AN HST IMAGING SURVEY OF THE ULTRALUMIMOUS IR GALAXIES: IN SEARCH OF THE POWER SOURCE

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Abstract

We present results derived from a recent Hubble Space Telescope imaging survey of the Ultraluminous IR Galaxies. The most significant issue related to this sample of galaxies has been identifying the nature of the primary energy source: starburst or AGN? Through a high-resolution imaging survey of a large sample. some properties of this class of objects are now being better defined, which is helping to clarify the nature of the energy source. Fine structure is seen within the central arcsecond of each galaxy in the sample. In some cases, the structure is smooth and centrally concentrated, suggestive of a bright nuclear energy source (AGN?). In many other cases. the sub-arcsecond morphology is chaotic and extended. suggestive of strong starburst activity. The peculiar, disturbed morphologies that are seen on large (kiloparsec) scales among this sample of galaxies are continued down to the smallest scales in the cores of these strongly starbursting systems. A variety of morphological features are noted, many of which are related to the recent intense interaction-induced star formation episode. These starburst-related features (e.g., numerous bright clumps of star formation, shells. and bubbles) are similar to those seen in previous HST imaging observations of the Cartwheel Ring Galaxy, the Antennae (NGC 4038/4039), NGC 7252. and other strongly interacting and merging galaxies.

1 Introduction and Motivation

The study of interacting and merging galaxies grew significantly after the discovery by IRAS that the most IR–luminous galaxies are quite often very disturbed. A number of follow-up studies focussed on the most luminous galaxies in this group. the ULIRGs (UltraLuminous InfraRed Galaxies). which have total bolometric luminosities (frequently derived only from the

60-μm luminosity) in excess of $10^{12}L_{\odot}$. Such studies have revealed that the ULIRGs are the most strongly starbursting of all galaxies in the local universe, have twice the space density of quasars, emit >90% of their power in the IR, are rich in the raw materials of star formation, and to a large extent owe their peculiar morphologies to encounters with other galaxies [12, 13, 7, 11].

Studies of well selected samples of these extraordinary objects will lead to a greater understanding of massive star formation, galaxy formation and evolution, metal enrichment in the universe, and cosmological evolution [11].

2 The HST (Hubble Space Telescope) Imaging Survey

We are carrying out an HST imaging survey of a well defined sample of ULIRGs. Our sample consists of 160 galaxies that were chosen from several published lists. Among these is the first "bright" sample of 10 galaxies that satisfied the $L_{IR} > 10^{12}L_{\odot}$ constraint that was compiled by Sanders et al. [12]. A second, partially overlapping, "warm" sample of 12 galaxies (9 new ones) was also identified at that time by Sanders et al. [13]. An additional, partially overlapping, "bright" sample of 17 galaxies in the south was later compiled by Melnick & Mirabel [7]. Lawrence et al. [6] found another 126 low-flux objects in the QDOT all-sky redshift survey of IRAS galaxies, while Kim et al. [5] and Clements et al. [2] have added to the numbers at low flux levels. Our final target selection was limited to galaxies with redshifts $z < 0.20$.

Our HST imaging survey utilizes the WFPC2 imager, with the F814W filter (wide I-band; $\lambda_{eff} \approx 8000\text{Å}$). Each object is imaged for 800 sec, via two 400-sec exposures (to assist in the removal of cosmic radiation events in the individual images). In most cases, the ULIRG is centered in one of the wide-field camera CCDs ($80'' \times 80''$). In 7 cases of bright ULIRGs, we also imaged the galaxy with its center in the planetary camera CCD ($35'' \times 35''$). Each CCD consists of 800×800 pixels, with FWHM ≈ 2 pixels. To date, we have obtained images for over 110 galaxies in our sample.

3 Ground-Based Comparisons, New Results, and Serendipity

Several new discoveries have been made through our HST imaging survey of the ULIRG sample.

