CIRCUMNUCLEAR SHOCK AND STARBURST IN NGC 6240: NEAR-INFRARED IMAGING AND SPECTROSCOPY WITH ADAPTIVE OPTICS

TAMARA BOGDANOVIĆ AND JIAN GE
Department of Astronomy and Astrophysics, Pennsylvania State University, 532 and 514 Davey Laboratory, University Park, PA 16802; tamarab@astro.psu.edu, jian@astro.psu.edu

CLAIRE E. MAX
Institute of Geophysics and Planetary Physics, L-413, Lawrence Livermore National Laboratory, 7000 East Avenue, Livermore, CA 94550; and Center for Adaptive Optics, University of California at Santa Cruz, Santa Cruz, CA 95064; max1@llnl.gov

AND

LYNNE M. RASCHKE
Department of Astronomy and Astrophysics, and Center for Adaptive Optics, University of California at Santa Cruz, Santa Cruz, CA 95064; lynne@ucolick.org

Received 2003 January 1; accepted 2003 August 6

ABSTRACT

We have obtained adaptive optics, high spatial resolution (0.15") K-band spectra and images of the region around the two active nuclei in NGC 6240, which show the presence of circumnuclear shocks. The data are consistent with thermal excitation being the dominant mechanism in the nuclear region. UV fluorescence and associative detachment may also contribute to the fraction of energy emitted through molecular hydrogen transitions. The near-IR continuum emission appears closely associated with the two active nuclei. The morphological similarities between the near-IR images and the Chandra X-ray images indicate that the same mechanisms may be responsible for the emission in the near-IR and X-ray bands.

Key words: galaxies: individual (NGC 6240) — galaxies: nuclei — galaxies: starburst — techniques: high angular resolution

1. INTRODUCTION

1.1. NGC 6240

NGC 6240 is one of the best studied composite galaxies, hosting a luminous starburst and two active galactic nuclei (AGNs) obscured by gas and dust. With a bolometric luminosity of $6 \times 10^{11} L_\odot$ (Rieke et al. 1985) emitted predominantly in the infrared, this galaxy is a borderline case of the ultraluminous infrared galaxies (ULIRGs, $L_{ULIRG} > 10^{12} L_\odot$). Moreover, NGC 6240 has the largest known near-infrared molecular hydrogen line luminosity, $L(H_2)_{tot} \approx 10^9 L_\odot$ (Draine & Woods 1990). Many of the ULIRGs are objects with a large amount of molecular hydrogen gas. Their extraordinary infrared luminosity originates either in a powerful starburst or in a gas-embedded AGN; NGC 6240 is an object with clear signatures of both.

We observed the two distinct nuclei at high angular resolution with adaptive optics. Both the northern and southern nucleus (hereafter the north nucleus and the south nucleus, respectively) are surrounded by bright gas components. The south nucleus shows strong nuclear activity and has been suggested to be the source of the AGN hard X-ray component (Iwasawa & Comastri 1998; Vignati et al. 1999; Ikebe et al. 2000). Being embedded in the gas, dust, and powerful starburst, the AGN is not directly observable at energies lower than 10 keV. Recent Chandra ACIS data (Komossa et al. 2003) reveal two active nuclei in hard X-ray emission, coincident with the optical and IR nuclei of NGC 6240.

NGC 6240 was observed in the near-infrared by many authors in the past (Joseph, Wright, & Wade 1984; Rieke et al. 1985; Lester, Harvey, & Carr 1988; Elston & Maloney 1990; Herbst et al. 1990; Van der Werf et al. 1993; Lester & Gafney 1994; Lancón, Rocca-Volmerange, & Thuan 1996; Oliva et al. 1999; Ohyama et al. 2000; Scoville et al. 2000; Tecza et al. 2000), with the latest works setting the quality and resolution criteria for near-IR spectroscopy and imaging of this object. An important goal of the past 20 years of study of this galaxy has been to determine and explain the dominant emission mechanism. This objective has been difficult to meet because both very accurate line ratios and spatial information about the emission lines are needed to draw firm conclusions. In the next section we review some of the proposed excitation mechanisms.

