Resolving IRAS 09111 − 1007 at 350 microns: a different
path to ULIRG formation?

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ABSTRACT
We have resolved the ultraluminous infrared galaxy (ULIRG), IRAS 09111 − 1007, with the new 350 µm-optimised Second Generation Submillimeter High Angular Resolution Camera (SHARC II) and present the first submillimetre fluxes and images for the system. IRAS 09111 − 1007 comprises two interacting luminous infrared galaxies (LIRGs) with a projected nuclear separation of 39 h−1 kpc. The Western galaxy is roughly four times more luminous in the submillimetre than its Eastern counterpart. It is an extremely bright LIRG with an AGN. The classification of the Eastern source is uncertain: it could be a Seyfert 2 galaxy or a LINER. We highlight IRAS 09111 − 1007 as a system that necessitates further study: a double AGN ULIRG whose molecular gas content differs from other widely separated pairs and whose ULIRG phase might not be explained by current multiple merger and/or final stage ULIRG scenarios.

Key words: infrared: galaxies – galaxies: starburst – galaxies: Seyfert – galaxies: interactions – galaxies: individual: IRAS 09111 − 1007

1 INTRODUCTION
Amongst the first results of extragalactic mid-IR astronomy was the discovery of a small number of galaxies that emit the bulk of their bolometric luminosity in the infrared (Low & Kleinmann 1968, Kleinmann & Low 1970a,b). The InfraRed Astronomical Satellite, IRAS, detected large numbers of these ultraluminous infrared galaxies (ULIRGs) (Soifer et al. 1984, Joseph & Wright 1985, and Soifer, Neugebauer & Houck 1987) with quasar-like luminosities of \( L_{\text{IR}}(8–1000 \mu m) > 10^{12} L_\odot \). There is still debate as to the nature of the far-IR power source in these galaxies: is the immense thermal energy driven by a dominant starburst, a dominant AGN or some combination of the two? These low-redshift IRAS-selected ULIRGs are expected to be the counterparts to the high redshift \( z > 1 \) SCUBA sources (see, e.g., Smail et al. 1998, Blain et al. 2002, Webb et al. 2003, Chapman et al. 2003).

Most ULIRG systems have been shown to be disturbed, interacting or merging in some way when the separation of nuclei is less than 10kpc (Sanders et al. 1988, Clements et al. 1996, Murphy et al. 1996, Farrah et al. 2001). The nature of widely separated ULIRG systems is less clear (Dinh-V-Trung et al. 2001, Meusinger et al. 2001): are the components of the ULIRG (supposedly the end phase of the galactic interaction) beginning another merger or is the ULIRG a result of a multiple merger event (Borne et al. 2000)? This latter scenario is possible in widely separated ULIRGs with resolved double nuclei but might not apply to the ULIRG system IRAS 09111 − 1007, which consists of two widely spaced but interacting luminous infrared galaxies (LIRGs), each with a single nucleus. The two LIRGs have a projected separation of 39 h−1 kpc and a velocity difference of 425 km s−1 (Duc, Mirabel & Maza 1997). In this letter we present 350 µm resolved images and fluxes for IRAS 09111 − 1007. We model the far-IR dust emission to constrain the nature of the interaction.

2 OBSERVATIONS AND DATA REDUCTION
The data were taken using the Second Generation Submillimeter High Angular Resolution Camera (SHARC II) at the Caltech Submillimeter Observatory on Mauna Kea, Hawai’i, in January and March 2004. SHARC II is a 350 µm-optimised camera (Dowell et al. 2003) built around a 12 × 32 element close-packed bolometer array (Moseley et al. 2004). It achieves a point-source sensitivity of \( \sim 1.14 \text{ Jy Hz}^{-1/2} \) in good weather. The 384 pixels of the SHARC II array image a region of around \( 1.0' \times 2.5' \). Its filled absorber array provides instantaneous imaging of the entire field of view, sampled at roughly 2.5 pixels per nominal beam area. The
Table 1. Coordinates, 350µm fluxes, luminosities and star formation rates for the system and both components of IRAS 09111 – 1007 (IRAS fluxes from Surace, Sanders & Mazzarella 2004). The FIR (40 – 500 µm) and IR (8 – 1000 µm) luminosities are derived as follows: \( L_{\text{FIR,SED}} \) is computed from best-fitting single temperature SED, \( L_{\text{FIR,IRAS}} \) and \( L_{\text{IR}} \) are calculated using the standard relations from Fullmer & Lonsdale (1989) and Sanders & Mirabel (1996) respectively. Note that the pair positions given in both NED and Surace, Sanders & Mazzarella (2004) are swapped.

