NICMOS OBSERVATIONS OF INTERACTION-TRIGGERED STAR FORMATION IN THE LUMINOUS INFRARED GALAXY NGC 6090

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ABSTRACT

High-resolution 1.1, 1.6, and 2.2 μm imaging of the luminous infrared galaxy NGC 6090 obtained with NICMOS on the Hubble Space Telescope is presented. These new observations are centered on the two nuclei of the merger and reveal the spiral structure of the eastern galaxy and the amorphous nature of the western galaxy. The nuclear separation of 3.2 kpc (H₀ = 75 km s⁻¹ Mpc⁻¹) indicates that NGC 6090 is at an intermediate stage of merging. Bright knots/clusters are also visible in the region overlapping the merging galaxies; four of these knots appear bluer than the underlying galaxies and have colors consistent with young (≤10⁷ yr) star clusters. The spatial coincidence of the knots with the molecular gas in NGC 6090 indicates that much of the present star formation is occurring outside the nuclear region of merging galaxies, consistent with recent studies of other double nucleus luminous infrared galaxies.

Subject headings: infrared: galaxies — galaxies: active — galaxies: individual (NGC 6090) — galaxies: starburst — stars: formation

1. INTRODUCTION

Luminous infrared galaxies have infrared luminosities L_{IR}(8–1000 μm) ≥ 10¹¹ L☉, making them some of the most luminous objects in the local universe. Interactions and mergers of gas-rich spirals are thought to play a significant role in production of the high infrared luminosities, although the exact nature of the luminosity source is still the subject of some controversy. Two of the more popular candidates for the energy source are dust-enshrouded active galactic nuclei (AGNs) or circumnuclear starbursts (Rieke et al. 1985; Joseph & Wright 1985; Sanders et al. 1988; Sanders, Scoville, & Soifer 1991), both of which are believed to be fueled by the large quantities of molecular gas concentrated at the merger nucleus. It is likely that both mechanisms play some role, and recent studies have focused on which of the two is the dominant mechanism (Sanders & Mirabel 1996 and references therein; Smith et al. 1998; Genzel et al. 1998; Lutz et al. 1998).

The luminous infrared galaxy NGC 6090 (Mrk 496 = UGC 10267; L_{IR} ≈ 3 × 10¹¹ L☉; e.g., Acosta-Pulido et al. 1996) is an interacting system in an intermediate stage of merging. At optical wavelengths, NGC 6090 appears as a double nucleus system. The separation of the radio nuclei is 5′.4, corresponding to a projected distance of 3.2 kpc. There is considerable evidence for starburst activity, but no evidence at optical or radio wavelengths for a compact AGN. Calzetti & Kinney (1992) used the dereddened Hα emission line and L₂₁ to estimate the star formation rates in NGC 6090 and show that the interacting system is undergoing a strong burst of star formation. Based on the presence of deep 2.3 μm CO absorption, Ridgway, Wynn-Williams, & Becklin (1994) argued that the near-infrared emission is probably dominated by late-type supergiants or metal-rich giant stars, as opposed to an AGN. Finally, Batsuik, Hanisch, & Burns (1992) found that the 6 cm radio emission is spatially extended (~3.9 kpc in extent), more indicative of a starburst origin than of an AGN. The emission-line spectra of both nuclei have been classified as H II based on the ratios of the [N II], [S II], and [O I] to Hα lines (Mazzarella & Boroson 1993; see also Veilleux et al. 1995), consistent with the starburst classification by Acosta-Pulido et al. (1996) based on the mid-infrared PAH features.

NGC 6090 is one of a large sample of luminous infrared galaxies to be studied as part of a program to investigate their morphologies and the source of their extremely high infrared luminosity (Scoville et al. 1999). In this paper, we concentrate on high-resolution imaging of NGC 6090 in three filters centered at 1.1, 1.6, and 2.2 μm obtained using the Near Infrared Camera and Multiobject Spectrometer (NICMOS) on the Hubble Space Telescope (HST). These images reveal new features not seen in the ground-based optical and infrared data, such as bright knots of star formation and a stellar bar in the primary galaxy. These features are compared with similar evidence of star formation in other double nucleus luminous infrared galaxies. Throughout this paper, we use H₀ = 75 km s⁻¹ Mpc⁻¹ and adopt a distance of 122.0 Mpc for NGC 6090 (Condon et al. 1990).

