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NGC 7552: A GALAXY WITH A DORMANT ACTIVE NUCLEUS?[1]

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ABSTRACT

Recent theoretical studies have suggested that small-scale bars may provide the mechanism for transporting material ("fuel") to a galaxy nucleus. Here we present high-resolution imaging of NGC 7552 in the infrared emission line of H_2 2.12 μm which reveals a possible nuclear bar. We also present Brγ imaging which clearly shows the kiloparsec-sized starburst ring previously identified in the radio by Forbes et al. 1994. Although this galaxy appears to possess a small-scale molecular bar and a large reservoir of molecular material, there is no evidence for current activity, either starburst or Seyfert-like, at the nucleus.

Subject headings: galaxies: individual (NGC 7552) — galaxies: nuclei — infrared: galaxies

1. INTRODUCTION

The fueling of galaxy nuclei has received considerable attention from both a theoretical and observational viewpoint. A key issue has been to understand the mechanism by which angular momentum is lost and material is transported down to parsec scales. Recent theoretical work in this area has concentrated on "bars" as a means for transporting material at larger radii toward the galaxy nucleus (e.g., Schwarz 1981; Shlosman, Frank, & Begelman 1989; Barnes & Hernquist 1992). The stellar bar creates a nonaxisymmetric potential, which leads to increased cloud-cloud collisions within the bar, causing gas to be driven inwards. This can result in the formation of an inner Lindblad resonance (ILR) in which material from the bar accumulates several hundred parsecs from the nucleus generating a ring of star formation (Elmegreen 1994). In order to drive this material to even smaller radii "bars within bars" (nuclear bars) have been suggested (Shlosman et al. 1989).

Observational studies of active galactic nuclei have been hampered by the pervasive dust and the need for high spatial resolution. One method of searching for nuclear bars that contain gas is to use near-infrared spectral-line imaging of molecular hydrogen (H_2). The extinction is largely reduced in the near-infrared compared to the optical and spatial resolution of 1″ or better is routinely available. The development of near-infrared Fabry-Perot spectrometers has allowed sufficient spectral resolution to isolate narrow emission lines.

We have chosen NGC 7552 to search for a molecular bar at small scales. This galaxy is a nearly face-on, barred spiral. Observations of CO indicate that large quantities of molecular material are concentrated in the central 45″ and with one of the highest CO/H I ratios observed in a galaxy nucleus (Claussen & Sahai 1992). In an earlier paper (Forbes et al. 1994) we identified a starburst ring, at radio wavelengths, associated with the ILR. This kiloparsec-sized ring was largely obscured from optical view by dust. Two larger scale star-forming rings were also seen emanating from the ends of the bar. The X-ray emission is consistent with a starburst origin (Charles & Phillips 1985). The radio map also revealed a "hint of elongated structure" from the ring toward the galaxy nucleus. Could this be a small-scale nuclear bar? Interestingly, NGC 7552 shows no evidence for an active nucleus, either Seyfert-like or starburst. It is located in the Grus loose group with NGC 7582, NGC 7590, and NGC 7599; the former two galaxies are listed as Seyfert 2 by Veron-Cetty & Veron (1993).

Here we present high spatial and spectral resolution images in the lines of H_2 2.12 μm and Brγ 2.17 μm. These lines trace warm molecular hydrogen gas and sites of recent massive star formation, respectively. At a distance of 32.7 Mpc, 1″ equals 158 pc ($H_0 = 50$ km s^{-1} Mpc^{-1}).

2. OBSERVATIONS AND DATA REDUCTION

The observations were obtained on 1993 September 3 using the ESO/MPI 2.2 m telescope at La Silla, Chile. We used the IRAC2B camera equipped with a 256 × 256 NICMOS3 array together with its associated Fabry-Perot (Moorwood et al. 1992) and a pixel scale of 0″.5 pixel^{-1}. The seeing, estimated from broad-band images taken just before and after the galaxy observations, was ~1″.3. We imaged the spectral lines of H_2 1–0 $S(1)$ 2.121 μm, Brγ 2.166 μm, and the corresponding continuum either side of the line, with a spectral resolution $\Delta\lambda/\lambda \sim 1000$. An integration sequence comprised 360 s on line and 360 s on the nearby continuum to either side of the line ($\delta\lambda = 0.001$ μm) and was repeated with the galaxy at four positions on the array yielding a total exposure time of 1440 s for each line image. Wavelength calibration was checked in the beginning of the night by observing the Orion nebula.

