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# THE NEAR-INFRARED MORPHOLOGY OF ULTRALUMINOUS INFRARED GALAXIES

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## ABSTRACT

Near-infrared images at 1.25 $\mu$m, 1.65 $\mu$m, and 2.2 $\mu$m have been obtained of nine galaxies from the *IRAS* Bright Galaxy Sample with infrared luminosities $L_{IR} \geq 10^{12}\ L_\odot$. Two of the 2.2 $\mu$m images reveal previously undetected double nuclei, increasing the number of close double nuclei known for this sample from two to four. For three of these four sources, the colors of *both* nuclei are substantially different from those of normal spiral galaxies, indicating that the high activity state in high-luminosity mergers tends to occur in both nuclei. Three sources show 2.2 $\mu$m emission that is more centrally concentrated than the emission at 1.3 $\mu$m, a result that can be explained as the effects of dust emission and/or extinction or, alternatively, as the result of direct emission at 2.2 $\mu$m from the accretion disk of a central active galactic nucleus. Implications of these results for the model that galaxy collisions lead to quasar formation are briefly discussed. Finally, from the frequency and separation of the double nucleus sources, the lifetime of the ultraluminous phase of galaxies is estimated to be $\sim 4 \times 10^8$ yr.

*Subject headings:* galaxies: interactions — galaxies: nuclei — infrared: general — quasars

## I. INTRODUCTION

The most luminous galaxies from the *IRAS* Bright Galaxy Sample (Soifer *et al.* 1989) are the "ultraluminous" infrared galaxies with infrared luminosities[1] $L_{IR} \geq 10^{12}\ L_\odot$. Sanders *et al.* (1988, hereafter S88) made an extensive study of the ultraluminous galaxies and have presented a model in which these galaxies represent a phase in the formation of quasars. This *Letter* presents near-infrared images of nine of the 10 ultraluminous infrared galaxies studied by S88. These are the first high-resolution images available of the nuclei of these galaxies at infrared wavelengths, and since these objects are known to be heavily obscured by dust, it is clear that knowledge of their infrared morphologies is essential to an understanding of their nature.

## II. OBSERVATIONS

The images were obtained using a near-infrared camera at the Cassegrain focus of the 200 inch (5 m) Hale telescope at the Palomar Observatory. The camera uses a 58 × 62 array of InSb photodiodes held to a temperature of 32 K and has a scale of 0".31 pixel$^{-1}$ at the f/70 Cassegrain focus, giving a field of view approximately 19" square. The images were all obtained between 1988 October and 1989 July in both photometric and nonphotometric conditions. The 2.2 $\mu$m seeing ranged from 0".8 to 2".5, with a mean of ~1".3. Broad-band 1.25 $\mu$m ($J$), 1.65 $\mu$m ($H$), and 2.2 $\mu$m ($K$) filters were used, with typical integration times between 30 and 120 s, depending primarily on radiation background (the ambient temperature). In all cases, sky subtraction was achieved by imaging the sky near the source immediately after the source was observed. Most of the objects were imaged more than once, and for those cases the multiple images were co-added by aligning the centroids of the brightest 2.2 $\mu$m peak. The galaxies observed are listed in Table 1.

[1] $L_{IR}$ is an estimate of the integrated luminosity between 8 and 1000 $\mu$m; see Sanders *et al.* (1988).

## III. RESULTS

Contour maps of the 2.2 $\mu$m images are shown in Figure 1, and magnitudes for 2".5 and 5" diameter beams are given in Table 1. The 5" photometry is from S88. The 2".5 magnitudes were calculated from the sky-subtracted images shown in Figure 1 and were calibrated by defining the flux in a 5" diameter beam, reconstructed in software on each image, to be that measured by S88 for that source. Hence the *difference* in flux between the 2".5 and 5" diameter beams is given directly by the images. The near-infrared colors are plotted in Figure 2.

A brief discussion is now given of those sources for which the near-infrared images are significantly different than the visible images. Note that frequent reference is made to the visible wavelength images which were presented by S88.

*IRAS 05189−2524.*—This source has a single nucleus at visible wavelengths with faint tails and was identified by S88 as possibly a nearly completed merger. The 2.2 $\mu$m image also shows a single nucleus, with near-infrared colors which do not change significantly with beam size. There is an apparent elongation in the northwest(NW)-southeast(SE) direction, not seen in the visible image, with a full width at half-maximum (FWHM) of 1".9, compared to 1".0 in the orthogonal direction. Stellar images taken during the night of observation appear circular, suggesting that this elongation is a genuine feature of the galaxy; however, an effect this small requires further confirmation.

