NICMOS IMAGING OF MOLECULAR HYDROGEN EMISSION IN SEYFERT GALAXIES

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ABSTRACT

We present near-infrared (NICMOS) imaging of broadband and molecular hydrogen emission in Seyfert galaxies. In six of 10 Seyfert galaxies we detect resolved or extended emission in the 1–0 S(1) 2.121 μm or 1–0 S(3) 1.9570 μm molecular hydrogen lines. We did not detect emission in the most distant galaxy or in two Seyfert 1 galaxies because of the luminosity of the nuclear point sources. In NGC 5643, NGC 2110, and Mrk 1066, molecular hydrogen emission is detected in the extended narrow-line region on scales of a few hundred parsecs from the nucleus. Emission is coincident with [O III] and Hz + [N II] line emission. This emission is also near dust lanes observed in the visible to near-infrared color maps, suggesting that a multiphase medium exists near the ionization cones and that the morphology of the line emission is dependent on the density of the ambient media. The high 1–0 S(1) or S(3) H₂ to Hz flux ratio suggests that shock excitation of molecular hydrogen (rather than UV fluorescence) is the dominant excitation process in these extended features. In NGC 2992 and NGC 3227 the molecular hydrogen emission is from 800 and 100 pc diameter “disks” (respectively) that are not directly associated with [O III] emission and are near high levels of extinction (A_V ≥ 10). The molecular hydrogen emission in NGC 4945 appears to be from the edge of a 100 pc superbubble. The molecular gas in these three galaxies could be excited by processes associated with local star formation. We confirm previous spectroscopic studies finding that no single mechanism is likely to be responsible for the molecular hydrogen excitation in Seyfert galaxies.

Subject headings: galaxies: Seyfert — infrared: galaxies — radio lines: galaxies

1. INTRODUCTION

The emission from molecular hydrogen (H₂) can be used to probe the distribution of excited dense molecular gas in active galactic nuclei (AGNs). H₂ emission [e.g., the 1–0 S(1) line at 2.121 μm] is known to be bright in Seyfert galaxies (e.g., Veilleux et al. 1997; Ruiz 1997; Mouri 1994; Koornneef & Israel 1996). Ultraviolet (UV) fluorescence (e.g., Black & van Dishoeck 1987), excitation by low-velocity shocks (e.g., Draine & Robergse 1982; Hollenbach & Shull 1977), and heating caused by X-rays are the primary emission mechanisms considered for the excitation of molecular hydrogen (e.g., Puxley et al. 1990; Veilleux et al. 1997; Mouri 1994; Moorwood & Oliva 1998 and references therein). These mechanisms require a source of dense gas (density ~10^3 cm^-3) to be either located near a source of illumination (an AGN or a starburst) or actively affected by slow shocks induced either by jets or by kinetic processes (winds, supernovas, and supernovae) resulting from star formation. Ground-based spectroscopic studies of Seyfert galaxies and LINERs have found that the 1–0 S(1) flux weakly correlates with [Fe II] 1.64 μm emission (e.g., Larkin et al. 1998; Ruiz 1997; Mouri 1994) and 6 cm radio flux density (Forbes & Ward 1993; Koornneef & Israel 1996; Veilleux et al. 1997), but with a substantial scatter. No correlation between the 1–0 S(1) line and hard X-ray flux in Seyfert galaxies has been observed (Ruiz 1997; Veilleux et al. 1997), suggesting that heating by X-rays cannot be the dominant cause of excitation. These results suggest that more than one process causes the H₂ emission.

High-resolution imaging of line emission makes it possible to discriminate between likely emission causes. For example, the morphological association between the narrow-line region emission lines (e.g., [O III] λ5007) gas and the radio emission suggests a connection between radio ejecta and the ambient gas (e.g., Wilson & Willis 1980; Unger et al. 1987; Pogge 1988). However, the difference in angle between jet axes, ionization axes, and galaxy axes (Nagar et al. 1999) suggests that the distribution of ambient gas in the galaxy also plays an important role in determining the morphology of the ionization cones (see also Quillen et al. 1999 for examples of direct spatial associations). The distribution of extended molecular emission therefore provides a clue to the source of dense gas either illuminated by the central source, affected by energetic motions caused by a jet, or excited by processes associated with star formation (e.g., Maiolino et al. 1997).

This paper presents a high angular resolution imaging study of molecular hydrogen emission in Seyfert galaxies. Images were observed with the near-infrared camera and multiobject spectrometer (NICMOS) cameras on board the Hubble Space Telescope (HST). We construct high angular resolution visible to infrared color maps from Wide Field Planetary Camera 2 (WFPC2) and NICMOS broadband images. Red features caused by extinction in these maps are likely to trace dust lanes containing cold dense gas. We compare the morphology of the molecular hydrogen emission with that seen in the color maps and, when possible, that of [O III] and Hz + [N II] emission from ionized gas.