2. OBSERVATIONS AND REDUCTIONS

NGC 6090 was observed with camera 2 of NICMOS on board the Hubble Space Telescope on 10 November 1997 UT. Camera 2 is a 256 × 256 HgCdTe array. It has a plate scale of 0′′0762 pixel⁻¹ in x and 0′′0755 pixel⁻¹ in y, resulting in a field of view of 19′5 × 19′3 (Thompson et al. 1998). Exposures of NGC 6090 were taken using the F110W, F160W, and F222M filters, centered at 1.1, 1.6, and 2.22 μm, respectively. The data are diffraction limited with resolutions of 0′′11 (F110W), 0′′16 (F160W), and 0′′22 (F222M). The data were taken in MULTIACCUM, where the detector is read out nondestructively at intermediate stages of the integration, making it easier to identify and remove cosmic-ray spikes during the reduction phase. The
Fig. 1.—Three-color composite image of the 1.1, 1.6, and 2.22 µm data for a 15″ field of view centered on NGC 6090. The intensity scale is logarithmic. The images have been deconvolved using the Richardson-Lucy algorithm beyond the resolution of the 1.1 µm data and then smoothed with a Gaussian transfer function to a resolution of 0.′13. North is up; east is to the left.

Data were obtained using a four-point spiral dither pattern, with a 1′9125 (25.5 pixel) dither step. The exposure time at each dither position was 96 s in the F110W and F160W filters and 136 s in the F222M filter. Similarly, F222M images offset from NGC 6090 by 95″ were obtained during the same orbit and immediately after the target observations in a three-point spiral dither to measure the thermal background. The thermal background in F222M amounted to 1.8 ADU s⁻¹ and was negligible in F110W and F160W.

Data reduction was carried out using the NICMOS calibration pipeline routine CALNICA developed by H. Bushouse at STScI (see Bushouse 1997). The reductions included dark current subtraction, nonlinearity correction, and flat-fielding using on-orbit flats. Refined offsets between the individual images for a given filter were obtained using the pipeline routine CALNICB. The images were combined using Variable-Pixel Linear Reconstruction (informally known as “drizzling”) developed for undersampled, dithered images by A. Fruchter and R. Hook. The algorithm first shrinks the input pixels before projecting them onto a finer output grid (see Hook & Fruchter 1997 for a more detailed description of the technique). The pixels were over-sampled by a factor of 2, which resulted in a halving of the pixel scale of the final combined image.

Flux calibration was achieved using the conversion factors 2.03 × 10⁻⁶, 2.19 × 10⁻⁶, and 5.49 × 10⁻⁶ Jy ADU⁻¹ s⁻¹ for F110W, F160W, and F222M, respectively, and corresponding magnitude zero points of 1775, 1083, and 668 Jy (Rieke et al. 1999). The calibration yields a photometric accuracy of less than 10%. The measured fluxes in the F160W and F222M filters (which can be regarded as H and K, respectively) for a 10″ diameter beam centered on the peak of the primary galaxy agree to within
10% with ground-based observations of NGC 6090 by Carico et al. (1990). Interpolating the 1.1 $\mu$m and 1.6 $\mu$m fluxes to get a measure of the $J$ magnitude, we find a similar agreement.

Observations of a point-spread function (PSF) star were not obtained for NGC 6090 because all the nearby guide stars resided outside a 2" radius of NGC 6090, which would have required a target reacquisition with an associated time penalty we could not afford. However, observations of a PSF star, obtained for another galaxy, were taken in an identical manner as the NGC 6090 data and in the same filters. Those data were obtained one day after the NGC 6090 observations (1997 November 11 UT).

