Galaxies and Their Constituents at the Highest Angular Resolutions
IAU Symposium, Vol. 205, 2001
R.T. Schilizzi, S. Vogel, F. Paresce and M. Elvis

Merging Galaxies with Multiple Nuclei from HST ULIRGs Snapshot Survey

J. Cui[1], X.-Y. Xia[1,2], Z.-G. Deng[1,3], S. Mao[4] and Z.-L. Zou[1]

[1] *Beijing Astronomical Observatory and Beijing Astronomical Center of the National Astronomical Observatories, Chinese Academy of Sciences, A20 Datun Road, Beijing 100012, China*

[2] *Dept. of Physics, Tianjin Normal University, Tianjin 300074, China*

[3] *Dept. of Physics, Graduate School, Chinese Academy of Sciences, Beijing 100039, China*

[4] *Jodrell Bank Observatory, University of Manchester, Macclesfield, Cheshire SK11 9DL, UK*

Abstract.

We perform photometric measurements on a large *HST* snapshot imaging survey sample of 97 ultraluminous infrared galaxies (ULIRGs). We classify all the sources into three categories with multiple, double and single nucleus/nuclei, mainly based on a quantitative criterion of *I*-band luminosity. The resultant fractions of multiple, double and single nucleus/nuclei ULIRGs are 18%, 39% and 43%, respectively. This supports the multiple merger scenario as a possible origin of ULIRGs, in addition to the commonly-accepted pair merger model. Further statistical studies indicate that the fraction of AGN increases from multiple (18%) to double (39%) and then to single (43%) nucleus/nuclei ULIRGs. For the single nucleus category, there is a high luminosity tail in the luminosity distribution, which corresponds to a Seyfert 1/QSO excess. This supports the statement that active galactic nuclei tend to appear at final merging stage. For multiple and double mergers, we also find a considerably high fraction of very close nucleus pairs (e.g., 2/3 for those separated by less than 5 kpc). This strengthens the conclusion that systems at late merging phase preferentially host ULIRGs.

1. Sample and data reduction

We use archive data from an *HST* snapshot imaging survey of ULIRGs (Borne *et al.* 2000). The sample images were taken using the *Wide Field Planetary Camera 2* (WFPC2) in the *I*-band pass (F814W), including 97 targets all centered in the WF3 chip, of which the resolution is 0.0996 *arcsec* per pixel and the FOV is 800×800 pixels. For each target in this survey, two 400 s exposures were taken.

The sample images were first preprocessed through the *standard Space Telescope Science Institute* (STScI) pipeline, using a standard WFPC2-specific calibration algorithm and the best available calibration files (Holtzman *et al.* 1995).

https://doi.org/10.1017/S007418090022086X Published online by Cambridge University Press

Our post-pipeline calibrations include detection and removal of warm pixels and cosmic ray events. The additional steps of data reduction are discussed below.

We use the standard *IRAF* task *imexamine* to browse carefully the sources in the ULIRGs sample. For each target, three plots are displayed and compared with each other – the contour plot, the surface plot and the snapshot image. By careful comparison, common local brightness enhancements appearing on each plot are marked as putative clumps.

In order to distinguish true physical clumps from Poisson fluctuation peaks in the images, we make rough FWHM measurements on the marginally detectable brightness peaks, and fluctuations are identified to be those peaks with FWHMs smaller than the typical value of observed PSF of *HST* WF3 chip with F814W filter. Then, we perform surface photometric measurements on the selected clumps to determine their *I*-band fluxes and luminosities.