2. OBSERVATIONS

Our sample consists of three Seyfert 1 and seven Seyfert 2 galaxies at a variety of inclinations. We chose nearby Seyfert galaxies with bright 1–0 S(1) H₂ fluxes from Ruiz (1997), Veilleux et al. (1997), and Koornneef & Israel (1996). Redshifts were restricted so that either the 1–0 S(1) or 1–0 S(3) line could be observed with existing NICMOS nar-
rowband filters. The $H_2$ 1–0 S(3) 1.9576 $\mu$m line is approximately as bright as the 1–0 S(1) line at 2.1213 $\mu$m in Seyfert galaxies (Black & van Dishoeck 1987). The sample is listed in Table 1.

2.1. Broadband and Archival Images

For most of the galaxies we were able to obtain broadband near-IR NICMOS images. Three of the galaxies (Mrk 6, NGC 5643, and Mrk 1066) were part of snapshot observation programs to observe at 1.60 $\mu$m (in the F160W filter), NGC 3227 and IC 4329A are part of a guaranteed NICMOS images in the same way we did the narrowband imaging; col. (8), narrowband filter containing the line; col. (9), continuum filter. Archive images were used when possible to display structure in the ionization cones in either H$\alpha$ + [N II] $\lambda$6548, 6583 or [O III] $\lambda$5007. For the studies discussing these $HST$ data see Mulchaey et al. (1994) on NGC 2110, Simpson et al. (1997) on NGC 5643, Bower et al. (1995) on Mrk 1066, and Capetti et al. (1995) on Mrk 6.

2.2. Narrowband Images

Because the continuum in these galaxies is bright and contains structure that can vary with position, we required observations with a narrowband filter near (in wavelength) to the narrowband filter containing the emission line to accurately subtract the continuum. One $HST$ orbit was spent per galaxy with approximately 128 s spent in the broadband filter (F205W or F222M) when possible and the remainder of the orbit evenly divided between the two narrowband filters.

The molecular hydrogen emission was observed with the F212N, F215N, F216N filters on Camera 2 or the F196N on Camera 3 depending on the observed (redshifted) wavelength of the object (see Table 1). For some of the objects in our list, the 1–0 S(1) 2.1213 $\mu$m line could not be observed but the 1–0 S(3) 1.9570 $\mu$m line, which is nearly as bright as the 1–0 S(1) line, could be observed with the F196N filter on
Camera 3. For all of the objects observed with the F196N filter the line is on the red side of the filter, so there is no danger of confusion caused by the [Si VI] 1.96 µm line, which would be outside the filter and should be narrow in the Seyfert 2 galaxies (Giannuzzo, Rieke, & Rieke 1995). NGC 3227 could be observed in either H2 line, but it has broad lines. To reduce possible confusion from the [Si VI], we chose to observe the 1–0 S(1) line. For this object the line lies at a position in the filter with only 60% of maximum transmission but the object is bright enough so that a good signal-to-noise ratio (S/N) was achieved with the same integration time as the other objects.

The galaxies were observed in each filter at four different positions on the sky with a separation of 0.57 (Camera 2) or 1.12 (Camera 3) apart. Images were reduced with the NICRED data reduction software (McLeod 1997) using on orbit darks and flats. Each set of four images in a given filter was then combined according to the position observed. The pixel size for NICMOS Camera 2 is ∼0.076 and ∼0.204 for Camera 3. Flux calibration for the NICMOS images was performed using the conversion factors based on measurements of the standard stars P330-E and P172-D during the Servicing Mission Observatory Verification program and subsequent observations (M. Rieke 1999, private communication).

To construct H2 line emission maps, the narrowband continuum image (lacking the line) was scaled and subtracted from the narrowband image containing the line. From broadband images we estimated the spectral index (or color) of the continuum. We then checked that variations in this index were unlikely to be responsible for the variations seen in the continuum subtracted image. This was the case for all galaxies except for NGC 2992 and except for the nuclei where the structure of the point-spread function makes it difficult to measure intensities and colors. About 50% of the variations seen in the continuum-subtracted image of NGC 2992 could have been a result of large changes in the continuum spectral index because of reddening. We therefore corrected the continuum image before subtracting it to account for variations in this index.

