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SPATIALLY RESOLVED NEAR-INFRARED SPECTROSCOPY OF NGC 6240

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ABSTRACT

We have observed the infrared-luminous galaxy NGC 6240 using a long-slit near-IR spectrometer. The very strong 1–0 $S(1)$ line of molecular hydrogen (H_2) is extended over about $9''$ and shows a distinct component of emission extending to the south-east of the nucleus, with a velocity of about 300 km s^{-1} lower than the diffuse nuclear emission. We find only very weak emission in the 5–3 $O(3)$ and 6–4 $Q(1)$ lines of H_2 ($1.61 \mu\text{m}$), suggesting little contribution from fluorescently excited H_2 . Fe II ($1.644 \mu\text{m}$) emission, which requires stronger shocks to excite than the 1–0 $S(1)$ line, is slightly more concentrated and displaced to the north of the nucleus and shows a different velocity structure than the $S(1)$ line. We find no strong $\text{Br}\gamma$ emission from the nucleus but some weak patches of extranuclear emission are probably detected. We suggest that the strong H_2 emission is due to slow shocks being driven into molecular clouds by the collision of the clouds with the diffuse interstellar medium (ISM) of the other galaxy in this merging system.

Subject headings: galaxies: individual (NGC 6240) — galaxies: interactions — galaxies: interstellar matter

I. INTRODUCTION

The highly irregular galaxy NGC 6240 was suggested to be a merger of two gas-rich galaxies by Fosbury and Wall (1979). Further evidence of the unusual nature of NGC 6240 was provided by *IRAS*, which revealed its extremely high far-infrared luminosity ($4 \times 10^{11} L_\odot$ for $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$). Even more remarkable was the discovery of intense emission from molecular hydrogen (Rieke *et al.* 1985; Joseph, Wright, and Wade 1985). Rieke *et al.* (1985) proposed that the infrared emission arises from a massive burst of star formation and that the strong H_2 emission results from collisions of interstellar clouds during the merger. Lester, Harvey, and Carr (1988, hereafter LHC) presented detailed near-IR spectra of NGC 6240 and suggested that the H_2 emission may be extended, supporting the notion that the strong H_2 emission may arise from galaxy-galaxy interaction. They also detected strong emission from Fe II at $1.644 \mu\text{m}$. Both LHC and DePoy, Becklin, and Wynn-Williams (1986, hereafter DBW) have argued that the observed ionizing flux in NGC 6240 is too small for star formation to power its bolometric luminosity.

The mystery of NGC 6240 is best illustrated by comparison with M82, a galaxy which is widely regarded as the prototype for “starburst” galaxies (Rieke *et al.* 1980). The bolometric luminosity of NGC 6240 is about 20 times that of M82 while the $2 \mu\text{m}$ luminosity is roughly 10 times higher. Thus, these measures of bolometric flux and total stellar content suggest that NGC 6240 is just a scaled up version of M82. However, the luminosity of NGC 6240 in the $\text{Br}\gamma$ line (computed using a flux of $\approx 10^{-17} \text{ W m}^2 \text{ s}^{-1}$ and $D = 96 \text{ Mpc}$) (LHC) is only a few times larger than that of M82 (computed using a flux of $\approx 10^{-15} \text{ W m}^2 \text{ s}^{-1}$ and $D = 3 \text{ Mpc}$) (Rieke *et al.* 1980; LHC), so that the ratio of ionizing photon flux to bolometric luminosity

is a few times smaller in NGC 6240 than in M82. The striking difference is indicated by the 1–0 $S(1)$ emission of NGC 6240: the luminosity in this line is more than 10^3 times larger than that of M82. Similarly, the Fe II line of NGC 6240 exceeds that of M82 by roughly a factor of several hundred. It would appear that there is a strong source of excitation present in NGC 6240 which is not present in the M82 starburst.

In this paper, we investigate the origin of the strong nuclear emission by studying its spatial and velocity structure. We compare its distribution to that of the continuum emission, Fe II emission, and $\text{Br}\gamma$ emission. In § II we discuss the new observations and present the data. In § III we discuss the implications of the observations for the origin of the nuclear emission in NGC 6240.

