A MORPHOLOGICAL CLASSIFICATION SCHEME FOR ULIRGS

Evidence for Multiple Mergers

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1. Introduction
The Hubble Space Telescope (HST) has been used to study a large sample of ultraluminous IR galaxies (ULIRGs). With a rich legacy database of ~150 high-resolution images, we are studying the fine-scale structure of this unique collection of violently starbursting systems (Borne et al. 1997a,b,c,d). We review here some of the latest results from our survey.

2. An HST Imaging Survey
Our combined data set includes ~120 WFPC2 I-band (F814W) images and ~30 NICMOS H-band (F160W) images. These are being used for multi-color analyses over a significant wavelength baseline. The NICMOS images are used specifically to probe through some of the dust obscuration that plagues the shorter wavelength images. The full set of images is being used to study the galaxies’ cores and starburst regions. Nearly all ULIRGs show evidence for a recent tidal interaction, and we are identifying the merger
progenitors near the center of each galaxy, a task made significantly easier with the H-band images. These images are proving to be particularly useful in mapping the spatial distribution of starburst activity in these galaxies, in verifying the presence or absence of a bright active nucleus, in deriving the distribution (in both size and luminosity) of the multiple nuclei seen in these galaxies, and in determining if these multiple cores are the merger’s remnant nuclei or super star clusters formed in the merger/starburst event.

3. HST Results and Serendipity

Several new discoveries have been made through our HST imaging survey of the ULIRG sample (see Fig. 1 for some representative images). A few specific results are presented in the following discussion.

3.1. MRK 273 = IR13428+5608

A strong dust lane and a system of extended filaments have been discovered near the center of Mrk 273. The filaments are similar to those seen in M82 and are probably indicative of a strong outflow induced by a massive starburst. The central region of the galaxy contains several separate cores, which may be remnant cores from more than 2 merging galaxies.

3.2. THE SUPERANTENNAE = IR19254–7245

One of the most interesting ULIRGs is IR19254–7245 (the SuperAntennae; Mirabel et al. 1991). With a morphology similar to the Antennae galaxies (N4038/39; Whitmore & Schweizer 1995), it is clearly the result of a collision between two spirals. In the case of the SuperAntennae, the tidal arms have a total end-to-end extent of 350 kpc — 10 times larger than the Antennae! We have resolved the two galaxies’ nuclei (8″ separation) and have discovered a small torus with diameter ≈ 2″ around the center of each galaxy (Fig. 1c). The southern component is known to have an active nucleus and the torus may be related to the AGN. It is possible that the northern galaxy also hosts an AGN, but the active nucleus is obscured from view by a large column of dust. Follow-up higher-resolution images with the HST PC have revealed a double-nucleus at the center of each galaxy, clearly suggesting a multiple-merger origin for the SuperAntennae.

3.3. INTERACTION / MERGER FRACTION

Given the high angular resolution (∼0.1–0.2″) of our HST images, a number of ULIRGs that were previously classified as “non-interacting” have now revealed secondary nuclei at their centers (remnant nuclei from a merger
Figure 1. HST I-band images of 6 representative ULIRGs. (a) Upper Left – IR1858+6527 – A significant fraction of the ULIRGs appear very disturbed, though primarily showing evidence for only a single remnant galaxy (presumably the remnant of a major merger event). In many of these cases, massive star formation is seen on all scales in the HST images, including super star clusters of the type seen in HST images of other colliding galaxies, indicating that a giant starburst is the dominant power source in most ULIRGs. (b) Upper Middle – IR00509+1225 – A star-like nucleus is seen in 15% of the ULIRGs, for which the dominant power source may be a dust-enshrouded AGN/QSO. (c) Upper Right – IR19254−7245 – Many ULIRGs show evidence for strong interactions among two or more galaxies. Several of the galaxies show clear evidence in HST images for a ring around the central nucleus (as shown here). These are very similar to the rings seen in HST images around the centers of other ‘black hole’-powered galaxies (e.g., NGC 4261). (d) Bottom Left – IR21130−4446 – There is evidence for at least one classical collisional ring galaxy in the sample, similar to the Cartwheel ring galaxy imaged by the HST. (e) Bottom Middle – IR1717+5444 – Some ULIRGs previously classified as non-interacting from ground-based images now show in HST images clear evidence of merging (a second nucleus) or of interaction (e.g., tidal tails). (f) Bottom Right – IR1353+2920 – Many ULIRGs appear to have physically associated companion galaxies, which may be related to the collision, merger, and subsequent burst of star formation. In these cases, the signs of interaction (e.g., distortions) are sometimes weak.