![Image](image_url)

**Fig. 1.**—Top left: NICMOS Camera 2 F160W (1.60 µm) image of NGC 3227. Contours 0.25 mag apart are overlaid with the faintest white counter roughly equivalent to 14.0 mag arcsec⁻² in Johnson H band. Top right: Visible/near-IR color map constructed from F606W and F160W images. Colors range from V–H = 2.6 (approximately Johnson bands; white) to V–H = 4.1 (black). Bottom left: F606W (0.606 µm) WFPC2 image. Contours are 0.25 mag apart. The nucleus is saturated in this image. Bottom right: 1–0 S(1) H2 line emission. This image was constructed using PSF-subtracted images. Dark colors refer to brighter emission. 1' is equivalent to 75 pc assuming H0 = 75 km s⁻¹ Mpc⁻¹. North is at the top and east is to the left. The axes are shown in arcseconds.
The factor as a function of position used to correct each pixel in this image was derived from the spectral index that we measure from the ratio of the F606W and F205W images of this galaxy. None of the resulting line emission maps show structure observed in the color maps. This suggests that they do indeed trace the distribution of the 1–0 $S(1)$ or $S(3)$ lines. To estimate the line fluxes we took into account the transmission of the filter at the redshifted wavelength of the line. Fluxes and surface brightnesses were measured in various regions from the continuum-subtracted images and are listed in Table 2. Fluxes agree within a factor of 2 of the published values (listed in Table 1) in similar apertures. We measure higher nuclear fluxes for NGC 2992 and NGC 5643 than the listed values. Some of the discrepancy could be due to extreme nuclear continuum colors.

2.2.1. NGC 3227

NGC 3227 contains a bright nuclear point source which hampers our ability to detect extended line emission. We attempted to subtract a nuclear point source using a model point-spread function (PSF) created by Tiny Tim$^4$ (Krist et al. 1998). However the PSF-subtracted narrowband images did not produce a line emission map significantly better than that using the images containing the nuclear point sources. Molecular hydrogen emission elongated about P.A. $\sim 100^\circ$ (agreeing with that observed by Fernandez et al. 1999) is detected in both PSF subtracted and non-subtracted line emission maps. The most straightforward interpretation (also put forth by Fernandez et al. 1999) for the extended H$_2$ emission is that it lies in a 100 pc diameter “disk” with a major axis P.A. $\sim 100^\circ$. This “disk” is not aligned with the ionization cone observed in [O III] at P.A. $\sim 30^\circ$ or that of the 18 cm radio emission at P.A. $\sim -10^\circ$ (Mundell et al. 1995). The position angle of the H$_2$ emission also differs from that of the major axis of the galaxy (P.A. $\sim 155^\circ$). There is evidence from the CO velocity field that a warped molecular disk is present in this region (Schinnerer et al. 1999). The color map shown in Figure 1 suggests that

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*Fig. 2.—Top left: NICMOS Camera 2 F205W (2.05 $\mu$m) image of NGC 2992. Contours 0.25 mag apart are overlaid with the faintest white counter roughly equivalent to 4.61 mJy arcsec$^{-2}$. Top right: Visible/near-IR color map constructed from F606W and F205W images. Colors range from $V-K = 4$ (approximately Johnson bands; white) to $V-K = 7$ (black). Bottom left: F606W (0.606 $\mu$m) WFPC2 image. Contours are 0.25 mag apart. The nucleus is saturated in this image. Bottom right: 1–0 $S(3)$ H$_2$ line emission constructed from NICMOS Camera 3 narrowband images. Dark colors refer to brighter emission. 1$'$ is equivalent to 153 pc (for $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$).*

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$^4$ The Tiny Tim User’s Guide (Krist 1997) is available at http://scivax.stsci.edu/~krist.tinytim.html
extinction is large along the axis of the molecular hydrogen emission.

2.2.2. NGC 2992

H$_2$ emission is extended along a P.A. $\sim 20^\circ$ similar to that of the major axis of the galaxy. The most straightforward interpretation is that it lies in a 800 pc diameter disk in the plane of the galaxy. H$_2$ + [N ii] emission is primarily detected above and below the plane of the galaxy (Wehrle & Morris 1988; see Fig. 2).

2.2.3. NGC 5643

Strong H$_2$ emission is observed near the nucleus as well as extended emission coincident with some of the features seen in line emission, such as [O iii]. The overall shape of the line emission is similar to but not coincident with dust lanes seen in the optical/near-infrared (F814W/F160W) color map (Quillen et al. 1999). East of the nucleus the radio jet (P.A. 87$^\circ$) lies along the southern edge of the ionization cone (Simpson et al. 1997; see Fig. 3).