A strong dust lane and a system of extended filaments have been seen near the center of IR13428+5608 = Mrk 273 (Figure 1a). The filaments are similar to those seen in M82 and are probably indicative of a strong outflow of material induced by a massive star formation event. The dust lane, which passes within $3''$ of the nucleus, is coincident with the strong tidal arm that stretches across the galaxy and extends out to several galactic radii. The core of the galaxy is very sharp, nearly unresolved, and very bright.

A second spiral arm has been detected in the Seyfert 1 (QSO?) IR00509+1225 = I Zw 1 (Figure 1b). The more extended arm (out to $14''$) was already recognized. The "new" arm, extending to a radius of $8''$, was previously detected (with some uncertainty) only via K-band speckle imaging by Eckart & Schinnerer (private communication). The difficulty in detecting this second arm was due to the extremely bright star-like nucleus in I Zw 1.

Among the most interesting galaxies in the ULIRG sample is IR19254−7245 (the Super-Antennae [7]). With a morphology similar to NGC 4038/4039 [15], it is clearly the result of a collision between two colliding spiral galaxies. In the case of the SuperAntennae, the tidal arms have a total end-to-end extent of 350 kpc [10]! We have resolved the two galaxies' nuclei ($8''$ separation) and have discovered a small torus (or dust ring) with diamater $\approx 2''$ around the center of each galaxy (Figure 2a). The southern component is a known Seyfert galaxy and this new torus may be related to the AGN inhabiting the core of the galaxy. It is possible that the northern galaxy also hosts an AGN, but the active nucleus is obscured from view by the massive quantities of dust in the system that are contributing to the strong IR flux.

A serendipitous discovery among the sample of Melnick & Mirabel [7] is the beautiful ring galaxy IR21130−4446, which appears to be caught in the act of formation (Figure 2*b*), with outer ring diameter $\approx 6''$. It looks very similar to an oblique view of a collision-induced ring galaxy shortly after pericenter passage (cf. Figure 9 of Mihos & Hernquist 1994 [8]), probably an early stage of the kind of event that produced the spectacular Cartwheel ring galaxy [1, 14]. This newly identified ring galaxy candidate (IR21130−4446) may prove to be very useful in the following sense. It may be possible to estimate (i) a dynamical age of the system from the morphological features of the system (cf. [8]), (ii) a photometric age for the system from the timing of the peak in the IR luminosity (usually occuring after the first pericenter passage or near the end of a strong merging encounter between two spiral galaxies [9]), and (iii) a spectrochemical age from stellar population spectral modeling (as in the excellent studies of Fritze-Von Alvensleben [3, 4]). A comparison of these three independently derived timescales would provide tremendous insight into the physics and the timing of all of these separate phenomena: the tidal interaction trigger, the ULIRG development, and massive star formation.

The major benefit of the HST images is in the high angular resolution ($\sim 0.1 - 0.2''$). With this resolving power, a number of ULIRGs that were previously classified as "non-interacting" have now revealed secondary nuclei at their centers (remnant nuclei from a merger event?) and additional tidal features (tails, loops). An example of one such system is shown in Figure 3: row 2, column 1. It now appears that the fraction of ULIRGs that show evidence for interaction is very close to 100%. Observational estimates of this number have varied from 30% to 100% over the past 10 years, but it now seems to be converging on a value significantly above 90%.