1.2. Proposed Excitation Mechanisms

There are four excitation mechanisms proposed by different authors to explain the dominant source of energy emitted in the near-IR from the nuclear region of NGC 6240. Thermal emission driven by collisional excitation (Sugai et al. 1997; Lester et al. 1988; Ohyama et al. 2000).—This type of excitation arises from the collision of H$_2$ molecules with other hydrogen molecules, atoms, and energetic electrons. NGC 6240 is a merger galaxy and the presence of shocks is expected as a consequence of both tidal effects and starburst-driven superwinds.

Ultraviolet fluorescence (Tanaka, Hasegawa, & Gatley 1991).—This mechanism is expected to arise in galaxies hosting a young starburst population of supergiant stars. Starburst galaxies typically have a large amount of gas that...
responds to UV radiation. The gas shows a characteristic disrupted morphology and strong infrared emission.

X-ray heating by the central source and supernovae (Draine & Woods 1990).—NGC 6240 is known to have two hard X-ray nuclei embedded in gas (Komossa et al. 2003). The central, high-temperature source ionizes the gas in its vicinity and creates high-energy electrons. These further participate in collisions with H and H$_2$. Since the column density of the gas in the nuclear region of NGC 6240 is high ($N_H \approx 10^{21}-10^{22}$ cm$^{-2}$; Komossa et al. 2003), X-ray emission is expected to be mostly thermalized and re-emitted in the IR continuum. Alternatively, X-rays can be produced by supernovae and high-velocity cloud-cloud collisions. The emission from this mechanism depends on the power of the source and column density of the gas.

A formation pumping mechanism driven by dissociative shocks (Mouri & Taniguchi 1995).—Fast, dissociative shocks passing through the molecular gas leave behind H atoms and ions that recombine into excited H$_2$ and give rise to formation pumping. This process is also called associative detachment.

Our observations allow further investigation into which mechanisms contribute the dominant fraction of energy radiated in near-IR. In §2 we describe the observations and data reduction procedures applied to the spectra and images. In §3 we present the results; in §4 we discuss their implications and give concluding remarks in §5.

2. OBSERVATION AND DATA REDUCTION

In 2000 June and 2001 August we obtained high spatial resolution ($\sim$0.15'') near-IR images and spectra of NGC 6240 with the Lick 3 m telescope and the natural guide star adaptive optics system (Gavel et al. 2000). The observations were carried out with the PICNIC 256 x 256 IR array IRCAL camera (Lloyd et al. 2000). The plate scale was 75.6 ± 0.2 mas pixel$^{-1}$, with a total field of view of 19.4'. For our spectroscopic observations we used a CaF$_2$ grism (Ge et al. 2003), which covered the wavelength band 1.9–2.4 $\mu$m, with a wedge angle of 30''95. One pixel corresponded to approximately 19.5 ˚A along the dispersion direction. The spectral resolution achieved was about 750 km s$^{-1}$, or $R = \lambda/\Delta\lambda = 400$. The total on-source spectroscopic exposure time was 6900 s (23 exposures, 300 s integration each; Table 1) and 4465 s total for imaging (Table 2).

2.1. Spectra of the NGC 6240 Nuclear Region

The angular separation of the two galactic nuclei measured in the H and K bands is about 1.8' (Lira et al. 2002). The slit was initially positioned on the center of the south nucleus, the brighter one, and then progressively shifted toward the north nucleus. The instrumental slit width of 0.15' and slit positioning allowed us to obtain coverage of the nuclei and the region between them. Spatially close frames, with similar spectral features were then combined in order to obtain higher signal-to-noise ratios for the five resulting spectral frames. The regions on the sky associated with every combined spectral frame are boxes of approximate sizes 0.3' x 5'', 0.3' x 5'', 1.0' x 5'', 0.6' x 5'', and 0.7' x 5'', positioned from the south toward the north nucleus, respectively. The area of each box is defined by the slit widths (which depend on how many spectra are combined for a particular frame) and slit length of 5''. The scheme of positions of the boxes on the sky associated with the five spectral frames is shown in Figure 1.

Data reduction was performed using the IRAF software package. The sky frames, obtained right after the target exposure, were subtracted from all object frames. The data were flat-fielded using dome flat lamp exposures, obtained at the end of each observation. For the spectral calibration we used a neon lamp, which has enough strong emission lines in the wavelength interval of interest to allow calibration. The flux units are arbitrary since absolute flux values are uncertain, as is common for spectra obtained with an adaptive optics systems. Later (§3.4) we base our analysis on relative line intensities. For this purpose we fitted every line with a Gaussian and calculated its equivalent width. The equivalent width of a line sensitively depends on the adopted continuum level. We estimated the continuum level in the vicinity of each emission line. This helps to minimize the error caused by the noise in the continuum that is not captured by the continuum fitting.