2.2.4. NGC 2110

The nucleus appears to be quite red in our visible/near-infrared color map (see Fig. 4) and so a straightforward subtraction of the F200N image from the F196N image results in oversubtraction of the nucleus. In the 1–0 S(3) line emission map we detect extended features near the nucleus at about 1$''$ from the nucleus and in a large loop about 3$''$ from the nucleus similar in position and shape to that observed in the H$_2$ + [N ii] and [O iii] line emission maps (which are discussed by Mulchaey et al. 1994). The overall shape of the line emission is similar to but not coincident with features seen in the optical/near-infrared (F814W/F160W) color map (Quillen et al. 1999) and avoids regions of emission from the S-shaped radio jet at P.A. $\sim 10^\circ$ (Mulchaey et al. 1994).

2.2.5. Mrk 1066

Mrk 1066 has narrow-line emission (e.g., [O iii]) in two narrow features that are aligned with radio emission from linear jets at P.A. 134$^\circ$ (Bower et al. 1995). Molecular...
hydrogen emission is detected in the same region as the brightest [O III] emission but is more extended in the direction perpendicular to the radio jets. The surface brightness in the 1–0 S(1) line is nearly flat, extending ~0′′.25 to either side of the western jet (and so is well resolved). In contrast, the [O III] line emission is brightest nearest the radio jet and quickly drops in surface brightness with increasing distance from the jet (see Fig. 5).

2.2.6. NGC 4945

The lack of [O III] emission and low 3 μm (L band) flux density suggest that a starbursting disk (rather than a low-luminosity AGN) is responsible for the conical shaped cavity observed in the visible/near-IR images of NGC 4945 (Moorwood et al. 1996). The cavity is interpreted to be a region where a bipolar superwind or bubble has evacuated denser material. Our H2 image resembles that of Moorwood et al. (1996), though more structure is seen. The morphology suggests that it forms a boundary between denser gas and a 100 pc scale “bubble” rather than a cone. Extinction on the southern side of the galaxy is so high at 2 μm that we would not expect to see molecular hydrogen emission from a southern bubble or cone if it exists (see Fig. 6).

3. EXTENDED EMISSION

We observed extended H2 emission from the 1–0 S(1) or S(3) line in six Seyfert galaxies: NGC 5643, NGC 3227, NGC 2992, NGC 2110, Mrk 1066, and NGC 4945. We do not resolve extended emission in the other galaxies (see Figs. 7–10). For Mrk 938 this may be because of its distance. For Mrk 6 and NGC 5506, the nuclear sources are so bright that it is difficult to observe any extended structure. Future attempts at modeling the PSF might yield detections of molecular hydrogen emission, particularly in Mrk 6, which has extended [O III] on a scale that we could resolve if the nuclear source could be subtracted reliably.

3.1. H2 Emission in a Dense “Disk”

The molecular hydrogen emission in NGC 3227 and NGC 2992 is coincident with extremely red continuum...
colors, suggesting that it is associated with large quantities of dense molecular material. The morphology of the $H_2$ emission in both cases is most easily interpreted as emission from "disks" of 100 and 800 pc in diameter in NGC 3227 and in NGC 2992, respectively. In both galaxies line emission from ionized gas and 6 cm radio emission (Wehrle & Morris 1988; Mundell et al. 1995) are observed along a different axis than the $H_2$ emission. Because this emission is associated with high levels of extinction, and not clearly associated with either the ionization cones or radio jets, it is unlikely that shocks or ionization associated with the jets and ionization cones can directly cause the excitation.

In NGC 3227 one possible interpretation is that the molecular hydrogen emission originates from the edge of a circumnuclear disk that has been observed in carbon monoxide submillimeter interferometry (Schinnerer et al. 1999; Fernandez et al. 1999). However, in NGC 3227 variations in the distribution and velocity components observed in $[O\text{ III}]$ and $Hz + [N\text{ II}]$ suggest that star formation is vigorous in its central regions (Gonzalez Delgado & Perez 1997), and that processes associated with star formation (hot stars and supernovae, e.g., Davies, Sugai, & Ward 1998) could also provide the $H_2$ excitation.

NGC 2992 also has evidence for active star formation. The galaxy has large-scale outflows observed in Hz and soft X-rays that could be driven either by jets or by a starburst (Colbert et al. 1998). Hz emission is observed hundreds of parsecs from the nucleus of the galaxy possibly along spiral arms (e.g., Wehrle & Morris 1988). The radial extent and narrow scale height of the $H_2$ emission are similar to those of the prototypical starburst galaxy M82 (Alonso-Herrero et al. 2000).