The most significant question pertaining to the ULIRG phenomenon is the identity of the power source. That power source is generating the ultra-high IR luminosities ($L_{\rm IR} > 10^{12} L_\odot$) through dust heating and the corresponding conversion of the shorter-wavelength radiation into IR radiation. Veilleux (these proceedings) has shown that the frequency of AGN-powered ULIRGs increases sharply at $L_{\rm IR} \geq 10^{12.3} L_\odot$. It is very likely then that a combination of starburst power and AGN power is responsible for the ULIRG phenomenon among the various galaxies comprising the whole sample, and it is even possible that both power sources contribute energy in varying proportions within each individual ULIRG. In the latter scenario, the higher-luminosity ULIRGs are dominated by the AGN power source and the lower-luminosity ULIRGs (still quite luminous) are dominated by the starburst power source. We have noted a particular morphological tendency in our HST images: objects that have clear stellar nuclei (i.e., unresolved nuclei) also seem to be those that have been classified (from ground-based spectral observations) to be AGN (Seyferts or radio galaxies or QSOs). For example, among a sample of the QDOT galaxies [6] shown in Figure 3, some of those with nuclei that appear most star-like are also those classified as AGN (e.g., Figure 3: row 1, column 2; row 2, column 3; and row 3, column 3). In total, about 10% of our total sample have AGN-like (i.e., stellar) nuclei. This may represent the true fraction of ULIRGs that are dominated by an AGN power source. In the other cases, the observed near-IR flux (in our HST images) is clearly spatially distributed among numerous bright star-forming (starbursting) knots, which are very likely therefore the primary energy sources for dust-heating.

4 Early Results from the HST Survey of ULIRGs

Our HST imaging survey of the ULIRG galaxy sample has led to the following early results:

1. The strong morphological disturbances that are ubiquitous on large scales are continued down into the nuclei. down to the smallest scales measurable by HST. All of the galaxies in the ULIRG sample show some structure on sub-arcsecond scales. The chaotic structures that are seen include: tidal loops; bubbles, shells. and rings; dust (sometimes organized, sometimes chaotic): and super star clusters (?).

2. There is clear evidence for distributed star formation (starburst regions) in and around the nuclei of the ULIRGs. These starburst regions are similar to the knots (young star clusters?) seen in previous HST imaging studies of the Cartwheel ring galaxy [1, 14], the Atoms-for-Peace galaxy NGC 7252 [16], and the Antennae NGC 4038/4039 [15].

3. In the majority of the galaxies, there is evidence for star formation on all scales. This wide, global distribution of heating from young, massive stars may indicate that the starburst event is the dominant heating source for the majority of ULIRGs.

4. A "stellar" (AGN-like) nucleus is seen in ~10% of the ULIRGs. For this small sample, the dominant heating source may be a dust-enshrouded active nucleus.

5. Several of the galaxies show clear evidence for a circumnuclear (starburst?) ring (with a diameter of a few hundred kpc). This may be related to a dusty torus surrounding an AGN, as seen in previous HST images of active galaxies.

6. Some of the galaxies previously classified as "non-interacting" show clear evidence for a secondary nucleus (merger remnant?) or other evidence for interaction (e.g., tidal tails) on small angular scales.

7. Some of the ULIRGs should be re-classified as "compact groups of galaxies". Additionally, in many instances, there are a significant number of small companion galaxies in the same CCD chip as the ULIRG, with fewer companions in the other WFPC2 CCD chips. This suggests that the small, fainter companions are physically associated with the ULIRG. Very few large companions are seen, though there are a few notable examples of this.

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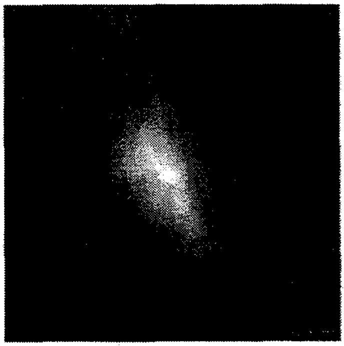


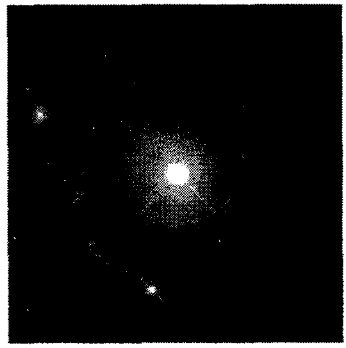
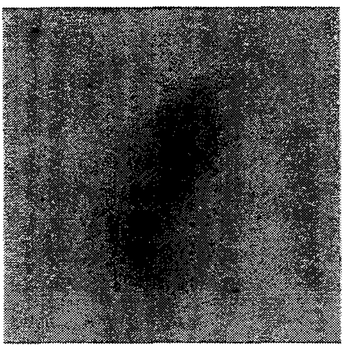


Figure 1: Left (Fig. 1a) = IR13428+5608 = Mrk 273. Right (Fig. 1b) = IR00509+1225 = I Zw 1. (See §3 text for details.)