II. OBSERVATIONS

We observed NGC 6240 using the Cryogenic Spectrometer (Joyce 1990) on the KPNO 2.1 m telescope in 1989 June. The Cryogenic Spectrometer is a long slit cooled grating spectrograph with a 62×58 SBRC InSb array detector. All observations were obtained with a $2''.5$ wide slit with a scale of $1''.5 \text{ pixel}^{-1}$. A $300 \text{ lines mm}^{-1}$ grating was used in second order, giving a scale of $0.00133 \mu\text{m pixel}^{-1}$ at $2.2 \mu\text{m}$, with a FWHM of 2 pixels for unresolved features. Observations were made using two settings. One setting covered the wavelength range from 1.62 to $1.72 \mu\text{m}$ so that the Fe II ($1.644 \mu\text{m}$) line, the 5–3 $O(3)$, 6–4 $Q(1)$, and several other lines of H_2 could be observed. The second setting included the range from 2.16 to $2.24 \mu\text{m}$ so that both the 1–0 $S(1)$ line of H_2 and the $\text{Br}\gamma$ line of hydrogen could be observed.

A typical cycle of observations consisted of 450 s of on-source integration followed by 450 s of sky observation. First-order sky subtraction and removal of dark current was obtained by differencing the on-source and off-source frames. Next the spectra were flattened using an average dome flat and any residual night sky emission was removed by fitting the sky

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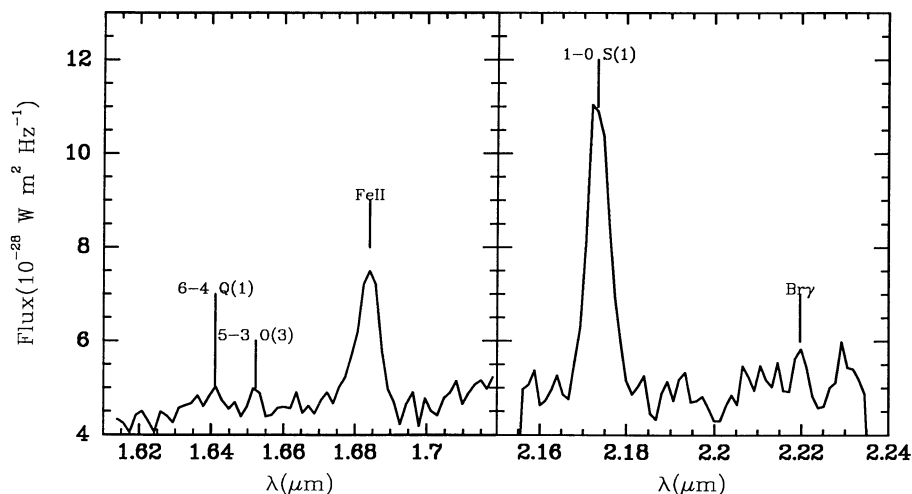


FIG. 1.—Cryogenic Spectrometer spectra of the nucleus of NGC 6240 taken through at 2".5 slit. The most prominent features are the 1-0 $S(1)$ line of H_2 and the 1.64 μm line of Fe II. Weaker features of Br γ and the 5-3 $O(3)$ and 6-4 $Q(1)$ lines of H_2 are marked.

in the cross dispersion direction. Typically, four to six separate exposures were taken at each setting, with the object being displaced along the slit between exposures. The separate images were then registered and a median was taken to produce the final image. Atmospheric absorption was removed by observing the F3V star σ Ser and the spectra were flux calibrated using observations of the standards from Elias *et al.* (1982). The flux standards typically reproduce to 20% for observations made with the 2".5 slit. The spectra were finally corrected to match the flux measurements of Rieke *et al.* (1985). The wavelengths of the spectra were calibrated using night-sky emission lines and typically have residuals less than 0.2 pixels.

We obtained spectra at 2 μm and 1.6 μm using a north-south slit and an east-west slit at several positions. All positions were referenced to the bright optical nucleus and are probably accurate to $\approx 1''$. Figure 1 presents the spectra taken through the nucleus and summed along 9" of the north-south slit. The only lines detected are the strong 1-0 $S(1)$ line, the Fe II line, and weak detections of the Br γ , 5-3 $O(3)$, and 6-4 $Q(1)$ lines. The line fluxes from the nuclear spectra for the central 9" of the 2".5 north-south slit are presented in Table 1. We also obtained spectra with the north-south slit displaced 3", 5", and 9" to the east and west to map the line emission. Figure 5 shows a composite image of the $S(1)$ line observed with a north-south slit with displacements of 3", 5", and 9" both east and west from the nucleus. No strong line emission was detected at 9". Two micron spectra were also taken with an east-west slit through the nucleus and displaced 3" both north and south, which confirm the data from the north-south slit.