3.2. $H_2$ Emission in the Extended Narrow Line Region

In NGC 2110, NGC 5643, and Mrk 1066 we detect emission from molecular hydrogen that appears to be associated
and coincident with features observed in [O III] and H\alpha + [N II] line emission maps tracing ionized gas. We can use the strength of the observed H\alpha emission to estimate the local radiation flux of ionizing photons. If the H_2 emission results from UV fluorescence, then this flux is directly related (via a spectral index in the UV) to the flux of UV photons that can disassociate molecular hydrogen (in the range 912–1100 Å). Models (e.g., Black & van Dishoeck 1987; Puxley et al. 1990) predict 1–0 S(1) molecular hydrogen line strengths as a function of the incident UV radiation field and the density of the molecular clouds. This results in an H\alpha to 1–0 S(1) line flux ratio typical of H II regions [or as used by Puxley et al. 1990, a Br\gamma to 1–0 S(1)] ratio. Here we follow the approach outlined by Davies et al. (1998) to determine if UV fluorescence is a feasible excitation mechanism.

Using the surface brightness in the H\alpha line (in NGC 2110, \(\sim 10^{-14}\) ergs s\(^{-1}\) cm\(^{-2}\) arcsec\(^{-2}\) along the northern loop 3\arcsec from the nucleus; in NGC 5643, \(\sim 5 \times 10^{-15}\) ergs s\(^{-1}\) cm\(^{-2}\) arcsec\(^{-2}\) in the diffuse emission along the dust lane; and in Mrk 1066, \(\sim 10^{-13}\) ergs s\(^{-1}\) cm\(^{-2}\) arcsec\(^{-2}\) on the northwest side), setting the Balmer recombination rate equal to the number of ionizing photons (as done by Mulchaey et al. 1994), and using a UV spectral index of 1.6 we estimate a UV radiation flux between 912 and 1100 Å of \(5 \times 10^{-2}\) ergs cm\(^{-2}\) s\(^{-1}\). From this, and using the models of Black & van Dishoeck (1987), we would predict 1–0 S(1) line fluxes of \(7 \times 10^{-17}\) for NGC 2110, \(5 \times 10^{-17}\) for NGC 5643, and \(2 \times 10^{-16}\) ergs s\(^{-1}\) cm\(^{-2}\) arcsec\(^{-2}\) for Mrk 1066 (assuming \(n_H = 10^4\) cm\(^{-3}\)). This corresponds to the ratio of the 1–0 S(1) to H\alpha flux density ratio of \(\sim 10^{-2}\). This is equivalent to a 1–0 S(1)/Br\gamma flux ratio \(\sim 1\) and agrees with the higher density models of Puxley et al. (1990). From our H_2 emission maps we estimate the surface brightness to be 10, 6, and 30 times higher than that predicted above for UV fluorescence in NGC 2110, NGC 5643, and Mrk 1066, respectively.

While extinction of H\alpha may to some extent reconcile the flux estimated for UV fluorescent excitation with that observed, we suspect that UV fluorescence cannot be the dominant H_2 excitation process in any of these regions. H_2 excitation by slow shocks is then a more likely process (e.g.,

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**Table 3**

1–0 S(1) H_2 Fluxes and FWHM from Ruiz 1997

| Galaxy     | Flux* \((10^{-14}\) ergs \(\text{cm}^{-2}\) \(\text{s}^{-1}\)) | FWHM \((\text{km s}^{-1})\) |
|------------|-------------------------------------------------|-----------------|
| Mrk 334    | 0.91                                            | 130             |
| Mrk 335    | 0.13                                            | 102             |
| Mrk 938    | 1.73                                            | 537             |
| Mrk 348    | <0.04                                           | ...             |
| Mrk 1040   | 0.24                                            | 185             |
| NGC 1275   | 3.71                                            | 382             |
| Mrk 1095   | 0.51                                            | 381             |
| NGC 2110   | 0.93                                            | 447             |
| MCG −8-11-11 | 1.19                                         | 386             |
| NGC 2273   | 0.68                                            | 251             |
| Mrk 6      | 1.95                                            | 234             |
| Mrk 376    | <0.02                                           | ...             |
| Mrk 79     | <0.05                                           | ...             |
| Mrk 704    | <0.06                                           | ...             |
| NGC 2992   | 0.41                                            | 327             |
| NGC 3227   | 2.90                                            | 331             |
| NGC 3516   | <0.01                                           | ...             |
| NGC 4051   | 0.87                                            | 253             |
| NGC 4151   | 0.20                                            | 232             |
| Mrk 766    | 0.24                                            | 214             |
| IC 4329A   | 1.18*                                           | 332             |
| NGC 5506   | 1.06                                            | 315             |
| Mrk 817    | <0.02                                           | ...             |
| NGC 7469   | 0.86                                            | 309             |
| Mrk 533    | 0.48                                            | 268             |

* Fluxes were extracted from a 1.2 slit.

