HST Images of Warm Ultraluminous Infrared Galaxies: QSO Host Progenitors.

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Abstract. We present *Hubble Space Telescope* (*HST*) images obtained with the WFPC2 camera at B & I of a nearly complete sample of ultraluminous infrared galaxies (ULIGs) chosen to have "warm" mid-infrared colors. We find that all of these objects: (1) appear to be advanced mergers; (2) contain compact, luminous blue knots presumably powered by star formation, however the total luminosity of these knots is unlikely to be a major fraction of the total bolometric luminosity of the galaxy; (3) contain either one or two compact sources whose optical/near-infrared properties are similar to those of reddened QSOs. We believe that these warm ULIGs represent a critical transition phase between "cooler" ULIGs and optically selected QSOs, and as such represent the immediate progenitors of optically selected QSO hosts.

1 Introduction

The discovery by the *Infrared Astronomical Satellite* (*IRAS*) of a significant population of ultraluminous infrared galaxies (ULIGs: $L_{\rm ir} > 10^{12}\ L_{\odot}$) with "warm" mid-infrared colors ($f_{25}/f_{60} > 0.2$) has the potential for providing important clues for understanding the origin and evolution of QSOs (see Sanders & Surace, this volume). Ground-based observations of warm ULIGs have shown that nearly all exhibit AGN-like optical spectra, and that the trigger for the intense infrared emission in the majority, if not all, of these objects appears to be the merger of gas-rich spirals. Warm ULIGs span a wide range of types of extragalactic objects including radio-loud and radio-quiet optically selected QSOs, powerful radio galaxies, and luminous starbursts. It appears possible that they represent an important transition stage in the evolution of powerful circumnuclear starbursts into AGN. (A more extensive review of the properties of luminous infrared galaxies in general and warm ULIGs in particular can be found in Sanders & Mirabel 1996)

2 Background: Ground-based Data

A sample of warm ULIGs that have proved particularly useful for study is the complete sample of 12 objects listed in Sanders *et al.* (1988). Ground-based images and spectral energy distributions (SEDs) for these objects are shown in Figures 1 and 2 respectively of Sanders & Surace (this volume). Morphologically, the majority of these objects have well-developed tidal tails and at least 3 (and possibly 5) objects appear to have double nuclei. Those objects with the largest mid-infrared excess are the most similar to optically selected QSOs (i.e. all have Seyfert 1 optical spectra and have the brightest and most compact optical nuclei). Additional observations of the molecular gas and dust distributions, as well as model simulations (e.g. Barnes & Hernquist 1992), suggest that the bulk of the luminosity is indeed generated in the inner few kpc of these objects; however, even this nearest sample of warm ULIGs is sufficiently distant ($z \approx 0.05 - 0.15$) that previously published ground-based optical and near-infrared observations are unable to resolve structure on scales smaller than ~1–2 kpc.

3 New HST Results

We have recently obtained *HST* images using the WFPC2 camera at B (F439W) & I (F814W) of the majority of objects (9/12) in our complete sample of warm ULIGs (Surace *et al.* 1997a)[1].

Figure 1 illustrates the new observations for two of the 9 warm ULIGs observed with *HST*. All of the warm ULIGs (except IRAS 01003–2238) clearly show tails, loops, and other features characteristic of the tidal debris associated with the advanced merger of two large spirals of relatively equal mass. No nuclei not already identified from ground-based images were revealed by *HST*: what were thought to be possible unresolved double nuclei in ground-based images (seeing $\sim 1''$) now appear to be single nuclei surrounded by "knots" of star formation.

All of the warm ULIGs have compact, blue knots distributed throughout their nuclear regions and in some cases also along what appear to be inner tidal features. These knots, with radii in the range 40–140pc, appear similar to the close packed groups of massive star clusters seen in *HST* images of more nearby luminous infrared mergers such as NGC 4038/39 (Whitmore & Schweizer 1995). Using spectral synthesis models (Figure 2), we derive typical ages for the knots of $\sim 6 \times 10^8$ years. However, there is a wide range in $B - I$ colors for the knots in any given system, suggesting that some of the knots may be as young as a few $\times 10^6$ years. Derived masses for individual knots are in the range $10^5 - 10^9\ M_\odot$, with apparent weak gradients in mass and age as a function of galactocentric radius. These estimated values are upper limits; reddening can reduce the derived ages by factors of ~10, and can also decrease the derived masses typically by factors of 2–5. However, regardless of reddening, there are knots which must be extremely young, indicating that star cluster formation is still on-going in some of these galaxies. It is also interesting that there appear to be no young, blue knots with estimated masses as high as some of the old, red knots.

Despite the relatively large number of identified starburst knots in some of our objects (e.g. up to 20–30 in IRAS 15206+3342, and Mrk 463), the observed luminosities of these knots are such that even in total they appear not to be significant contributors to the high bolometric luminosity of any of these galaxies.

