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HIGH-RESOLUTION IMAGING OF BRACKETT-γ AND H_2 1–0 S(1) EMISSION IN THE SEYFERT GALAXY NGC 1068

V. ROTACIUC, A. KRABBE, M. CAMERON, S. DRAPATZ, R. GENZEL, A. STERNBERG, AND J. W. V. STOREY[1]
Max-Planck-Institut für Physik und Astrophysik, Institut für extraterrestrische Physik, D-8046 Garching bei München, Federal Republic of Germany
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ABSTRACT

We report 1″ resolution imaging of 2 μm H I Brγ and H_2 1–0 S(1) line emission toward the nucleus of the Seyfert 2 galaxy NGC 1068. The data, taken with a new imaging Fabry-Perot, show that the emission in both infrared lines originates from within 2″ (170 pc) of the peak of radio, near-infrared, and visible continuum radiation. The vibrational H_2 emission has a double-lobed shape, with a minimum toward the nucleus and two peaks about 1″.3 on either side of the nucleus along position angle 70° east of north. In contrast, the Brγ emission is peaked on the nucleus, similar to the central radio continuum structure and the narrow-line region (NLR) in the visible. The Brγ emission has a $\approx$1″ (FWHM) diameter and is more compact than the distributions of visible NLR tracers.

The H_2 emission is probably produced in hot gas with mass a few $10^3\ M_\odot$. However, the total H_2 mass in the circumnuclear region hydrogen may approach $10^8\ M_\odot$. The H_2 emission is not produced in a 1 pc size obscuring torus but probably comes from a system of molecular clouds in the vicinity of the NLR. The molecular clouds probably contribute significantly to the extinction of the nuclear source.

We propose that the circumnuclear Brγ and H_2 emission lines are excited in gas heated by UV or X-ray photons emitted by a central nonstellar source.

Subject headings: galaxies: individual (NGC 1068) — galaxies: nuclei — infrared: spectra — interstellar: matter

1. INTRODUCTION

NGC 1068 is one of the brightest and best studied active galaxies. It is the archetype Seyfert 2 galaxy, it is nearby (18.1 Mpc, 1″ = 81 pc, for $H_0 = 75$ km s^{-1} Mpc^{-1}), and it has been extensively observed from radio to X-ray wavelengths. The central luminosity of NGC 1068 is dominated by a compact 10 μm source (Becklin et al. 1973; Tresch-Fienberg et al. 1987) which emits $\sim 1.5 \times 10^{11}\ L_\odot$ (Telesco et al. 1984). Optical line studies of the narrow-line region (NLR) reveal complicated gas motions (Cecil, Bland, & Tully 1990). A bipolar 13″ synchrotron radio jet is centered on the nucleus. Broad-line optical emission is visible in polarized light which is probably scattered from within a (1 pc) dusty torus that obscures the central engine (Antonucci & Miller 1985).

Extragalactic molecular hydrogen (H_2) vibrational 1–0 S(1) line emission was first detected in NGC 1068 by Thompson, Lebofsky, & Rieke (1978), who also detected Brγ emission from the central regions. Further line observations have been presented by Neugebauer et al. (1980), Hall et al. (1981), and Oliva & Moorwood (1990). However, these studies did not spatially resolve the emission-line regions. We have used our new infrared imaging spectrometer in order to study the spatial distribution of the H_2 and Brγ emission regions. Our results are reported in this *Letter*.

2. OBSERVATIONS

The measurements were made in 1990 January at the ESO/Max-Planck-Society 2.2 m telescope at La Silla (Chile) with the MPE Fabry-Perot-Array-Spectrometer (FAST; Krabbe et al. 1991). FAST is equipped with a 58 × 62 pixel InSb array detector manufactured by Santa Barbara Research Corporation. The array is characterized by a typical readout noise of 700 electrons in "signal minus reset" mode and a dark current of 120 electrons s^{-1} at the operational temperature of 8 K. The optical arrangement provides an image scale of 0″.8 per pixel and an unvignetted field of view of 45″ diameter at the f/35 focus of the telescope. A spectral resolving power of 950 in the K band is obtained with a Queensgate Instruments, Ltd scanning Fabry-Perot interferometer located in the converging beam in front of the dewar, in series with a cold circular variable filter (CVF) order sorter.

