THE 2 MICRON SPECTRUM OF NGC 6240: EVIDENCE FOR MORE THAN A STARBURST

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ABSTRACT

The exceptionally luminous interacting galaxy NGC 6240 has been studied with infrared spectroscopy and photometry. Emission lines of molecular hydrogen and the Paschen-α line of ionized hydrogen have been detected. Broad-band 10 μm and 20 μm emission has also been observed. Combined with previous optical spectroscopy and results from IRAS, the observations show that NGC 6240 cannot be explained along the lines of a superstarburst of massive stars such as is seen in M82. It may be more easily understood in terms of an active nucleus similar to Seyfert galaxies.

Subject headings: galaxies: individual — galaxies: Seyfert — infrared: spectra — stars: formation

I. INTRODUCTION

The galaxy NGC 6240 has been identified with the IRAS source 16304+0228 (Wright, Joseph, and Meikle 1984). At a redshift of 7597 km s⁻¹ (de Vaucouleurs, de Vaucouleurs, and Corwin 1976), it has a luminosity in the IRAS 60 μm and 100 μm bands of \( \sim 4 \times 10^{13} L_\odot \) \( (H_\alpha = 75 \text{ km s}^{-1} \text{ Mpc}^{-1} \) is assumed throughout this paper). It is hence one of the most luminous infrared galaxies known.

NGC 6240 is morphologically chaotic, with an asymmetric form, at least two appendages and loops, and a double nucleus of 1° separation (Fried and Schulz 1983). Both Vorontsov-Velyaminov (1977) and Zwicky, Herzog, and Wild (1961) noted that the galaxy is peculiar. In general, it is agreed that this galaxy is undergoing an interaction or merger (see Fosbury and Wall 1979).

Previous investigations have shown several facets of the nature of NGC 6240. Optical spectroscopic observations led Fosbury and Wall (1979) and Fried and Schulz (1983) to suggest that the optical spectrum was caused by shocks produced by cloud-cloud collisions during the interaction. NGC 6240 is also a strong radio source, with the radio emission coextensive with the region of intense optical line emission; the double nucleus is clearly resolved in VLA maps at 4885 MHz (Condon et al. 1982). CO observations by Young et al. (1984) have indicated a large amount \( (\sim 3 \times 10^{10} M_\odot) \) of molecular gas in the system.

The high luminosity of NGC 6240 seen by IRAS has been discussed in terms of a massive burst of high-mass star formation (cf. Wright, Joseph, and Meikle 1984; Rieke et al. 1985). In this paper we present observations that show that this scenario is unlikely and that NGC 6240 may be more closely related to galaxies with active nuclei, such as the Seyfert galaxies NGC 1068 and NGC 7469.

II. OBSERVATIONS

Spectroscopic measurements of NGC 6240 were made on 1984 July 22–26 at the United Kingdom Infrared Telescope (UKIRT) with the seven-channel cooled-grating spectrometer (Wade 1983). The instrument employs two back-to-back gratings, allowing fast changes between the high-resolution (485 km s⁻¹ at 2.2 μm) and the low-resolution (1300 km s⁻¹ at 2.2 μm) settings. All these observations were made using a 5° circular aperture that was centered on the optically brightest part of the galaxy as seen with the television camera system and that enclosed both of the nuclei. Sky reference beams were 30° away in an east and west direction.

The wavelength regions covered were always observed after stepping the grating half a resolution element so as to fully sample the spectrum. The variations in the channel-to-channel response were accounted for by comparison with the assumed featureless nearby F0 star SAO 121790 \( (V = 5.9) \), which was observed immediately after each part of the spectrum was obtained. The data were flux-calibrated using the infrared standard HD 161903 (Elias et al. 1982) and corrected for any residual atmospheric extinction.