| Name | Coordinates (J2000) | 350µm Flux [Jy] | \( \log(L_{\text{FIR,SED}}) \) \( [L_\odot] \) | \( \log(L_{\text{FIR,IRAS}}) \) \( [L_\odot] \) | \( \log(L_{\text{IR}}) \) \( [L_\odot] \) | SFR \([M_\odot yr^{-1}]\) |
|------|---------------------|-----------------|------------------|------------------|------------------|------------------|
| IRAS 09111 – 1007 | 09 13 36.4 -10 19 31.8 | 0.85±0.13 | 11.80 | 11.75 | 11.98 | 63 |
| IRAS 09111 – 1007W | 09 13 38.8 -10 19 21.5 | 0.23±0.04 | 11.25 | 11.20 | 11.43 | 18 |

Figure 1. 350 µm continuum emission map of IRAS 09111 – 1007 taken with SHARC II. The contours are in levels of 50 mJy/beam (dashed contours are negative and are an artifact of data reduction).

3 RESULTS

We are able to resolve the IRAS 09111 – 1007 system and obtain 350 µm fluxes and positions. An absolute pointing offset of 2.0′′ (\( \Delta \alpha = 1.0′′, \Delta \delta = 1.7′′ \)) from the 2MASS positions was attributed to a pointing error (due to the imprecise absolute pointing knowledge of the CSO) and removed from the SHARC II image presented in this letter. The Eastern LIRG is called the ‘Eastern source’ or IRAS 09111 – 1007E (Murphy et al. 1996). Together they form the ‘ULIRG system’. Figure 2 shows the resolved components of IRAS 09111 – 1007 imaged with the DSS, 2MASS and IRAS (HIRES processed; Surace, Sanders & Mazzarella 2004) respectively. The 350 µm fluxes for each component are presented in Table 1. The signal–to–noise in the detection is 89 for the Western source and 29 for the Eastern source. The Western source is roughly four times more luminous in the submillimetre than its Eastern counterpart.

4 SED MODELLING

4.1 Dust Temperature Blackbody Fitting

A modified blackbody is used to model the total dust emission of the IRAS 09111 – 1007 system, specifically:

\[
F_\nu = (M_{\text{dust}}/D^2)\kappa(\lambda)B_\nu(\lambda, T_{\text{dust}})
\] (1)

where \( B_\nu \) is the Planck function, \( \kappa \) the mass absorption coefficient of the dust (\( \kappa(\lambda) \propto \lambda^{-\beta} \), see Dwek 2004), \( T_{\text{dust}} \) and \( M_{\text{dust}} \) the equilibrium dust temperature and mass respectively, and \( D \) the distance of the galaxy. For the distance we
use WMAP cosmology ($H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.27$, and $\Omega_{\Lambda} = 0.73$ (Bennett et al. 2003)).

In order to better constrain the SED of each component, we determined the ratio of the fluxes of the two components at 60 µm. Beginning with the IRAS 60 µm HIRES-processed image of Surace et al. (2004), we sliced along the axis of the known 350 µm sources. A pair of Gaussian intensity functions were fitted to the measured flux along this slice, constraining them to have the same width and a fixed spacing as determined at 350 µm (see Figure 3). The remaining four free parameters (one position, the width, and the two intensities) are then well-constrained, with the flux ratio being $4.9 \pm 0.8$ (the total system flux as measured by IRAS is still valid, since the IRAS fluxes are derived with an aperture large compared to the source separation). The ratio derived from the 350 µm measurement is $3.7 \pm 1.1$. Alternatively, the fraction of the flux from the brighter LIRG is $83 \pm 3$ per cent at 60 µm and $79 \pm 16$ per cent at 350 µm, an entirely consistent measurement. The ratio of 79 per cent is accurate enough for the fits that follow.

