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MOLECULAR HYDROGEN LINE EMISSION IN SEYFERT GALACTIC NUCLEI

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ABSTRACT

We report on 2 μm spectroscopy of three Seyfert and two star burst galactic nuclei. We have detected line emission from vibrationally excited H_2 in the Seyfert galactic nuclei NGC 1275, NGC 3227, and NGC 4151. For NGC 1275 and NGC 4151, these detections are the first reported detections of molecular line emission. We have also measured the Brγ line flux in NGC 4151 and obtained an upper limit on the Brγ line flux in NGC 1275. There is a large range in the observed $S(1)$ to Brγ line ratio for both Seyfert and starburst galaxies (measured in this work and by others).

We rule out UV fluorescence based on the $S(1)$ to Brγ line ratio and the H_2 line ratios in the Seyfert galaxy NGC 1275. Shocks probably excite the H_2 emission in this galaxy. UV fluorescence may be the excitation mechanism in the Seyfert 1 galaxies NGC 4151 and NGC 3227. The H_2 lines are not formed in the broad-line regions of these Seyfert 1 galaxies based on our measured upper limits on the $S(1)$ line widths.

Simple starburst models cannot account for the highest of the measured ratios of $S(1)$ to Brγ line flux, most notably in the starburst galaxy NGC 6240 and in the peculiar Seyfert NGC 1275. Since the galaxies with the largest values of this ratio also have strong morphological evidence of galaxy-galaxy interactions, global shocks rather than shocks within young stellar outflows and remnants may be responsible for the excitation of the molecular hydrogen in these galaxies.

Subject headings: galaxies: Seyfert — infrared: spectra — interstellar: molecules — stars: formation

I. INTRODUCTION

It is generally accepted that strong middle and far-infrared continuum emission in galaxies is powered by recent bursts of star formation (e.g., Rieke and Low 1975). Condon (1980) conjectured that the strong, extended, steep spectrum radio sources in the nuclei of spiral galaxies are supernovae remnants resulting from rapid bursts of star formation induced by collisions with companion galaxies. Condon *et al.* (1982) found that the 10 μm and radio flux densities in these strong radio sources are roughly proportional, as they are in galactic star-formation regions. It is interesting, but therefore not unexpected, that many of the most luminous galaxies selected from the *IRAS* survey are included in Condon *et al.*'s (1982) list of strong radio sources in bright spiral galaxies. These galaxies are also often found to contain large amounts of molecular gas, traced by their strong emission in the CO ($J = 1$–0) line (Sanders and Mirabel 1985). Other characteristics of this starburst activity are strong optical emission lines, blue colors, and luminous X-ray emission (Rieke *et al.* 1980; Weedman *et al.* 1981). The radio, infrared, optical, and X-ray properties of the starburst galaxies M82, NGC 253, NGC 7714, and NGC 3690 have been modeled in detail by Rieke *et al.* (1980) (M82 and NGC 253), Weedman *et al.* (1981) (NGC 7714), and Gehrz, Sramek, and Weedman (1983) (NGC 3690) to obtain starburst parameters that are consistent with the multiwavelength data. Although Seyfert galactic nuclei are not generally believed to be powered primarily by starbursts, they share many of the same observed properties, particularly in the infrared spectral region. In type 2 Seyfert galaxies the ratio of radio to infrared luminosity resembles that of starburst-type galaxies (deBruyn and Wilson 1978). Type 1 Seyfert galaxies have a similar relationship between radio and infrared fluxes but on average, type 2 Seyferts have a higher radio luminosity for a given infrared luminosity than type 1 Seyferts (deBruyn and Wilson). Blue visual color is another property shared by Seyferts and starburst galaxies. Seyfert galaxies such as NGC 1068, NGC 4051, and NGC 3227 have strong CO ($J = 1$–0) emission (Rickard *et al.* 1977; Bieging *et al.* 1981). In contrast, stringent upper limits have been obtained on the CO ($J = 1$–0) line emission in the bright Seyfert 1 galaxies NGC 1275 and NGC 4151 (Bieging *et al.* 1981).

The discoveries of vibrationally excited molecular hydrogen lines in the type 2 Seyfert galaxy NGC 1068 (Thompson, Lebofsky, and Rieke 1978) and in the starburst galaxy NGC 3690 (Fischer *et al.* 1983) motivated the present study of molecular hydrogen line emission in Seyfert and starburst galaxies. In our Galaxy, emission from vibrationally excited H_2 is associated with phenomena related to star formation (e.g., bipolar outflows and H II regions), with planetary and protoplanetary nebulae and supernovae remnants, and with activity in the nucleus, all of which produce copious amounts of infrared and radio emission. Thus for this study we chose galaxies with strong infrared and radio emission. While the present work has been in progress, 2 μm H_2 line emission has been reported in two other starburst galaxies, NGC 6240 and IC 4553 (Arp 220) (Joseph, Wright, and Wade 1984; Rieke *et al.* 1985; Depoy, Becklin, and Wynn-Williams 1986) and in the Seyfert 1 galaxy NGC 7469 (Heckman *et al.* 1986). The present

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work, in which molecular hydrogen line emission was detected in three additional galactic nuclei, thus brings the number of reported extragalactic vibrationally excited H_2 line sources to eight. In this paper we study the H_2 and Brγ line emission in this small sample of galaxies in an attempt to understand how the excited molecular gas is related to other known components of these galaxies and if its excitation can be accounted for by shocks in individual young stellar outflows or supernova remnants produced by a starburst or both.

II. OBSERVATIONAL TECHNIQUES

Spectroscopic observations in the 2.0 μm–2.5 μm wavelength range were obtained between 1983 December and 1987 January using the circular variable filter-wheel (CVF) spectrometer at the 4 m telescope of the Kitt Peak National Observatory (KPNO) and the CVF spectrometer (UKT9) and grating spectrometer (CGS2) at the United Kingdom Infrared Telescope (UKIRT). The H_2 transitions studied were the $v = 1$–0 $S(1)$, $S(0)$ and the $v = 2$–1 $S(1)$ lines. The Brγ recombination line of hydrogen was also observed. Tabulated in Table 1 are the telescopes and instruments used, the dates of the observations, the nominal instrumental velocity resolutions, the apertures used, and the transitions studied for each galaxy. The aperture was positioned by pointing at the brightest position in the optical image. This position is the galactic nucleus for the Seyfert galaxies. For NGC 3504 and NGC 3310 the brightest portions of the optical images were larger than the beam; in these cases the aperture was centered on the brightest regions. Chopper throws of 1′–2′ were used. Flux calibration was based upon spectra obtained of infrared standard stars and on published broad-band photometry of these stars, and their effective temperatures and is accurate to within 10%.