event?) and additional tidal features (tails, loops). An example of one such system is shown in Figure 1e. 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% (as indicated in the early work by Sanders et al. 1988).
3.4. AGN FRACTION

The most significant question about the ULIRG phenomenon is the nature of the power source. That power source is generating the ultra-high IR luminosities ($L_{\text{IR}} > 10^{12}L_{\odot}$) through dust heating and the corresponding conversion of UV/optical radiation into IR radiation. Veilleux et al. (1997) have shown that the frequency of AGN-powered ULIRGs increases sharply at $L_{\text{IR}} \geq 10^{12.3}L_{\odot}$. 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 unique proportions within each individual ULIRG. In the latter scenario, the power source for the higher-luminosity ULIRGs is mainly the AGN and for the lower-luminosity ULIRGs (still quite luminous) it is the starburst. We have noted a particular morphological tendency in our HST images: objects whose nuclei appear most star-like (i.e., unresolved) also seem to be those that have been classified (from ground-based spectroscopic observations) to be AGN. About 15% of our total sample have unresolved nuclei (similar to the AGN fraction found by Genzel et al. 1998, and others). 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 HST images) is clearly spatially distributed among numerous bright star-forming (starbursting) knots, which therefore are very likely the primary energy sources for dust-heating.

4. Morphological Classification of ULIRGs

We have examined a complete subsample of ULIRG images and have identified 4 main morphological classes, plus 2 additional sub-classes (which are included in the main classes for statistical counting purposes). Figure 1 depicts 6 representative ULIRGs, one from each of these classes:

1. Strongly Disturbed Single Galaxy (Fig. 1a)
2. Dominant AGN/QSO Nucleus (Fig. 1b)
3. Strongly Interacting Multiple-Galaxy System (Fig. 1c)
4. Weakly Interacting Compact Groupings of Galaxies (Fig. 1f)
5. Collisional Ring Galaxy (Fig. 1d)
6. Previously Classified Non-Interacting Galaxy (Fig. 1e)

We show in Table 1 the distribution of ULIRGs among these morphological classes. It is seen here that there is little luminosity dependence among the classes and that there is a roughly equal likelihood that a ULIRG will appear either single (classes 1 and 2) or multiple (classes 3 and 4).
TABLE 1. ULIRG Morphological Classes

| Class                     | Number | Fraction | $< \log L_{IR}/L_{\odot} >$ | Notes          |
|---------------------------|--------|----------|-----------------------------|----------------|
| Disturbed Singles         | 30     | 34%      | 11.85                       | morph. class 1 |
| AGN/QSO Nucleus           | 13     | 15%      | 11.74                       | morph. class 2 |
| Interacting Multiples     | 29     | 33%      | 11.81                       | morph. class 3 |
| Compact Groupings         | 14     | 16%      | 11.94                       | morph. class 4 |
| Collisional Rings         | 1-3    | ~1-3%    | ...                         | re-classified  |
| “Non-Interacting”         | ~5     | ~5%      | ...                         | re-classified  |

5. Evidence for Multiple Mergers

Many of the recent results on ULIRGs are pointing to a complicated dynamical history. It is not obvious that there is a well-defined dynamical point during a merger at which the ULIRG phase develops, nor is it clear what the duration of the ultraluminous phase is. Our new HST imaging surveys indicate that the mergers are well developed (with full coalescence) for some ULIRGs. Others show clear evidence for 2 (or more) nuclei. While others (~5%) can best be described as wide binaries, still a long way from coalescence. One possible explanation for this dynamical diversity has been proposed recently by Taniguchi & Shioya (1998). They suggested a multiple-merger model for ULIRGs. In this scenario, the existence of double nuclei is taken as evidence of a second merger, following the creation of the current starburst nuclei from a prior set of mergers. In fact, this would indicate for some systems (with double AGN or double starburst nuclei) that the currently observed merger is the third (at least) in the evolutionary sequence for that galaxy. This may seem unrealistic, but it may not be so unreasonable if these particular ULIRGs are remnants of previous compact groups of galaxies. Compact groups are known to be strongly unstable to merging, and yet examples are seen in the local (aged) universe. These may be the tail of a distribution of dynamically evolving galaxy groups. Similarly, the ULIRGs are presumed to be historically at the tail end of a distribution of major gas-rich mergers. A connection between the two populations, if only in a few cases, is therefore not unreasonable. Figure 2 presents images of 12 ULIRGs from our HST sample that appear to have evolved from multiple mergers. The evidence for this includes: >2 remnant nuclei, or >2 galaxies, or an overly complex system of tidal tails, filaments, and loops.
Figure 2. Sample of ULIRGs whose morphologies appear to be derived from > 1 merger.

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