χ² minimization determined the best-fitting emissivity index ($\beta$) and corresponding single fit dust temperature for the system using the SHARC II 350 µm flux with the 60 µm and 100 µm IRAS fluxes derived in Surace et al. (2004) (the 100 µm flux was used as the normalization). The best-fitting was $\beta = 1.9 \pm 0.1$, $T = 31 \pm 1 \text{ K}$, and is shown in Figure 4. We also model both the Western and Eastern sources assuming that the IRAS fluxes are distributed in the same way as the 350 µm emission. Dust masses are calculated assuming the 100 µm mass absorption coefficient, $\kappa_{100}$, is $40 \text{ cm}^2 \text{ g}^{-1}$ (Draine & Lee 1984).

With only two independent colours we cannot constrain the cold and warm dust masses and simultaneously fit the dust temperatures in a two temperature model. Using $\beta = 2$ (as in Dunne & Eales 2001), if we assume equal amounts of cold and warm dust in the system we get best-fitting temperatures of $T_{\text{cold}} = 26 \pm 5 \text{ K}$ and $T_{\text{warm}} = 32 \pm 2 \text{ K}$. If we adopt a dust mass distribution typical of the highest luminosity galaxies from the SCUBA Local Universe Galaxy Survey (SLUGS), as given in Dunne & Eales (2001), we get a ratio $M_{\text{cold}}/M_{\text{warm}} = 11$. The best-fitting values are then $T_{\text{cold}} = 29 \pm 1 \text{ K}$, $T_{\text{warm}} = 36 \pm 3 \text{ K}$.

As an alternative to these approaches, we also used a more physically-based dust grain model (the single temperature DL dust model – Draine & Lee 1984, Laor & Draine 1993), an equal mixture of silicates and graphites with $\kappa_{100}$ of 31 and 54 cm² g⁻¹ for the silicate and graphite grains respectively.

### Table 2. Best-fitting SED parameters

| Model                  | Source                  | $\beta$ | $T_{\text{dust}}$ [K] | $M_{\text{dust}}$ [10^7 M⊙] |
|------------------------|-------------------------|---------|-----------------------|-------------------------------|
| Single Temperature     | System                  | 1.9 ± 0.1 | 31 ± 1 | 220 ± 30          |
|                        | Western source          | 1.9 ± 0.1 | 31 ± 1 | 170 ± 30          |
|                        | Eastern source          | 1.9 ± 0.1 | 31 ± 1 | 50 ± 10           |
| Two Temperature Mcold/Mwarm=1 | System                  | 2.0 | 32 ± 2 | 300 ± 190          |
|                        | (fixed)                 |         | 26 ± 5                    |
| Two Temperature Mcold/Mwarm=11 | System                  | 2.0 | 36 ± 3 | 280 ± 70          |
|                        | (fixed)                 |         | 29 ± 1                    |
| Single Temperature     | System                  | n/a | 30 ± 1       | 250 ± 30          |
|                        | Eastern source          | n/a | 30 ± 1       | 200 ± 30          |
| DL Dust Model          | Western source          | n/a | 30 ± 1       | 60 ± 10           |
|                        | Eastern source          | n/a | 30 ± 1       | 60 ± 10           |

Figure 2. DSS Optical, 2MASS Ks, and IRAS 60 µm images of IRAS 09111 – 1007, with 350 µm contours overlaid on each (in levels of 100 mJy/beam).

Figure 3. Fit to the spatial variation in intensity for the HIRES-processed IRAS 60 µm image, cut through both galaxies.
spectively. In this case, the best-fitting temperature of the system was 30 ± 1 K.

The dust temperature of ∼31 K is within 1.5σ of the average temperature of 38 ± 6 K from the previous 350 μm LIRG study by Benford (1999), with the first SHARC camera (although that survey did not include any widely separated LIRG systems). The result that the 60 μm dust is distributed in very similar ratios to the 350 μm dust (Figure 3) is responsible for the identical SED temperatures for both components.

4.2 Ratio of Molecular Gas To Dust

The molecular gas mass in the Western source is 2.3 × 10^{10} M⊙ (Mirabel et al. 1990). The Western source’s dust mass is derived from the best-fitting SED to give a molecular gas-to-dust ratio of 140 and 120 for the single temperature and DL dust models respectively. In this case, the best-fitting temperature of the system was 30 ± 1 K.

The dust temperature of ∼31 K is within 1.5σ of the average temperature of 38 ± 6 K from the previous 350 μm LIRG study by Benford (1999), with the first SHARC camera (although that survey did not include any widely separated LIRG systems). The result that the 60 μm dust is distributed in very similar ratios to the 350 μm dust (Figure 3) is responsible for the identical SED temperatures for both components.