[1] New ground-based observations of these systems at H & K' using a fast tip/tilt image stabilizer at the UH 2.2m telescope ($0.25''$resolution) are also being obtained, and will be discussed in greater detail elsewhere (Surace & Sanders 1997b)

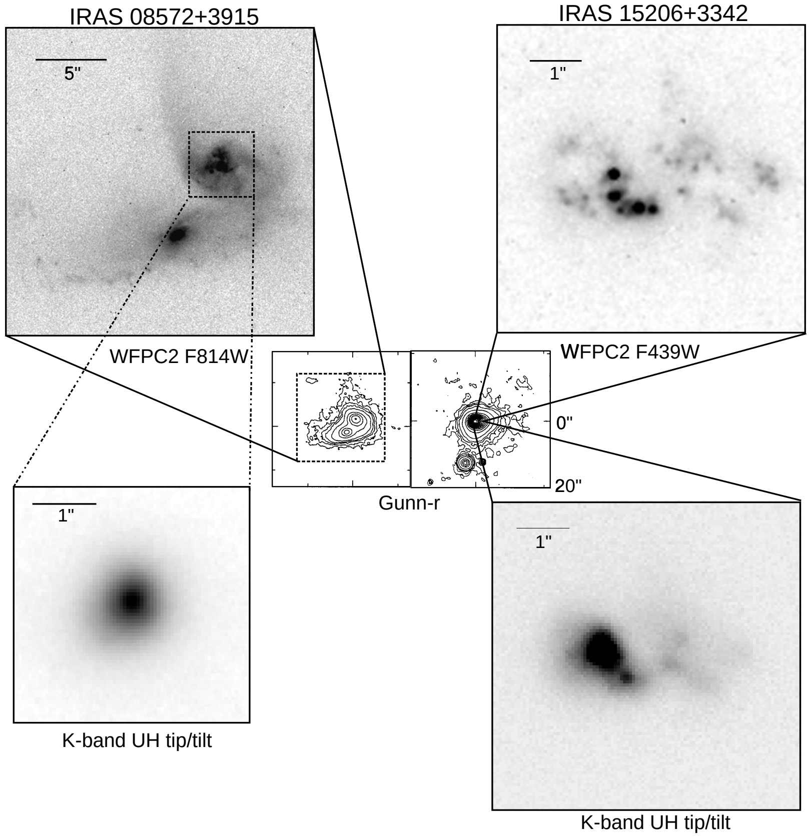

Fig. 1. Ground-based gunn-r, tip/tilt–K', and *HST*/WFPC2–B&I images of IRAS 08572–3915 and IRAS 15206+3342.

Furthermore, they are insufficiently dense to allow construction of an ultraluminous starburst from a hidden population of similar knots as the resulting ensemble would subtend nearly a kpc—such a large obscured region would have been detected in our images. Any ultraluminous starburst must have far more extreme properties than any of the starburst knots identified in our *HST* images.

We also have found that each of the warm ULIGs has at least one "knot" (or 2 "knots" in the case of 4 objects) whose luminosity and color (see Figure 3) would result in an extremely large derived stellar mass ($> 10^{10}$ $M_{\odot}$) inside an unreasonably small radius (often < 30 pc). We suggest that these knots are the 'active' nuclei that are responsible for the dominant AGN-like optical spectrum (Seyfert 1 or 2) seen in ground-based optical spectra—e.g. Sanders *et al.* (1988), Veilleux et al. (1995). Compared to the other less luminous knots that are more likely to be powered by star formation, these putative nuclei are too luminous for their size and could only be attributed to the most extreme of starburst models. However, their luminosities and colors can plausibly be explained as AGN reddened by $A_V\sim$1–4 mag. Those "nuclei" which appear

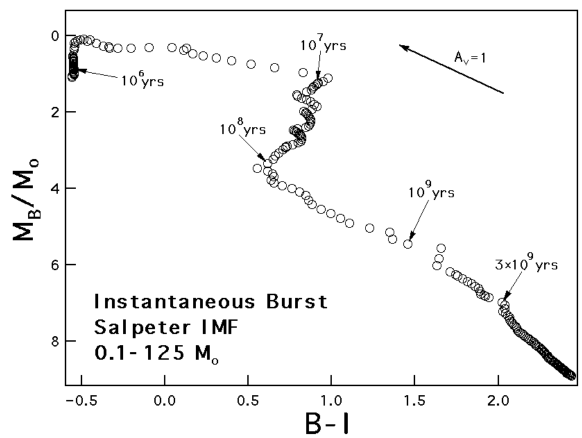

Fig. 2. Spectral synthesis model for an instantaneous starburst with a Salpeter IMF, normalized to $1 M_{\odot}$ (Bruzual & Charlot 1993). The vector (lower left) represents $A_V = 1$.

radially symmetric lie very nearly on the quasar reddening line in Figure 3, while those that appear distorted (suggestive of patchy extinction and scattering) lie as expected slightly below and to the left of where they would be if $A_V = 0$.