2. Identification of galactic nuclei

Given one of the remarkable features of ULIRGs is that there always exist many kpc or sub-kpc scale luminous clumpy structures; and the key issue in our work is to distinguish galactic nuclei from star cluster associations. It is found that typical masses for both galactic nuclei in ULIRGs and the giant elliptical cores are several times of $10^9 M_\odot$ (Sakomoto *et al.* 1999). This is typically larger than the mass found for star formation knots at nearby starburst galaxies. On the theoretical side, too massive complexes with more than $10^9 M_\odot$ mass may suffer from disintegration (Noguchi 1999). In addition, Taniguchi *et al.* (1998) suggested that a large mass of $10^9 M_\odot$ corresponds to a maximum star formation efficiency of 1 for knots evolving from superclouds in gravitationally unstable gas disks. Since the real star formation efficiency must be smaller (e.g., 0.1 from observations of the Galaxy), observed knots are always less massive than $10^9 M_\odot$. Given these, we conservatively adopt $1 \times 10^9 M_\odot$ as the lower mass limit to pick out galactic nuclei from bright clumps in the first step.

To express the above threshold in an observational quantity, the lower mass limit is converted to *B*-band luminosity using a constant mass-to-light ratio of 6.5 appropriate for spheroids (Fugukita *et al.* 1998). And the resultant value of $1.54 \times 10^8 L_\odot$ corresponds to $M_\mathrm{B} = -15.0$. Adopting the statistical results of Surace *et al.* (1998) that the typical $B - I$ color index for putative nuclei in ULIRGs is 2.0 with the root mean square of 0.7, we obtain the lower M_I limit of -17.0 mag as a quantitative criterion to pick out galactic nuclei from bright clumps. This is consistent with the argument that bright knots may have an upper luminosity limit for intense star-formation in a star cluster (Hutchings 1995).

3. Results

Based on the quantitative criterion discussed in Sec. 2 as well as morphological structures, we pick out all the putative galactic nuclei from clumpy structures in each sample galaxy. And all the 97 ULIRGs can be classified as three categories according to the number of their nuclei:

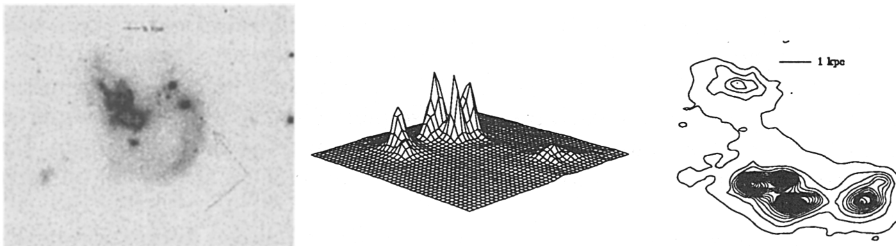

Figure 1. Snapshot image, surface and contour plots for IR 18580+6527. Scale ruler is 5 *kpc* in the snapshot image and 1 *kpc* in the contour plot. The morphology of this galaxy is rather complicated. A strong tidal ring can be seen from the image and its diameter is about 20 kpc. The main galxy is clearly composed of four compact nuclei as shown in the surface and contour plots. These four nuclei are very bright each with I-band absolute magnitute around -20.0 mag. 6 kpc away to the north of these four nuclei locates the fifth nucleus with I-band absolute magnitude of nearly -19.0, which is not very likely to be a star cluster association.

1. Multiple nuclei ULIRGs (multiple mergers), 2. Double nuclei ULIRGs (double/pair mergers) and 3. Single nucleus ULIRGs (single remnants)

Our results show that among all the 97 ULIRGs of the treated sample, 17 are multiple nuclei systems, 38 are double nuclei systems, while the remaining 42 have only one identifiable galactic nucleus. This gives plausible fractions of ULIRGs with multiple, double and single nucleus/nuclei as 18%, 39% and 43%, respectively. These results evidently support the multiple merger scenario as a possible origin of ULIRGs, in addition to the widely-accepted pair merger picture. Figure 1 is an example of ULIRGs with multiple nuclei.

Besides putative nuclei, there often exist several bright knots in most of the sample galaxies. One of the significant characters of these bright knots is that they tend to distribute around nuclear regions, or in regions between/among separate nuclei. This is consistent with the argument that star-forming concentrations are preferentially situated along the overlapping areas of interacting galactic disks.