Data reduction was performed within the ESO MIDAS system using software routines written by R. Peletier. After bias subtraction, the sky emission was removed from each image by subtracting a different image in which the galaxy has been shifted by ~35″ across the array. The results were then flat-fielded using difference images of a diffusing screen in the dome with and without illumination by a halogen lamp (to remove any external thermal contribution to the dark current) and bad pixels removed and replaced by values interpolated from neighboring pixels. The galaxy continuum was removed

[1] Based on observations collected at the European Southern Observatory, La Silla, Chile.

by subtracting the average of the continuum images obtained on either side of the lines, and the line-only images were then co-aligned and added to produce the final images. Calibration using observations of photometric standard stars gave integrated fluxes in the images of 6.4×10^{-14} ergs s^{-1} cm^{-2} for Brγ and 4.25×10^{-14} ergs s^{-1} cm^{-2} for H_2 in a $6'' \times 6''$ aperture. This is in good agreement with the values of 6.5 and 3.9×10^{-14} ergs s^{-1} cm^{-2}, respectively, measured by Moorwood & Oliva (1990) with a grating spectrometer.

3. DISCUSSION

3.1. *The Starburst Ring*

In Figure 1 (Plate L1) we show the Brγ line emission for the circumnuclear region of NGC 7552. A partial ring of recent star formation is clearly seen, with regions of local enhancement (hot spots) and little or no nuclear emission. The general morphology was expected based on the radio and Hα imaging presented by Forbes et al. (1994). We have overlaid the 3 cm radio emission (beam size $\sim 1''$) in Figure 1 assuming that the near-infrared continuum peak is coincident with the center of the radio ring ("nucleus") located at $\alpha = 23^h13^m24^s.84$, $\delta = -42°51'27''.5$ (1950). There is fairly good positional agreement between the Brγ and radio hot spots. The hot spots are probably local complexes of young stars and supernova remnants (as indicated by their steep radio spectral indices). We would expect imaging in [Fe II] 1.64 μm to also reveal a hot spot–embedded ring (Forbes & Ward 1993), and we hope to obtain such an image in the future.

Figure 1 also shows the H_2 line emission with the 3 cm radio emission overlaid. Its morphology is different from that of the Brγ and radio emission in that, although extending slightly further than the starburst ring, the H_2 peaks in a N-S structure centered on the "nucleus" and shows diffuse emission interior to the ring but exhibits local minima at the position of the prominent hotspots.

Small ($2''$ diameter) aperture Brγ and H_2 measurements have been made at the locations of the radio hot spots and the nucleus. These are given in Table 1, along with the ratio H_2/Brγ and the visual extinction (A_V). The extinction toward each hot spot is estimated following Landini et al. (1984), assuming case B recombination:

$$A_V = 3.9 \log (104 I_{\mathrm{Br}\gamma}/I_{\mathrm{H}\alpha}) ,$$

where the Hα flux comes from Forbes et al. (1994). Their Hα map showed that the emission was concentrated in the northern half of the ring, suggesting strong obscuration to the south. This is confirmed by the derived A_V values for the hot spots. Forbes et al. assumed an average A_V of 1.6 (from Ward et al. 1980) across the entire circumnuclear region; this appears to be a reasonable value for the nucleus but underestimates the extinction within the ring, which has an average value toward the hot spots of $A_V \sim 4$. The larger A_V values for the hot spots located in the S-W part of the ring confirms that the incompleteness of the ring in Brγ and Hα is due largely to increased dust obscuration. Following the method of Forbes et al., the extinction-corrected Brγ flux implies that each hot spot contains about 10^5 O stars with a high mass star formation rate of $0.5\ M_\odot$ yr^{-1}.

The H_2/Brγ ratio throughout the central region including the ring is typical of starburst nuclei; in particular, the hot spots vary from 0.1 to 0.7 which is similar to the range observed for star-forming regions in our own Galaxy (Moorwood & Oliva 1988). The ratio of H_2 2–1 $S(1)$/1–0 $S(1)$ in the central region found by Moorwood & Oliva (1990) indicates that most of the 1–0 $S(1)$ line emission is of thermal rather than fluorescent origin, suggesting that it arises in gas heated by a mixture of hot stars (UV and shocks) and SNRs (X-rays and shocks).

