2)	*W*(H_2) (3)	*W*(H I) (4)	*W*(OH) (5)	*W*(CO) (6)	References (7)
NGC 1068	1100	300	120	...	325	1
NGC 3690	100	?	300	?	?	2, 3
Arp 220/IC 4553	500	?	450	250	$\sim$500	2, 4, 5, 6
NGC 6240	1000	800	700	$\sim$400	$\sim$500	2, 6, 7
NGC 7469	400	$\leq$500	$\geq$70	?	$\sim$450	4, 8

Col. (2).—Full width at half-maximum of the [O III] λ5007 emission-line profile. In all cases but NGC 3690, the line is blue-asymmetric (as in most active nuclei), implying that *radial* gas motions are important.

Col. (3).—Full width at half-maximum of the $v = 1$–0 $S(1)$ line of H_2 at 2.12 μm. The line width in NGC 3690 and Arp 220 has not been well determined.

Col. (4).—Width of the H I 21 cm *absorption* line measured at the 20% intensity level. Since these are line-of-sight velocities (toward the central radio source), the broad lines imply that *high-velocity radial motions are occurring.*

Col. (5).—Width of the OH 1667 MHz line at the 20% intensity level. This line is seen in emission (maser) and absorption in Arp 220 and in absorption in NGC 6240.

Col. (6).—Width of the 2.6 mm $J = 1$–0 CO emission line at the 20% intensity level.

Col. (7).—References for line widths, according to the following key: (1) Whittle 1985; Hall *et al.* 1981; Dickey 1985; Blitz, Mathieu, and Bally 1986. (2) Heckman *et al.* 1983*b*). (3) Dickey 1982; Baan 1985. (4) Mirabel 1982. (5) Baan and Haschick 1984. (6) Young *et al.* 1984. (7) Joseph, Wright, and Wade 1984; Heckman *et al.* 1983*a*; Baan *et al.* 1985. (8) Present paper; W. Baan 1985, private communication.

are dominated by radial motion, as evidenced by the preferential blue asymmetry of the emission-line profiles (e.g., Heckman, Miley, and Green 1984; Whittle 1985). In contrast, the starburst nuclei produce symmetric profiles consistent with rotation (Whittle 1985). Long-slit spectroscopy of the spatially resolved emission-line gas provides more detailed evidence for high-velocity mass outflow in a few well-studied Seyferts (Wilson, Baldwin, and Ulvestad 1985; Phillips *et al.* 1983*a*, *b*).

2. Heckman *et al.* (1983*a*) have interpreted the available data on H I absorption lines seen against nuclear radio sources in active galaxies to suggest that galaxy collisions/mergers are a very effective way of inducing high-velocity turbulent motions in gas on circumnuclear (< 1 kpc) scales. Specifically, they showed that the average widths of the H I absorption lines were ~300 km s^{-1} for the morphologically peculiar galaxies in their sample as compared with only ~120 km s^{-1} for the morphologically normal galaxies.

d) *Gas Collisions in a Multiphase Medium*

The kinematic evidence summarized above and in Table 2 implies that noncircular gas motions of several hundred km s^{-1} are occurring in the galactic nuclei with detected H_2 emission. These velocities are far too high to correspond directly to the shocks which excite the H_2 ($V_{shock} \sim$ 10–30 km s^{-1}; cf. Kwan 1977 and Draine, Roberge, and Dalgarno 1983). Moreover, direct collisions between the high-density ($n_{H_2} \sim 10^4$–10^5 cm^{-3}), highly clumped molecular gas clouds may be rare.

A more plausible possibility is that the shocks which excite the H_2 emission are driven by the high-velocity collisions between dense clumps of molecular gas with a less dense, but more ubiquitous, gas phase:

$$V_{shock} \approx V_{collision}\left[\frac{\rho_{cloud}}{\rho_{intercloud}}\right]^{-1/2} .$$

Molecular shock models imply $V_{shock} \sim$ 10–30 km s^{-1}. For the galaxy merger/interaction picture, $V_{collision} \sim$ 300 km s^{-1}, and so a density contrast between the two media of 10^2–10^3 is required. For shocks driven by mass outflow associated with the nuclear activity (see below) a value for $V_{collision}$ is more difficult to estimate, but the outflow velocities inferred for the optically emitting gas are in the range of $10^{2.5}$–10^3 km s^{-1}.