The I-band magnitude distributions of multiple/double mergers and single nucleus galaxies give a median I-band magnitude of -19.3 $(2.3 \times 10^9 L_\odot)$ and -20.1 $(4.7 \times 10^9 L_\odot)$, respectively. The high median luminosity for the single nucleus category is partly due to the merger-induced formation of massive, bright bulges, and partly due to the triggering of active galactic nuclei (AGN) phenomenon in a substantial fraction of merger remnants

Further investigation based on the optical spectra available in the literature shows that the proportions of HII region-like spectra are 64% (9/14), 35% (8/21) and 20% (5/25) for multiple, double and single nucleus/nuclei galaxies, respectively. While the proportions of AGN for these three categories are 36% (5/14), 65% (13/21) and 80% (20/25). This clear trend of gradually changing proportions of different spectral types suggests that the M$\rightarrow$D$\rightarrow$S sequence is also one with energetics from dominated by starburst to considerably powered by central AGN.

4. Some hints for merging dynamics

From luminosity distributions for three categories, it is obvious that galactic nuclei in single nucleus ULIRGs tend to be more luminous than those in multiple/double mergers. Statistical studies on available spectral information also reveal that there is a Seyfert 1/QSO excess in the single nucleus category. Therefore, our results strongly support the argument of Kauffmann & Haehnelt (2000) that bulge and supermassive black hole may both grow in galaxy merging. And they also give some hints to a possible close relation of central black hole with properties of its host galaxy's bulge (Gebhardt *et al.* 2000).

Based on the morphology investigation for all snapshot images, it is no doubt that most ULIRGs with single nucleus have weak interacting signatures (in many cases, only weak plume structures are detectable). On the other hand, peculiar morphologies frequently emerge in double/multiple nuclei ULIRGs, such as long tidal tails and distinct ring structures. This indicates that strong interacting features always thin out at final merging phase, which is consistent with results from numerical simulations (e.g., Barnes & Hernquist 1996).

From the detailed analysis for this high resolution image sample, we can see that multiple merger processes may be very complicated and the morphologies of their intermediate products may be very diverse. This indicates that the evolutionary history of interactions/mergers in galaxy groups must vary due to different initial conditions. When a group of galaxies begins to merge, the central massive spiral may swallow its satellite galaxies one by one; on the other hand, merging process may also happen between several galaxy pairs or among sub-groups simultaneously, then these separate parts start a second merging step. Major mergers between comparably massive spirals alone cannot account for the dynamical diversity of the ULIRG population (Borne *et al.* 2000).

References

Barnes, J.E., & Hernquist, L. 1996, ApJ, 471, 115

Borne, K.D., Bushouse, H., Lucas, R.A., & Colina, L. 2000, ApJ, 529, L77

Fugukita, M., Hogan, C.J., Peebles, P.J.E., 1998, ApJ, 503, 518

Gebhardt, K., Bender, R., Bower, G., Dressler, A., Faber, S.M., *et al.* 2000, ApJ, 539, 13

Holtzman, J., Hester, J., Casertano, S., Trauger, J.T., Watson, A.M., *et al.* 1995, PASP, 107, 156

Hutchings, J.B. 1995, AJ, 111, 712

Kauffmann, G. & Haehnelt, M. 2000, MNRAS, 331, 576

Noguchi, M. 1999, ApJ, 514, 77

Sakamoto, K., Scoville, N.Z., Yun, M.S., Crosas, M., Genzel, R., *et al.* 1999, ApJ, 514, 68

Surace, J.A., Sanders, D.B., Vacca, W.D., Veilleux, S., & Mazzarella, J.M. 1998, ApJ, 492, 116

Taniguchi, Y., Trentham N. & Shioya, Y. 1998, ApJ, 504, L79