The spectra were taken at wavelength steps of approximately half the instrumental resolution. At the resolution of the CVF observations velocity profiles of the individual lines are unresolved and the Brγ and $S(1)$ line pair is just separated.

III. OBSERVATIONAL RESULTS

a) The CVF Spectroscopy

The CVF spectra of NGC 1275 are shown in Figure 1. The strong $S(1)$ line and upper limit on the Brγ line that we measured in 1983 December at KPNO (Fig. 1*a*) were indicative of shock excitation of the H_2 (see § IV*c*[i]). The spectra shown in Figure 1*b* and 1*c* were taken on the UKIRT in 1987 January in order to verify these results. The $v = 1$–0 $S(1)$ and $S(0)$ lines are clearly visible in these spectra. Broad Brγ line emission may be present at the 1 σ or 2 σ level and the $v = 2$–1 $S(1)$ line flux is below our detection limit. The continuum flux density levels in Figure 1*a*, 1*b*, and 1*c* are consistent to within the 10% calibration accuracy.

Line fluxes of the $S(1)$ and Brγ lines were calculated by multiplying the flux density enhancement above an interpolated linear fit to the end points of the 2.1 μm spectra, by the nominal instrumental resolution. The measured line fluxes, statistical 1 σ errors, and upper limits are tabulated in Table 2. Since the $S(1)$ line flux measured in the 10″ and 12″ apertures were identical, the spatial extent of the $S(1)$ line emission in NGC 1275 is probably less than or equal to 10″.

b) Grating Spectroscopy

The grating spectroscopy of NGC 4151 and NGC 3227 is shown in Figures 2, 3, and 4. In Figure 2, the observed FWHM widths of the $v = 1$–0 $S(1)$ line of H_2 are (885 ± 250) km s^{-1} (NGC 4151) and (700 ± 250) km s^{-1} (NGC 3227). Although the nominal resolution in this spectrum is 430 km s^{-1} (FWHM), the measured line widths may have been broadened due to slippage of the grating (as suggested by a FWHM width of 620 km, s^{-1} measured for an argon line of the calibration lamp during these observations). Taking the width of the line in the calibration spectrum as the measured resolution, the deconvolved spectral line widths for NGC 4151 and NGC 3227 are (630 ± 300) km s^{-1} and (325 ± 600) km s^{-1}. We therefore use 900 km s^{-1} as an upper limit on the $S(1)$ line velocity in these galaxies. The $S(1)$ line was not detected in our spectra of NGC 3310 and NGC 3504. The measured line fluxes, statistical 1 σ errors, and upper limits are given in Table 2.

In order to determine whether the H_2 emission in the Seyfert galaxy NGC 3227 is shock-excited or excited by UV-fluorescence we used a lower resolution grating (with nominal resolution of ΔV[FWHM] = 1200 km s^{-1}) to obtain measurements of the $v = 1$–0 $S(1)$, $S(0)$ and $v = 2$–1 $S(1)$ lines. The

TABLE 1

SUMMARY OF THE OBSERVATIONS

Observatory/Telescope	Instrument	Dates	Instrumental Resolution at 2.12 μm (km s^{-1})	Aperture Size	Lines Observed	Galaxies Observed
KPNO 4 m	CVF	1983 Dec	3900	10″	H_2 $v = 1$–0 $S(1)$ Brγ	NGC 1275
UKIRT 3.8 m	Grating spectrometer	1983 Dec–1984 Jan	430	5″.4	H_2 $v = 1$–0 $S(1)$	NGC 4151, NGC 3227, NGC 3310, NGC 3504
	Grating spectrometer	1983 Dec–1984 Jan	1200	5″.4	H_2 $v = 1$–0 $S(1)$ H_2 $v = 2$–1 $S(1)$ H_2 $v = 1$–0 $S(0)$	NGC 3227
	Grating spectrometer	1985 Feb	430	5″.4	H_2 $v = 1$–0 $S(1)$ Brγ	NGC 4151
	CVF	1986 Jan	2400	12″	H_2 $v = 1$–0 $S(1)$ H_2 $v = 2$–1 $S(1)$ H_2 $v = 1$–0 $S(0)$ Brγ	NGC 1275