The images are diffraction limited, so the resolutions in the different filters are not the same. For this reason, we deconvolved the images beyond the resolution of the 1.1 $\mu$m image using the Richardson-Lucy algorithm and the observed PSF star. Figure 1 shows a three-color composite of the deconvolved images, which have been resmoothed to the same resolution (0.13") using a Gaussian transfer function. The Richardson-Lucy algorithm does not conserve flux, especially in the presence of a background; therefore, we have not used the deconvolved images for any of the flux measurements made in this paper. Gray-scale representations of the undeconvolved images and their respective contour diagrams are shown in Figure 2.
3. RESULTS

3.1. Morphology and Nuclear Structure

Figures 1 and 2 clearly show that NGC 6090 is in an intermediate stage of interaction. The galaxies are widely separated (3.2 kpc) compared to the separation of the nuclei of Arp 220 (∼350 pc), which is thought to be an advanced-stage merger. The optical image of NGC 6090 in Mazzarella & Boroson (1993) shows two galaxies of roughly equal size that are almost completely overlapping and a pair of tidal tails with a full extent of ≈50 kpc (80°). The NICMOS images are centered on the nuclei; while the southwestern nucleus (NGC 6090W) appears amorphous, the northeastern galaxy (NGC 6090E) clearly has distorted spiral structure. The most striking feature of NGC 6090E is the abundance of luminous blue and red knots along the western arm (i.e., the side of the galaxy closest to NGC 6090W) and the paucity of similar clusters on its eastern spiral arms. NGC 6090W also shows a similar abundance of blue knots along the western side, and one extremely luminous knot at the northern end. For simplicity, we will refer to the regions containing the knots as the overlap region.

3.2. Registration

Figure 3 shows contours of the 1.49 GHz radio continuum emission overlaid on the 2.22 μm image. The radio data with a resolution of 1′.5 were published in Condon et al. (1990) and obtained via the NASA/IPAC Extragalactic Database. The astrometric precision of HST is insufficient to register the radio contours with the NICMOS image using their absolute positions. Therefore, radio coordinates were compared with astrometry of the NGC 6090 nuclei derived from the positions of USNO-A1.0 database stars within a 7′ × 7′ R-band image of the merger (J. Mazzarella 1999, private communication). Condon et al. (1990) and Hummel et al. (1987) measured the coordinates of the northeastern radio peak to be \( \alpha_{1950} = 16^h10^m24^s56, \delta_{1950} = +52^\circ35'05''2 \) and \( \alpha_{1950} = 16^h10^m24^s54, \delta_{1950} = +52^\circ35'05''3 \), respectively. These coordinates are consistent with R-band coordinates of the northeastern nucleus, i.e., \( \alpha_{1950} = 16^h10^m24^s57, \delta_{1950} = +52^\circ35'04''8 \). However, it appears from our high-resolution NICMOS data that the southwestern radio nucleus does not correspond to the bright point source in the southwestern galaxy; thus this source is not likely the nucleus of NGC 6090W. In fact, there is evidence for enhanced diffuse emission near the southwestern radio nucleus that is a more likely candidate for the nuclear region of NGC 6090W. This enhanced emission is more apparent in the 2.2 μm contour plot in Figure 2.

3.3. Nuclear and Global Infrared Colors

Figure 4 shows \( (m_{1.1} - m_{1.6}) \) and \( (m_{1.6} - m_{2.2}) \) color maps of NGC 6090 constructed from the ratios of the 1.1, 1.6, and 2.22 μm images. In order to avoid spurious color variations due to the mismatch in the PSFs among the different filters, the shorter wavelength image was convolved with a Gaussian so that the PSFs at both wavelengths matched before taking the ratio. Some residual structure from the first diffraction ring is still apparent in Figure 4 for the bright point source in NGC 6090W. In order to minimize amplification of the noise in the color maps, only regions with signal greater than 6 times the noise are displayed.