3.2. *A Molecular Bar*

As noted above, the ratio of the integrated Brγ to H_2 fluxes is typical for starburst galaxies and the H_2 flux is probably dominated by the circumnuclear starburst. However, the Brγ emission is weak interior to the ring, whereas the H_2 emission actually peaks close to its center. We find that about 20% of the H_2 emission appears to arise in a small-scale "bar." This molecular bar extends from just inside the northern part of the ring, through the ring center (nucleus), and toward the southern edge of the ring. The placement and position angle ($\sim 0°$) coincide with the extension seen in the radio emission toward the nucleus. Forbes et al. (1994) also noted evidence for such an elongation in a J/K ratio map. This structure could be interpreted as a nuclear bar which lies perpendicular to the primary large-scale bar. The bar has dimensions of $\sim 2''.9 \times 1''.3$ (450×200 pc). The flux within the bar is 0.83×10^{-14} ergs s^{-1} cm^{-2}, which corresponds to a luminosity of 3.2×10^5 $L_\odot$ (after correcting for $A_V = 1.7$). Assuming a temperature of 2500 K and thermal excitation (Moorwood & Oliva 1990), we estimate the mass of warm H_2 in the bar to be $\sim 500\ M_\odot$. Claussen & Sahai (1992) infer a total H_2 mass in the central $45''$ of $\sim 8 \times 10^9\ M_\odot$. As seen in other galaxies, including our own, the fraction of warm H_2 gas compared to the total H_2 mass is negligible. If 5%–10% of the total H_2 mass is contained in the nuclear bar, then the bar has a comparable mass and mass density to nuclear bars seen in other galaxies (Devereux, Kenney, & Young 1992).

Forbes et al. (1994) suggested that the ILR ring could play a role in funneling an outflowing superwind. However, the presence of large quantities of molecular material interior to the

TABLE 1

HOT SPOT PARAMETERS

Hot Spot	Position	H_2 (10^{-14} ergs s^{-1} cm^{-2})	Brγ (10^{-14} ergs s^{-1} cm^{-2})	H_2/Brγ	A_V (mag)
Nucleus	$24^s.84 + 27''.5$	0.74	0.16	4.6	1.7
A	25.06 + 27.6	0.40	0.92	0.43	3.3
B	24.98 + 29.7	0.40	2.00	0.20	6.0
C	24.58 + 27.8	0.44	0.57	0.77	3.9
D	24.70 + 25.1	0.22	1.71	0.13	4.8

NOTES.—Approximate positions are given relative to R.A. = $23^h13^m00^s$, decl. = $-42°51'00''$ (1950). Fluxes are measured in a $2''$ diameter circular aperture. Extinction (A_V) = 3.9 log ($104 I_{\mathrm{Br}\gamma}/I_{\mathrm{H}\alpha}$).