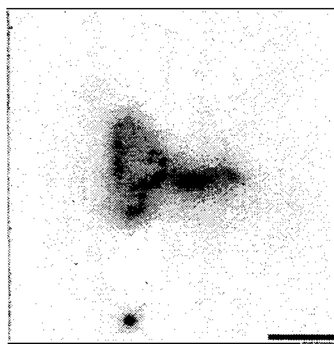


Figure 2: Left (Fig. 2a) = IR19254−7245 = SuperAntennae. Right (Fig. 2b) = IR21130−4446. (See §3 text for details.)

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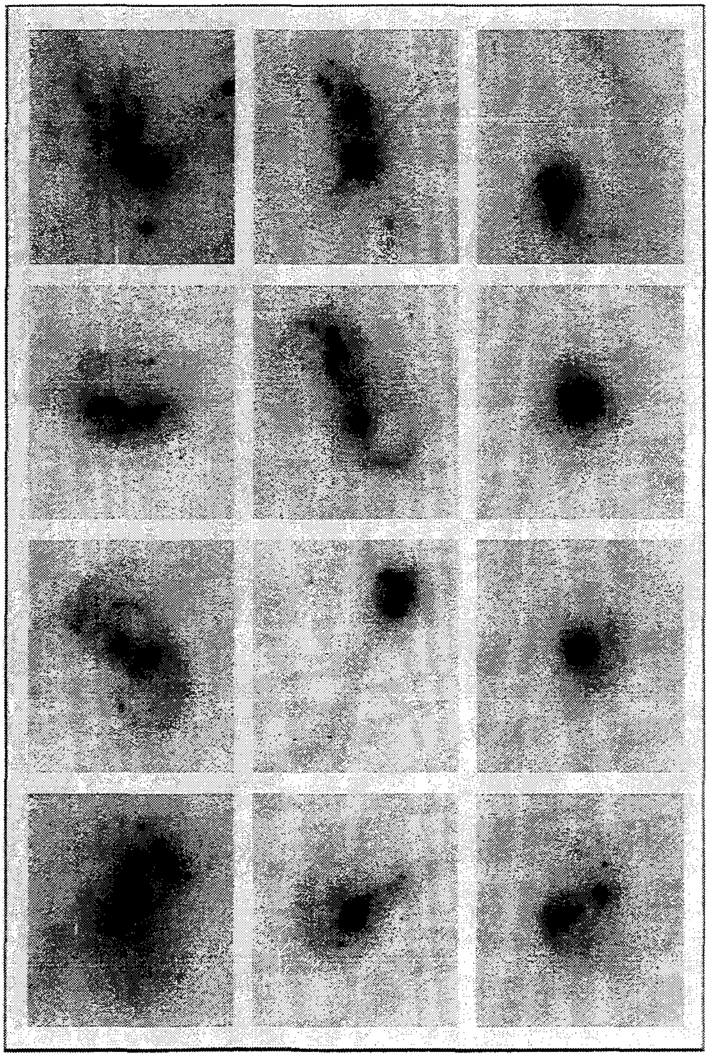

Figure 3: Selected HST WFPC2 I-band images (each 10″ square) for 12 ULIRGs selected from the QDOT sample of galaxies [6]. Note the clear interaction/merger morphology for most of the galaxies, but also note the AGN-like appearance of at least 3 of them: #2 in the first row, #3 in the second row, and #3 in the third row. Each of these latter three objects have ground-based spectra corresponding to an AGN (Seyfert, QSO, or radio galaxy).