Figure 1 shows the spectrum of NGC 6240 between 2.05 μm and 2.50 μm taken with the low-resolution grating. Several features are clearly apparent. The strongest are the \( v = 1-0 \ S(1) \) and \( v = 1-0 \ Q\text{-branch lines of molecular hydrogen. Marginally seen at the 2} \ σ \text{ level are the } v = 1-0 \ S(0) \text{ line and the } v = 0-2 \text{ and } v = 1-3 \text{ first overtone CO absorption bandheads. The presence of the CO absorption was noted by Rieke et al. (1985) but was not resolved into individual components.}

Hydrogen Brackett-γ was not detected in the spectrum of NGC 6240, so we made observations of the potentially much stronger Paschen-γ line with a resolution of 590 km s⁻¹. The rest wavelength of this line falls in a deep terrestrial \( \text{H}_2 \text{O} \) absorption band but in NGC 6240 the line is redshifted to a position observable from Mauna Kea. The effect of atmospheric extinction on the observations can be significant (Neugebauer et al. 1980). The spectrum (Fig. 2) shows a Pas line that is firmly detected with a signal-to-noise ratio greater than 5. A \( \chi^2 \) fit to the data of a single Gaussian on a constant background gives a full width at half-
maximum (FWHM) of $810 \pm 300$ km s$^{-1}$, after correction for the instrumental resolution.

The S(1) line was also observed at a higher resolution of 485 km s$^{-1}$. Figure 3 shows that the line is barely resolved; an unresolved calibration line of argon is given for reference. A single Gaussian plus a constant background $\chi^2$ fit to the observations gives an FWHM after correction for the instrumental resolution of $530 \pm 240$ km s$^{-1}$ for the S(1) line. This is consistent with the widths of the H$\beta$, P$\alpha$, and forbidden emission lines (Fosbury and Wall 1979; Fried and Schulz 1983; Rieke et al. 1985). The fitted line peak wavelength of 2.176 $\mu$m agrees with the optically determined redshift.

The line strengths for some interesting detected and undetected lines are given in Table 1. Since the P$\alpha$ line was resolved, the line strength was found by integrating under the Gaussian $\chi^2$ fit. All other line strengths are from the 1300 km s$^{-1}$ resolution data. The upper limits given are 3 $\sigma$. The continuum level at 2.2 $\mu$m implies a K magnitude for NGC 6240 in a 5.5 beam of 10.5 $\pm$ 0.2.

During 1984 March, the spectrum of NGC 6240 was observed from 4.0 $\mu$m to 4.17 $\mu$m with the same instrumentation as above (Becklin, DePoy, and Wynn-Williams 1984). No features were detected, and the 3 $\sigma$ upper limit for the Br$\alpha$ line in Table 1 was determined.

Fig. 1.—2 $\mu$m spectrum of NGC 6240 with a resolution of 1300 km s$^{-1}$. The wavelength scale is as observed, so the lines fall as indicated for a redshift of 7597 km s$^{-1}$. A typical $\pm 1$ $\sigma$ error is given.

Fig. 2.—Spectrum of NGC 6240 around 1.92 $\mu$m. The expected position of the P$\alpha$ line is indicated; $\pm 1$ $\sigma$ error bars are shown.
Photometric observations of NGC 6240 were taken at $M(4.8 \mu m)$, $N(10.1 \mu m)$, and $Q(20 \mu m)$ at the NASA Infrared Telescope Facility (IRTF) bolometer on 1984 March 9–10. The measurements were made through a 5.5' aperture and calibrated against BS 6406 ([M] = -3.45, [N] = -3.94, [Q] = -4.17; Tokunaga 1984). The results are given in Table 2.

### III. COMPARISON WITH PREVIOUS OBSERVATIONS

#### a) Photometry

Rieke et al. (1985) and Wright, Joseph, and Meikle (1984) have previously published 10 μm and 20 μm photometric results (see Table 3) that are comparable to the above observations. Rieke et al. reported a 10 μm flux that was identical within the observational uncertainties to our flux at $N$. Wright et al. found fluxes at 10 μm and 20 μm that are roughly consistent with our measurements in a larger beam.