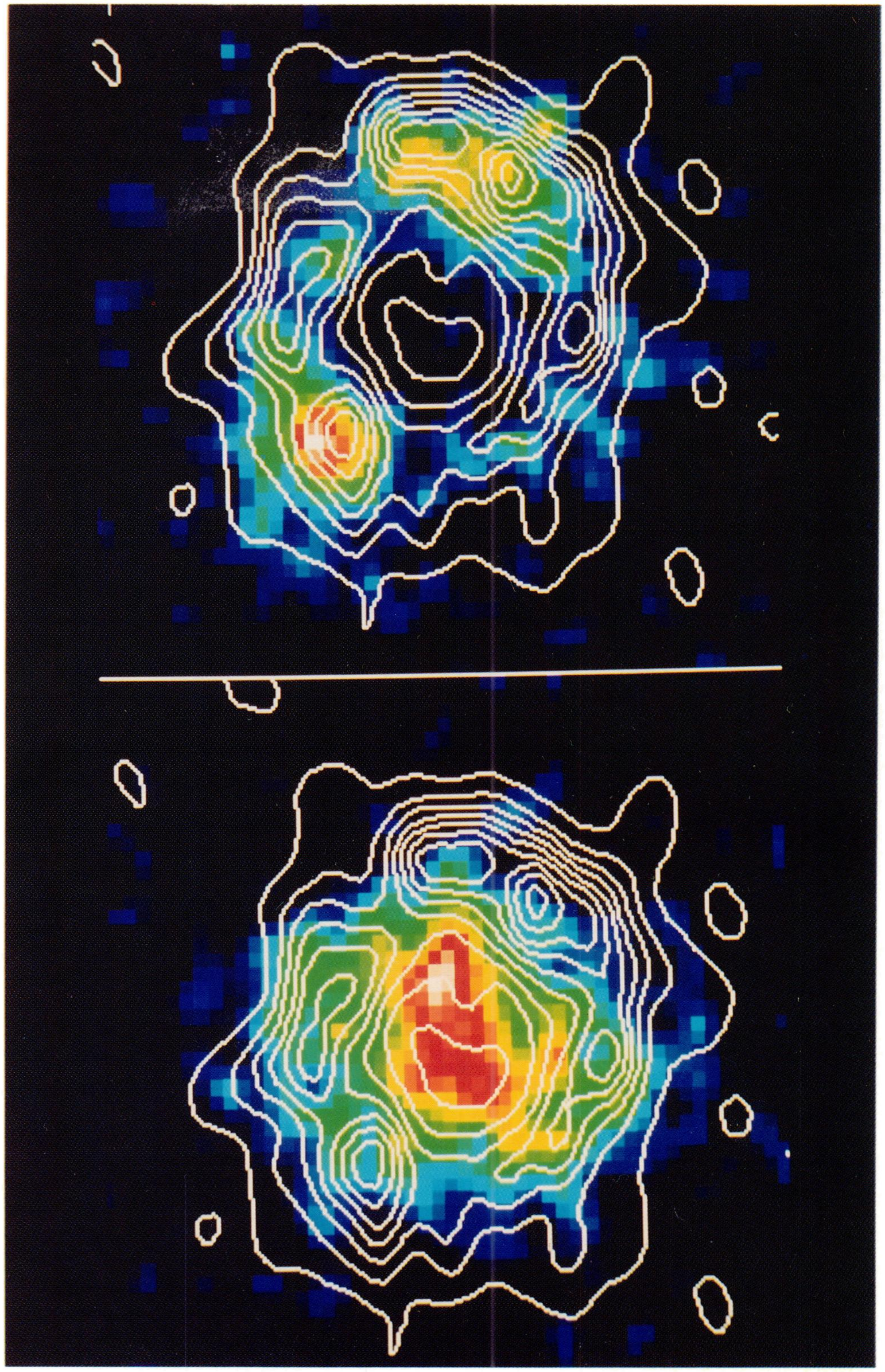

FIG. 1.—*Top:* Color image of the central 13″ × 13″ of NGC 7552 in the Brγ emission line showing a partial ring of star formation. Both images show a linear range of intensity of 1×10^{-15} ergs $^{-1}$ s $^{-1}$ cm $^{-2}$ per pixel. The image has been resampled to 0″.25 pixel^{-1} and the 3 cm radio contours from Forbes et al. (1994) have been overlaid (beam size ∼1″). *Bottom:* Color image of NGC 7552 in the 1–0 $S(1)$ H_2 (molecular hydrogen) with the same scale as above. A nuclear bar is seen to emanate from the northern part of the radio ring.

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ring suggests that a superwind of the type inferred for M82, that is, a molecular torus surrounding a circumnuclear region devoid of molecular material (Nakai et al. 1987), has not occurred in NGC 7552.

The nuclear H_2/Brγ ratio of 4.6 is much higher than that observed in the starburst ring due, presumably, to the absence of hot ionizing stars. This ratio alone, however, would not exclude the presence of a nuclear starburst. On the basis of UV-heating models by Puxley, Hawarden, & Mountain (1990) this ratio corresponds to a single star with an effective temperature $\simeq$35,000 K or an assemblage of H II regions with an upper mass cutoff $\simeq 30\ M_\odot$ and SNRs that would contribute additional H_2 but very little Brγ emission. Although global ratios this high have not been observed for other starburst galaxies it should be stressed that the global integrated ratio for NGC 7552 is typical of starburst galaxies, and the additional nuclear component is only apparent with the relatively high spatial resolution of our images. Other galaxies that have been imaged in these lines do in fact show large spatial variations in this ratio (see Moorwood & Oliva 1994a for a recent review and references). Starburst galaxies tend to show clumpy but not well-correlated H_2 and Brγ morphologies while Seyfert galaxies exhibit additional H_2 emission which may be excited by winds or X-rays associated with the active nucleus. NGC 4945, for example, shows a "halo" of H_2 emission that probably originates in gas heated by X-rays from an active nucleus that is so heavily obscured along the line of sight that it has only been directly observed in hard X-rays (Moorwood & Oliva 1994b). The Circinus galaxy even exhibits some similarity with NGC 7552 in that it also shows a partial Brγ ring, whereas the H_2 emission peaks on the nucleus and is both more extended and diffuse (Moorwood & Oliva 1994a). Unlike NGC 7552, Circinus clearly exhibits an active nucleus and an associated Brγ peak although the H_2/Brγ ratio $\simeq 2$ on the nucleus is also relatively high. Given the lack of any evidence for an AGN in NGC 7552, an evolved nuclear starburst would probably provide the most plausible "conventional" explanation for the high central H_2/Brγ ratio.