Such collision processes will transform the mechanical energy of the circumnuclear gas into forms other than just the H_2 infrared emission lines (e.g., EUV/soft X-ray line emission from the shocked low-density medium). This poses no problem, provided that this shock energy is effectively reprocessed into thermal infrared emission (it is observed that $L_{IR} \sim 10^4$–$10^5 L_{S(1)}$; see Table 1). In a more speculative vein, such shocks may also help to trigger star formation in the dense molecular clumps.

e) *A Wind in NGC 7469?*

As discussed above, optical spectroscopy has provided abundant evidence for high-velocity radial gas flow in active galaxies. We have suggested that this radial flow can shock-heat ambient molecular clouds to produce near-infrared H_2 emission. While the mechanism which propels the observed flow is not known, one plausible possibility is a large-scale wind such as those hypothesized in recent theoretical papers by Krolik and Vrtilek (1984), Schiano (1985), Begelman (1985), and Clegg and Chevalier (1985). Indeed, recent X-ray imaging observations suggest that winds may be common features of active galaxies (Watson, Stanger, and Griffiths 1984; Elvis, Briel, and Henry 1983; Fabbiano and Trinchieri 1984; Maccacaro, Perola, and Elvis 1982).

A detailed consideration of a wind model in the context of the H_2 emission in NGC 7469 is not yet justified by the existing observational data. However, some rather basic constraints can already be placed on such a wind. For example, the observed luminosity in the v = 1–0 S(1) line of H_2 ($\sim 3 \times 10^{40}$ ergs s^{-1}) implies that the total molecular shock luminosity is $> 10^{42}$ ergs s^{-1} ($L_{shock} \approx \frac{1}{2}\rho_{cloud} V_{shock}^3 A_{shock}$). The wind's ram pressure must be large enough to drive shocks of $V_{shock} \sim$ 10–30 km s^{-1} into dense molecular clouds, that is,

$$P_{Ram} = \rho_{cloud} V_{shock}^2 = 3.3 \times 10^{-8} n_4 V_{10}^2 \text{ dynes cm}^{-2} ,$$

where n_4 is the H_2 number density in units of 10^4 cm^{-3} and V_{10} is the shock velocity in units of 10 km s^{-1}. P_{Ram}, evaluated at a distance r from the nucleus, can also be expressed as

$$P_{Ram} = (\dot{M} V_{wind})/(4\pi r^2 f_{wind}) ,$$

where $\dot{M}$ and V_{wind} are the mass flux and velocity of a wind flowing out into $4\pi f_{wind}$ steradians. Equating these expressions for P_{Ram} then yields

$$\dot{M} = 638 r_{kpc}^2 V_{1000}^{-1} n_4 V_{10}^2 f_{wind} M_\odot \text{ yr}^{-1} ,$$

$$\dot{E} = \tfrac{1}{2}\dot{M} V_{wind}^2 = 5.1 \times 10^{10} r_{kpc}^2 V_{1000} n_4 V_{10}^2 f_{wind} L_\odot ,$$

where V_{1000} is the wind velocity in units of 1000 km s^{-1}.

The total surface area of the shocked molecular material in NGC 7469 may be parameterized as

$$A_{shock} = 4\pi r_{kpc}^2 f_{cloud} = (2L_{shock})/(\rho_{cloud} V_{shock}^3) ,$$

where f_{cloud} is the fraction of the sky (as seen from the nucleus) covered by shocked molecular clouds. For $L_{shock} \sim 10^{42}$ ergs s^{-1}, this gives

$$r_{kpc} = 0.7 n_4^{-1/2} V_{10}^{-3/2} f_{cloud}^{-1/2} .$$

Inserting this expression for r_{kpc} in the above expressions for $\dot{M}$ and $\dot{E}$ then implies

$$\dot{M} = 319 V_{1000}^{-1} V_{10}^{-1} (f_{wind}/f_{cloud}) M_\odot \text{ yr}^{-1} ,$$

$$\dot{E} = 2.5 \times 10^{10} V_{1000} V_{10}^{-1} (f_{wind}/f_{cloud}) L_\odot .$$