The atmospheric absorption correction was carried out with the A0 V star HD 203856, observed on the same night as the object, by dividing the target spectra by the A0 V star spectrum. The Br$\gamma$ absorption region in the spectrum of the star was approximated with a Gaussian and then removed.

We estimated the error for the calculated line ratios from the error contribution for both lines. The uncertainty in the measurement of the relative intensity of a single line is contributed by the finite signal-to-noise ratio and finite resolution.

2.2. Images of the NGC 6240 Nuclear Region

We obtained three sets of images: with the K$_c$-band filter and the H$_2$- and Br$\gamma$-narrowband filters, with exposure times of 60, 1722, and 2633 s, respectively (Table 2). The K$_c$ filter has a central wavelength of $\lambda_c = 2.150$ $\mu$m and an FWHM of 0.320 $\mu$m. The H$_2$ and Br$\gamma$ filters have central wavelengths of $\lambda_c = 2.125$ $\mu$m and $\lambda_c = 2.167$ $\mu$m, respectively, and an FWHM of 0.020 $\mu$m. The latter two filters have approximately the same transmission, close to 80%.

Due to the redshift of the object ($V_{sys} = 7339$ km s$^{-1}$; Downes, Solomon, & Radford 1993) the H$_2$ filter samples the continuum emission and the Br$\gamma$ filter samples the redshifted molecular hydrogen emission line 1–0 S(1) as well as the underlying continuum. The H$_2$ v = 2–1 S(3) emission line, observed at a $\nu_{obs} = 2.1243$ $\mu$m object frame, may contaminate the continuum emission observed with the H$_2$.
filter. However, the expected contamination effect should be small, since the line intensity of this transition in NGC 6240 is very weak (Ohyama et al. 2000; see § 3.4). The sky was subtracted from every object frame. The twilight flats taken at the beginning of the evening were used for the flat-fielding of object frames.

We used Keck NIRSPEC and NIRC2 spectra, with spectral resolution ($R = 2000$ with a 0"047 slit and $R = 2787$, with a 0"06 slit) taken by one of us (C. M.) as an independent check of the relative brightness scale for images obtained with the two narrowband filters. The 1–0 S(1) emission line was resolved in each of two spectra. Both spectra showed that the peak brightness of the south nucleus is about a factor of 1.3 higher in the Brγ filter bandpass (comprised of line plus continuum emission) than in the H2 filter bandpass (contributed by the continuum emission). The scaling factor confidence is about 3σ. We rescaled the H2-band image in order to make its peak brightness at the south nucleus equal to 1/1.3 times that seen in Brγ and then subtracted the rescaled image from the Brγ image. As a result we obtained an image that emphasizes the molecular emission region (Fig. 2a).

![Diagram](image.png)

**TABLE 2**

| Image   | Obs. Date | Exposure | Size      | Filter         | $\lambda_0$ | FWHM  | S/N  |
|---------|-----------|----------|-----------|----------------|-------------|-------|------|
| Fig. 1  | 2000 Jun 25 | 60       | 11.34 × 9.07 | Ks             | 2.150       | 0.320 | 110, 38 |
| Fig. 2a | 2001 Aug 6  | 2633     | 11.34 × 9.07 | Brγ–H2         | 2.167       | 0.020 | 47, 20 |
| Fig. 2b | 2001 Aug 6  | 1772     | 11.34 × 9.07 | H2             | 2.125       | 0.020 | 102, 45 |

Notes.—Col. (1): image name; col. (2): observing date; col. (3): exposure time in seconds; col. (4): size of image in figure; col. (5): filter; col. (6): central wavelength in microns; col. (7): FWHM; col. (8): signal to noise ratio per pixel for compact and diffuse emission.

Fig. 1.—$K_s$-band image of the nuclear region with the scheme of five regions on the sky associated with five different spectral frames. The length of all boxes marking the regions on the sky is 5", and the width is as marked on the figure.
2a we also marked the locations of the north and south nuclei as seen in the near-IR continuum image in Figure 2b.