Individual frames on the line and on the continuum to either side of the line were taken with integration times between 100 and 300 s. The data were reduced with MIDAS software. Dark current effects were eliminated by subtracting from each frame a "dark" frame of the same integration time. Flat-fielding was achieved by dividing by sky images taken through the CVF with the Fabry-Perot removed. Final frames of "line only" (sky emission and continuum removed) were then made by subtracting the average of the continuum "off-line" frames (on both sides of the line) from the "on-line" frames. In order to remove small (< 1″) tracking error image shifts the location of the bright, compact 2 μm continuum source was used as a reference point. The total on-source integration times were about one-half hour for Brγ and 1 hr for the H_2 line. Fluxes were calibrated using the standard star GL 105.5. Wavelength were calibrated by observing Orion. The visible seeing during the measurements was between 0″.9 and 1″.5, resulting in K-band stellar images of $\approx$1″.4 FWHM diameter, including the effect of the finite pixel size.

[1] Postal address: School of Physics, University of New South Wales, P.O. Box 1, Kensington, N.S.W. 2033, Australia.

3. ANALYSIS

3.1 *Morphology*

Figure 1 shows the images of the 2.1212 μm H_2 1–0 *S*(1) and 2.166 μm Brγ lines, along with a continuum image taken through the CVF alone. The continuum image shows a bright nuclear source (FWHM 2″.7) embedded in a stellar cluster with a prominent NE–SW bar component and agrees well with the data of Scoville et al. (1988) and Thronson et al. (1989).

The Brγ map in Figure 1 is of the line core only ($\Delta v = 316$ km s^{-1}) with an integrated flux of 4×10^{-14} ergs cm^{-2} s^{-1}. We find good agreement with the line flux reported by Oliva & Moorwood (1990) once our line flux is multiplied by the ratio ≈3 between the total line width of 900 km s^{-1} and our spectral resolution. Our scaled flux is about 50% lower than the values quoted by Thompson et al. (1978) and Hall et al. (1981), although the measured fluxes are consistent within the combined error bars. The Brγ emission source is compact and slightly elongated (FWHM 1″.9 × 1″.4 at p.a. 39° east of north) and is centered and peaked on the compact 2 μm continuum source within a measurement accuracy of ~0″.3. Scoville et al. (1988) and Thronson et al. (1989) have shown that the 2 μm continuum source is centered on the classical visible NLR at R.A. = 02ʰ40ᵐ07ˢ.08, decl. = −00°13′31″.5 (1950). It appears that the Brγ emission is produced in the NLR, a conclusion that is reinforced by the similarity between the Brγ and visible NLR line profiles (Hall et al. 1981; Alloin et al. 1983; Oliva & Moorwood 1990; Cecil et al. 1990). We note that the Brγ source is somewhat more compact than the visible NLR (FWHM 3″ × 2″.3 along p.a. 32°) as traced, for example, by [N II] emission (Cecil et al. 1990). This fact may indicate that extinction of the ionized gas increases toward the nucleus, or that the visible emission lines are influenced by radiative transport.