*IRAS 08572+3915.*—The visible image shows two galaxies of roughly comparable brightness separated by ~6" (6 kpc at the source). The 2.2 $\mu$m image also shows both galaxies, but the NW source appears much brighter than the SE source; the color differences between the two nuclei are $\Delta(J-H) = 0.45 \pm 0.1$ mag and $\Delta(H-K) = 1.15 \pm 0.4$ mag. The SE nucleus has colors significantly redder than those expected for a "normal" galaxy, with a ~0.4 mag excess at $K$. The NW source shows the most extreme $H-K$ color of any source in this sample, a fact representative of its extremely unusual near-infrared energy distribution (see Carico *et al.* 1988); further-

TABLE 1

OBSERVATIONAL DATA

| Object Name | Log[$L_{IR}/L_{\odot}$] | Separation Between Nuclei (kpc) | Position[a] | Beam Diameter (″) | Near Infrared Colors[b] (mag) K | H–K | J–H |
|---|---|---|---|---|---|---|---|
| IRAS 05189–2524 | 12.10 | <1.6 | | 5.0 | 10.22 | 1.23 | 1.27 |
| | | | | 2.5 | 10.55 | 1.26 | 1.33 |
| IRAS 08572+3915 | 12.09 | 6.3 | NW | 5.0 | 13.11 | 1.54 | 0.95 |
| | | | | 2.5 | 13.29 | 1.84 | 1.14 |
| | | | SE | 2.5 | 15.52 | 0.69 | 0.69 |
| UGC 5101 | 12.01 | <0.6 | | 5.0 | 11.13 | 1.08 | 0.95 |
| | | | | 2.5 | 11.57 | 1.29 | 1.03 |
| IRAS 12112+0305 | 12.29 | 4.0 | MID | 5.0 | 13.25 | 0.69 | 0.92 |
| | | | SW | 2.5 | 14.21 | 0.81 | 0.92 |
| | | | NE | 2.5 | 14.42 | 0.76 | 0.82 |
| Mrk 231 | 12.52 | <1.0 | | 5.0 | 8.87 | 1.17 | 1.31 |
| | | | | 2.5 | 9.12 | 1.37 | 1.34 |
| IRAS 14348–1447 | 12.29 | 5.3 | MID | 5.0 | 13.27 | 0.82 | 0.89 |
| | | | SW | 2.5 | 13.75 | 0.94 | 0.96 |
| | | | NE | 2.5 | 14.29 | 0.85 | 0.95 |
| IRAS 15250+3609 | 12.00 | <2.0 | | 5.0 | 13.05 | 0.52 | 0.76 |
| | | | | 2.5 | 13.70 | 0.64 | 0.74 |
| Arp 220 | 12.19 | <0.7 | | 5.0 | 11.18 | 0.76 | 1.15 |
| | | | | 2.5 | 11.80 | 0.90 | 1.34 |
| IRAS 22491–1808 | 12.13 | 2.4 | MID | 5.0 | 13.55 | 0.46 | 0.72 |
| | | | W | 1.9 | 14.97 | 0.39 | 0.77 |
| | | | E | 1.9 | 15.07 | 0.23 | 0.83 |

[a] The position of the beam relative to the two nuclei for sources with a double nucleus. "MID" refers to a position midway between the two nuclei, encompassing both; all other designations refer to a position centered on the indicated nucleus.

[b] Uncertainties in the 2″.5 photometry are ~0.07 mag, except for the southeast nucleus of IRAS 08572+3912 for which the uncertainty at $K$ is ~0.4 mag. The data for a 5″ diameter beam are from Sanders *et al.* 1988.

more, this nucleus is more compact at 2.2 μm than at 1.3 μm, as evidenced by the change in near-infrared colors with beam diameter (see Fig. 2). Note, however, that the 10″ diameter beam presumably contains emission from both nuclei.