Figure 3 shows an X-ray logarithmic isocontour image of binned counts obtained from the Chandra Data Archive. The Chandra observation was carried out with the HRC-I microchannel plate detector (Murray et al. 1997) in the 0.08–10.0 keV energy band with an exposure time of 8.8 ks. The image size is 23′′ × 18′′.

3. RESULTS

3.1. Ks Broadband Image and Narrowband Images

Figure 1 shows the Ks-band image, obtained with the Ks broadband filter, transparent to near-IR photons in a wavelength range of 1.99–2.31 μm. The flux in this wavelength range is contributed by the emission from the continuum and molecular hydrogen lines. Our Ks-band image closely resembles the high-resolution images reported by Scoville et al. (2000), taken in the 1.1 and 2.2 μm rest frame. Two compact nuclei are easily distinguished in the image. Also noticeable is the faint, extended emission around the nuclei.

The narrowband images (Fig. 2) allow the continuum emission and emission from molecular lines to be observed separately. They show that what is seen as emission from the continuum is consistent with the emission coming from the active nuclei, while molecular line emission is coming from the surrounding gas component.

The narrow band image in the 2.12 μm rest frame H2 ν = 1–0 S(1) [hereafter 1–0 S(1)] transition (Fig. 2a) reveals diffuse emission of a gas component. Tacconi et al. (1999) presented a detailed study of the H2 gas dynamics in the nuclear region, traced in the CO millimeter emission. The CO emission maps revealed the existence of a large concentration of molecular gas (2–4 × 109 M⊙) between the two nuclei, which is confined to a geometrically and optically thick disk, where the dust in the disk efficiently shields the emission from the molecular hydrogen gas. The H2 emission seen in our images then probably originates from the parts of nuclear region outside the circumnuclear disk and from the orders-of-magnitude smaller mass of molecular hydrogen than in the disk.

The diffuse emission region extends 400–800 pc east and west from the long axis of the system connecting the two nuclei. The strongest H2 1–0 S(1) emission is observed at the position of the south nucleus and between the two nuclei. The peak of the H2 emission at the south nucleus appears about 0′′.3 displaced from the center of the nucleus (as determined from the near-IR continuum image, Fig. 2b) toward the northeastern rim of the south nucleus. This is consistent with the previous detections of the H2 1–0 S(1) emission in the region between the two nuclei (Herbst et al. 1990; Van der Werf et al. 1993; Sugai et al. 1997; Tecza et al. 2000).
and implies that emission from this gas component is probably not powered by the X-rays coming from the nuclei, but rather by the circumnuclear shocks. A gaseous blob seen in molecular hydrogen emission located ∼1 kpc southwest of the south nucleus coincides with the blob emission as seen in the X-ray contour image (Figs. 2a and 3). The size of the blob is about 700 pc. The same region is not seen in the continuum emission, which appears associated with the nuclear activity (Fig. 2b). This indicates that emission of the gaseous blob may be driven by local starburst activity, nested inside this region. The north nucleus exhibits low brightness in the 1–0 $S(1)$ molecular transition, while it is distinct on the continuum image. We conclude that the north nucleus is more quiescent, with a lower rate of starbursts and shock waves.

We compare our near-IR images to the H$\alpha$ images of the nuclear region in Lira et al. (2002) and Zezas et al. (2001). We find that the general geometries of the extended emission in these two images do not resemble each other. Near-IR images show more centralized emission on the scale of ∼3–4″. The only example of very faint filamentary structure seen in the 1–0 $S(1)$ near-IR image is stretching southeast to the nuclear region. The filament is not observed in the continuum emission, nor in the X-ray contour image. Near-IR emission is thus spatially more associated with the nuclear activity and the circumnuclear starburst than with the larger scale outflows and superwinds as further shown in the X-ray contour image (Fig. 3). The hourglass symmetry of the region (Heckman, Armus, & Miley 1990) and the conelike outflows (Lira et al. 2002), typical of superwinds and seen in H$\alpha$ images, cannot be uniquely identified on the 1–0 $S(1)$ image.

Both nuclei appear brighter and more distinct in the near-IR H$_2$ emission than in the visible H$\alpha$ emission since the near-IR line is less affected by extinction. The extinction toward the nuclei, estimated from IR observations (Tecza et al. 2000), is found to be $A_V=5.8$ mag and $A_V=1.6$ mag. The extinction toward the extended emission, estimated from optical observations (Thronson et al. 1990), is $A_V\approx 1$ mag.