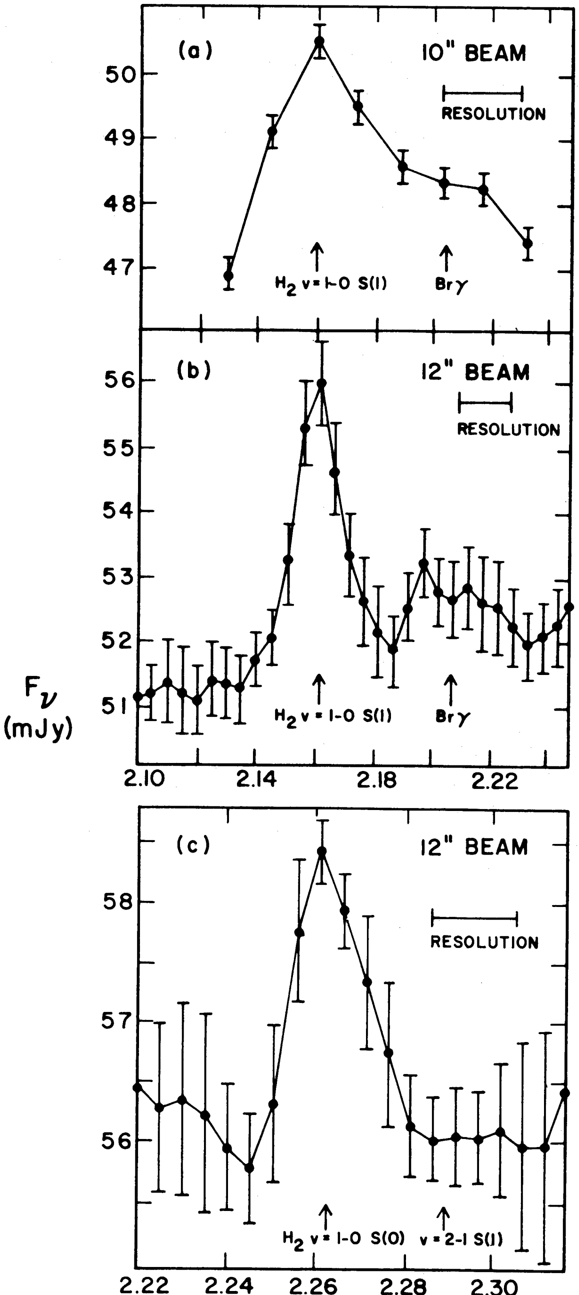

FIG. 1.—Circular variable filter wheel spectra of NGC 1275. The redshifted wavelengths of several of the H_2 emission lines and of the Brγ hydrogen recombination line are indicated along the ordinate. The spectra were taken at resolutions of 1.3% (*a*) and 0.8% (*b*) and (*c*). The spectra shown in (*b*) and (*c*) have been smoothed.

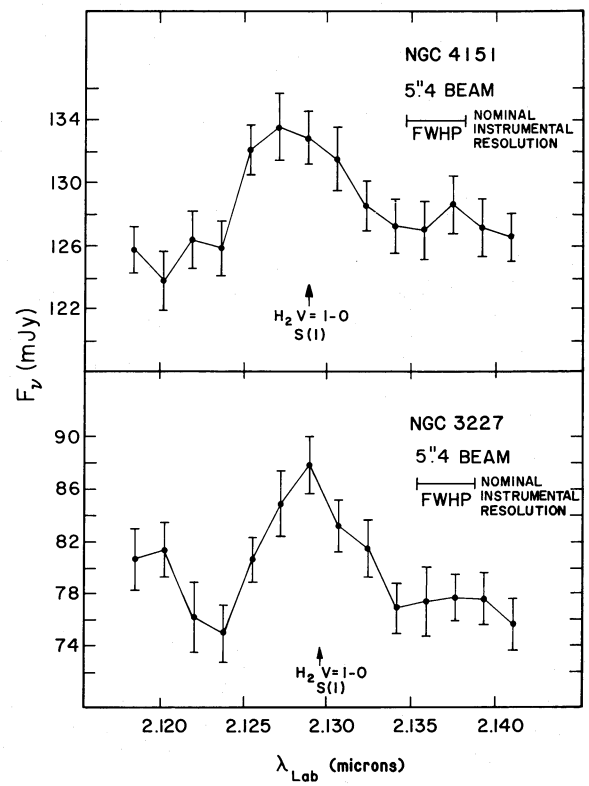

FIG. 2.—Grating spectra of the *S*(1) line in the nuclei of NGC 4151 and NGC 3227. The redshifted wavelengths of the H_2 $v = 1$–0 *S*(1) line are indicated for both galaxies along the ordinate. At the nominal resolution of the grating spectrometer at this wavelength, $\Delta V = 430$ km s^{-1}, these lines appear velocity-resolved. However, due to possible slippage of the grating we use the apparent velocity widths as upper limits.

observed spectrum is shown in Figure 3. The $v = 2$–1 *S*(1) and $v = 1$–0 *S*(0) lines were detected with relative strengths (with respect to the $v = 1$–0 *S*(1) line) of (0.8 ± 0.5) and (0.7 ± 0.3). The strength of the 2–1 *S*(1) line is especially uncertain, largely due to the anomalously high data point at ~2.26 μm, a wavelength which should lie beyond the half-power point of the 2–1 *S*(1) line. We are not sure whether this point reflects a high intensity in the 2–1 *S*(1) line, a contribution from an unidentified line to the red of the 2–1 *S*(1) line, or is simply a large noise fluctuation.

The spectrum shown in Figure 4 was obtained in order to measure the ratio of the *S*(1) line to the Brγ line in NGC 4151. The instrumental resolution was 430 km s^{-1}, and the spectrum shown was smoothed by averaging adjacent spectral points with 0.5 weighting. Although this spectrum was obtained when there was some windshake of the telescope, the accuracy of the relative strengths of the lines should be minimally affected, since the lines were alternately scanned many times. The measured line ratio derived from this spectrum is Brγ/*S*(1) = 6 ± 2. In this spectrum the measured FWHM of the *S*(1) line is 565 km s^{-1}, consistent with its being unresolved. The measured FWHM of the Brγ line is 1500 km s^{-1} and the FWZI is about 3000 km s^{-1}. For comparison, the FWHM of the core of the Hβ line in NGC 4151 is 450 km s^{-1} while the FWHM of the wing component is about 7000 km s^{-1} (Oke and Sargent 1968).

c) The Infrared Continua

The values of the continuum at 2.1 μm were calculated by interpolating spectroscopic data outside regions of line emission. These 2.1 μm continuum flux densities of the observed galaxies are tabulated in Table 3 and compared to the most recent published photometric *K* band (2.2 μm) measurements. In column (3) our continuum flux measurements and the statistical errors are listed. NGC 1275 is variable (Lebofsky and Rieke 1980), but our measurements fall within the general range of what has previously been measured for this galaxy. Of

TABLE 2

TWO MICRON SPECTROSCOPIC MEASUREMENTS FOR STARBURST AND SEYFERT GALACTIC NUCLEI

Galaxy	Type	Distance [H = 75 km s^{-1} Mpc^{-1}] (Mpc)	v = 1–0 S(1) Line Flux (10^{-14} ergs cm^{-2} s^{-1})	Brγ Line Flux (10^{-14} ergs cm^{-2} s^{-1})	v = 2–1 S(1) Line Flux (10^{-14} ergs cm^{-2} s^{-1})	v = 1–0 S(0) Line Flux (10^{-14} ergs cm^{-2} s^{-1})	V(FWHP) of the v = 1–0 S(1) Line (km s^{-1})
NGC 1068[a]	Seyfert 2	15	16.5	18.5		5	265 ± 30
NGC 1275	Seyfert 1 (peculiar)	70	6.3 ± 0.7	≤1.5	<1	2.4 ± 0.5	
NGC 3227	Seyfert 1	16	3.3 ± 0.6		2.6 ± 1.3	2.1 ± 0.5	<900
NGC 3310	Starburst	14	<2				
NGC 3690[b]	Starburst	42	29 ± 4	26 ± 5			
NGC 3504	Starburst	20	<3				
NGC 4151	Seyfert 1	13	3.0 ± 0.4	17 ± 1			<900
IC 4553[c]	Starburst	74	7.2	3			
NGC 6240[c]	Starburst	97	39	3.1			
NGC 7469[d,e]	Seyfert 1	66	6.6 ± 1.1	5.1 ± 0.9			