The $N$ and $Q$ photometry can also be compared to the fluxes seen in the 12 μm and 25 μm bands by IRAS (see Table 3). Since the flux distribution of NGC 6240 is significantly different from that of the 10 and 20 μm standards and the $v^{-1}$ spectral shape assumed in the IRAS data reduction, corrections must be applied to the reported flux at each wavelength (see Beichman et al. 1985 and King 1952 for discussion). The correction factors can be found by assuming that the emission is characterized by a power law ($F_v \propto v^{-\alpha}$). The magnitude of

### Table 1

<table>
<thead>
<tr>
<th>Line</th>
<th>$\lambda_{abs}$ (μm)</th>
<th>$I_{10^{-16}}$ W m$^{-2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P$ (n = 4-3)</td>
<td>1.922</td>
<td>0.68 ± 0.13</td>
</tr>
<tr>
<td>$Br\gamma$ (n = 7-4)</td>
<td>2.220</td>
<td>&lt;0.33</td>
</tr>
<tr>
<td>$Br\alpha$ (n = 5-4)</td>
<td>4.15</td>
<td>&lt;1.5</td>
</tr>
<tr>
<td>$v$ = 1-0 (90)</td>
<td>2.280</td>
<td>&lt;0.39</td>
</tr>
<tr>
<td>$v$ = 1-0 (91)</td>
<td>2.176</td>
<td>1.84 ± 0.15</td>
</tr>
<tr>
<td>$v$ = 1-0 (92)</td>
<td>2.086</td>
<td>0.52 ± 0.13</td>
</tr>
<tr>
<td>$v$ = 2-1 (91)</td>
<td>2.304</td>
<td>&lt;0.39</td>
</tr>
<tr>
<td>$v$ = 1-0 (91)</td>
<td>2.467</td>
<td>1.30 ± 0.15</td>
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<tr>
<td>$v$ = 1-0 (92)</td>
<td>2.474</td>
<td>&lt;0.36</td>
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<tr>
<td>$v$ = 1-0 (93)</td>
<td>2.486</td>
<td>1.25 ± 0.16</td>
</tr>
</tbody>
</table>

**Note:** For emission lines in NGC 6240 ($z = 0.025$) in a 5.5' aperture centered on the nuclear region. The magnitude of the errors is 1 $\sigma$, and the magnitude of the upper limits is 3 $\sigma$.

### Table 2

<table>
<thead>
<tr>
<th>$\lambda$ (μm)</th>
<th>Flux Density (mJy)</th>
<th>Corrected Flux Density* (mJy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.2</td>
<td>39 ± 8</td>
<td>...</td>
</tr>
<tr>
<td>4.8</td>
<td>&lt;84</td>
<td>...</td>
</tr>
<tr>
<td>10</td>
<td>261 ± 19</td>
<td>252</td>
</tr>
<tr>
<td>20</td>
<td>1379 ± 115</td>
<td>1655</td>
</tr>
</tbody>
</table>

**Note:** 5.5' aperture, except for the 2.2 μm flux, which was derived from the spectral data; 1 $\sigma$ errors and 3 $\sigma$ upper limit.

* From correction applied to account for the difference in spectral types between NGC 6240 and the standard stars (see text).

### Table 3

<table>
<thead>
<tr>
<th>$\lambda$ (μm)</th>
<th>Flux Density (mJy)</th>
<th>Corrected Flux Density* (mJy)</th>
<th>Beam</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>252 ± 10</td>
<td>...</td>
<td>578</td>
<td>1</td>
</tr>
<tr>
<td>20</td>
<td>120</td>
<td>...</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>12</td>
<td>1090</td>
<td>...</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>25</td>
<td>570</td>
<td>620</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>36</td>
<td>3520</td>
<td>3860</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>60</td>
<td>23200</td>
<td>23200</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>100</td>
<td>25900</td>
<td>25650</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

* Accounting for difference in flux distribution between NGC 6240 and the assumed standard (see text).

**References:**
the corrections can then be found by integrating the source spectrum over the filter passbands. For the IRAS data, the correction factors are given in Beichman et al. (1985). The correction can be applied and the procedure iterated until a self-consistent answer is reached.

The power law for both the ground-based and IRAS data has $\alpha = 2.5$. The corrected fluxes at each wavelength are given in Tables 2 and 3.