From the comparison with the recent Chandra ACIS-S images (Komossa et al. 2003), we notice that the morphology of the near-IR continuum image (Fig 2b) corresponds closely to that of the hardband (6.0–6.7 keV) X-ray image of the same region, showing ∼4″ scale nuclear emission. The near-IR 1–0 $S(1)$ image (Fig. 2a) corresponds in scale and morphology to an ACIS-S intermediate energy band image (1.5–2.5 keV), showing more diffuse emission around the nuclear region. Finally, the morphology of the ACIS-S soft energy band image (0.5–1.5 keV) does not correspond to any of the near-IR images but matches well the H$\alpha$ HST image (Lira et al. 2002) in both scale (∼20″) and morphology. The morphological similarities between the X-ray and near-IR bands suggest that the same mechanisms may be responsible for the emission unless the structure is significantly under-resolved in one of the bands.

3.2. X-Ray Contours

Figure 3 is an X-ray logarithmic isosurface of the same region observed with the Chandra HRC in the energy range of 0.08–10 keV. The image shows the X-ray emission on the scale of 23″7 × 18″7. The central region (−11″3 × 9″1; Fig. 3, box), which is also shown in Figure 2, is part of a larger scale structure that is presented here for clarity.

The contours are plotted on a logarithmic scale to emphasize the faint, extended emission dominated by the nuclear emission. The rich gaseous structure seen in the X-ray contours matches well the size and morphology of the structure seen in the H$\alpha$ emission images (Zezas et al. 2001; Lira et al. 2002).

X-ray contours show both nuclei in emission. The nuclei are in a north-south orientation with a positional angle of ∼15° and an angular separation of 1″4. Also marked on the X-ray contour image are locations of the nuclei as observed in the near-IR continuum. The measured near-IR angular separation of the nuclei is 1″8. The conelike outflows and filaments expanding into the surrounding medium are noticeable to the west of the nuclear region (Fig. 3, arrows). Visible in the X-ray, these are likely to be superwinds capable of heating the medium and initiating a new sequence of starbursts. The emission to the east of the nuclear region is more extended but appears to have less filamentary structure.

3.3. Observed Spectral Features

All of our IRCAL frames show a prominent molecular hydrogen 1–0 $S(1)$ line (Fig. 4). This line is formed as a forbidden quadrupole transition at $\lambda=2.12$ μm. It can be excited collisionally at temperatures larger than 1000 K or radiatively by UV resonant fluorescence. CO (2–0) absorption, noticeable for all slit positions, is characteristic of late spectral type (K and M) giants and supergiants. The typical age of these stars is about $10^7$ yr. This is consistent with a starburst initiated about $10^7$ yr ago, around both nuclei and in the middle region, most likely as a consequence of tidal interaction (Tecza et al. 2000; Ohyama et al. 2000). Today these evolved stars contribute a significant amount of radiation to the infrared. Due to the finite spectral resolution we are only able to place an upper limit on the velocity dispersion, $\sigma<750$ km s$^{-1}$, and we do not observe a significant change in the CO (2–0) absorption width toward the north nucleus. Tecza et al. (2000) measure

![Figure 4](image-url)
\( \sigma \approx 360 \) and \( 270 \text{ km s}^{-1} \) for the north and south nuclei, respectively, with a spectral resolution of \( R = 2000 \) and a spatial resolution of \( 1^\prime \). After correction for the inclination of the nuclei, they find dynamical masses of \( 10^9 M_\odot \) and \( 10^8 M_\odot \), respectively, with a spectral resolution of \( 1000 \). These values imply that we are witnessing a merger of the nuclei with very massive bulges.

The emission associated with the associative detachment mechanism is characteristic for \( v = 1, 2 \) vibration levels and high rotational levels. The latter allows this mechanism to be discriminated from two other competing processes: collisional and fluorescent emission. In high-density regions, molecules are de-excited collisionally, which then leads to thermalization of the molecular population at low rotational levels. In that case associative detachment lines are suppressed, and it is hard to distinguish it from the other two mechanisms. Formation pumping depends strongly on the properties of the gas and the \( \text{H}, \text{H}^- \) reaction cross section. These are not well constrained, and the contribution of this mechanism is hard to estimate (Mouri & Taniguchi 1995).