Alternatively, the H_2 emission in the nucleus could be the result of gas heating due to cloud-cloud collisions and streaming motions within a bar. We note that Durret & Bergeron (1988) have detected [O I] 6300 Å (suggestive of shocks) in the circumnuclear region but not on the nucleus itself. If shocks are present, then the required parameters at the molecular cloud interface can be estimated from the H_2/Brγ ratio. In the C-shock models of Draine, Roberge, & Dalgarno (1983) virtually no Brγ emission is produced. However, the J-shock models of Hollenbach & McKee (1989) can reproduce the observed nuclear ratio of 4–5 for shock velocities $v_s \leq 40$ km s^{-1}, density $n = 10^3$–10^4 cm^{-3}, or $v_s \leq 35$ km s^{-1} and $n = 10^4$–10^6 cm^{-3}. Such slow shocks have also been inferred for the merging galaxy NGC 6240 (van der Werf et al. 1993) and are not expected to generate strong near-infrared [Fe II] line emission. Thus the "excess" H_2 emission seen in other active galaxies may also be associated with currently undetected molecular bars excited by internal shocks.

Although several galaxies with ILR rings are known to have nuclear bars (Buta & Crocker 1993), it is not clear how many contain molecular material. Devereux et al. (1992) presented the only known example to date of a galaxy with both a nuclear molecular bar and ILR ring. This galaxy, NGC 3351, shares many similarities with NGC 7552. It is classified as SBb, reveals a starburst ring at the ILR and the nuclear bar is perpendicular to the primary bar. The bar dimensions are $\sim$900 × 300 pc, with a total H_2 mass of $1.8 \times 10^8\ M_\odot$. One significant difference between the two galaxies is that NGC 3351 shows strong Hα emission, that is, recent star formation, at the nucleus. Here the nuclear bar may have played a role in fueling the active nucleus. Spectral-line imaging in H_2 for a large sample of galaxies may reveal many more small-scale molecular bars. The frequency of such bars with nuclear activity class would be of great interest.

How are the nuclear bars formed? Shlosman et al. (1989) proposed that as gas falls in along the bar, it becomes unstable, generating a secondary bar within the primary one. This process of "bars within bars" may continue down to the nucleus. Pfenniger & Norman (1990) have shown that a nuclear bar may have in general a different orientation to the primary bar (perpendicular in the case of NGC 7552) due to different pattern speeds. Corotation for the nuclear bar is probably located at the ILR of the primary bar.

Both theoretical and observational studies have suggested that interactions, and the presence of bars, have a causal connection with increased activity in a galaxy, be it a starburst or Seyfert-like activity (see Barnes & Hernquist 1992 and references therein). This activity is often concentrated at the galaxy nucleus. In NGC 7552 we appear to have all the necessary ingredients, that is, distorted outer isophotes suggesting a previous interaction, a large-scale bar to transport material down to kiloparsec scales, a large reservoir of molecular material, and a nuclear bar thus making "fuel" available at the nucleus, and yet there is no evidence for any current nuclear activity. Perhaps the density of material at the nucleus has not yet passed a critical value and so the nucleus has yet to "turn-on." Alternatively, we are currently observing the nucleus in a dormant phase. Heller & Shlosman (1993) have suggested that the inflow of material occurs in cycles as instabilities within the ILR ring drive the mass inflow down the nuclear bar. High spatial resolution spectroscopy and population synthesis modeling of the nucleus would help to identify an evolved population of stars associated with a previous period of nuclear star formation activity that died out long ago.

4. CONCLUDING REMARKS

We have presented high-resolution infrared line images of the circumnuclear region of NGC 7552 which reveal a previously known starburst ring and indicate the presence of a newly identified molecular bar. Using the Brγ flux we have derived the extinction and star formation rate for individual hot spots (stellar complexes) within the starburst ring. Within the ring, the Brγ and H_2 emission line maps show a striking anticorrelation, with H_2/Brγ ratios typical of star-forming regions in our Galaxy. Although the molecular bar appears to reach down to the nucleus, thus providing a potential supply of material, it has not led to enhanced nuclear activity. Molecular bars may be a necessary but not sufficient requirement for nuclear activity. We speculate that the nucleus in NGC 7552 may eventually become "active." Future searches for molecular bars by imaging the spatial distribution of the H_2 1–0 $S(1)$ emission line are warranted.

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