The \( (m_{1.1} - m_{1.6}) \) color range from 1.0 mag in the nuclear region of NGC 6090E to 0.7 mag in the outer spiral arms, which are defined by prominent dust lanes. Aside from the spiral pattern, NGC 6090E has a relatively smooth and flat color structure that suggests that dust, if present, is uniformly distributed across the galaxy. The \( (m_{1.6} - m_{2.2}) \) color is similarly flat, roughly 0.2–0.3 mag across the galaxy. In contrast, NGC 6090W shows small-scale variations in color that are probably due to the presence of faint knots, but neither color map shows obvious organized structure. Its average colors are \( (m_{1.1} - m_{1.6}) = 0.7–0.8 \) mag and \( (m_{1.6} - m_{2.2}) = 0.1–0.2 \) mag. The colors derived for NGC 6090W and E are consistent with those typical of starburst galaxies and a normal late-type stellar population, \( J - H = 0.6–0.8 \) mag and \( H - K = 0.1–0.4 \) mag (Hunt et al. 1997). Ridgway et al. (1994) have detected a strong 2.3 μm CO absorption feature in NGC 6090. Since this feature is produced in the atmospheres of red giants and supergiants, the near-infrared emission is most likely dominated by supergiant or metal-rich giant stars with some reddening by interstellar dust (Ridgway et al. 1994).

3.4. Cluster Colors

As mentioned in §3.1, the new high-resolution images of NGC 6090 reveal a number of luminous knots, or clusters, several of which appear to be much bluer \( (m_{1.1} - m_{1.6} < 0.6) \) than the underlying galaxies. The positions, apparent magnitudes, and colors of 12 knots measured in NGC 6090W and E are given in Table 1. The positions are listed as offsets from the peak emission in the 2.22 μm image. Table 1 includes only those knots with magnitudes brighter than 20 mag for which we were able to obtain reliable flux measure-
ments. The magnitudes were calculated from aperture photometry using the IRAF task APPHOT. Because of potential confusion from the background, the flux in each knot was first measured in a small aperture (typically 4–6 pixels in radius) and adjusted later based on aperture correction tables computed from the observed PSF star. The background galaxy flux was estimated using the median of the flux in a 3–5 pixel annulus located at a radius of typically 7–11 pixels from the center of the knot. This was far enough from the source to ensure that the flux in the far wings of the diffraction pattern was not included in the background measurement, but close enough to obtain a measure of the true surrounding flux.

In order to estimate the uncertainty in the photometry, we simulated the data by scaling the PSF star to magnitudes ranging from the brightest ($\sim 16$ mag) to the faintest ($\sim 20$ mag) observed clusters and adding the scaled PSFs into various regions in the data of NGC 6090. We then tried to recover the known flux using our aperture photometry technique. Not surprisingly, the largest uncertainty at faint magnitudes is caused by difficulty in determining the background level. At 18 mag and brighter, we found the uncertainty to be 0.1 mag in all three bands, consistent with the formal error in the flux due to Poisson noise and detector readout. This is also consistent with the uncertainties in the photometric calibrations. For magnitudes between 18 and 20 mag, the uncertainty grows to as much as 0.3 mag at 1.1 and 1.6 $\mu$m. The error is slightly worse at 2.2 $\mu$m because of a combination of poorer signal-to-noise ratio data and broader PSF. Since we are interested in the colors of the clusters, we have tried to be consistent in our measurements of the cluster fluxes among the different filters. Given that