For a wind model to be reasonable, $\dot{M}$ and $\dot{E}$ should not substantially exceed other known forms of mass and energy loss in NGC 7469. The bolometric luminosity of NGC 7469 is $\sim 10^{11.5}$ $L_\odot$, and the starburst models of Rieke *et al.* (1985) imply a star formation rate $\sim 10^2$ $M_\odot$ yr^{-1}. This suggests that a plausible wind model would be characterized by $r_{kpc} < 1$, $(f_{wind}/f_{cloud}) \sim 1$, and $V_{1000} \sim$ 1–10.

Finally, the predicted X-ray emission from such a wind can be calculated. For illustrative purposes, take a mass-conserving wind with $T \sim 10^7$ K (for maximum effectiveness in producing keV X-rays), a constant velocity of V_{1000}, a density profile going as r^{-2} exterior to some radius r_{min}, and a ram pressure capable of driving a 10 km s^{-1} shock into a cloud with $n_{H_2} \sim 10^4$ cm^{-3} at $r_{kpc} \sim 0.3$. The X-ray luminosity of the wind is then given by

$$L_x \sim 10^{10}\left[\frac{r_{min}}{20 \text{ pc}}\right]^{-1} V_{1000}^{-4} L_\odot .$$

Since $L_x \sim 10^{10}$ $L_\odot$ is observed from NGC 7469, some (most?) of which is probably associated with the compact nuclear activity, a fast wind is suggested.

V. SUMMARY

The detection of the type 1 Seyfert galaxy NGC 7469 brings to five the number of published examples of galactic nuclei with strong H_2 near-infrared emission lines. The high luminosities (4×10^{39} to 5×10^{41} ergs s^{-1} in the $v = 1$–0 $S(1)$ 2.12 μm line alone) suggest that some global excitation mechanism may be responsible (cf. Rieke *et al.* 1985). Two clues as to the nature of this mechanism have emerged. First, at least three and perhaps all five of the detected galaxies contain *both* a compact active nucleus and a vigorous circumnuclear starburst. Second, most of the detected galaxies have highly disturbed optical morphologies suggestive of galaxy mergers/collisions. The production of H_2 line emission requires raw material (molecular clouds, which are associated with the starburst) and an excitation source (mechanical energy in the form of either mass outflow [a wind?] driven by the compact active nucleus or noncircular gas motions of gravitational/tidal origin). The presence of abundant molecular gas is demonstrated by the fact that galaxies with detected near-IR H_2 line emission are among the most luminous known sources of 2.6 mm $J = 1$–0 CO emission lines. Evidence for both of the above forms of energy input has also surfaced recently in observational investigations of the kinematics of gas located on kpc-scale regions around the nuclei of active and interacting galaxies (including the five galaxies with detected H_2 emission). Specifically, we argue that the observed H_2 lines are excited by slow (10–30 km s^{-1}) shocks driven into dense ($n_{H_2} \sim 10^4$–10^5 cm^{-3}) molecular clouds as they collide at high velocity (≥ 300 km s^{-1}) with less dense, but more ubiquitous, material.

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Note added in proof.—We have reobserved the H_2 line emission in NGC 7469 during 1985 December with the facility cooled grating spectrometer (CGSII) on the UKIRT using a 4″.5 aperture (we thank Tom Geballe and Martin Ward for their help in obtaining and reducing these data). The flux through this smaller aperture is only about one-quarter of that observed with the 7″.5 aperture using the Cornell cooled grating spectrometer (present paper). This implies that the region emitting the 2.12 μm H_2 line is not centrally concentrated on scales of several arcsec (~ 1 kpc) around the nucleus of NGC 7469. Inspection of cols. (4) and (5) in Table 1 for NGC 3690, Arp 220, and NGC 6240 suggests that a similar situation exists in these galaxies. A large spatial extent for the excited molecular gas places severe energetic and mass-loss constraints on global wind models (see § IV*e*).