Figures 2a and 2b show the distribution of the $S(1)$, Fe II, and continuum emission through the nucleus along the north-south and east-west slit. In each direction the $S(1)$ is more

extended than the continuum and covers an area of six pixels (9"). As expected, the continuum is more extended in the north-south direction, along the line which separates the double nucleus of NGC 6240 (Fried and Schultz 1983). As shown in Figure 2a, the distribution of the Fe II emission differs from that of the $S(1)$ emission: it is displaced to the north of the

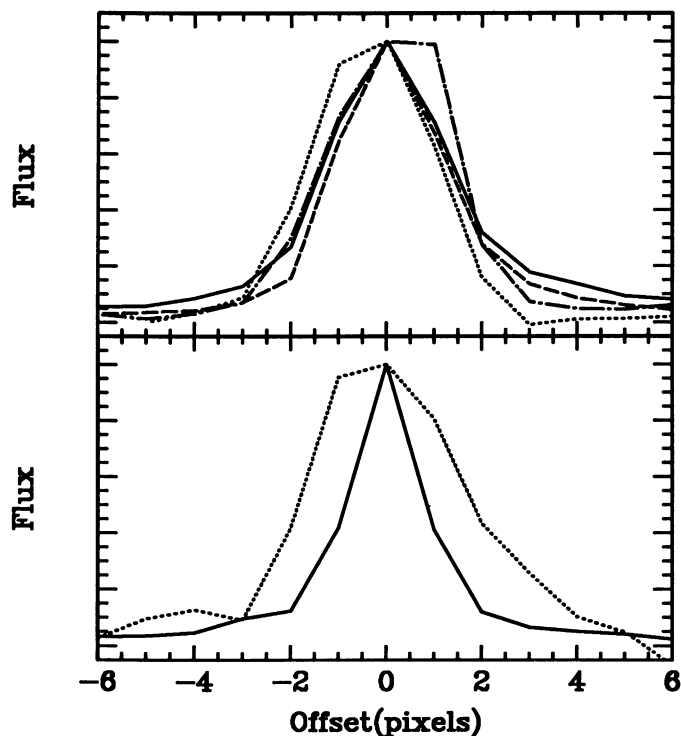


FIG. 2.—Distribution of line emission in NGC 6240. The top panel shows the distribution of Fe II (dot-dashed line), 1-0 $S(1)$ (dotted line), the 1.6 μm (dashed line), and 2.2 μm (solid line) continuum along a north-south slit. Positive displacements are toward the north with one pixel being 1".5. The higher excitation species of Fe II and Br γ are displaced toward the north of the continuum peak in the direction of the second nucleus of NGC 6240. The bottom plate shows the distribution of the 1-0 $S(1)$ and 2.2 μm continuum along an east-west slit through the nucleus. None of the line emission appears to be correlated with the continuum emission.

TABLE 1

NUCLEAR SPECTRA LINE FLUXES

Line	Wavelength (μm)	Flux ($W m^{-2}$)
6-4 $Q(1)$	1.64109 ± 0.0005	$1.9 \pm 0.9 \times 10^{-17}$
5-3 $O(3)$	1.65232 ± 0.0005	$2.1 \pm 0.8 \times 10^{-17}$
Fe II	1.68397 ± 0.0005	$2.1 \pm 0.2 \times 10^{-16}$
1-0 $S(1)$	2.17334 ± 0.0004	$2.8 \pm 0.3 \times 10^{-16}$
Br γ	2.2197 ± 0.0004	$1.8 \pm 0.4 \times 10^{-17}$

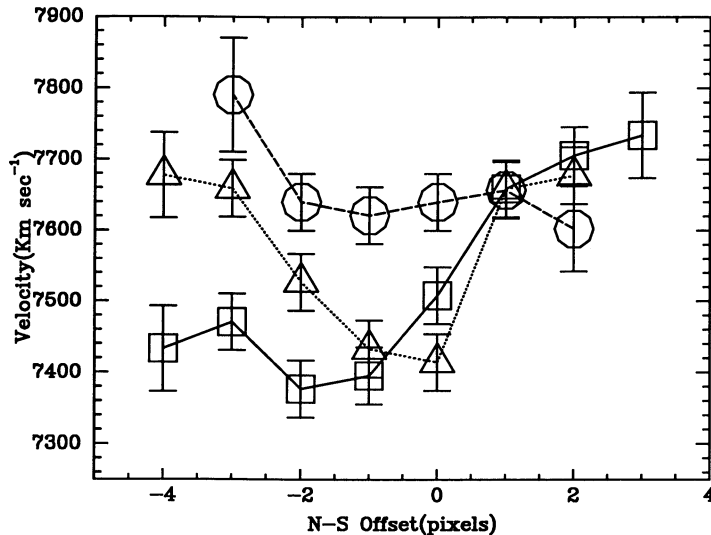


FIG. 3.—Velocity center of the 1–0 $S(1)$ line along north-south slits. The dotted line connects observations taken through the nucleus (*triangles*). The solid line connects observations taken 3'' to the east of the nucleus (*squares*), and the dashed line connects observations taken 3'' to the west of the nucleus (*circles*). We see no evidence for the rotation, but rather there appears to be a low-velocity component extending from the nucleus to the south-east.