*UGC 5101*.—The visible image shows a nearby companion, ~50″ to the west, and considerable tidal structure. The 2.2 μm image shows a single nucleus (the companion is well outside of the field of view of the image), which is more compact at 2.2 μm that at 1.3 μm, as seen in a color difference of almost 0.5 mag in $H-K$ between the 2″.5 and 10″ diameter beams (see Fig. 2).

*IRAS 12112+0305*.—The visible image is dominated by a single bright nucleus; there appears to be a second, much fainter nucleus about 6″ (~9 kpc) south, and the morphology is highly distorted at low light levels. The 2.2 μm image does not show this faint nucleus but does show two clearly distinct nuclei separated by 3″ (4 kpc). These nuclei are roughly similar in their near-infrared colors, both being considerably redder than normal galaxies.

*IRAS 14348−1447*.—The visible image shows two nuclei, separated by ~3″.5 (6 kpc), with extended tidal structure. In the 2.2 μm image, the two nuclei are more clearly delineated, presumably due to the improved resolution of the near-infrared images. The nuclei have similar near-infrared colors, both being considerably redder than normal galaxies.

*Arp 220*.—The visible image shows extended tidal structure and two apparent peaks separated by ~7″ (2.6 kpc); the dominant visible peak is to the north. The infrared peak is located roughly midway between the visible peaks (Joy *et al.* 1986) and is extended in the E-W direction, with a FWHM in that direction of ~2″ (0.7 kpc). No evidence is seen at 2.2 μm for the second visible peak, adding further support to the interpretation of this peak as an effect of a dust lane in the galaxy. Also, the 2.2 μm emission is more centrally concentrated than the 1.3 μm emission, as seen in the color change between the 2″.5 and 10″ diameter beams (see Fig. 2); this fact was noted earlier by Neugebauer *et al.* (1987).

*IRAS 22491−1808*.—This galaxy is the only one of the galaxies studied by SBB with an H II region spectrum rather than that of an active galactic nucleus (AGN). The visible image shows tidal tails but only a single nucleus, whereas the 2.2 μm image clearly shows two distinct nuclei, separated by ~1″.6 (2.5 kpc). The near-infrared colors of the two nuclei are similar to those of normal galaxies, with evidence for a small amount of reddening.

## IV. DISCUSSION

The 2.2 μm emission in these systems is a combination of reddened starlight, thermal emission by hot dust, and possibly direct emission by the accretion disk of the dust-enshrouded AGN. As is clear from the energy distributions of these objects presented by S88, the relative contributions of these components vary significantly from source to source.

Three of the galaxies—IRAS 05189−2524, Mrk 231, and Arp 220—were classified by S88 as probably completed mergers, based on the presence of tidal tails extending from a single nucleus. Neither IRAS 05189−2524 nor Mrk 231 show