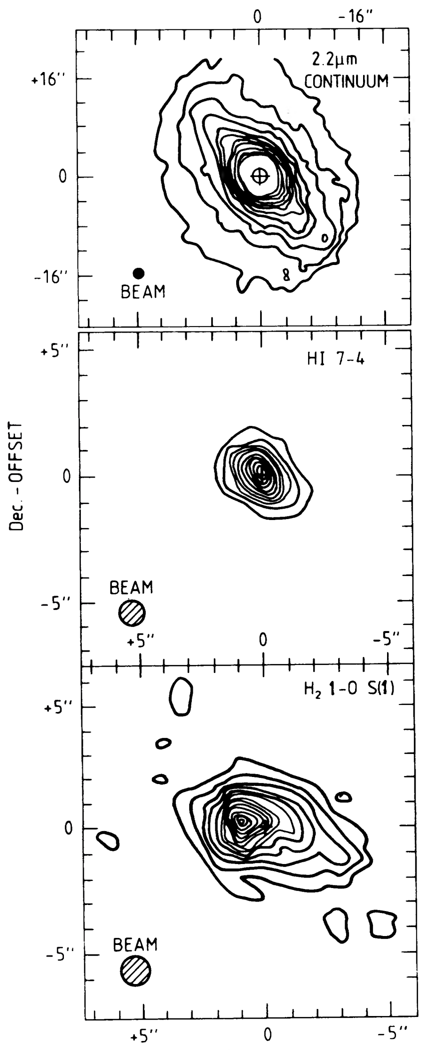

FIG. 1.—*Top:* 2.2 μm continuum map of NGC 1068, smoothed to a resolution of 1″.6. The peak flux is 2.3×10^{-13} ergs cm^{-2} s^{-1} $arcsec^{-2}$, and the integrated fluxes in the central 6″ and 16″ diameter regions are 9.3 and 16×10^{-13} ergs cm^{-2} s^{-1}. *Middle:* Brγ map of the line core with a velocity width of 316 km s^{-1}. The contour unit is 5.9×10^{-16} ergs cm^{-2} s^{-1} or 2.5×10^{-5} ergs cm^{-2} s^{-1} sr^{-1}. The cross denotes the position of the peak of the 2 μm continuum emission. *Bottom:* H_2 1–0 *S*(1) map of the line core with a velocity width of 300 km s^{-1} and centered at $v_{LSR} = 1200$ km s^{-1}. The contour unit is 3.9×10^{-16} ergs cm^{-2} s^{-1} or 1.6×10^{-5} ergs cm^{-2} s^{-1} sr^{-1}.

The H_2 1–0 *S*(1) line mapping was centered at $v_{LSR} = 1200$ km s^{-1}, approximately 110 km s^{-1} off the line center determined by Hall et al. (1981). The integrated H_2 line flux is 8.6×10^{-14} ergs cm^{-2} s^{-1} and is consistent with the fluxes obtained by Hall et al. (1981) and Oliva & Moorwood (1990) after correcting for the fraction of the 230 km s^{-1} wide line that passed through the Fabry-Perot. The H_2 emission is offset from the continuum source by ≈0″.9 east, and it is more extended than the Brγ emission. The H_2 source has a FWHM diameter of about 2″.3, and the lower contours extend about 8″ (700 pc) along p.a. 70°. By selecting data with the best visible seeing and optimum focusing (2 days out of 3), it is possible to obtain even better spatial resolution and show that the H_2 source possesses an intensity *minimum* at the location of the compact continuum source with two unequal emission peaks ~1″.3 (110 pc) along p.a. 70° on either side of it. Figure 1 displays the torus-like structure of the selected H_2 data superposed on a schematic of the Wilson & Ulvestad (1983) 5 GHz continuum map of the 13″ radio jet.

Figure 2 shows that the molecular and ionized emission are spatially distinct. This conclusion is supported by the differing

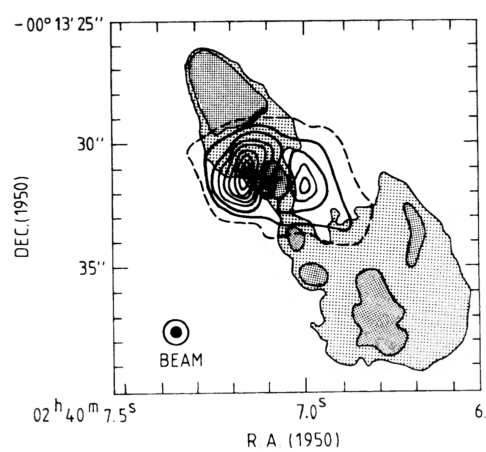

FIG. 2.—Map of the highest quality H_2 data (best seeing and focusing), superposed on a schematic of the 5 GHz radio continuum map of Wilson & Ulvestad (1983). The contour unit is 4.9×10^{-16} ergs cm^{-2} s^{-1} or 2×10^{-5} ergs cm^{-2} s^{-1} sr^{-1}. The cross denotes the position of the 2 μm continuum peak which is coincident with the radio peak to better than 1″ (Thronson et al. 1989; Scoville et al. 1988).