| Number | $\Delta\alpha^a$ | $\Delta\delta^a$ | $m^b_{1.1}$ | $m^b_{1.25}$ | $m^b_{1.6}$ | $m^b_{2.2}$ | $m^b_{1.25-1.6}$ | $m^b_{1.6-2.2}$ |
|--------|-----------------|-----------------|--------------|--------------|--------------|--------------|------------------|------------------|
| 1 …….. | W 5.78          | −3.09           | 17.23        | 17.00        | 16.39        | 15.87        | 0.69             | 0.23             |
| 2 …….. | W 5.49          | −3.84           | 20.11        | 20.00        | 19.63        | 19.25        | 0.45             | 0.10             |
| 3 …….. | W 5.02          | −4.72           | 19.69        | 19.45        | 18.84        | 18.50        | 0.69             | 0.06             |
| 4 …….. | W 4.92          | −5.03           | 19.93        | 19.73        | 19.18        | ...          | 0.63             | ...              |
| 5 …….. | W 5.17          | −3.57           | 19.81        | 19.60        | 19.03        | 18.79        | 0.65             | −0.04            |
| 6 …….. | W 5.21          | −3.28           | 19.70        | 19.53        | 19.04        | 18.56        | 0.57             | 0.20             |
| 7 …….. | W 2.56          | 1.70            | 19.79        | 19.68        | 19.31        | ...          | 0.45             | ...              |
| 8 …….. | W 1.84          | 1.98            | 19.23        | 19.01        | 18.42        | 17.67        | 0.67             | 0.47             |
| 9 …….. | W 0.96          | 0.76            | 19.13        | 19.11        | 19.03        | 18.55        | 0.16             | 0.10             |
| 10 ……. | W 1.16          | 0.34            | 18.73        | 18.71        | 18.59        | 18.08        | 0.20             | 0.13             |
| 11 ……. | W 1.62          | −0.40           | 18.24        | 18.25        | 18.18        | 17.60        | 0.15             | 0.30             |
| 12 ……. | W 0.78          | −1.42           | 20.14        | 20.13        | 20.00        | 18.55        | 0.21             | 1.17             |

* Offsets are in arcseconds relative to the peak of NGC 6090E in the 2.2 $\mu$m image, $\alpha_{1950} = 16^\text{h}10^\text{m}24.56^s$, $\delta_{1950} = +52°35'05.2''$.

* Magnitudes have typical uncertainties of $\pm 0.1$–$0.3$ mag.

* Magnitudes interpolated from $m_{1.1}$ and $m_{1.6}$ magnitudes.
we expect the errors to be systematic, we estimate the associated uncertainty in the colors to be roughly the same as that of the flux measurements, i.e., 0.1–0.3 mag.

The average colors of clusters 1–8 in Table 1 are $J - H = 0.60$ and $H - K = 0.17$, consistent with the colors of an old stellar population. The colors are similar to those of the old globular cluster systems around the galaxy NGC 5128 with ages greater than $10^6$ yr (Frogel 1984), but are also consistent with the colors of highly reddened young star clusters. In addition to the red clusters, there are four relatively blue clusters in the spiral arm of NGC 6090E that have colors consistent with a younger population of stars. The average $J - H$ color for clusters 9–12 is $\sim 0.18$ mag. The average $H - K$ color is 0.43 mag, but it has a large spread, probably reflecting the fact that the uncertainties can be quite large in $K$ at the faintest magnitudes. Compared with the typical colors for a population of stars with ages less than or equal to $6 \times 10^6$ yr, $J - H \simeq 0.25$, and $H - K \simeq 0.50$ mag, the clusters appear to be consistent with young star-forming regions with little infrared reddening by interstellar dust. Two colors are not sufficient to fully constrain the ages of the clusters, and spectroscopy is needed to confirm whether they really are young stars reddened by interstellar dust or evolved unreddened stars.

The brightest point source in NGC 6090W is considerably brighter than any of the other clusters in the galaxy. In fact, in the 1.1 and 1.6 $\mu$m images, it has a peak brightness that is greater than that of the nucleus of NGC 6090E. We have assumed throughout this section that this source is a very luminous star cluster. This is a reasonable assumption based on its colors, which are consistent with the rest of the clusters in NGC 6090W, but we cannot rule out the possibility that it may be a foreground star.