* Derived from Giannuzzo et al. 1995.
Fig. 7.—Top left: NICMOS Camera 2 F205W (2.22 μm image) of Mrk 938. Contours 0.25 mag apart are overlaid with the faintest white contour corresponding to 4.21 mJy arcsec$^{-2}$. Top right: Visible/near-IR color map constructed from F606W and F205W images. Colors range from $V - K = 2.8$ (approximately Johnson bands; white) to $V - K = 4.8$ (black). Bottom left: F606W (0.606 μm) WFPC2 image. Bottom right: 1–0 S(1) $H_2$ line emission constructed from NICMOS Camera 2 narrow band images. We do not detect any extended emission in molecular hydrogen. Dark colors would refer to brighter emission. 1" is equivalent to 384 pc (for $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$).

The line widths of $H_2$, while smaller than the widths of [Fe II] (Ruiz 1997; Veilleux et al. 1997) are still significantly higher than that expected for the low-velocity shocks capable of heating the molecular hydrogen without dissociating the molecules ($\lesssim 50$ km s$^{-1}$). If the $H_2$ emission results from slow shock, then these shocks may be produced by collisions in a multiphase, interstellar medium, or in other words a medium with patches of molecular material embedded in a more diffuse atomic medium (e.g., Heckman et al. 1986). The association of emission from ionized gas with emission from molecular hydrogen itself implies that a multiphase medium must exist in or near these ionization cones.

The line emission in NGC 5643 and NGC 2110 is also near dust lanes observed in optical/near-infrared color maps (Quillen et al. 1999). We see that emission is coincident with $H\alpha + [N \text{ II}]$ and $[O \text{ III}]$ emission; however, the dust lanes seen in the color maps, though similar in shape, appear to be offset from the line emission. If the morphology and orientation of the cone are influenced by the density distribution of the ambient media (e.g., as simulated by Mulchaey, Wilson, & Tsvetanov 1996), then we would expect that the line emission would peak at a position on the sky that is somewhat different from that of the maximum extinction or gas density. In fact the proximity of dust lanes with the line emission is good evidence for a dependence of the line excitation on the density of the ambient medium. We might hope that any future set of models for the excitation processes occurring in the ionization cone might be constrained by the observed association and offsets.

Since the UV radiation field implied by the $H\alpha + [N \text{ II}]$ and $[O \text{ III}]$ emission is relatively intense, we expect that molecular gas should be disassociated relatively quickly. Either the molecular material exists outside the UV radiation field, is self-shielded, or it must be replenished on timescales of $\sim 10^6$–$10^7$ years. The proximity of molecular
material also suggests that dust is present in the ionization cone. This possibility could be tested with future high-resolution mid-IR imaging.

4. CORRELATIONS BETWEEN H$_2$ EMISSION AND RADIO AND HARD X-RAY FLUX

By comparing the H$_2$ flux with that in hard X-rays and 6 cm radio, previous spectroscopic studies (Veilleux et al. 1997; Koornneef & Israel 1996; Vanzi, Alonso-Herrero, & Rieke 1998; Ruiz 1997) have concluded that more than one emission mechanism is likely to cause the molecular hydrogen emission in Seyfert galaxies. Our imaging study has shown that this is indeed likely. However, these studies were hampered by small samples, so we take the opportunity here to combine the samples of these previous studies.

Molecular hydrogen measurements from Ruiz (1997) are listed in Table 3.

Figure 11 shows 6 cm and hard X-ray fluxes plotted with molecular hydrogen fluxes. A weak correlation noted previously (Ruiz 1997; Forbes & Ward 1993; Koornneef & Israel 1996) between 6 cm and molecular hydrogen emission is seen. The scatter is much larger than that observed in [Fe II] versus 6 cm flux (e.g., Forbes & Ward 1993; Simpson et al. 1996). For most galaxies the hard X-ray flux can heat the molecular gas sufficiently to result in the observed molecular hydrogen emission; however, the lack of correlation between the hard X-ray and molecular hydrogen implies that this mechanism is not dominant.