values of the H_2 and Brγ line widths (Hall et al. 1981). Our observations demonstrate that the molecular hydrogen emission from the nucleus of NGC 1068 arises in a region a few hundred parsecs in extent. We confirm the conclusion of Oliva & Moorwood (1989) that the H_2 emission is not produced in a parsec-size obscuring torus surrounding the central continuum source (Antonucci & Miller 1985). The H_2 emission probably arises in a system of massive molecular clouds in the vicinity of the NLR, which also may lie in the galactic disk plane. The H_2 double-lobed structure appears to envelop and possibly confine the dense ionized gas of the NLR and part of the radio jet.

3.2. *Excitation Mechanisms*

The ratio of the 1–0 $S(1)$ 2.12 μm and 2–1 $S(1)$ 2.25 μm H_2 lines is greater than 7 in the nuclear region of NGC 1068 (Oliva & Moorwood 1989) implying that the H_2 emission is probably collisionally excited in hot ($T \lesssim 2500$ K) dense gas. A hot molecular mass of $\sim 3 \times 10^3$ $M_\odot$ is required to produce the observed 1–0 $S(1)$ line luminosity of 1.7×10^6 $L_\odot$ (cf. Thompson et al. 1978). The hot mass may be a very small fraction of the total molecular mass in the nucleus of NGC 1068. Planesas, Scoville, & Myers (1990) have detected a CO 2.6 mm line flux of $\sim$200 K km s^{-1} in a 3″ beam within the central few arcsecs of the nucleus which, using the Galactic conversion factor between H_2 column density and CO line flux (Bloemen 1989), corresponds to an H_2 column density of 4×10^{22} cm^{-2} and a total molecular mass of $\sim 3 \times 10^7$ $M_\odot$, so that $f_{\rm hot} \equiv M_{\rm hot}/M_{\rm total} \sim 10^{-4}$. We note that the *surface* brightness of the H_2 emission from NGC 1068 (2×10^{-4} ergs cm^{-2} s^{-1} sr^{-1}) is comparable to the surface brightness of the H_2 emission produced in the circumnuclear disk surrounding the central 1.5 pc of our own Galaxy (Gatley et al. 1984, 1986) where $f_{\rm hot} \sim 10^{-5}$ (Genzel et al. 1985). If $f_{\rm hot}$ in NGC 1068 and the Galactic center are similar, we again infer a large H_2 column density and total molecular mass of 10^{23} cm^{-2} and 10^8 $M_\odot$ in the central 200 pc region of NGC 1068. These column density and mass estimates suggest that regions of high extinction with $A_v \gtrsim 50$ (assuming Galactic dust properties) are associated with molecular gas in the vicinity of the NLR where much lower extinctions ($A_v \sim 1$) have been inferred from optical and infrared line studies of the ionized gas (Wampler 1971; Neugebauer et al. 1980). The average molecular hydrogen density in the emitting region is 50 cm^{-3} and the density required for thermal population of the H_2 vibrational levels is $\gtrsim 5 \times 10^4$ cm^{-3}, so the molecular emission region is probably sheetlike or very clumpy with a cloud filling factor less than 10^{-3}.

The thermal vibrational H_2 emission in NGC 1068 may be produced dynamically in shock waves (cf. Draine, Roberge, & Dalgarno 1983) associated with supernova remnants (Oliva & Moorwood 1990), star formation (Hall et al. 1981), or a nuclear outflow. The H_2 emission may also be produced in gas heated by X-ray photons generated by supernova explosions (Draine & Woods 1990) or emitted by the central nonstellar source, or in gas heated by far-UV photons (Sternberg & Dalgarno 1989; Burton, Hollenbach, & Tielens 1990) emitted from OB stars or the central nonstellar source.