To estimate the fraction of the IRAS flux that arises within the 5.5\,\mu m diameter beam covered by the ground-based measurements, we can again assume that the emission is a power law with $\alpha = 2.5$. This estimate shows that we see about 50% of the IRAS flux at 10\,\mu m and 70–80% at 20\,\mu m. Therefore, the 10\,\mu m continuum may be significantly more extended spatially than the 20\,\mu m emission. Conversely, the 20\,\mu m emission is mainly concentrated in the nuclear region. Given the uncertainties in the methods employed and in the absolute flux scales in each photometric system, this implies that most of the emission longward of 20\,\mu m comes from within an $\sim 3''$ radius of the nucleus.

b) Spectroscopy

The detection of the $v = 1 \rightarrow 0$ (S1) molecular hydrogen or the Br$\gamma$ lines in NGC 6240 has been previously reported by Becklin, DePoy, and Wynn-Williams (1984); Rieke et al. (1985); and Joseph, Wright, and Wade (1984). These results are summarized in Table 4.

Our present measurement of the S(1) line is consistent with that of Joseph, Wright, and Wade (1984) and somewhat larger than our previous measurement, which was undersampled and observed during marginal atmospheric conditions. The difference between our result and that of Rieke et al. is significant and may indicate that the H$_2$ emission is extended.

The only previously recorded Br$\gamma$ line strength (Rieke et al. 1985) is in an 8.7\,\mu m beam and is consistent with our 3\,\sigma upper limit. However, the Br$\gamma$ line strength implied by our Paz measurement and case B recombination at $10^4$ K is $\sim 5$ times lower than Rieke et al.'s result. The difference is surprising, since it would imply that $\sim 80\%$ of the Br$\gamma$ emission originates in an annulus 5.5 and 8.7\,\mu m in diameter. There is no support for this morphology in the visible image of NGC 6240; we therefore view Rieke et al.'s detection of the Br$\gamma$ line with skepticism. Note that Cutri, Rieke, and Lebofsky (1984) have reported that the ratio of Paz to Br$\gamma$ in the luminous Seyfert galaxy Mrk 231 is larger than that predicted by case B recombination, which makes the discrepancy more severe.

IV. DISCUSSION

The measurement of the Paz line and the upper limit on the Br$\gamma$ and Br$\alpha$ line strengths can be used to derive several of the properties of NGC 6240. These in turn can be used to draw conclusions about the nature of the physical conditions within the galaxy.

a) Reddening

Combined with the Hz and H$\beta$ line strengths reported by Fosbury and Wall (1979), the infrared hydrogen line strengths can be used to estimate the extinction to the line-emitting region. The comparison of the H$\beta$ and Paz line strengths is particularly useful because the lines originate from the same upper level (see Lacy et al. 1982), and therefore their ratio is less dependent on the physical parameters existing in the emitting region. Since the line strengths given by Fosbury and Wall were based on spectroscopy through a 3'' x 6'' slit, they were directly compared to our measurements through a 5.5\,\mu m circular aperture. Since most of the slit is covered by the larger 5.5\,\mu m circular aperture, the direct comparison leads to overestimates of the extinction. Therefore, to the extent that the comparison is not valid, the reddening estimates below can be regarded as upper limits.

The Paz/H$\beta$ ratio implies an $A_r$ of 2.9 $\pm$ 0.4 mag, assuming case B recombination and an electron temperature of $10^4$ K (Savage and Mathis 1979; Becklin et al. 1978; Wynn-Williams 1984). The measured Fosbury and Wall Hz/H$\beta$ ratio gives an $A_r$ of $\sim 3$ mag, using the parameters of Fried and Schulz (1983) to decouple the Hz line from the nearby [N II] lines. The upper limits on the Br$\gamma$ and Br$\alpha$ line strengths set in ratio to H$\beta$ indicate that the $A_r$ are less than 3.4 mag and less than 3.8 mag respectively.

Infrared lines can probe to a higher optical depth in dust extinction than optical lines, so extinction estimates should increase as the wavelengths of the lines used to derive the extinction increase if the emission and absorption are mixed. Since the extinction determinations are all close to an $A_r = 3$ mag, the observations imply that the reddening is primarily in front of the line-emitting regions.