4. DISCUSSION

The close nuclear separation, the high infrared luminosity, the extended optical tidal tails, and the double nucleus of NGC 6090 are all evidence of galaxy-galaxy interaction. Of the two merging systems, NGC 6090E most resembles its progenitor—a spiral disk seen face-on—with evidence for a stellar bar in its inner disk. The bar is most evident in the 2.22 $\mu$m contour plot in Figure 2. Numerical simulations show that during a merger, tidal forces from a companion galaxy trigger the formation of a bar in the disk of the perturbed galaxy (Noguchi 1988; Shlosman, Frank, & Begelman 1989; Shlosman, Begelman, & Frank 1990). The bar acts to trigger starburst activity by rapidly funneling large amounts of gas to the nuclear regions. A correlation between stellar bars and stellar activity appears to be present for Seyfert galaxies (Maiolino et al. 1997), and there is evidence that a significant fraction of starburst galaxies may contain stellar bars in their disks (Colina et al. 1997; Contini, Considere, & Davoust 1998). The star formation rate derived for NGC 6090E by Calzetti & Kinney (1992) indicates that the galaxy is undergoing an intense burst of star formation, where the present star formation rate (SFR) is a factor of 10 above the average SFR. If the SFR is primarily associated with the nucleus of NGC 6090E, the nuclear starburst region is only 135 pc ($\sim 0\!':25$) in extent.

The evidence for luminous clusters in the overlap region of NGC 6090 indicates that most of the star formation visible at these wavelengths may actually be off-nuclear. This is supported by millimeter (CO) observations of this merger, which show a single dominant component of molecular gas, centered approximately midway between the two nuclei (Bryant & Scoville 1999). The CO emission appears elongated and aligned along the direction between the radio nuclei (P.A. $= 60^\circ$). Using the standard conversion factor, the molecular gas mass is determined to be $1.4 \times 10^{10} M_\odot$ (Sanders et al. 1991). In contrast, the velocity width of CO emission is narrow ($\Delta v = 136$ km s$^{-1}$ FWHM), indicating a dynamical mass of $M_{dyn} = 4.60 \times 10^9 M_\odot$ for the molecular gas complex, although it is unlikely to be self-gravitating or virialized (Bryant 1996). Given the abundance of molecular gas and its spatial coincidence with the putative young star clusters, the most likely scenario for the activity in the overlap region is that the gas has been stripped from the progenitors, and that localized star formation has resulted (e.g., Barnes & Hernquist 1996; Mihos & Hernquist 1996).

The presence of molecular gas and star formation in the overlap region of merging galaxies may be quite common. Both the luminous infrared galaxies NGC 6240 (Bryant & Scoville 1999; Tacconi et al. 1999) and VV 114 (Yun, Scoville, & Knop 1994; Frayer er al. 1999) have most of their molecular gas and dust mass in the overlap region. Recent NICMOS images of VV 114 show the presence of numerous star clusters between the two nuclei (Scoville et al. 1999). The slightly less luminous merger Arp 244 (also known as the Antennae galaxies) also has a substantial fraction of its molecular gas concentrated between the two nuclei (Stanford et al. 1990), and recent Infrared Space Observatory (ISO) imaging and spectroscopy has shown that the most significant starburst occurring in that merger is occurring in the overlap region (Mirabel et al. 1998). However, this morphology is not ubiquitous among mergers that still harbor separated nuclei—the ultraluminous ($L_{IR} > 10^{12} L_\odot$) infrared galaxy Arp 220, which is a comparatively advanced merger, has a significant amount of its molecular gas and mid-infrared emission associated with the nuclei (Sakamoto et al. 1999; Soifer et al. 1999). Thus, the presence of star formation in the overlap region likely depends on the structure of the merging galaxies and the stage of the merger (e.g., Mihos & Hernquist 1996).

5. SUMMARY

We have obtained high-resolution images of the luminous infrared galaxy NGC 6090 with NICMOS on the Hubble Space Telescope in three broadband filters centered at 1.1, 1.6, and 2.22 $\mu$m. The images show the eastern galaxy to have spiral structure and a nuclear bar, and the western galaxy to be amorphous. The galaxies involved in the interaction exhibit bright blue knots, which we interpret as star-forming regions. The spatial coincidence of the knots and the molecular gas in the region overlapping the two merging galaxies is similar to that observed in other luminous infrared galaxies, and provides evidence that much of present star formation in intermediate-stage mergers may occur outside the nuclei of mergers.

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