[a] Hall *et al.* 1981.
[b] Fischer *et al.* 1983.
[c] Rieke *et al.* 1985.
[d] Heckman *et al.* 1986.
[e] McAlary *et al.* 1986.

the other observed galaxies, allowing for 10% calibration errors in both our measurements and those of other observers, only NGC 3310 has discrepant measurements. For NGC 3310, we attribute the apparent discrepancy to the difference in apertures, since the nucleus of NGC 3310 does have extended structure.

IV. DISCUSSION

a) The H_2 *Line Widths in Seyfert 1 Nuclei*

In Seyfert 1 galaxies the Balmer lines have broad wings several thousand km s^{-1} wide, which are not seen on the forbidden lines. Galaxies in which the emission lines are broader than ~500–1000 km s^{-1}, but which have the same profile for all lines are classically called Seyfert 2 galaxies (Feldman *et al.* 1982). Thus the Seyfert 2 nuclei are similar to that part of the Seyfert 1 nuclei in which the forbidden lines arise (Osterbrock 1979). This volume in Seyfert 1 nuclei is now called the narrow-line region to distinguish it from the smaller volume in which the permitted lines only are found (the broad-line region). Heckman *et al.* (1981) find evidence to support the idea that the narrow emission-line region consists of gas and dust flowing radially (probably outward) with respect to the nucleus.

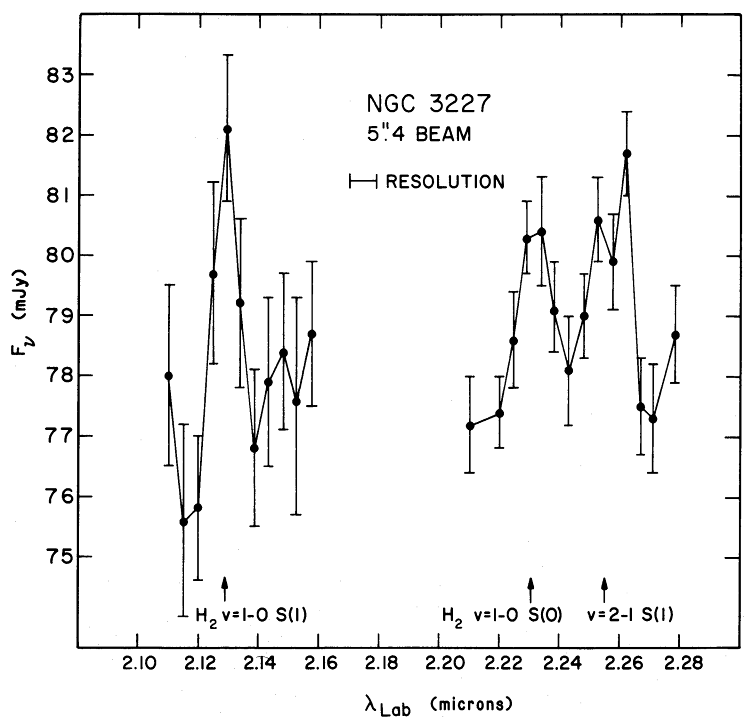

FIG. 3.—Low-resolution grating spectroscopy of NGC 3227. The redshifted wavelengths of the three detected H_2 lines are indicated along the ordinate. The spectral resolution in this spectrum is $\Delta\lambda/\lambda = 0.4\%$.

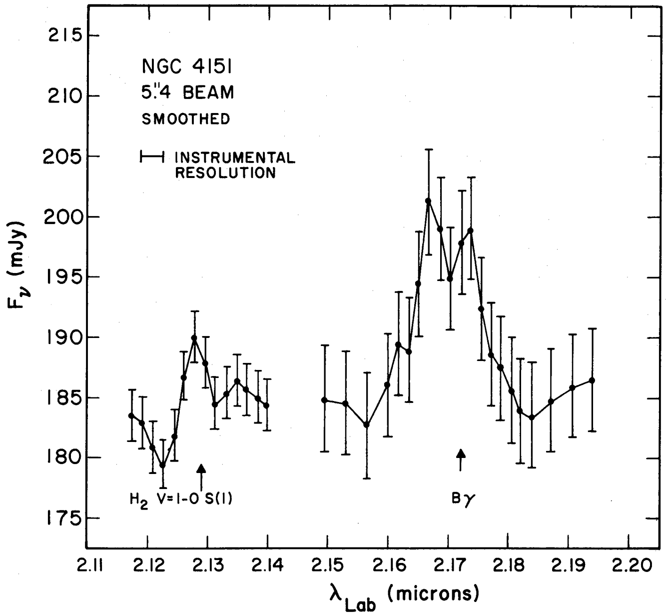

FIG. 4.—Grating spectroscopy of the H_2 $v = 1$–0 $S(1)$ and the Brγ lines in NGC 4151. The redshifted wavelengths of the $v = 1$–0 $S(1)$ and Brγ lines are indicated. This spectrum was taken with resolution of $\Delta V = 430$ km s^{-1} and was subsequently smoothed.