3.4. Line Ratios: Comparison of Observations with Model Predictions

We calculate line ratios for detected molecular transitions and list them in Table 4. The flux units in the listed spectra are arbitrary. Consequently, the intensities of observed emission lines are expressed relative to the strongest transition \( 1–0 \text{ S}(1) \), which has an assumed intensity of 1.0. Therefore, the values for line ratios listed in Table 4 are identical to relative line intensities. Line ratios for transitions detected with less than 3 \( \sigma \) confidence are put as upper limits. This is always determined by the detection confidence of the weaker line, since the \( 1–0 \text{ S}(1) \) transition is always detected with confidence higher than 3 \( \sigma \).

Line ratios measured at locations 1, 2, 3, 4, and 5 (see Table 1), are compared against model-predicted line ratios, calculated for cases of pure fluorescent excitation and pure thermal excitation (Black & van Dishoeck 1987) and “mixture” cases: a mixture of associative detachment plus fluorescent excitation and thermal plus fluorescent excitation for two different UV field strengths (Black, Porter, & Dalgarno 1981).

The first model is purely fluorescent (also referred to as UV pumping) and the modeled line ratios are functions of total density \( n_\text{H} \), temperature \( T \), incident UV flux, and visual extinction \( A_V \). The model-predicted values do not constrain physical parameters for the nuclear region of NGC 6240 but indicate the observable trend in line ratios. In the case of fluorescent excitation as the dominant excitation mechanism, line ratios typically have higher values, close to 0.50. The

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**TABLE 3**

| Emitter | Transition | Rest (\( \mu \text{m} \)) | Obs. (\( \mu \text{m} \)) |
|---------|------------|-----------------|-----------------|
| \( \text{H}_2 \) | \( v = 1–0 \text{ S}(2) \) | 2.0338 | 2.0836 |
| \( \text{H}_2 \) | \( v = 2–1 \text{ S}(3) \) | 2.0735 | 2.1243 |
| \( \text{H}_2 \) | \( v = 1–0 \text{ S}(1) \) | 2.1218 | 2.1738 |
| \( \text{H}_2 \) | \( v = 2–1 \text{ S}(2) \) | 2.1542 | 2.2070 |
| \( \text{H} \) | \( \text{Br}^- \) | 2.1661 | 2.2192 |
| \( \text{H}_2 \) | \( v = 1–0 \text{ S}(0) \) | 2.2233 | 2.2778 |
| \( \text{H}_2 \) | \( v = 2–1 \text{ S}(1) \) | 2.2477 | 2.3028 |

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**TABLE 4**

| Observed/Modeled | \( 1–0 \text{ S}(2)/1–0 \text{ S}(1) \) | \( 1–0 \text{ S}(0)/1–0 \text{ S}(1) \) | \( 2–1 \text{ S}(1)/1–0 \text{ S}(1) \) |
|------------------|-----------------|-----------------|-----------------|
| 1\(^a\) | 0.36 ± 0.12 | \ldots | <0.37 |
| 2\(^a\) | 0.38 ± 0.16 | <0.38 | <0.34 |
| 3\(^a\) | 0.24 ± 0.10 | \ldots | <0.42 |
| 4\(^a\) | <0.32 | <0.36 | \ldots |
| 5\(^a\) | <0.40 | 0.45 ± 0.23 | \ldots |
| Fluorescence\(^b\) | 0.50 | 0.45 | 0.56 |
| Thermal (2000 K)\(^b\) | 0.37 | 0.21 | 0.082 |
| Assoc. Detach. + Fluorescence (1000 K)\(^c\) | 0.41 | 0.43 | 0.55 |
| Assoc. Detach. + Fluorescence (5000 K)\(^c\) | 0.42 | 0.32 | 0.53 |
| Thermal + Fluorescence (1000 K)\(^d\) | 0.41 | \ldots | 0.54 |
| Thermal + Fluorescence (5000 K)\(^d\) | 0.37 | \ldots | 0.19 |

Notes.—Line ratios are calculated for lines detected with more than 3 \( \sigma \) confidence. The errors reported are 1\( \sigma \). The upper limits are calculated for transitions detected with >1.5 \( \sigma \) confidence.

\(^a\) Observed line ratios. See text.