continuum peak and is slightly more compact than the $S(1)$ emission. This displacement is in the direction of the second nucleus, which is about 2'' north of the continuum peak. The 5–3 $O(3)$ and 6–4 $Q(1)$ lines are only detected in spectra through the nucleus, but the signal-to-noise is too low to determine if its extent is similar to that of the $S(1)$ emission. The weak $\text{Br}\gamma$ emission appears in a small unresolved patch one pixel north of the nucleus; no nuclear concentration is seen. Thus, the $\text{Br}\gamma$ and Fe II emission seems concentrated to the north of the continuum peak, while the $S(1)$ emission is concentrated to the south.

The spectra of the $S(1)$ line, with a resolution of 1000, shows complex velocity structure as seen in Figure 5. At the nuclear position, we measure a systemic heliocentric velocity $V_0 = 7408 \pm 40 \text{ km s}^{-1}$, with a line FWHM $\Delta V = 586 \pm 28 \text{ km s}^{-1}$ for the $S(1)$ line. For the Fe II line, we measure $V_0 = 7473 \pm 60 \text{ km s}^{-1}$ and $\Delta V = 685 \pm 42 \text{ km s}^{-1}$. The systemic velocities of the Fe II and $S(1)$ are consistent, while the larger measured velocity dispersion for the Fe II line is probably real. Both the systemic velocities and the line widths are consistent with those measured for the optical emission lines (Fosbury and Wall 1979). The velocity center of the $S(1)$ line varies by about 300 km s^{-1} over the extent of the emission. Such shifts in line velocity can be caused by resolved emission varying in intensity across the slit. To check this possibility, we obtained spectra with the slit rotated 90° . These observations confirm the observations taken with a north-south slit. Figure 3 shows the velocity of the $S(1)$ line centroid over the nuclear region. The velocity field shows no indication of any organized rotation. The main feature is a ridge of low velocity emission extending from the nucleus to the south-east. The $S(1)$ line shows complex velocity structure at many positions (Fig. 5). Figure 4 shows the line profile at several positions along a north-south slit through the nucleus and 3'' to the east. To try to untangle the complex velocity structure we fit two Gaussians to the line profile at each position. Since the line is only modestly resolved, the fits were quite good but uncertain. A high-velocity component ($V = 7700 \text{ km s}^{-1}$) is seen throughout the nucleus. There is also a component at lower velocity (7400 km s^{-1}) which is present along the ridge of emission extending from the nucleus to the south-east. The shift in the velocity centroid seen in Figure 4 reflects a change in the relative intensities of these two components. We interpret the two velocity components as being due to the velocity difference between the galaxies in the interaction. This is supported by the large velocity shear between the two nuclei. The Fe II line is not as well resolved as the 1–0 $S(1)$ line but it does not seem to show the same complex velocity structure (Fig. 6).