Feldman *et al.* measured 375 km s^{-1}, 510 km s^{-1}, and 160 km s^{-1}, respectively, for the median FWHM of the [O III] line in their sample of Seyfert 1, Seyfert 2, and starburst galaxies. They find that the Seyfert 1 galaxies NGC 3227 and NGC 4151 have [O III] FWHM widths of (560 ± 30) km s^{-1} and (380 ± 30) km s^{-1}, respectively. The FWHM of the Hβ line in NGC 3227 is 2500 km s^{-1} (Osterbrock 1977) and the FWHM of the broad wing component of Hβ in NGC 4151 is about 7000 km s^{-1} (Oke and Sargent 1968). Thus our measured upper limits of 900 km s^{-1} for the H_2 $v = 1$–0 $S(1)$ line widths of these two galaxies suggest that the H_2 lines are not formed in the broad-line regions of these galaxies but may be formed in regions with kinematics similar to the narrow-line regions of these Seyfert 1 galaxies.

b) The H_2 *Emission: Its Excitation Mechanism and Driving Source*

Considering that both high ultraviolet radiation flux as well as high-velocity gas motions are present in the nuclei of these galactic nuclei, it is unclear whether the molecular hydrogen line emission is shock-excited or excited by ultraviolet fluorescence. The possibilities for powering shocks include (1) gas ejection from a "central engine," (2) outflows from large numbers of supernovae remnants and young stars, and (3) gas motions due to the interactions of the spiral galaxies in which they are located. The sources of the UV could include hot stars, a star-formation process producing UV, or an accretion disk around one or more massive nuclear objects. We examine several of these possibilities in this section.

i) *UV Excitation*

For H_2 of density $n = 10^3$ cm^{-3} that is radiatively excited, the ratios of the intensities of the $v = 2$–1 $S(1)$ line and the $v = 1$–0 $S(0)$ line to the $v = 1$–0 $S(1)$ line are 0.55 and 0.67, respectively (Black and Dalgarno 1976). For postshock cooling characterized by an excitation temperature of 2000 ± 500 K, such as is observed in many galactic sources, the predicted ratios are 0.08 ± 0.06 and 0.21 ± 0.02. Our measured upper limits on the 2–1 $S(1)$ line in the peculiar Seyfert 1 galaxy NGC 1275 and the upper limits previously measured in NGC 1068 (Hall *et al.* 1981) and in the interacting starburst galaxy NGC 6240 (Joseph, Wright, and Wade 1984) rule out pure ultraviolet excitation in these galaxies and suggest that the emission is due to shock excitation. Thus it is somewhat surprising that for the Seyfert 2 galaxy NGC 3227 the observed ratios of the $v = 2$–1 $S(1)$ and $v = 1$–0 $S(0)$ lines, (0.8 ± 0.5) and (0.7 ± 0.3), respectively, are more consistent with UV fluorescence. It is therefore of interest to calculate the amount of ultraviolet radiation that is available in the 912–1108 Å spectral range in Seyfert galactic nuclei to excite molecular hydrogen via transitions of the Lyman and Werner bands.

Under Menzel Case B conditions, the Brγ line flux can be used to calculate the number of ionizing photons. Further, because the spectral shape of the ultraviolet through X-ray continuum in Seyfert nuclei is known, the number of UV photons available between 912–1108 Å to excite H_2 molecules can be derived. The ratio of the number of photons *available* in this range to the number of photons in this range *required* to excite the emitting H_2 molecules is proportional to the measured Brγ to $S(1)$ line ratio. Thus this measured ratio can be used to evaluate the viability of the UV excitation mechanism in Seyfert nuclei. Specifically, if the ultraviolet continua in Seyfert galaxies are assumed to have a spectral dependence of the form $f_\nu \propto \nu^{-\beta}$ $(1.2 \le \beta \le 1.6;\ 228 \le \lambda \le 3000$ Å), as has been found by Ferland and Osterbrock (1986), then the ultraviolet flux between 912–1108 Å can be calculated by normalizing the integrated ionizing flux between 228–912 Å such that

TABLE 3

THE 2 μm CONTINUA

Galaxy (1)	This Work (2.1 μm) Dates (2)	Flux (mJy) (3)	Aperture (″) (4)	Other Measurements (2.2 μm) Dates (5)	Flux (mJy) (6)	Aperture (″) (7)	Ref. (8)
NGC 1275	1983 Dec	46.3 ± 0.3	10	1978 Aug–1979 Dec	63–93	7.8–8.5	1
	1987 Jan	51.6 ± 0.5	12	1980 Oct	38	6	2
NGC 3227	1984 Jan	77.6 ± 0.7	5.4	1980 Mar	81	10.3	3
NGC 3310	1984 Jan	16 ± 5	5.4	1980 Mar	42	10.3	3
NGC 3504	1984 Jan	102.6 ± 0.3	5.4	1980 Mar	87	10.3	3
NGC 4151	1984 Jan	126.4 ± 0.5	5.4	1978 Apr–1979 May	130–240	7.8–8.5	1
				1980 Mar	218	10.3	3

REFERENCES.—(1) Lebofsky and Rieke 1980; (2) Rudy *et al.* 1982; (3) Balzano and Weedman 1981.

there are 77 photoionizations per Brγ recombination line photon (2.2 photoionizations per Hα photon) as predicted by Menzel Case B recombination theory at $T \approx 10^4$ K and $n \leq 10^6$ cm^{-3} (Giles 1977; Brocklehurst 1971). In the UV fluorescence mechanism there is a probability of ~ 0.02 that an $S(1)$ photon will be emitted for each UV line photon absorbed by H_2 (Black and Dalgarno 1976). We thus obtain the relationships

$$R_{uv} = 0.0044 f \frac{F(H\alpha)}{F[S(1)]} = 0.51 f \frac{F(Br\gamma)}{F[S(1)]} \quad (\text{for} \quad \beta = 1.2) \quad (1a)$$

$$R_{uv} = 0.0056 f \frac{F(H\alpha)}{F[S(1)]} = 0.64 f \frac{F(Br\gamma)}{F[S(1)]} \quad (\text{for} \quad \beta = 1.6)\,, \quad (1b)$$

where R_{uv} is the ratio of UV photons available between 912–1108 Å (based on the measured Brγ flux and the normalization described above) to UV photons required by the measured $S(1)$ line flux. The flux F is that emitted in a spectral line and f is the fraction of UV photons in the 912–1108 Å region that can be absorbed in the Lyman and Werner bands by the molecular gas in the nucleus. The fraction f is a function of the ultraviolet photon density per hydrogen density as well as the ratio of gas to dust. Since these parameters are not well known for the region where the H_2 is excited, we use the upper limit $f \lesssim 0.3$ calculated by A. Sternberg (private communication) for a normal gas-to-dust ratio. It is interesting to note that if the dust is depleted by a factor of 10, the upper limit on f is ~ 0.9. Not included in equations (1a) and (1b) is an unknown geometric factor taking into account absorption by dust within the emission regions. In addition, R_{uv} may be smaller than given by the expression in equations (1a) and (1b), if significant optical depth in the photoionization continuum of carbon ($\lambda < 1100$ Å) is present (Carlson and Foltz 1979). When $R_{uv} \geq 1$, the observed $S(1)$ line flux can be understood in terms of UV excitation by the same power-law continuum that ionizes the hydrogen gas. When $R_{uv} < 1$, the $S(1)$ line is stronger than can be accounted for by this mechanism. The values of R_{uv} calculated from the $S(1)$ line and Brγ line fluxes given for the Seyfert galaxies in Table 2, are tabulated in Table 4. For NGC 3227 the value of R_{uv} is from Paβ observations by Ward *et al.* (1987)