Oliva & Moorwood (1990) suggested that the H_2 emission is produced by supernova remnants in a region of enhanced star formation. Draine & Woods (1990) estimate that shocks convert 6×10^{-4} of supernova blast wave energy into 1–0 $S(1)$ line emission. Thus, if supernova shocks produce the H_2 emission, a supernova rate of at least $\dot{N}_{\rm SN} = 0.4$ SN yr^{-1} is required within the central 250 pc. Such a high supernova rate (comparable to the rate in the central 1 kpc of M82) is probably inconsistent with the lack of radio continuum emission from the H_2 torus. Assuming that radio flux and supernova rate are directly proportional to each other (Völk 1989) and taking the proportionality factor $\dot{N}_{\rm SN} = 8.6 \times 10^{-3}$ $S_{5\,\rm GHz}$(Jy)D^2(Mpc) obtained from radio flux and supernova rate in the starburst galaxy M82, we estimate that a 5 GHz flux of about 150 mJy ought to be emitted from the H_2 torus. There is, however, no structure resembling the H_2 emission torus on the VLA maps of Wilson & Ulvestad (1983) to a flux density limit of $\sim$20 mJy. Draine & Woods (1990) have demonstrated that transient X-ray heating from supernova blast waves may convert up to $\sim$10 times more energy into 1–0 $S(1)$ line emission than is produced in the supernova shocks. The observed X-ray luminosity of the NGC 1068 nucleus is 2.5×10^8 $L_\odot$ (Monier & Halpern 1987) close to the supernova X-ray luminosity of 3.4×10^8 $L_\odot$ that is required to produce the H_2 emission. However, if the H_2 emission is produced by supernova explosions then the X-rays must be emitted from an extended (200 pc) region rather than from electron scattering clouds within a few pc of the central continuum source as suggested by Antonucci & Miller (1986). We conclude that the production of the H_2 emission in supernova remnants is not or only marginally consistent with the radio and X-ray emission from NGC 1068.

Could the H_2 emission be driven by outflow shocks associated with the 13″ radio jet? The fraction of molecular shock energy converted into H_2 1–0 $S(1)$ line emission reaches a maximum value of about 0.02 for (slow) shock velocities ranging from 30 to 50 km s^{-1} (Draine et al. 1983; Draine & Woods 1990). Thus, if the H_2 emission is generated by shocks they must dissipate energy at a rate $\gtrsim 8.6 \times 10^7$ $L_\odot$. Wilson & Ulvestad (1987) inferred a total jet luminosity of $\sim 2 \times 10^8$ $L_\odot$ from their bow shock model of the nuclear outflow which powers the synchrotron radio source. Since only a small fraction of the $\sim 10^3$ km s^{-1} outflow energy is likely to be dissipated in slow shocks, it is unlikely that the H_2 emission is produced by jet shocks.

Hall et al. (1981) suggested that the H_2 emission in NGC 1068 is produced in a circumnuclear starburst containing many Orion-type OB star formation regions, and that the mid-infrared (MIR) thermal dust continuum, with a luminosity $L_{\rm MIR} = 1.5 \times 10^{11}$ $L_\odot$ (Telesco et al. 1984), is reradiated OB luminosity, $L_{\rm OB}$. However, the spatial distributions of the MIR and H_2 sources are different. Chelli et al. (1987) and Tresch-Fienberg et al. (1987) find the MIR source to be distributed 2″ × 0″.7 along p.a. 45°/33°, similar to the NLR and not to the H_2 emission torus. Furthermore, if $L_{\rm MIR} = L_{\rm OB}$, the Brγ flux should be considerably greater than is actually observed. The measured Brγ flux implies a Lyman-continuum photon production rate of $\dot{N}_{\rm Lyc} = 6 \times 10^{53}$ s^{-1} if case B recombination and a small extinction correction ($A_{2.1\,\mu\rm m} = 0.1$; Neugebauer et al. 1980) are assumed. For OB stars the average energy of Lyc photons is $\sim$15 eV, so that the Brγ flux corresponds to an OB ionizing luminosity of $L_{\rm Lyc} = 4 \times 10^9$ $L_\odot$. Thus, the Brγ flux implies $L_{\rm Lyc}/L_{\rm MIR} = 0.03$, whereas $L_{\rm Lyc}/L_{\rm OB}$ ranges from 0.1 to 0.3 for typical OB clusters (Ho & Haschick 1981; Ho, Beck, & Turner 1990).