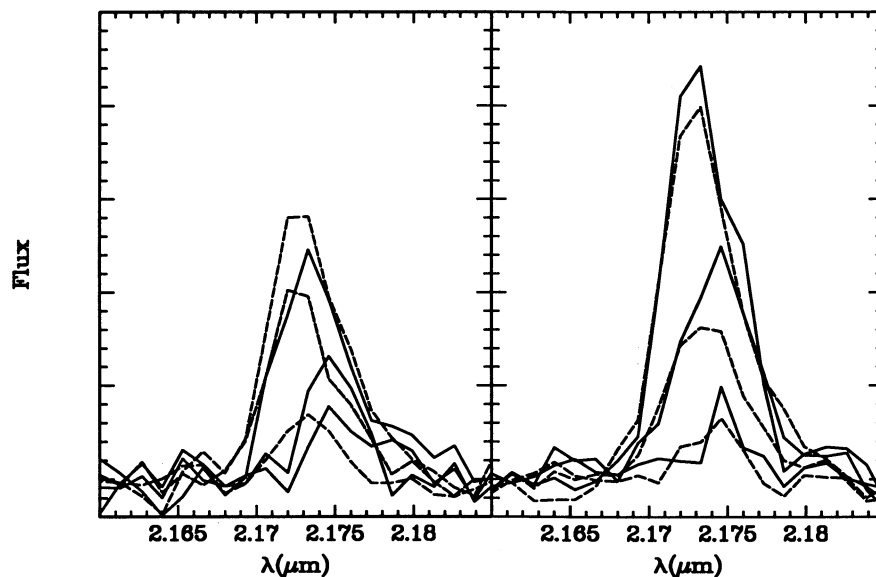


FIG. 4.—Spectrum of the 1–0 $S(1)$ line along a 2''.5 wide slit oriented north to south. The panel on the right has spectrum taken through the nucleus and the panel on the left are spectrum taken 3'' east of the nucleus. The solid lines are spectra spaced every 1''.5 toward the north of the continuum peak. The dashed lines are spectrum taken every 1''.5 south of the nucleus. The complex line shapes can be fit by two velocity components being present in the nuclear region of NGC 6240. The change in line center seen in Fig. 3 reflects the change in relative intensity of these components from place to place.

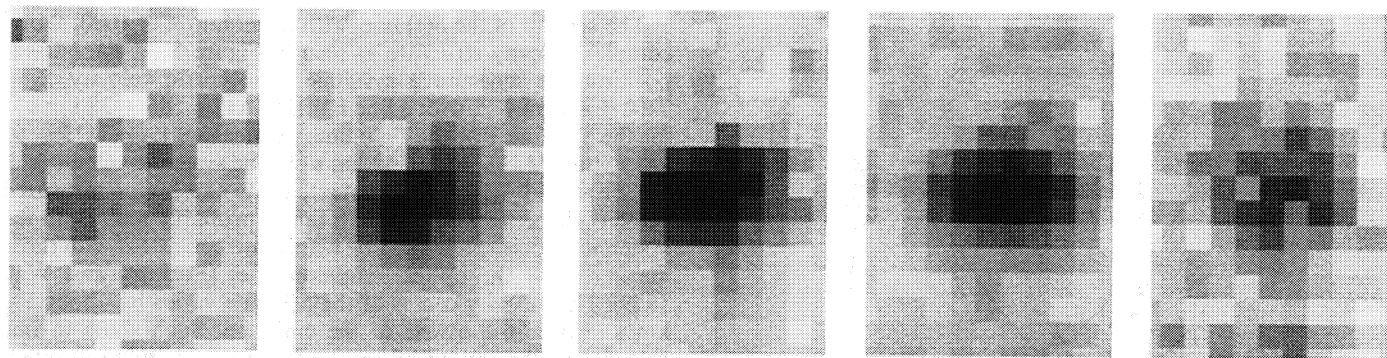


FIG. 5.—Long-slit spectrum of the 1–0 $S(1)$ line of NGC 6240 with the continuum removed. The slit is oriented north-south, and the pixels are $1''.5$ by $0.00133 \mu\text{m}$. North is toward the top, and red is to the right. The center panel is taken through the nucleus. The panels to the right are with the slit displaced $3''$ and $6''$ toward the west of the nucleus. The panels to the left were taken with the slit displaced $3''$ and $6''$ toward the east. A strong low-velocity component is present extending from the nucleus to south east.

III. DISCUSSION

What is the origin of the strong nuclear emission in NGC 6240? There are several approaches one can take to answer this question. First, the line ratios can be used to try to determine the mechanism of excitation. Second, we can use the relative locations of the emission components to look for causal connections between various components. The first approach has been taken by several authors (Rieke *et al.*; LHC; DBW) and we can only add a small amount to these previous discussions. We can make a substantial contribution to the second approach since these observations provide good spatial resolution. We have four useful tracers. The $2 \mu\text{m}$ continuum provides an estimate of the total stellar population. The $\text{Br}\gamma$ emission provides a measure of the current high-mass star formation. The 1–0 $S(1)$ line traces the location of molecular gas that is being excited either by slow shocks ($< 50 \text{ km s}^{-1}$) (Shull and Beckwith 1982) or by UV/soft X-ray radiation (Black and van Dishoeck 1987; Lepp and McCray 1983). The Fe II emission traces faster shocks ($> 50 \text{ km s}^{-1}$) than the $S(1)$ and in general is not expected to be radiatively excited, since most of the Fe will be in more highly ionized states (Moorwood and Oliva 1988).