TABLE 4

RADIATION FLUX AVAILABLE FOR ULTRAVIOLET FLUORESCENCE TO EXCITE H_2 EMISSION

GALAXY	R_{uv}[a] $\beta = 1.2$	R_{uv}[a] $\beta = 1.6$
NGC 1068[b]	0.20	0.24
NGC 1275[c,d]	≤0.04	≤0.05
NGC 3227[c,e]	0.32	0.40
NGC 4151[c,d]	0.96	1.21
NGC 7469[f,g]	0.12	0.15

[a] Ratio of UV photons available between 912–1108 Å to UV photons required by $S(1)$ line flux.

[b] Based on Brγ and $S(1)$ line fluxes measured by Hall *et al.* 1981.

[c] Based on $S(1)$ line flux measured by in this work.

[d] Based on Brγ line flux measured in this work.

[e] Based on Paβ ($\lambda = 1.28$ μm) flux of 3.7×10^{-13} ergs s^{-1} cm^{-2} measured by Ward *et al.* 1987. For Menzel Case B theory, Paβ/Br$\gamma \approx 6$.

[f] Based on Brγ line flux measured in 9″ aperture by McAlary *et al.* 1986.

[g] Based on $S(1)$ line flux measured in 7″.5 by Heckman *et al.* 1986.

since we have not measured the Brγ line flux. We find that $R_{uv} < 1$ for all galaxies in Table 4 except NGC 4151. This would rule out UV fluorescence for these galaxies if the Brγ line flux were an accurate measure of the UV flux. More conservatively, because of the apparent uncertainty in that conjecture, we feel that UV fluorescence of H_2 can be ruled out from the Brγ/$S(1)$ line ratio certainly in the case of NGC 1275 where $R_{uv} \ll 1$, and probably in NGC 7469 and NGC 1068 where R_{uv} is also small. These conclusions are consistent with those based on measurements of the H_2 $v = 2$–1 $S(1)$ and $v = 1$–0 $S(0)$ line intensities where they have been made. It remains a real possibility, albeit an unexpected one, that the H_2 emission in NGC 3227 and NGC 4151 is primarily excited by UV fluorescence.

ii) *The Star-Formation Rate and H_2 Excitation*

Comparison of the Brγ line, $S(1)$ line, and the infrared luminosity can provide a means of evaluating the possibility that the H_2 emission is excited within individual young stellar outflow (YSO) regions that resemble YSOs in our Galaxy, e.g., the Orion K-L region. The Brγ and infrared luminosities can be predicted for a given initial mass function (IMF). It is more difficult to predict the $S(1)$ line luminosity for a given IMF since the luminosities of H_2 emitters within our Galaxy are not well known. Nevertheless, we can compare our sample of galaxies to the well studied galactic objects to see what similarities do exist.

In columns (2) and (3) of Table 5 we list the measured infrared luminosity and the $S(1)$ line luminosity (uncorrected for extinction) of each galactic nucleus. The infrared luminosity, L_{IRAS}, is calculated from the *IRAS Point Source Catalog* (1985) by using a color-corrected, two-temperature fit to integrate and extrapolate the *IRAS* point-source fluxes. If we assume that the vibrational-rotational temperature of the shocked H_2 gas is, like that measured for the Orion gas, about 2000 K, then the total mass (in $M_\odot$) of H_2 at this temperature is 1.5×10^{-3} times the $S(1)$ line luminosity in $L_\odot$. In column (4) of Table 5 we list the number of Orion-like H_2 regions (neglecting the extinction to the extragalactic H_2) based on the $S(1)$ line luminosity of ~ 40 $L_\odot$ in Orion (estimated from the measured 2.5 $L_\odot$ [Beckwith *et al.* 1978] by Davis, Larson, and Smith [1982], taking into account the extinction to the H_2). The number of Orion-like stars, i.e., outflow sources similar to the one in the Orion molecular cloud, can then be estimated by assuming a typical lifetime of such an outflow source to be 10^4 yr (Fischer *et al.* 1985). These estimates are listed in column (5) of Table 5.

We can estimate the star-formation rate from the Brγ line flux independently, by using the initial mass function (IMF) models tabulated by Gehrz, Sramek, and Weedman (1983) in which they estimate the star-formation rate from intrinsic Hα fluxes. Column (6) of Table 5 lists the intrinsic Hα fluxes based on the measured Brγ line fluxes (which are not strongly affected by extinction) according to Menzel Case B recombination theory for moderate densities $n \leq 10^6$ cm^{-3} and temperatures $T \approx 10^4$ K (Giles 1977; Brocklehurst 1971). In columns (7) and (8) we list the predicted bolometric luminosity, L_{bol}, and star-formation rate derived from the Hα entries in column (6) using the IMF for which $\alpha = 3.5$ and for stars in the range 6–25 $M_\odot$ in Gehrz, Sramek, and Weedman. Alpha (α) is defined such that the number of stars formed per unit time in a mass interval within a single generation is proportional to $m^{-\alpha}$ where m is the stellar mass. We chose this particular model because it was the model chosen by them to best fit their radio, infrared, and optical data. Their models did not include stars with $m < 6$

TABLE 5

DERIVED QUANTITIES FOR STARBURST MODELS[a]