5 DISCUSSION

5.1 Source Characterisation

The optical image from the Digitized Sky Survey (Figure 2, left) shows the disturbed morphology of the Eastern source. In the 2MASS Ks band image (Figure 2, centre) the Western source is slightly more luminous than the Eastern, a trait even more prominent in the submillimetre (Figure 1). Merger models such as Barnes & Hernquist (1991) predict gas and dust to be concentrated in the galaxy centre as the ULIRG interaction condenses large amounts of the ISM into the nuclear region.

Line ratios from Duc et al. (1997) classify the Western source as a Seyfert 2. Dudley (1999) found prominent polycyclic aromatic hydrocarbon features in the 8–13 μm dust emission spectra – indicative of a starburst. The Eastern source is either a Seyfert 2 or LINER galaxy (Duc et al. 1997), while Gonçalves, Véron-Cetty & Véron (1999) also find evidence for a starburst. Neither of the two sources in the IRAS 09111 – 1007 system were detected in the ROSAT All-Sky Survey. A non-detection in the ROSAT band does not necessarily mean that a source is intrinsically weak since the soft X-ray band is sensitive to X-ray absorption, which is common in AGN.

5.2 Merging Stage

Without additional submillimetre data we are unable to constrain the relative temperatures and masses of the cold and warm dust components. Whether the dust temperature of the system is related to the stage of merging is not clear. Mazzarella, Bothun & Boroson (1991) find an increase in warm dust temperature with merging stage, although Klaas et al. (2001) argue the cold dust temperature would increase as well. The wide separation of the pair would suggest that IRAS 09111 – 1007 is at the beginning of a merger, a notion supported by the value of the IR luminosity–to–H2 mass ratio, which falls within a region of LIR/M(H2) vs LIR space that is common for early merging systems (Sanders, Scoville & Soifer 1991).

5.3 Widely Spaced ULIRG Pairs

Unlike the wide pair sample of Xu & Sulentic (1991) both components are enhanced in the far-IR. With a velocity difference of 425 km s⁻¹ (Duc et al. 1997) and a projected separation of 39 h_7^−1 kpc, Monte Carlo simulations give the probability of the pair being bound as 0.88 (Schweizer 1987).

Although widely separated ULIRG pairs are not uncommon the nature of their interaction is still uncertain. Murphy et al. (1996) postulated the presence of a third nucleus in widely separated pairs, though no double nucleus has been detected in either component of IRAS 09111 – 1007. The
galaxies were shown to be unresolved at 0.75 resolution in a 6 cm search by Crawford et al. (1996). However the non-detection of a double nucleus cannot rule out a multiple merger since the time-scale of nuclei coalescence is short (Surace, Sanders & Evans 2000, Meusinger et al. 2001). In multiple approach merger models (e.g., Dubinski, Mihos & Hernquist 1999) the merging process is a series of encounters where bound components approach and separate. A previous encounter may have triggered the starburst/AGN in the system. High resolution optical imaging (Borne et al. 2000) could decide between these scenarios by either detecting multiple nuclei or confirming single nuclei. High resolution CO imaging would be needed to detect whether gas has been disturbed by a previous phase of the merging event (Mihos & Hernquist 1996).

6 CONCLUSIONS

We have resolved the widely separated ULIRG system of IRAS 09111–1007 with the SHARC II detector at 350 µm. This system comprises two LIRGs with a projected separation of 39 h_71^{-1} kpc, or around two optical diameters. The Western component dominates the far-IR flux at both 60 µm and 350 µm, carrying 79 percent of the total system luminosity. Although the luminosity of the system is large, our fluxes suggest a dust temperature of 31 K for this system, with both components at the same temperature to within the sensitivity of this measurement. The wide separation and the value of the IR luminosity–H_2 mass ratio suggest that the pair are at an early stage of interaction. But the high luminosity of the system (L_IR = 1.2 x 10^{12} L_☉) would be unusual for such a stage, unless the components had experienced a previous merger or interaction. A high resolution optical search for multiple nuclei within each component is needed. Their absence could indicate that the double AGN–LIRG system of IRAS 09111–1007, and perhaps other widely spaced ULIRG pairs, might be unexplained by current theories of ULIRG formation and evolution.

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