Four models have been proposed to explain the nuclear

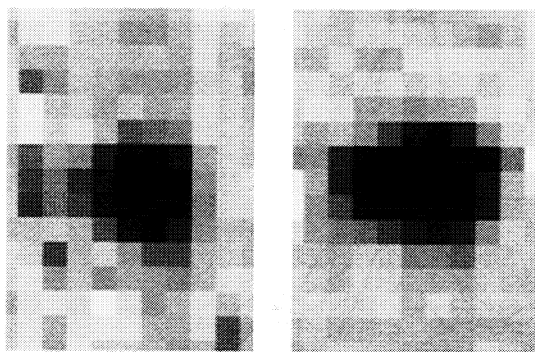


FIG. 6.—Long-slit spectrum of the Fe II line of NGC 6240 with the continuum removed. The slit is oriented north-south, and the pixels are $1''.5$ by $0.00172 \mu\text{m}$. North is toward the top, and red is to the right. The right-hand panel was taken with the slit through the nucleus, and the left panel was taken with the slit displaced $3''$ to the east of the nucleus. The Fe II emission is distributed toward the north of the 1–0 $S(1)$ emission and shows a different velocity distribution than the 1–0 $S(1)$ line.

emission in NGC 6240. On the basis of the deep $2 \mu\text{m}$ CO band head in NGC 6240, Rieke *et al.* (1985) proposed that there had been extensive recent star formation. The strong H_2 line emission could either be excited by the UV radiation from hot stars or by shocks produced by supernovae and stellar winds. Also, Woods and Draine (1988) suggested that supernova shocks would produce a large flux of soft X-rays which could penetrate into dense molecular clouds, exciting near-IR line emission. An alternative to these models, which require recent massive star formation, is suggested by the probable merger nature of NGC 6240. Harwit *et al.* (1987) propose that collisions between the molecular cloud components of the merging galaxies could provide the nuclear emission. We shall consider each of these possibilities in turn.

Rieke *et al.* argued against UV radiation from hot stars as the excitation mechanism for the H_2 emission, since their measured $\text{Br}\gamma$ flux indicated that the UV radiation field is too weak to pump the 1–0 $S(1)$ emission unless a very abnormal initial mass function, deficient in O stars is assumed. LHC and DBW also argue against this mechanism, because of the weakness of $\text{Br}\gamma$ and the H_2 line ratios, which are more consistent with a $\approx 2 \times 10^3 \text{ K}$ thermal distribution than a UV-pumped cascade. We can compare the ratio of the 5–3 $O(3)$, 6–4 $Q(1)$, and 1–0 $S(1)$ lines in our spectra with that predicted by the UV-fluorescence model of Black and van Dishoeck (1987) and to a thermal distribution. The UV excitation model predicts a 5–3 $O(3)$ line intensity relative to 1–0 $S(1)$ that is too high by a factor of 5. For a thermal model the 1–0 $S(1)$ to 5–3 $O(3)$ ratio requires an excitation temperature of $6 \times 10^3 \text{ K}$ (0.5 eV). This temperature seems rather high compared to those derived for the lower levels of H_2 by LHC, suggesting that at least part of the H_2 is probably excited by UV radiation. The ratio of 6–4 $Q(1)$ and 5–3 $O(3)$ emission of unity is consistent with UV fluorescence models. If we assume that all of the 5–3 $O(3)$ emission is excited by ultraviolet radiation, we get an upper limit of 20% for the contribution of fluorescence to the observed 1–0 $S(1)$ emission. Even this upper limit is probably too generous. Assuming case B recombination and electron temperature $T_e = 10^4 \text{ K}$, one $\text{Br}\gamma$ photon is emitted for every 72 photoionizations (Brocklehurst 1971; Giles 1977). The observed $\text{Br}\gamma$ flux, corrected for extinction (assuming $A_V = 3$; LHC) corresponds to a $\text{Br}\gamma$ line luminosity of $2.3 \times 10^6 L_\odot$. The required number of ionizing photons is $N_{\text{Ly}\alpha} = 7 \times 10^{53} \text{ photons s}^{-1}$. Fluorescence of the H_2 molecule depends on the photon flux between 912 and 1130 Å. A thermal radiation field with tem-

perature T_{eff} between 30,000 and 50,000 K emits about half as many photons between 912 and 1130 Å as are emitted shortward of the Lyman limit. Using the models of Black and van Dishoeck (1987), which predict that roughly 1% of the incident radiation intensity between 912 and 1130 Å is reradiated in molecular hydrogen lines, and that the fraction of the emitted intensity in the 5–3 $O(3)$ line is about 1% of the total line emission, we get a predicted 5–3 $O(3)$ flux of $\sim 4 \times 10^{-19} \text{ W m}^{-2}$. This is more than an order of magnitude smaller than the observed line flux, although the assumed values are probably too uncertain (depending on geometry, local intensity of UV radiation, and gas density) for this argument to be definitive (see also Black and van Dishoeck 1987). The range in derived excitation temperatures can also plausibly result from temperature fluctuations in the emitting gas (LHC). Thus, we agree with previous investigations which suggest that the molecular hydrogen emission is predominantly thermally excited. An additional argument against the UV fluorescence being the dominant excitation mechanism is the fact that neither the Br γ emission or the 2 μm continuum traces the 1–0 $S(1)$ emission.