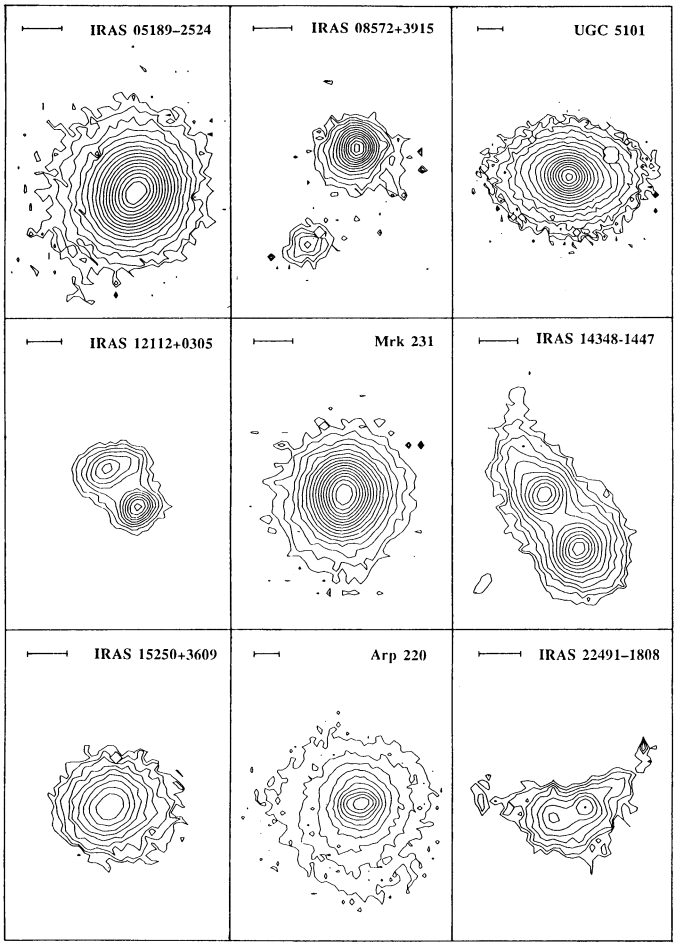


FIG. 1.—Images at 2.2 μm of nine ultraluminous infrared galaxies listed in Table 1. In all plots, north is toward the top of the figure, and east is to the left. The horizontal bars in the upper left-hand corner of each plot represent an angular distance of 2″; the contours are logarithmic with a factor of $2^{1/2}$ between levels.

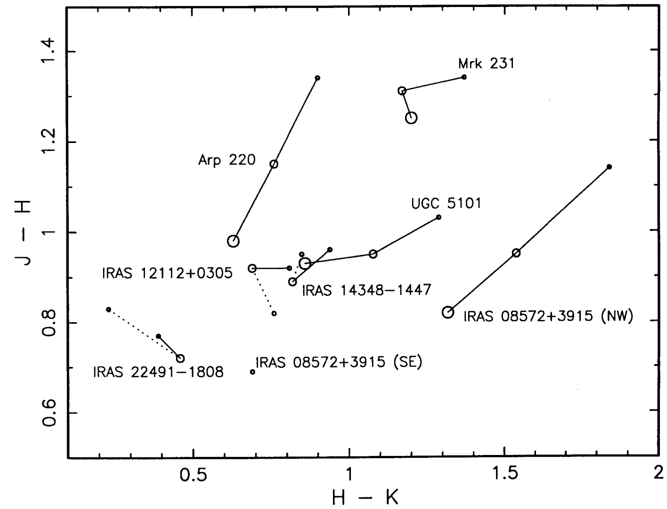


FIG. 2.—The near-infrared colors of the ultraluminous galaxies. Two of the sources which show essentially no change in near-infrared colors with beam size—IRAS 05189 – 2524 and IRAS 15250 + 3609—have been left out to simplify the figure. The smallest circles represent the colors measured from the near-infrared images using a 2″.5 diameter "beam" (see text); the mid-sized and largest circles are the colors obtained from S88 using their 5″ and 10″ diameter beam measurements, respectively. Lines connect the colors for each source determined from the various beam sizes. For sources with two nuclei, colors corresponding to the brighter nucleus are connected with a solid line, and those corresponding to the fainter nucleus are connected with a dashed line. Note that the larger diameter beams encompass *both* nuclei in IRAS 12112 + 0305, IRAS 1438 – 1447, and IRAS 22491 – 1808, but only the brighter (NW) nucleus in IRAS 08572 + 3915.

any clear evidence for more than one nucleus at 2.2 μm either, adding further support for the hypothesis that these mergers are essentially complete. However, for Arp 220, the 2.2 μm peak seen in Figure 1 is clearly extended, and recent higher resolution images have succeeded in resolving this feature into two distinct 2.2 μm peaks, which may indicate a double nucleus for this source (Graham *et al.* 1990).

The colors in Table 1 and Figure 2 show a clear increase in the central concentration of the 2.2 μm emission relative to that at 1.3 μm for three of the sources—IRAS 08572 + 3915, UGC 5101, and Arp 220. There are three possible causes for this effect:

1. Extinction from dust in the central 1–2 kpc would deplete the observed 1.3 μm emission relative to the 2.2 μm emission.

2. Emission from dust in the interstellar medium within the central 1–2 kpc can contribute at 2.2 μm. The dust would have to be extremely hot or the emission would have to be dominated by temperature fluctuations in small grains.

3. It is possible that direct 2.2 μm emission from the accretion disk of the AGN is being seen at the smallest radii (cf. Phinney 1989; Sanders *et al.* 1989).

In three of the four sources which show double nuclei at 2.2 μm—IRAS 08572 + 3915, IRAS 12112 + 0305, and IRAS 14348 – 1447, the near-infrared colors of *both* nuclei exhibit unusually red energy distributions at near-infrared wavelengths. Thus, the formation of an ultraluminous infrared galaxy appears to be generally a process of the collision of two galaxies wherein both galaxy nuclei undergo a high-activity phase. This result should be contrasted with the result for more widely separated interacting galaxies, where typically only one member of the pair shows unusual infrared colors (Joseph *et al.* 1984). In the fourth double-nucleus source, IRAS 22491 – 1808, the near-infrared colors in a 5″ diameter beam were known to be only slightly redder than those of normal galaxies (S88), and the present analysis shows that both nuclei have essentially normal colors.