Galaxy (1)	L_{IRAS} ($10^9 L_\odot$) (2)	$S(1)$ Luminosity ($10^6 L_\odot$) (3)	Number of Orion-like H_2 Regions[b] (4)	Number of Orion-like Stars per Year[b,c] (yr^{-1}) (5)	$L(H\alpha)$[d] (10^{42} ergs s^{-1}) (6)	L_{bol}[e] ($10^9 L_\odot$) (7)	Star-Formation Rate[e] (yr^{-1}) (8)	L_{IRAS}[e]/L_{bol} (9)	$R_{outflow}$ (see text) (10)
NGC 1068[f]	190	1.1	3×10^4	3	0.50	100	0.9	1.9	3.2
NGC 1275[g]	150	8.8	2×10^5	20	≤0.90	≤170	≤1.5	≥0.9	≥14
NGC 3227[g]	8	0.25	6×10^3	0.6	0.19	35	0.32	0.2	1.9
NGC 3690[h]	530	15.0	4×10^5	40	5.5	1100	9	0.5	4.4
NGC 4151[g]		0.15	4×10^3	0.4	0.39	80	0.7		0.6
IC 4553[i]	1330	11.4	3×10^5	30	1.9	370	3.3	3.6	8.5
NGC 6240[i]	580	106.0	3×10^6	260	3.5	680	5.9	0.9	45
NGC 7469[j]	360	8	2×10^5	20	2.6	500	4.4	0.7	4.5

[a] Based on measured $S(1)$ line and Brγ fluxes in galaxies uncorrected for extension. For NGC 3227, the Paβ flux measured by Ward *et al.* 1987 was used.
[b] Based on an $S(1)$ line flux of 40 $L_\odot$ (corrected for extinction) in Orion (Davis, Larson, and Smith 1982).
[c] Based on a lifetime of 10^4 yrs for an Orion-like H_2 region.
[d] Based on measured Brγ flux and recombination theory for $T \approx 10^4$ and $n = 10^6$ cm^{-1} (Brocklehurst 1971 and Giles 1977).
[e] Based on col. (6) and Gehrz, Sramek, and Weedman 1983 models with IMF 6–25 $M_\odot$ and $\alpha = 3.5$.
[f] Line fluxes measured by Hall *et al.* 1981.
[g] Line fluxes measured in this work, except for the Paβ flux measured in NGC 3227 by Ward *et al.* 1987.
[h] Line fluxes measured by Fischer *et al.* 1983.
[i] Line fluxes measured by Rieke *et al.* 1985.
[j] Line fluxes measured by Heckman *et al.* 1986 and McAlary *et al.* 1986.

because the total luminosity and the recombination line luminosities are dominated by upper main-sequence stars. Of the models tabulated by them, it was the model with the highest star-formation rate. We can now compare the bolometric luminosity and star-formation rate predicted by this model based on the observed Brγ line luminosities, with the infrared luminosities calculated from the *IRAS Point Source Catalog* and the number of Orion-like H_2 regions formed per year. In column (9), we tabulate the ratio L_{IRAS}/L_{bol}. The differences in the *IRAS* beam sizes and the aperture sizes of our Brγ line measurements will not affect this ratio if the emission from the galactic nuclei dominates the disk emission in the *IRAS* point source fluxes and in our measured Brγ line fluxes. In column (10), we tabulate the ratio of the birthrate of Orion-like outflow sources [derived from the $S(1)$ line luminosity] to the star-formation rate (derived from the Brγ line luminosity), $R_{outflow}$. Since the Brγ line and the $S(1)$ lines suffer similar extinction, this ratio is minimally affected by extinction that is external to the emission regions. Our interpretation of the fact that the values of the ratio L_{IRAS}/L_{bol} are about unity (to within a factor of 5) is that the infrared luminosities and Brγ line luminosities are consistent within the context of the starburst models calculated by Gehrz *et al.* This assumes little extinction is present at the 2 μm Brγ line. In contrast, we see from the values of $R_{outflow}$ that the birthrate of Orion-like outflow sources appears to be greater (by factors of 3–40) than that predicted by the star-formation rate inferred from the Brγ line flux and the Gehrz *et al.* models in all galactic nuclei except NGC 4151. It should be noted that we chose the Gehrz *et al.* model which produced the highest star-formation rate; other models would have produced even larger values of $R_{outflow}$. In a simple starburst scenario, we expect the values of $R_{outflow}$ to be ~ 1 because we expect that each star that forms will undergo an outflow phase similar to the one in Orion with an $S(1)$ line luminosity about equal to that in Orion.

There are a number of possible explanations for this discrepancy, within the framework of a simple starburst model in which the line emission originates from individual star-forming regions. (1) There may be stages within a stellar lifetime with either larger H_2 luminosities or longer outflow expansion times than were used here. For example, the supernova remnant IC 443 has a total measured $S(1)$ line luminosity of about 15 $L_\odot$ (T. R. Geballe [1986] private communication) and a lifetime of 1–6 × 10^4 yr (Davies, Lyre, and Seiradakic 1972; Parkes *et al.* 1977). If the obscuration to the H_2 emission is high and if supernova remnants in starbursts resemble IC 443, supernova remnants could contribute significantly to the H_2 emission in starbursts. (2) Various evolutionary stages of low-mass stars, e.g., HH objects, that contribute little to the Brγ line and infrared luminosities of a starburst (and therefore were not included in the models of Gehrz *et al.*) may contribute significantly to the $S(1)$ line luminosity. (3) The Brγ line emission regions may suffer higher obscuration than the H_2 regions, possibly because they are closer to the star. Last, (4) conditions in the environment of a starburst in a galactic nucleus could differ substantially from conditions in star-formation regions in our Galaxy.