Two other methods can be used to investigate the extinction to the nucleus of NGC 6240. First, the molecular hydrogen $v = 1 \rightarrow 0$ (S1) to $v = 1 \rightarrow 0$ (Q3) line ratio implies $A_r < 6$ mag (these two lines arise in the same upper level of the hydrogen molecule, and, if stimulated absorption is ignored, should always have a ratio of 0.7). Also, from the near-infrared photometry of Rieke et al. (1985), the $J(1.25\mu m)$ to $H(1.65\mu m)$ and $H$ to $K(2.2\mu m)$ colors give an $A_r$ of $\sim 3$ mag, assuming that the intrinsic colors of NGC 6240 are similar to those of other galactic nuclei. Thus, the extinction to the line-emitting region based on the H$\beta$ to Paz ratio is consistent with several other estimates and implies an $A_r$ of 3 mag.

Rieke et al. adopt a much higher value of $A_r = 15$. This estimate is founded primarily on the color difference between $K$ and $L(3.5\mu m)$ and the shape of the 3.2–3.6\,\mu m continuum, and secondarily on an estimate of the silicate absorption from the ratio of a narrow-band 10\,\mu m measurement to the broad-band 10\,\mu m flux. Each of these determinations has severe limitations and great uncertainties, because of structure in the emission spectrum. Since there is strong 3.3\,\mu m emission in NGC 6240 (Rieke et al. 1985), it is likely that a population of small, hot dust grains such as seen by Seigler, Werner, and Dinerstein (1983) exists. These grains may cause excess emission over the stellar continuum in the 2–10\,\mu m region. Such a scenario has been proposed for the excess emission observed in NGC 2903 and other spiral galaxies by Wynn-Williams and Becklin (1985) and is consistent with the 10\,\mu m being more

<table>
<thead>
<tr>
<th>Line</th>
<th>$I$ (10$^{-14}$ W m$^{-2}$) Beam</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>v = 1\rightarrow 0 (S1) H$_2$</td>
<td>$1 \pm 0.2$ 555</td>
<td>1</td>
</tr>
<tr>
<td>v = 1\rightarrow 0 (S1) H$_2$</td>
<td>$1.5 \pm 0.1$ 5.5</td>
<td>2</td>
</tr>
<tr>
<td>v = 1\rightarrow 0 (S1) H$_2$</td>
<td>$3.9$ 8.7</td>
<td>3</td>
</tr>
<tr>
<td>Br$\gamma$</td>
<td>$0.31$ 8.7</td>
<td>3</td>
</tr>
</tbody>
</table>

extended than the 20 μm emission. If so, then deriving the extinction from the K–L continuum could be seriously compromised by this excess forcing the continuum to appear much cooler than would otherwise be expected from stellar continuum radiation alone, and hence giving an overly large extinction estimate. A similar situation exists with the shape of the 3.2–3.6 μm continuum, which is also greatly influenced by the very strong 3.3 μm emission feature itself. Strong 8.6 μm and 11.3 μm emission is probably also present (Gillett et al. 1975; Phillips, Aitken, and Roehl 1983), which would cause the implied silicate depth to be nonrepresentative of the true depth. The small, hot grains will strongly affect any extinction estimate based on continuum observations beyond 3 μm.

An A_v of 3 mag will therefore be adopted for further calculations because it is derived from the ratio of two lines that originate in the same upper level and is consistent with all the atomic and molecular hydrogen lines observed and JHK continuum measurements.

b) The Ionizing Continuum

The observed Paα line strength and an A_v = 3 mag can be used to calculate the number of Lyman continuum photons being emitted from the source. In a starburst model, the Lyman-α photon flux N(Lyα) is a measure of the number of high-mass stars and hence, given assumptions about the star formation conditions (e.g., the initial mass function), the star formation rate in the system. The observations indicate that N(Lyα) = 9.9 × 10^{53} photons s^{-1}. This rate is a factor of 15 lower than Rieke et al. (1985), since it is based on a weaker measured hydrogen line strength and a much smaller estimated extinction.