\(^b\) Model 14 of Black & van Dishoeck 1987.

\(^c\) Combined effects of associative detachment and UV pumping, Black et al. 1981.

\(^d\) Combined effects of thermal and fluorescent excitation, Black et al. 1981.
second model is calculated for purely thermal excitation at 2000 K and has typically lower values of line ratios with respect to the fluorescence model.

The third and fourth models indicate the combined effects of associative detachment and fluorescent excitation for the gas illuminated by blackbody radiation for blackbody temperatures of 1000 and 5000 K. The line ratio predictions in the $v = 1-0$ band for these two models are close to the values predicted by the thermal model. Unless the $v = 1-0$ band ratios are measured with great precision the only sure discriminant is the $v = 2-1$ band.

Models 5 and 6 predict line ratios from collisional and fluorescent excitation of a gas illuminated by radiation from $T = 1000$ and 5000 K blackbodies. The rate of radiative excitation versus collisional excitation by electrons is the same for both models. The values of the line ratios exhibit degeneracy with other models, except for the $2-1S(1)/1-0S(1)$ ratio. Model-predicted line ratios for $1-0S(0)/1-0S(1)$ are not available.

We find that all the $1-0S(2)/1-0S(1)$ measured line ratios are consistent with purely thermal excitation or a mixture of thermal and fluorescent excitation. Some of the ratio values within the error bars could be consistent with associative detachment plus fluorescence mechanism. The purely fluorescence model can be eliminated based on this set of ratios, since there is only one ratio that marginally supports it.

The values for the line ratios $1-0S(0)/1-0S(1)$ and $2-1S(1)/1-0S(1)$, show the same consistency with the purely thermal or thermal plus fluorescence models, and a few of them show it with the associative detachment plus fluorescence model. The purely fluorescent model is not a favored scenario based the values of the line ratios.

The Br$\gamma$ emission line, a tracer of young stellar populations, is not seen in our near-IR spectra. Br$\gamma$ has been observed by other authors as a very weak transition with the intensity of about 0.07 relative to the intensity of the 1-0 $S(1)$ transition (Sugai et al. 1997; Ohyama et al. 2000). Similarly, we do not detect 2-1 $S(2)$ and 2-1 $S(3)$ transitions in our spectra (not listed in Table 4) but they were detected by Sugai et al. (1997) and Ohyama et al. (2000) with relative intensities of 0.03 and 0.08, respectively. The fluorescence model–predicted ratios for these transitions are 0.28 for $2-1S(2)/1-0S(1)$ and 0.35 for $2-1S(3)/1-0S(1)$. The $T = 2000$ K thermal model predicts 0.03 and 0.08 ratios, respectively (Black & van Dishoeck 1987). The measured line ratios are therefore closely consistent with the predicted values for this thermal model and exclude the possibility of significant contribution from the X-ray heating, which would result in weaker relative intensities of these lines (Sugai et al. 1997).

The line ratios are a necessary tool to determine the nature of the emission mechanism. In the case of NGC 6240, line ratios imply that the whole nuclear region is excited thermally, while there may be some contribution from the radiative excitation mechanism. However, the line ratios do not necessarily discriminate among the excitation progenitors. For example, thermally excited transitions can be powered by heating from red giant stars or circumnuclear shocks but also by high energy electrons, created by ionization from the central X-ray source. On the other hand, fluorescent radiatively powered transitions are characteristic of young stellar populations only. For $N_H \approx 10^{21}$–$10^{22}$ cm$^{-2}$ measured column density (Komossa et al. 2003), high-energy photons emitted from the central source are expected to be mostly thermalized, so they do not participate in radiative excitation in the near-IR band. By the same argument all radiative transitions are likely to come from smaller optical depths. Otherwise, they are obscured by gas and dust and thermalized during radiative transfer.

4. DISCUSSION

We notice the following similarities in the apparent morphology of the nuclear region as seen in different spectral bands (near-IR, X-ray observed by Komossa et al. 2003, and optical observed by Lira et al. 2002): (a) the near-IR continuum image corresponds to the 6.0–6.7 keV band Chandra X-ray image; (b) the near-IR 1–0 $S(1)$ image corresponds to the 1.5–2.5 keV band Chandra image, while (c) the Chandra 0.5–1.5 keV image matches well the HST H$\alpha$ image. This correlation indicates that the same mechanism may be responsible for the emission in bands with apparent morphological similarities.