Irradiation of dense molecular clouds by soft X-rays from supernovae will produce thermal excitation of H_2 (Wood and Draine 1988). The fast supernova shocks needed to produce the soft X-rays will be traced by the Fe II emission. Since the 1–0 $S(1)$ emission and the Fe II emission are spatially distinct and do not show the same dynamics, it would appear that strong supernova shocks are not intimately related to the 1–0 $S(1)$ emission. This same reasoning also argues against direct excitation of the 1–0 $S(1)$ line by supernova shocks. While there certainly are fast shocks (associated with Fe II), it does not appear that they can explain all the 1–0 $S(1)$ emission which pervades the inner 9" of NGC 6240.

Basically, we are left with a picture in which shock excitation appears to be the most appealing excitation mechanism for both the 1–0 $S(1)$ emission and the Fe II emission. But observationally, the H_2 -exciting shocks and the somewhat faster shocks required by the Fe II emission are not spatially associated with each other or with the past or current star formation. This sort of picture can be understood if the shock excitation is due to the galaxy merger occurring in NGC 6240. In the Harwit *et al.* (1987) model, the molecular cloud populations of the two interacting galaxies collide. This produces strong shocks, with velocities equivalent to the interaction speed (several hundred km s^{-1}), which would dissociate and ionize the molecular clouds. While it is possible to produce molecular hydrogen emission in this scenario, it is not clear whether the areal filling factor of molecular gas in even the inner regions of spiral galaxies is high enough that direct collision of a large fraction of the molecular clouds will be likely. Perhaps more plausible is production of the H_2 and Fe II emission by the much slower shocks driven into the molecular clouds of one galaxy by collision with the intercloud medium of the other galaxy. As suggested by LHC, if molecular clouds are interacting with the low-density diffuse ISM, the velocities of the shocks being driven in the clouds will be much lower than the interaction speed, with $V_{\text{cl}} \approx V_{\text{int}} \sqrt{(\rho_{\text{ISM}}/\rho_{\text{cl}})}$. In order to shock a large fraction of the molecular clouds in one galaxy, they must interact with a component of the ISM which has both a large filling factor and scale height. In the disk of our galaxy the warm neutral medium (WNM) and warm ionized medium (WIM) have both a large scale height and filling factor (see Kulkarni and Heiles 1987 for a review). If the WIM and WNM have $T \approx 6 \times 10^3$ and are in pressure equilibrium with

the molecular gas, the shocks being driven into the molecular clouds would be a factor of ≈ 20 slower than the interaction speed. The confinement of Fe II emission to the nucleus could be the result of a gradient in the pressure (and thus density) of the intercloud medium, so that outside a certain radius the speed of the shocks being driven into the clouds is too low to excite Fe II emission. In this picture, the extremely high luminosities in the $S(1)$ and Fe II lines in NGC 6240 are the consequence of the shocking of the inner 4 kpc of the gas disk. This requires an unusually favorable interaction geometry: the nearly face-on collision of two gas disks, as first suggested by Rieke *et al.* (1985). If the geometry was not face-on the size of the shocked region would be comparable to a disk scale height (few $\times 100$ pc), which is much smaller than the observed region.

Driving shock into molecular clouds by a galaxy-galaxy interaction is analogous to "cloud crushing" by supernova shocks. Cowie, McKee, and Ostriker (1981) found that about $\approx 30\%$ of the energy of a supernova shock was dissipated by cloud crushing. Depending on the clumping of the ISM only a fraction of the shocks will have velocities between 30 and 50 km s^{-1} , which can efficiently excite molecular hydrogen. For reasonable clumping, it seems that $\approx 20\%$ or more of the interaction energy can be transformed into shocks capable of exciting molecular hydrogen, although this is quite uncertain. Draine, Roberge, and Dalgarno (1983) found that about 2% of the shock energy will be emitted in the 1–0 $S(1)$ line for efficient shock velocities. Thus, the 1–0 $S(1)$ line will represent about 4×10^{-3} of the interaction energy. The 1–0 $S(1)$ line has a luminosity of $10^8 L_{\odot}$, so that the total luminosity of the interaction would be $\approx 10^{10} L_{\odot}$, which is only a fraction of the bolometric luminosity of NGC 6240. For a collision between two galaxy ISMs with masses of $10^{10} M_{\odot}$ at 500 km s^{-1} a total interaction energy of 5×10^{58} ergs is available. Thus, at the current rate of emission, the lifetime of the luminous line emission would be a few $\times 10^7$ yr. Such a lifetime is consistent with the disturbed morphology of NGC 6240 (the dynamical time scale of the system) and the statistical likelihood of finding such an object. Since the total luminosity is much higher than that inferred for the interaction luminosity an additional source of luminosity is required. Given the Br γ luminosity and the depth of the CO band head (LHC; Rieke *et al.* 1985), it does appear reasonable that recent star formation can supply the needed luminosity, possibly supplemented by the contribution from an active galactic nucleus (AGN).