The luminosity of the Lyman-α photon flux L(Lyα) and the bolometric luminosity L_{bol} can be combined to define the “infrared excess” of a source:

\[ \text{infrared excess} = L_{bol} / L(Lyα) - 1 \]

(Jennings 1975). By using the IRAS data to define the bolometric luminosity and an atomic hydrogen line plus the appropriate extinction to define the Lyman continuum, this number can be calculated (the luminosity of a particular source outside the IRAS bands has been accounted for by correcting by a factor of 1.4, following Beichman et al. 1985). H II regions typically have IR excesses of between 2 and 9, larger than one due to heating of the dust grains by photons below the Lyman limit (Jennings 1975). Based on a measurement of the Brα line strength in a 30′′ beam (Willner et al. 1977) and the IRAS fluxes, M82, the archetypal starburst galaxy, has an excess of 10–20 depending on the reddening adopted. NGC 1068, the well-known Seyfert 2 galaxy, has an excess of ~70, for the 1″–2″ diameter nuclear region (Hall et al. 1981; Telesco et al. 1984).

NGC 6240 has an IR excess of 140. If we assume that at least half the IRAS flux originates in the central 5′′, as suggested by the 20 μm observations, then the excess is greater than 70. Therefore, NGC 6240 has an infrared excess much larger than M82 or a Galactic H II region and similar to that observed in the nucleus of Seyfert galaxies such as NGC 1068. Thus, for its luminosity, NGC 6240 has about 10 times fewer ionizing photons than expected from a starburst galaxy, but about the number of ionizing photons expected from a Seyfert 2 galaxy. If the luminosity is being produced by a starburst, the burst must have very few high-mass stars producing ionizing radiation.

c) Molecular Hydrogen Emission Lines

The strongest features in the 2 μm spectrum of NGC 6240 are the extremely intense molecular hydrogen emission lines. Table 5 shows that the H_2 line ratios are similar to those in the Orion molecular cloud and in the nuclear region of NGC 1068. The ratios are consistent with the models for shock excitation (cf. Shull and Beckwith 1982) and are certainly inconsistent with UV excitation (Black and Dalgarno 1976). Additionally, since the UV pumping mechanism is due to the absorption of ~1000–1100 Å photons in the Werner and Lyman bands and subsequent radiative cascade, the probability of any given \( v = 1 \rightarrow 0 \) transition is only 0.01–0.03 (Black and Dalgarno 1976), so the S(1) luminosity observed implies a 1000–1100 Å photon flux of more than \( 5 \times 10^{46} \) photons s^{-1}. As the total photon flux shortfall of the Lyman limit is ~10^{54} photons s^{-1}, it seems unlikely that there would be enough photons to reproduce the observations by UV pumping. It appears, based on both H_2 line ratios and the H_2 luminosity, that UV fluo-

### Table 5

<table>
<thead>
<tr>
<th>Line</th>
<th>NGC 6240^b</th>
<th>NGC 3690^c</th>
<th>NGC 1068^d</th>
<th>Orion^#</th>
<th>UV Pump^#</th>
<th>Shock^#</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paα</td>
<td>0.37</td>
<td>...</td>
<td>10.3</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Brγ</td>
<td>&lt;0.18</td>
<td>1.58</td>
<td>1.12</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>v = 1–0 S(0)</td>
<td>&lt;0.21</td>
<td>...</td>
<td>0.30</td>
<td>0.27</td>
<td>0.67</td>
<td>0.22</td>
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<td>v = 1–0 S(1)</td>
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<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
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<td>v = 1–0 S(2)</td>
<td>0.28</td>
<td>...</td>
<td>0.42</td>
<td>0.29</td>
<td>...</td>
<td>0.36</td>
</tr>
<tr>
<td>v = 2–1 S(1)</td>
<td>&lt;0.21</td>
<td>...</td>
<td>...</td>
<td>0.09</td>
<td>0.55</td>
<td>0.19</td>
</tr>
<tr>
<td>v = 1–0 Q(1)</td>
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<td>...</td>
<td>0.93</td>
<td>1.21</td>
<td>0.79</td>
</tr>
<tr>
<td>v = 1–0 Q(2)</td>
<td>&lt;0.19</td>
<td>...</td>
<td>...</td>
<td>0.32</td>
<td>0.82</td>
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<tr>
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<td>0.86</td>
<td>0.70</td>
<td>0.70</td>
<td></td>
</tr>
</tbody>
</table>

^a Ratios of line strengths to the \( v = 1 \rightarrow 0 \) S(1) H_2 line strength as measured in NGC 6240, NGC 3690, the nucleus of NGC 1068, the H_2 emission peak in Orion; and as predicted by UV pumping fluorescence theory and by shock (\( n = 3 \times 10^{12} \) cm^{-2} s^{-1} and \( v = 10 \) km s^{-1}) models.