The weak correlation between H$_2$ and 6 cm emission and lack of correlation with the hard X-ray flux suggests that
more than one process causes the molecular hydrogen emission in Seyfert galaxies. Our imaging study suggests that in some of these galaxies a substantial fraction of the emission could be associated with star formation. Unfortunately, in starbursting galaxies the flux of $H_2$ emission does not correlate with any other indicator, suggesting that processes other than supernovae and young stars are important (C. Engelbracht 1999, private communication; Vanzi et al. 1998). To test this we looked for (and failed to find) any correlation between the IRAS 1225 $\mu$m spectral index (which should be dependent on the fraction of infrared emission from the nucleus) and the ratio of $H_2$ emission and hard X-ray flux and the ratio of $H_2$ and 6 cm fluxes.

5. SUMMARY AND DISCUSSION

This paper presents NICMOS/HST imaging of molecular hydrogen emission in the 1–0 $S(1)$ or 1–0 $S(3)$ lines in Seyfert galaxies. We have detected extended emission in six of 10 galaxies (one of three Seyfert 1 galaxies and five of seven Seyfert 2 galaxies). We did not detect extended emission in Mrk 938, possibly because of its distance, and NGC 5506, IC 4329A, and Mrk 6, probably because of the luminosity of their nuclear sources. Improvements in techniques for subtraction of the NICMOS point-spread function (e.g., Krist et al. 1998) may make it possible to detect extended molecular hydrogen emission from these images, particularly in Mrk 6.

The molecular hydrogen emission in NGC 2992 and NGC 3227 is from 800 and 100 pc diameter “disks,” respectively, which are not coincident with [O III] or Hz emission and are near high levels of extinction. The molecular hydrogen emission in NGC 4945 appears to be from the edge of a 100 pc superbubble. The molecular gas in these three galaxies could be excited by processes associated with local star formation. The emission in NGC 3227 might arise from the edge of a circumnuclear torus (Fernandez et al. 1999) or warped disk.

In NGC 5643, NGC 2110, and Mrk 1066, molecular hydrogen emission is detected in the extended narrow line region on scales of a few hundred parsecs from the nucleus. Emission is found in the ionization cones coincident with [O III] and Hz + [N II] line emission. This emission is also
We see only a weak correlation between 6 cm and molecular hydrogen flux. The weakness of the correlation is similar to that presented in Veilleux et al. (1997) and Ruiz (1997). A correlation was also reported by Forbes & Ward (1993) and Koornneef & Israel (1996). H$_2$ and 6 cm fluxes are compiled from Koornneef & Israel (1996); Ruiz (1997); Veilleux et al. (1997); and Moorwood & Oliva (1988).

(b) Molecular hydrogen line flux vs. hard X-ray flux. Points below and to the right of the solid line have sufficient X-ray flux to account for the heating of the molecular gas [as estimated by Lepp & McCray 1983, $F(X) = 400/(H_{2}\lambda 2.121)$]; this plot is similar to that shown in Veilleux et al. 1997. However, the lack of correlation between molecular hydrogen emission and X-ray flux suggests that heating by X-rays is unlikely to be the dominant heat source for the molecular hydrogen emission. For the Seyfert 2 galaxies hard X-ray fluxes are compiled from Bassani et al. (1999) and for the Seyfert 1 galaxies from Reynolds (1997).

Near dust lanes observed in the visible to near-infrared color maps. The coincidence of H$_2$ emission with that from ionized gas implies that a multiphase medium is near or within the ionization cone. The proximity to dust lanes seen in the color maps suggests that processes causing the line emission are dependent on the density of the ambient media. The high $I_0$ S(1) or S(3) H$_2$ to Hz flux ratio suggests that shock excitation (not UV fluorescence) of molecular hydrogen is the dominant excitation process in these extended features.

We have compiled the spectroscopic observations of molecular hydrogen (from Veilleux et al. 1997; Koornneef & Israel 1996; Ruiz 1997) to look for correlations between 6 cm radio and hard X-ray flux. We find no correlation between H$_2$ emission and hard X-ray flux, confirming the results of these previous studies and ruling out heating by X-rays as the dominant cause of H$_2$ excitation. There is only a weak correlation between H$_2$ emission flux and 6 cm flux density (see Fig. 11). Both our imaging study and this compilation confirm the finding of previous spectroscopic studies (Ruiz 1997; Koornneef & Israel 1996; Veilleux et al. 1997; Forbes & Ward 1993): no single mechanism is likely to be responsible for the molecular hydrogen excitation in Seyfert galaxies. Future higher resolution observations may allow us to distinguish between likely processes and isolate molecular hydrogen emission from the circumnuclear environment.