Our ground-based near-infrared imaging (Surace & Sanders 1997b) also indicates that in all of the warm ULIGs the total luminosity is increasingly dominated by the putative nuclei at the longer wavelengths. The near-infrared images are also of sufficient resolution and depth to detect many of the starburst knots that we have identified in the *HST* data, and they seem to have the near-infrared colors expected for regions of massive star-formation. The nuclei, however, have very red colors and high K'-band luminosities, indicative of increasing contributions from hot dust. Additionally, the near-infrared images fail to detect any sizable population of knots sufficiently reddened so as to be hidden from optical detection yet still be detectable at K'. Any additional star formation knots must be hidden by substantially greater extinction than affects the more widespread starburst regions detected at optical wavelengths.

4 Future Work

Our *HST*/WFPC2 images of warm ULIGs support earlier conclusions based on ground-based imaging that these objects are indeed advanced mergers. A major new result has been the discovery of a population of luminous "knots" of star formation in the inner few kpc of all of these galaxies that accompany the putative AGN. Future high-resolution spectroscopy with *HST* is required to confirm the AGN identifications and to more precisely determine the ages and masses of the star clusters.

The morphology of the complete sample of warm ULIGs suggests that the warm infrared phase coincides with a relatively brief time interval (few $\times 10^7$

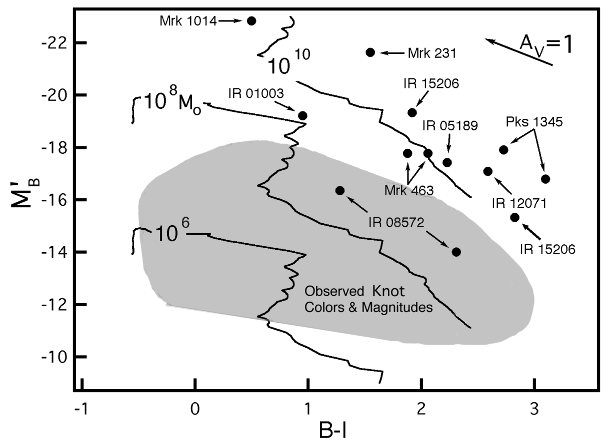

Fig. 3. Observed *B-I* colors and absolute *B* magnitudes of the galaxy nuclei (•) and star-forming knots (shaded region). The solid lines represent total cluster masses based on spectral synthesis modeling of starburst populations. Mrk 1014 (= PG 0157+001) is an infrared-loud, radio-quiet optically-selected QSO typical of the region populated by QSOs in the color-magnitude diagram. The vector (lower left) represents $A_V = 1$.

years) surrounding the actual merger of the two nuclei. This time interval is short compared to the time that it should take for the knots of star formation and larger scale tidal features currently observed in the warm ULIGs to completely fade from view (few $\times 10^8$ years). Thus it seems reasonable to expect that starburst knots and tidal features similar to those identified in our *HST* images of warm ULIGs, although fainter, should still be recognizable in *HST* images of many optically selected QSOs. Recent *HST* images of QSOs presented by Bahcall (this conference, and Bahcall et al. 1997) and by Boyce *et al.* (1997), would appear to confirm that a substantial fraction of optically selected QSOs may indeed have tidal features and knots similar what is observed in warm ULIGs. Deeper images and spectroscopy of optically selected QSO hosts may provide the additional evidence needed to establish whether the majority if not all QSOs begin their lives in an intense infrared phase.

References

Bahcall, J.N., Kirhakos, S., Saxe, D.H., Schneider, D.P. (1997): ApJ. in press
Barnes, J.E., Hernquist, L. (1992): ARAA. **30**, 705
Boyce, P.J., Disney, M., Blades, J.C. *et al.* (1997): ApJ. in press
Bruzual, G., Charlot, S. (1993): ApJ. **405**, 538
Sanders, D.B., Mirabel, I. (1996): Luminous Infrared Galaxies. ARAA. **34**, 749
Sanders, D.B., Soifer, B.T., Elias, J.H. *et al.* (1988): ApJ. **328**, L35
Surace, J.A., Sanders, D.B., Vacca, W.D. *et al.* (1997a): ApJ. submitted
Surace, J.A., Sanders, D.B. (1997b): ApJ. in preparation
Veilleux, S.V., Kim, D.-C., Sanders, D.B. *et al.* (1995): ApJS. **98**, 171
Whitmore, B.C., Schweizer, F. (1995): AJ. **109**, 960