The Brγ to MIR continuum luminosity ratio is too *large* for both to be produced by a central nonstellar source with a power-law ($f_\nu \sim \nu^{-\alpha}$) spectrum with $\alpha > 1$. If $L_{\rm MIR} = L_{\rm PL}$, where L_{PL} is the power-law source luminosity, the spectrum must extend to a maximum wavelength

$$\lambda_{max} = \left[\frac{\alpha \dot{N}_{Lyc}\ \mathrm{Ryd}}{(\alpha - 1)L_{MIR}}\right]^{1/(1-\alpha)} \lambda_0 ,$$

where Ryd = 13.6 eV and $\lambda_0 = 912$ Å. The index α is observed to range from 1.5 ($\lambda_{max} = 20\ \mu$m) to 2 ($\lambda_{max} = 2\ \mu$m) between 1 μm and 10 keV (Edelson & Malkan 1986; Monier & Halpern 1987). Furthermore, the Brγ flux implies that $L_{Lyc} = 3.3 \times 10^9\ L_\odot\ \alpha/(\alpha - 1)$ while the observed Lyc luminosity of the nonstellar source is only $\sim 6 \times 10^8\ L_\odot/(\alpha - 1)$ (Neugebauer et al. 1980; Monier & Halpern 1987). If this discrepancy is due to some extinction of the Lyc radiation (Neugebauer et al. 1980; Malkan & Oke 1983), then the intrinsic nonstellar spectrum is presumably flatter than observed, and λ_{max} may actually extend beyond the MIR. We conclude that if a power-law source with $\alpha > 1$ produces the Brγ line, then only a small fraction of the MIR luminosity can be reradiated optical, UV, and X-ray luminosity from the nonstellar source.

It is possible that the observed Brγ to MIR intensity ratio is due to the combined dust heating by OB stars and a $\alpha > 1$ power-law source. Alternatively the MIR and Brγ emission may actually be produced by a $\sim 10^{11}\ L_\odot$ nonstellar source of ionizing radiation for which $\alpha < 1$ over a large spectral range, and it appears likely that the circumnuclear H_2 emission is also produced by this radiation source.

If the nonstellar source emits mainly at UV wavelengths (8–15 eV) then most of the ionizing luminosity must be absorbed without producing recombination lines, possibly in dusty H II regions (cf. Petrosian, Silk, & Field, 1972). The molecular clouds, at a mean distance $\langle R \rangle = 100$ pc from the galactic nucleus, may absorb at least as many far-UV photons (8–13.6 eV) as the number of ionizing UV photons absorbed by the H II gas. The calculations of Sternberg & Dalgarno (1989) show that clouds with hydrogen densities $\gtrsim 5 \times 10^5$ cm^{-3} exposed to such a far-UV photon flux will emit 1–0 $S(1)$ line radiation with a surface brightness $\sim 10^{-4}$ ergs cm^{-2} s^{-1} sr^{-1}, close to the observed value.

Alternatively, if the nonstellar source emits primarily at X-ray wavelengths then the calculations of Lepp & McCray (1983) show that only 7×10^{-3} of the $10^{11}\ L_\odot$ must be absorbed by the molecular clouds in order to produce the observed H_2 emission luminosity. For 0.5 keV X-rays, the Brγ flux corresponds to $L_{Lyc} = 1.3 \times 10^{11}\ L_\odot$ and the MIR source could then be produced by the dust absorption of scattered Lyα photons.

The observed UV and X-ray luminosity of NGC 1068 is considerably less than $10^{11}\ L_\odot$. Our interpretation requires that almost all of the nonstellar luminosity is absorbed by gas and dust in the vicinity of the NLR (cf. Krolik & Begelman 1987). These seems plausible in view of the large column densities of molecular material that we infer from the H_2 measurements.

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