NICMOS OBSERVATIONS OF LUMINOUS & ULTRALUMINOUS INFRARED GALAXIES

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Abstract.

HST NICMOS observations of a sample of 24 luminous (LIGs: $L_{\rm IR}[8-1000\mu{\rm m}] = 10^{11.0-11.99} L_\odot$) and ultraluminous (ULIGs: $L_{\rm IR}\gtrsim 10^{12.0} L_\odot$) infrared galaxies are presented. The observations provide, for the first time, high resolution HST imaging of the imbedded 1.1 - 2.2 μm nuclear regions of these mergers. All but one of the ULIGs are observed to have at least one compact (50-200 pc) nucleus, and more than half contain what appear to be blue star clusters. The warm infrared galaxies (i.e., the transition sources) are observed to have bright nuclei which account for most of the light of the galaxy. This, combined with the tendency for the light of ULIGs to become more centrally concentrated as a function of increasing wavelength, implies that most of their energy is generated within a region 50-200 pc across.

1. Introduction

There exists strong morphological and spectroscopic evidence that ultraluminous infrared galaxies (ULIGs) are the by-products of the merger/interaction of molecular gas-rich galaxies, and that their extreme luminosities result from circumnuclear starbursts and active galactic nuclei (AGN). During the ultraluminous phase, the radiation from the starburst/AGN, most of which is emitted at UV-to-optical wavelengths, is absorbed by circumnuclear dust and re-emitted at infrared/submillimeter wavelengths.

Of direct relevance to this conference is whether stars or AGN account for the majority of the energy output of ULIGs. Based on the similarities in the luminosity functions of ULIGs and QSOs, and the evidence for morphological pecularities and large molecular gas masses in some QSOs, Sanders et al. (1988a,b) proposed an evolutionary connection between ULIGs and QSOs. A population of "warm" ULIGs (i.e., $f_{25}/f_{60} > 0.2$, similiar to the colors of Seyfert galaxies) were singled out as an advanced stage of

TABLE 1
ULTRALUMINOUS INFRARED GALAXIES

Name	Class[a]	z	$\log L_{ir}$ $\log L_{\odot}$	Nuclear Separation	NICMOS Characteristics
NGC 4418	...	0.0073	11.00	24 kpc	Linear nuclear structure with biconical dark lanes
Zw049.057	H II	0.0131	11.22	...	Inclined spiral with linear dust lane
NGC 6090	H II	0.0294	11.51	3.6 kpc	Galaxies separate - early in merger phase
NGC 2623	...	0.0185	11.54	...	Clusters surrounding an extended nucleus
IC 883	LINER	0.0231	11.60	...	Disk with clusters and a tidal tail
NGC 7469	Seyfert 1	0.0166	11.60	28 kpc	Point-like nucleus in spiral
VV 114	H II	0.0201	11.62	5.2 kpc	Colliding galaxies
NGC 6240	LINER	0.0243	11.82	0.8 kpc	Double nuclei with tails
VIIZw031	H II	0.0542	11.94	...	Compact spiral with asymmetric outer structure
IR 15250+36	LINER	0.0534	12.00	...	Nucleus surrounded by clusters
IR 09320+61	LINER	0.0400	12.01	...	Point-like nucleus with twisting spiral isophotes
IR 10565+24	H II	0.0430	12.02	6.2 kpc	Spiral galaxy interacting with companion
IR 08572+39	LINER	0.0582	12.09	5.6 kpc	point-like nuclear galaxy with companion
IR 22491-18	H II	0.0773	12.10	2.2 kpc	Double nuclei + tidal tails
IR 05189-25	Seyfert 2	0.0427	12.10	...	Elliptical-like galaxy with Point-like nucleus
Mrk 273	LINER	0.0378	12.11	0.7 kpc	Diffuse and point-like nuclei
Arp 220	LINER	0.0185	12.19	0.3 kpc	Embedded double nuclei in close proximity
PKS 1345+12	Seyfert 2	0.1224	12.22	4.0 kpc	Radio galaxy with double nuclei
IR 12112+03	LINER	0.0727	12.26	3.8 kpc	Point-like + extended nuclei with sickle-shaped tail
IR 14348-1447	LINER	0.0825	12.27	4.9 kpc	Colliding spirals
IR 17208-00	H II	0.0429	12.40	...	Complex, Arp220-like nucleus surrounded by clusters
IR 07598+65	Seyfert 1	0.149	12.45	...	Point-like source with extended structure
Mrk 1014	QSO	0.163	12.49	...	QSO nucleus + spiral tails
3C 48	QSR	0.398	12.50	...	QSR with extended structure

[a]Based on optical emission-line ratios (Kim 1995; Veilleux et al. 1995).

the ULIG phenomenon, occuring between the "cool" ultraluminous phase, when enhanced star formation is occuring and the AGN is being built, and the optical QSO phase, when most of the gas and dust have been consumed/blown out by star formation and the AGN.