Direct collision of molecular clouds may contribute to the emission. This is one possible explanation for the 5–3 $O(3)$ and 6–4 $Q(1)$ emission that is observed, although detailed modeling of the nonequilibrium conditions in high-velocity dissociating shocks is necessary to evaluate this suggestion. In addition, supernovae are a possible source of the Fe II emission. From the supernova observations of Oliva, Moorwood, and Danziger (1989), it would appear that a few $\times 10^5$ supernova remnants will be needed. Given the lifetime of the radiant phase of an SNR ($\approx 10^6$ yr), only a rather modest SN rate will be required (one every 10 yr). All that is needed is a substantial young stellar population. The deep CO band head observed by Rieke *et al.* (1985) and confirmed by both HLC and DBW suggests that large numbers of supergiants, which would be logical progenitors to supernova, are present in the nucleus of NGC 6240. It does not appear that we can rule out cloud-cloud collisions or supernova remnants as plausible contributions to the observed emission.

IV. CONCLUDING REMARKS

Not surprisingly, NGC 6240 has turned out to be a rather complex source, possibly requiring several different forms of excitation. The ratio of the 5–3 $O(3)$ line intensity to that in the 1–0 $S(1)$ line indicates that at most a small amount of the H_2 1–0 $S(1)$ emission may be excited by UV fluorescence. Temperature fluctuations in the emitting regions also provide a plausible explanation for the emission from higher vibrational levels. Since much of the 1–0 $S(1)$ emission comes from a region distinct from the Fe II emission, we propose that relatively slow shocks are being driven into the molecular clouds by collision with the diffuse ISM of the interacting galaxies; the different distributions of the 1–0 $S(1)$ and Fe II emission result from gradients in the density of the diffuse ISM. The complex dynamics of the 1–0 $S(1)$ line suggest that we are seeing the interaction of two galaxy disks with differential velocities of about 300 km s^{-1} .

Collision of the molecular clouds with the diffuse ISM of another galaxy lowers the shock velocities below the interaction velocity and provides a mechanism to shock essentially all the molecular clouds in a disk at once. Shocked clouds such as these are often suggested to be unstable and therefore likely to form stars. Yet in NGC 6240 we see no correspondence between the weak Br γ emission and the 1–0 $S(1)$ line, suggesting that star formation is rather modest and weakly correlated to shocking of molecular clouds over the 4 kpc region of 1–0 $S(1)$ emission.

In the case of NGC 6240, it seems that we have identified the extra source of excitation needed to explain the strong nuclear line emission with shocks excited by the merger occurring in this system. Given that the 1–0 $S(1)$ emission and Fe II are both several orders of magnitude stronger in NGC 6240 than in a typical “starburst” (M82), and the Br γ emission is a few times

weaker, it seems fair to ascribe the required shocks to the merger event rather than to massive star formation. It is also interesting to note that the optical spectrum of NGC 6240 is rich in strong low-excitation lines typical of shock excitation (Fosbury and Wall 1979). The optical line ratios of NGC 6240 lead to its classification as a “liner” galaxy (Heckman 1980). Since the optical emission lines are characteristic of shock excitation and have an extent similar to the 1–0 $S(1)$ line, NGC 6240 appears to be a very good example of a liner galaxy that is shock excited. The line luminosity of NGC 6240 ($L_{H\alpha} = 6 \times 10^{42} \text{ ergs s}^{-1}$) is much higher than is typical for liner galaxies (10^{38} – $10^{40} \text{ ergs s}^{-1}$) found in the optically selected sample of Heckman (1980). Also NGC 6240 is an unusual liner, since it is found in a gas-rich galaxy while most liners are found in early-type galaxies (S0 and Sa). Thus, it may be better to regard NGC 6240 as a prototype for luminous shock-excited liner galaxies than as a typical ultraluminous starburst galaxy. Along with the disturbed morphology and high-line luminosities, near-IR spectroscopy of molecular hydrogen may be useful for separating liner galaxies which are shock excited from those which are photoionized.

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