The results of these observations have several implications which tend to support the model proposed by S88 that the ultraluminous *IRAS* galaxies represent a stage in the formation of a quasar. First of all, the strongest evidence for galaxy collisions is the presence of close double nuclei. With the current results, the number of close double nuclei in the ultraluminous galaxies has been increased to four, and ultimately five (referring to the results mentioned above for Arp 220 from Graham *et al.* 1990). Second, the fact that three of the four confirmed double-nucleus sources have excessively red near-infrared colors in *both* nuclei implies a high gas/dust content in both nuclei, which is what was hypothesized in the statement of the theory by S88. Finally, the increased compactness of the 2.2 μm emission relative to the 1.3 μm emission in IRAS 08572 + 3915, UGC 5101, and Arp 220 suggests an increase in the concentration of gas and dust with decreasing radius in these sources, which may be evidence for the funneling of molecular gas into the nuclear regions as a result of the dissipation of orbital angular momentum, as required by the galaxy collision model.

From the frequency of double nuclei in the current sample, one can estimate crudely the lifetime of the ultraluminous phase of infrared bright galaxies. The starting point is the assumption that the ultraluminous galaxies represent snapshots at different stages of an evolutionary sequence, in which two galaxies undergo a collisional interaction. Then, if there is no change in luminosity with time during the ultraluminous phase (there is certainly no obvious ordering of luminosity with the double nuclei or single nuclei in Table 1, and in any case the range in luminosity in Table 1 is only a factor of $\sim 3$), the fraction of the sources in a particular phase is proportional to the lifetime of the sources in that phase. The four double-nucleus sources of Figure 1 represent roughly half of all the ultraluminous infrared galaxies in the *IRAS* Bright Galaxy Sample, a complete, flux-limited sample. The remaining ultraluminous galaxies in this sample appear to be either completely merged, as with the single-nucleus sources, or in a postcollision phase, as with the galaxies with nearby companions seen in the visible wavelength images in S88. This suggests that the lifetimes of the premerged and postmerged (or postcollision) phases of the ultraluminous stage are roughly the same.

One can get an order-of-magnitude estimate of the lifetime for the premerged phase from the average separations. $N$-body simulations indicate that a reasonable approximation for the time scale for orbital decay of two merging nuclei from dynamical friction is given by $t_{\rm dyn} \sim (M/m) \times t_{\rm orb}$, where $M$ and $m$ are the masses of the nuclei, $M$ referring to the more massive of the two, and $t_{\rm orb}$ is the orbital period (E. S. Phinney, private communication). The average separation of the nuclei in the current sample (projected onto the plane of the sky) is $\sim 4.5$ kpc, so that a typical orbital velocity of 300 km s$^{-1}$ gives $t_{\rm orb} \sim 10^8$ yr. One can then assume that $M/m$ is equal to the ratio of observed fluxes of the two nuclei at 1.65 $\mu$m, where the stellar continuum from the nuclei presumably dominates. For the four double nuclei in this sample, the ratios of the 1.65 $\mu$m flux densities lie in the range 1–3. Using $M/m \sim 2$, one then obtains $t_{\rm dyn} \sim 2 \times 10^8$ yr, which gives a total lifetime for the ultraluminous infrared galaxy phase of $\sim 4 \times 10^8$ yr.

If this estimate for the lifetime of the ultraluminous infrared phase in galaxies is accepted, and if one adopts the model proposed by S88 that such systems evolve into quasars, it is possible to make an order-of-magnitude estimate of the lifetime of quasars. Sanders *et al.* (1989) show that the space density of the ultraluminous infrared galaxy phase essentially equals or slightly exceeds that of the optically selected quasars at the same bolometric luminosity. Thus the lifetime of the quasar phase roughly equals that of the ultraluminous phase, i.e., $t_{\rm qso} \sim 4 \times 10^8$ yr. This estimate is the same as the Eddington lifetime of such objects (see, e.g., Rees 1984).

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