The high column densities intrinsic to ULIGs have made attempts to image their nuclear regions at optical wavelengths difficult. Observations with ground-based arrays sensitive to radiation emitted at near-infrared wavelengths (where the extinction is ten times lower than at optical wavelengths) have improved our ability to observe the morphology and colors of imbedded regions, but have been limited by atmospheric seeing (FWHM $\approx 0.7''$: Murphy et al. 1996; Kim 1996). The availability of the Near-Infrared Camera and Multiobject Spectrometer (NICMOS), recently installed on the Hubble Space Telescope (HST), thus offers a unique opportunity to study ULIGs by combining near-infrared technology with the high resolution and photometric accuracy possible with a space-based instrument.

As part of NICMOS GTO program, a sample of 15 ULIGs (9 cool, 4 warm, 2 QSOs) were observed with Camera 2 of NICMOS at 1.1, 1.6, and 2.2 μm. For comparison, images of a sample of 9 LIGs were also obtained. Camera 2 provides a $0.1'' - 0.2''$ resolution (FWHM) at 1.1–2.2 μm and a 19″ field of view, which correspond to a resolution of 25-200pc and projected field of view of 4-40 kpc for the redshift range of 0.01–0.15. The specific issues to be addressed are: 1) Is there evidence of imbedded star clusters or multiple/unresolved nuclei that may be responsible for the far infrared emission? 2) Is there evidence for interactions/mergers in infrared galaxies that were previously observed to show none? 3) Is there evidence that a large fraction of the light from ULIGs emanates from increasingly more compact regions as a function of increasingly wavelength, as might be expected for an AGN? 4) How do the imbedded cluster colors compare with the colors of the underlying galaxy? Below, each of these issues is addressed. An $H_0 = 75$ km s^{-1} Mpc^{-1} and $q_0 = 0.0$ are assumed throughout.

2. Morphologies and Nuclear Luminosities

Table 1 contains a general summary of the properties of the 24 galaxies observed, and Figure 1 shows several examples of their near-infrared morphologies. The statistics of the data are as follows: 22/24 galaxies show morphological disturbances to varying degrees (note that the two exceptions, IR 05189-25 and 07598+65, have large-scale, low surface-brightness optical debris outside of the nuclear region: Surace et al. 1998); 11/24 of the galaxies show evidence of spiral structure/arms; 11/24 have double nuclei with projected separations ranging from 0.3–7.0 kpc (two additional galaxies, NGC 4418 and 7469, have companion galaxies ≈26 kpc away, i.e., out of the NICMOS field of view); 16/24 have one or more blue star clusters.

In ground-based images of VIIZw031 (Figure 1) and IR 10565+24, both have elliptical galaxy-like nuclear appearances (Djorgovski et al. 1990; Murphy et al. 1996). In the NICMOS images, the central 0.5–1.0″ of the galaxies have spiral structure, supporting the idea that the formation of a LIG or ULIG involves at least one spiral galaxy. Similar nuclear spiral structure is also revealed in HST images of NGC 7252 (Whitmore et al. 1993).

Putative nuclei with $L_{2.2\mu\rm m} \approx 2 \times 10^7 - 10^{11}$ L$_\odot$ have been identified in all galaxies. Several of these "nuclei" have been detected in CO, and all but a few have strong Paα and radio emission. With the exception of IR 17208-00, all of the ULIGs contain at least one compact (i.e., FWHM $\lesssim$70-200 pc) nucleus. The more compact cores tend to be the more luminous. In particular, all of the warm ULIGs, whose nuclei at first glance look like stars, have very luminous nuclei.

3. Nuclear Concentrations

Using 1.1″ and 11″-diameter apertures, the percentage of the total galactic light contained within the nucleus of the galaxies were measured. The smaller aperture size was selected to contain the first airy disk of the un-

Figure 1. NICMOS images of six of the LIGs/ULIGs. Blue=1.1 μm, Green=1.6 μm, and Red=2.2 μm. The galaxy name and $\log(L_{\rm IR})$ are provided in the bottom corners of each panel. The field of view is $\approx 19'' \times 19''$/panel. North is up, east is to the left.

resolved 2.2 μm nuclei, thus minimizing photometric errors due to the different resolutions of the 1.1, 1.6, and 2.2 μm images. The ULIGs with the lowest f_{60}/f_{100} ratio (e.g. the cool ULIGs Arp 220, IR 12112+03) had the lowest value of $f(1.1'')/f(11'')$ [$\approx$ 0.15-0.3 at 2.2 μm], whereas the warm ULIGs, which have high f_{60}/f_{100} ratios, have high values of $f(1.1'')/f(11'')$ [$\approx$ 0.70]. The galaxy UGC 5101 (IR 09320+61: Figure 1), has an intermediate value of $f(1.1'')/f(11'')$ [=0.42], indicating that its 2.2 μm emission emanates from the nucleus and underlying disk in nearly equal amounts.