^b Present work.

^c Fischer et al. 1983.

^d Hall et al. 1981.

^e Scoville et al. 1982.

^f Black and Dalgarno 1976.

^g Hollenback and Shull 1977.
ence is probably not the excitation mechanism, and that the 
H2 emission is more likely due to shocks.

The luminosity contained in the v = 1–0 S(1) line is 
\( \sim 8 \times 10^{-5} L_\odot \), or \( \sim 0.02\% \) of the bolometric luminosity.

Hence, the molecular hydrogen lines contain a substantial fraction of
the total luminosity of the system, \( \sim 0.35\% \) if the molecular gas is
shock-excited (Hollenbach and Shull 1977; Kwan 1977). This value is similar to that of the luminosity contained in
all the atomic hydrogen lines except those of the Lyman
series. NGC 6240 has the highest ratio of molecular to atomic
hydrogen emission of any galaxy observed and is the most
luminous source of molecular hydrogen emission known.

The observed S(1) line in NGC 6240 is also very broad in
velocity, with a width of \( \sim 500 \text{ km s}^{-1} \) FWHM. This width is
consistent with the optical forbidden and atomic hydrogen
lines. It is the broadest H2 line observed in any galaxy, much
broader than the S(1) line in NGC 1068, which has a velocity
FWHM of 265 km s\(^{-1}\) (Hall et al. 1981).

The source of the luminosity that excites the molecular
hydrogen emission is not clear. The mechanism is unlikely to
be associated with star formation, since the ratio of S(1) line
strength to Br\( \gamma \) line strength is one to two orders of magnitude
larger than in Galactic star formation regions or starburst gal-
axies such as M82 or NGC 3690 (Fischer et al. 1983). If it is a
starburst that is producing the H2 emission, then again it must
have many fewer massive stars that give ionizing photons than
are typically seen in most galaxies.

The galaxy is certainly disturbed on a large scale. If, for
example, the molecular hydrogen emission is caused by the
collision of two gas-rich galaxies, then the \( 3 \times 10^{10} M_\odot \) of H2
(Young et al. 1984) colliding with a relative velocity of 300 km
s\(^{-1}\) would produce \( \sim 10^{58} \) ergs. For a nominal emission time
scale of \( 10^7 \) yr, this corresponds to a luminosity of \( 10^{10} L_\odot \).
About 10\% of this needs to be converted into molecular
hydrogen emission to account for the observations, so perhaps
this is a viable explanation.

Alternatively, the emission could be associated with activity
in the nucleus of the galaxy, such as is observed in NGC 1068
and NGC 7469. In both these Seyfert galaxies, molecular
hydrogen emission has been reported (Hall et al. 1981; Heckman et al. 1985). In each case the emission may be caused
by cloud-cloud interactions in the narrow line regions of the
nuclei.

d) CO Absorption Lines and the Stellar Continuum

The CO band head at 2.3 \( \mu \text{m} \) from late-type stars is seen in
Figure 1, although the signal-to-noise ratio is low. The
depth shown is consistent with the presence of either giant or super-
giant stars, based on data in Kleinmann and Hall (1985), who
found that these bands are sensitive to both luminosity and
gravity in high spectral resolution studies of late-type stars.
The depths are also in agreement with the lower resolution
spectrum of Rieke et al. (1985).