In order to discriminate between the scenario in which the $S(1)$ line emission originates from individual star clusters and scenarios in which the $S(1)$ line emission is a global phenomenon, e.g., it originates from shocks due to interacting disks, we have plotted in Figure 5 the logarithm of the $S(1)$ flux versus the logarithm of the Brγ line flux using the data in Table 2. If in these galaxies starbursts with similar IMFs and similar starburst lifetimes are responsible for the $S(1)$ line and Brγ line emission, there should be a constant $S(1)$/Brγ line ratio. For reference, the locus of points coinciding with the measured $S(1)$ line to Brγ line ratio in H_2 region in DR 21 and IC 443 is plotted. The ratio plotted for DR 21 is based on the total $S(1)$ line flux measured by Garden *et al.* (1986) and the total Brγ line flux in the DR 21 compact H II region measured by us (unpublished). For IC 443 the ratio is based on the total $S(1)$ line flux observed by Geballe (private communication), and the Brγ line flux is derived from the Hα line flux corrected for

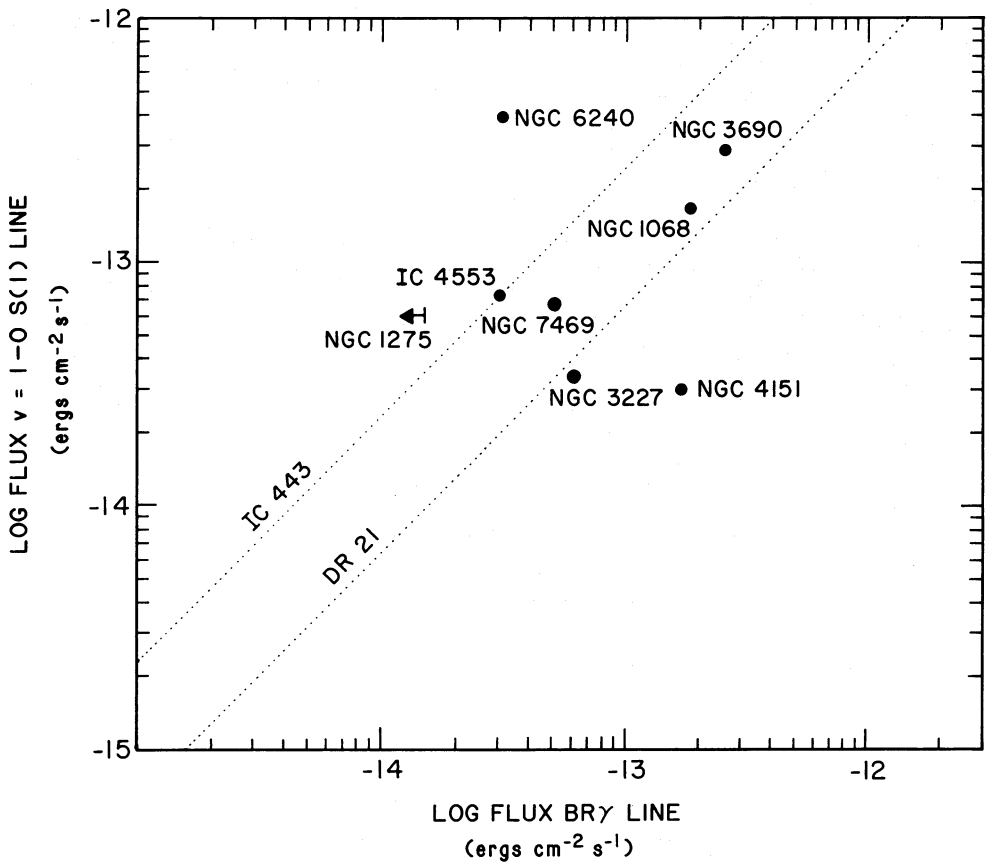

FIG. 5.—Logarithm of the $S(1)$ line flux vs. the logarithm of the Brγ line flux. For comparison the ratio is plotted for the DR 21 H_2 source and the supernova remnant IC 443. For DR 21 the observed $S(1)$ line flux is from Garden *et al.* (1986) and the Brγ flux in the DR 21 compact H II region was measured by us (unpublished). For IC 443 the total $S(1)$ line flux is from observations of Geballe *et al.* (private communication) and the Brγ flux is derived from the Hα flux corrected for extinction (Parker 1963) assuming Menzel Case B conditions.

extinction assuming Menzel Case B conditions (Parker 1963). There appears to be no correlation between the $S(1)$ and the Brγ line fluxes for the galaxies plotted in Figure 5. Thus it appears that a simple individual star cluster scenario with a single IMF is not responsible for the $S(1)$ line emission in all the galaxies. Different mechanisms, with varying relative $S(1)$ line strengths, may excite the H_2 line emission. It is interesting that many of the galaxies have ratios of $S(1)$ to Brγ line flux similar to those of DR 21 and IC 443. This suggests that in galaxies in which the $S(1)$ line to Brγ line flux ratio is similar to that in DR 21 and IC 443, e.g., NGC 1068, NGC 3690, IC 4553, and NGC 7469, the observed $S(1)$ line emission may originate mainly from an ensemble of individual star-formation regions. For those galaxies with high $S(1)$ line to Brγ line ratios, such as NGC 6240 and NGC 1275, the $S(1)$ line emission may emanate from shocks in the colliding gaseous disks that have initiated the starburst. UV fluorescence may be the dominant mechanism in galaxies such as NGC 4151 and NGC 3227. Further observations, such as high signal-to-noise ratio observations of the relative line strengths of the $v = 1$–0 $S(1)$ and $S(0)$ and $v = 2$–1 $S(1)$ lines, and images of the $v = 1$–0 $S(1)$ and Brγ lines in some of these galaxies may help discriminate between these and other alternatives.

V. SUMMARY

1. For both Seyfert and starburst galaxies there is a large range in the observed $S(1)$ line to Brγ line ratio, from ≤ 0.18 in NGC 4151 to ~ 13 in NGC 6240. The range in $S(1)$ line luminosity is nearly three decades.

2. Our measured upper limits on the $S(1)$ line velocity widths in the Seyfert 1 galaxies NGC 4151 and NGC 3227 suggest the H_2 lines are not formed in the broad-line regions of these galaxies.

3. UV fluorescence can be ruled out in NGC 1275 and NGC 1068, and probably in NGC 7469. UV fluorescence is a viable mechanism in NGC 4151 and possibly in NGC 3227. NGC 3227 appears to have H_2 line ratios that are consistent with UV fluorescence, to within the large measurement uncertainties.

4. For the galaxies in which both the far-infrared and the Brγ line fluxes have been measured, they are consistent (to within a factor of several) with models of starburst galaxies in these galaxies.

5. Several of the galaxies, most notably NGC 6240 and NGC 1275, have $S(1)$ lines that are overluminous compared to their Brγ lines. In these galaxies the $S(1)$ line may be excited in shocks that are presumably producing the starburst activity rather than in the individual young stellar outflows and remnants. The galaxies with high $S(1)$ to Brγ line ratios also have strong morphological evidence of galaxy-galaxy interactions, further suggesting global shocks in these galaxies.

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