Finally, $f(1.1'')/f(11'')$ increases as a function of increasing wavelength in nearly all of the galaxies, possibly indicating that their emission becomes more centrally concentrated at longer wavelengths. This is due in part to the waning contribution of light from the extended underlying stellar population at wavelengths longward of 1.6 μm.

4. Infrared Colors

Figure 2 is a plot of $m_{1.1-1.6}$ vs. $m_{1.6-2.2}$ for all of the galaxies in the sample, extracted using a 1.1″-diameter aperture. Most of the LIGs and cool ULIGs are in a linear scatter with a slope consistent with starlight reddened by a screen of cold dust, however, a QSO embedded in warm (> 1000K) dust cannot be ruled out for galaxies at the high end of the linear scatter of points (e.g., Arp 220, IR 17208-00, IC 883, NGC 2623). Whether starlight or AGN, the nuclear energy sources of these galaxies are heavily embedded.

While all of the galaxies have $m_{1.1-1.6}$ colors between 0.7 and 2.0, the warm ULIGs have high values of $m_{1.6-2.2}$ and lie on or to the right of the QSO–1000K dust line. Thus, in addition to being extremely compact and bright, the nuclei of the warm galaxies are also abnormally red. The similarities in the colors and nuclear compactness of warm ULIGs and QSOs lends strong support to the idea that warm ULIGs possess QSO nuclei.

Two LIGs and one cool ULIG also lie in the region of Figure 2 occupied by the warm ULIGs. One of the LIGs, NGC 7469, is a warm infrared galaxy ($f_{25}/f_{60} = 0.22$) with a bright Seyfert 1 nucleus embedded in a spiral galaxy. The cool ULIG, UGC 5101, contains a bright nucleus embedded in a spiral galaxy. In an 11″-diameter aperture, both galaxies are indistinguishable from any of the other cool ULIGs. Thus, UGC 5101 and NGC 7469 may be intermediate cases, possessing warm, QSO-like infrared nuclei embedded in cool (and very luminous) infrared galaxies.

5. Star Clusters

A similar color analysis has been done of the clusters ($L_{2.2\mu\mathrm{m}} \approx 10^4 - 10^7 L_\odot$) in a few of the galaxies. While no attempt has been made to constrain the ages of the clusters, the cluster colors appear to be bluer than the underlying

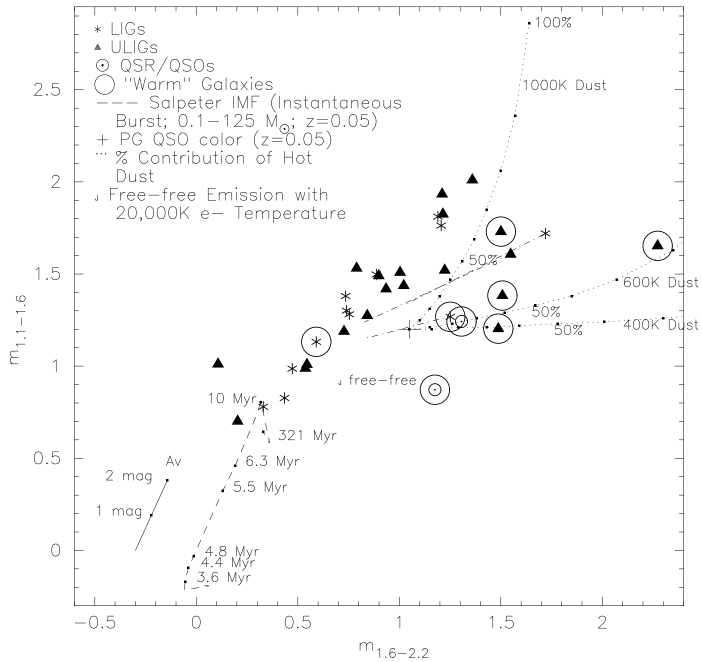

Figure 2. Infrared Magnitude Color Diagram for LIGs/ULIGs measured in 1.1″-diameter aperture. The dash-dotted line extending from UGC 5101 (triangle), VV 114 (*), and NGC 7469 (*) indicate how far the galaxies move on the diagram when their colors are measured in 11″-diameter apertures. Adapted from Scoville et al. (in prep).

galaxies, which are bluer than the nuclei. If the assumption is made that the effects of extinction are moderate or negligible outside of the nuclear region, the star clusters are much younger than the underlying stellar population and are probably by-products of the merger event.

Acknowledgements

It is a pleasure to thank my collaborators N. Scoville, N. Dinshaw, M. Rieke, D. Hines, R. Thompson, J. Surace and the NICMOS GTO Team. This research was supported NASA grant NAG 5-3042.

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