The observed continuum has been interpreted by Rieke et al.
(1985) as coming primarily from the underlying stars; we agree
with that conclusion, but because of the different reddening
that we derive for NGC 6240, we differ in the amount of stellar
light required. Our continuum in a 5′5 beam (2700 pc
radius) corresponds to an absolute K magnitude of \( M_K = –24.7 \)
when corrected for 3 mag of visual extinction (6 IV\( \alpha \)).
Again, this extinction is consistent with the observed 1.25 and
1.65 \( \mu \text{m} \) colors of Rieke et al. (1985.)

Devereux, Becklin, and Scorville (1985) have shown that
many spiral galaxies can have nuclear absolute magnitudes of
\( M_K = –23.6 \) within the central 2700 pc; this flux is shown to
 correlate with mass and probably come from evolved late-
type giant stars. Because there are probably two bright gal-
axies whose nuclei are within 2′ of each other in the system, it
is possible to explain most of the observed 2.2 \( \mu \text{m} \) nuclear flux
in the central 5′5 of NGC 6240 as coming from evolved M
 giants stars, although an additional contribution to the flux
may come from young supergiant stars, dust emission, or a
nonthermal source. Because we see only a very weak Paz line,
we prefer one of the latter two explanations.

e) Nature of the Activity

The source of the large infrared luminosity in NGC 6240 is
unknown. It does not appear to be caused by the same mecha-
nism that is causing the infrared luminosity in M82 and is,
hence, probably not a burst of high-mass star formation, since
the ratio of luminosity to UV photon flux is much higher.
There is nothing to rule out a burst of low-mass stars causing
the luminosity, however, since low-mass stars would not
produce a large ionizing photon flux.

The kinetic energy of the collision does not produce enough
energy to power the luminosity observed, unless released on a
very short time scale. As noted above, a rough estimate of
the total energy available during the collision is \( \sim 10^{58} \) ergs. To
produce the luminosity observed, from the interaction alone,
this energy would have to be released with a characteristic time
scale of \( \sim 2 \times 10^7 \) yr. This seems unrealistically short, espe-
cially since many examples of interacting galaxies with high
infrared luminosity are known.

The luminosity in NGC 6240 may be due to a nonstellar
source in the center of one or both of the galaxies that are
interacting. Certainly, interacting galaxies have a higher inci-
dence of activity than noninteracting galaxies (Dahari 1985;
Kennicutt and Keel 1984). The strong molecular hydrogen
emission is reminiscent of the known Seyfert galaxies NGC
1068 and NGC 7469 (Hall et al. 1981; Heckman et al. 1985). The
bulk of the IRAS luminosity, which is at wavelengths
longer than 20 \( \mu \text{m} \), is concentrated on a scale of less than 1.5
kpc in radius. There are known compact sources of radio emis-
ion in the nucleus of this galaxy (Condon et al. 1982), and the
emission line widths are typical of Seyfert 1 galaxies. Also,
galaxies with known active nuclei are capable of producing the
large infrared luminosity observed, for example, Mrk 231 and
3C 273, and show similar infrared excesses. However, the
optical emission line ratios are more like a LINER’s (Heckman
1980) than a Seyfert galaxy’s.

V. CONCLUSIONS

We have performed a series of observations of NGC 6240,
an interacting galaxy with the exceptionally high 60 \( \mu \text{m} \) and
100 \( \mu \text{m} \) luminosity of \( 4 \times 10^{11} L_\odot \). We find very strong emis-
sion lines of H2, with line ratios that are consistent with shock
excitation. No Br\( \gamma \) emission was detected, but the observed
Paz line strength together with previous measurements of
optical hydrogen lines implies an extinction corresponding to
an A\( \_V \) = 3 mag and an ionizing photon flux of \( \sim 10^{44} \) s\(^{-1}\).
Broad-band observations around 10 \( \mu \text{m} \) and 20 \( \mu \text{m} \) show that
the majority of the IRAS flux comes from within \( \sim 1.5 \) kpc of
the nucleus of the galaxy.

The high-infrared luminosity in NGC 6240 is probably not
due to a burst of high-mass star formation such as seen in M82
and NGC 253, since the ratio of measured bolometric lumin-
osity to estimated ionizing photon flux is 10–20 times lower. It may be more easily understood in terms of an active nucleus similar to what is observed in Seyfert galaxies.

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