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REFERENCES

Alonso-Herrero, A., Rieke, M. J., et al. 2000, in preparation
Bassani, L., Dadina, M., Maiolino, R., Salvati, M., Risaliti, G., Della Ceca, R., Matt, G., & Zamorani, G. 1999, ApJS, 121, 473
Black, J. H., & van Dishoeck, E.F. 1987, ApJ, 322, 412
Bower, G., Wilson, A., Morse, J. A., Gelderman, R., Whittle, M., & Mulchaey, J. 1995, ApJ, 454, 106
Capetti, A., Axon, D. J., Kukula, M., Macchetto, F., Pedlar, A., Sparks, W. B., & Boksenberg, A. 1995, ApJ, 454, L85
Colbert, E. J. M., Baum, S. A., O’Dea, C. P., & Veilleux, S. 1998, ApJ, 496, 786
Davies, R. L., Sugah, H., & Ward, M. J. 1998, MNRAS, 300, 388
Draine, B. T., & Roberge, W. G. 1982, ApJ, 259, L91
Fernandez, B. R., Holloway, A. J., Meaburn, J., Pedlar, A., & Mundell, C. G. 1999, MNRAS, 305, 319
Forbes, D. A., & Ward, M. J. 1993, ApJ, 416, 150
Giannuzzo, E., Rieke, G. H., & Rieke, M. J. 1995, ApJ, 446, L5
Gonzalez Delgado, R. M., & Perez, E. 1997, MNRAS, 284, 931
Heckman, T. M., Beckwith, S., Blitz, L., Skrutskie, M., & Wilson, A. S. 1986, ApJ, 305, 157
Hollenbach, D. J., & Shull, J. M. 1977, ApJ, 216, 419
Koornneef, J., & Israel, F. P. 1996, NewA, 1, 271
Krist, J. E., Golimowski, D. A., Schroeder, D. J., & Henry, T. J. 1998, PASP, 110, 1046
Larkin, J. E., Armus, L., Knop, R. A., Soifer, B. T., & Matthews, K. 1998, ApJS, 114, 59
Lepp, S., & McCray, R. 1983, ApJ, 269, 160
Maiolino, R., Ruiz, M., Rieke, G. H., & Papadopoulos, P. 1997, ApJ, 485, 552
McLeod, B. 1997, in Proc. HST Calibration Workshop, ed. S. Casertano, R. Jedrzejewski, T. Keyes, & M. Stevens (Baltimore: STScI), 281
Moorwood, A. F. M., & Oliva, E. 1988, A&A, 203, 278
Moorwood, A. F. M., van der Werf, P. P., Kotilainen, J. K., Marconi, A., & Oliva, E. 1996, A&A, 315, L1
Mouri, H. 1994, ApJ, 427, 777
Mulchaey, J. S., Wilson, A. S., Bower, G. A., Heckman, T. M., Krolik, J. H., & Miley, G. K. 1994, ApJ, 433, 625
Mulchaey, J. S., Wilson, A. S., & Tsvetanov, Z. 1996, ApJ, 467, 197
Mundell, C. G., Holloway, A. J., Pedlar, A., Meaburn, J., Kukula, M. J., & Axon, D. J. 1995, MNRAS, 275, 67
Nagar, N. M., Wilson, A. S., Mulchaey, J. S., & Gallimore, J. F. 1999, ApJS, 120, 209
Pogge, R. W. 1988, ApJ, 332, 702
Puxley, P. J., Hawarden, T. G., & Mountain, C. M. 1990, ApJ, 364, 77
Quillen, A. C., Alonso-Herrero, A., Rieke, M. J., McDonald, C., Falcke, H., & Rieke, G. H. 1999, ApJ, in press, (astro-ph/990223)
Reynolds, C. S. 1997, MNRAS, 286, 513
Ruiz, M. 1997, Ph.D. thesis, Univ. Arizona
Schinnerer, E., Eckart, A., & Tacconi, L. J. 1999, ApJ, 524, L5
Simpson, C., Forbes, D. A., Baker, A. C., & Ward, M. J. 1996, MNRAS, 283, 777
Simpson, C., Wilson, A. S., Bower, G., Heckman, T. M., Krolik, J. H., & Miley, G. K. 1997, ApJ, 474, 121
Unger, S. W., Pedlar, A., Axon, D. J., Whittle, M., Meurs, E. J. A., & Ward, M. J. 1987, MNRAS, 228, 671
Vanzi, L., Alonso-Herrero, A., & Rieke, G. H. 1998, ApJ, 504, 93
Veilleux, S., Goodrich, R. W., & Hill, G. J. 1997, ApJ, 477, 631
Wehrle, A. E., & Morris, M. 1988, AJ, 95, 1689
Wilson, A. S., & Willis, A. G. 1980, ApJ, 240, 429