The near-IR continuum emission and hard band 6.0–6.7 keV X-ray emission can be associated with the compact emission from the two nuclei. The hard X-ray nuclei ionize the surrounding gas and create high-energy electrons, which further participate in collisions with hydrogen atoms and molecules.

The diffuse 1–0 $S(1)$ molecular emission, as well as the intermediate X-ray energy band emission, are associated with the circumnuclear region. The near-IR line ratios indicate that the 1–0 $S(1)$ transition in this region is predominantly excited by a thermal mechanism. Circumnuclear shocks are thought to be carriers of thermal excitation. The shocked H$_2$ component probably originates from a different volume than that occupied by the thick gaseous disk, from which stars are forming (Tacconi et al. 1999). In parts of nuclear region a mixture of thermal and fluorescent excitation may also take place, the latter tracing the presence of a young stellar population capable of UV heating. UV fluorescence is expected to originate at smaller optical depths and therefore trace the star formation only at a certain physical depth in the nuclear region, meaning that the young stellar population could potentially be larger than observed from radiatively excited transitions.

Based on the line ratio analysis, certain contributions from the associative detachment cannot be excluded. Furthermore, associative detachment is expected in regions where fast shocks pass through the molecular gas. Fast shocks that contribute their energy to near-IR through molecular emission are also likely to contribute to X-ray emission, which is observed in the Chandra ACIS-S intermediate X-ray energy band.

Optical H$\alpha$ emission is observed on an angular scale of 20″, much larger than the ∼3″–4″ scale of near-IR molecular line emission. Morphologically similar to soft X-ray band emission, the H$\alpha$ emission is likely to be associated with large-scale outflows and superwinds.

The morphological comparison of the nuclear region as seen in different energy bands is valid under the assumption that dominant features in the nuclear region are resolved in all of the bands. This could be questioned if the longer imaging integration reveals scale and features in the nuclear region that are significantly different from those in images we refer to.
In the whole nuclear region we also detect the presence of an aged starburst population, initiated ~10^7 yr ago, probably as a consequence of tidal interaction of two nuclei (Lester & Gafney 1994). These are mostly found to be late-type supergiants that contribute all of the CO absorption and a fraction of thermally induced emission to 2 μm band transitions.

5. CONCLUSIONS

In this work we base our conclusions on high spatial resolution near-IR imaging and spectroscopy and available X-ray imaging. NGC 6240 is revealed as a luminous galaxy with multiple components in emission. We find that near-IR luminosity emitted from the nuclear region of NGC 6240 is spatially associated with the central kiloparsec (3″–4″ scale). We observe both nuclei in emission with the south nucleus being the more prominent. We also observe the diffuse emission from the gas component distributed around and between the nuclei.

The values of measured line ratios in the near-IR are consistent with thermal excitation as the dominant excitation mechanism. Thermal emission can be driven by collisional excitation in small-scale circumnuclear shocks and also contributed by late-type giant and supergiant stars. A smaller fraction of energy can be contributed radiatively, through UV fluorescence and comes from young stellar population. The associative detachment emission mechanism cannot be excluded based on our data. This mechanism is likely to contribute to near-IR emission, since it is typically triggered in molecular regions in the presence of fast shocks. The X-ray radiation under 10 keV emitted by the two active nuclei is scattered and thermalized. Its contribution to the near-IR band is most noticeable in the continuum emission, associated with the north and south nuclei. Near-IR data, compared to the X-ray and optical data available, indicate that thermal excitation is the dominant mechanism but not the only one.

We are indebted to J. R. Graham for allowing us to use the IR camera and S. A. Severson, J. P. Lloyd, and D. T. Gavel for the observing. We are very grateful to W. N. Brandt for his help with the X-ray image. This work is supported in part by Pennsylvania State Eberly College of Science, the National Science Foundation with grant AST 01-38235, NASA with grants NAG 5-12115 and NAG 5-11427, and under the auspices of the US Department of Energy, National Nuclear Security Administration by the University of California, Lawrence Livermore National Laboratory under contract W-7405-Eng-48. This work was supported in part by the National Science Foundation Science and Technology Center for Adaptive Optics, managed by the University of California at Santa Cruz under cooperative agreement AST 98-76783. We acknowledge the anonymous referee for useful suggestions.

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