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(U)LIRG Morphology and Color: 70μm Selected Galaxies in the COSMOS Field

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Abstract. We present the results of a morphological and color analysis of a sample of 110 70μm selected luminous and ultraluminous infrared galaxies ($11.3 < \log(L_{\rm IR}/L_\odot) < 12.8$) for a single redshift bin ($0.8 < z < 1.0$) in the COSMOS field. We then compare our results to a similar analysis of an optically selected sample in the same redshift bin. Over 70% of the 70μm selected sources are found to be major mergers at late stages of interaction while only 21.5% of the optically selected sample are major mergers. This is in rough agreement with the morphology of local (U)LIRGs where all ULIRGs and most LIRGs are found to be gas-rich major mergers. We also find that the $U - V$ color of the (U)LIRGs peaks in the "green valley," in between the dichotomous "red sequence" and "blue cloud" of the optically selected galaxy population.

1. Introduction

One of the most important unsolved questions in galaxy evolution is understanding the connection between the massive IR-luminous galaxies seen at intermediate and high redshifts to their counterparts seen locally. Luminous and ultraluminous infrared galaxies (LIRGs, $L_{\rm IR} > 10^{11}L_\odot$ and ULIRGs, $L_{\rm IR} > 10^{12}L_\odot$) are a rarity in the local universe (Sanders & Mirabel 1996) but become more numerous at higher redshifts and dominate the cosmic star formation rate at $z > 1$ (Le Floc'h et al. 2005). Locally, these sources have been observed to be merging systems of approximately equal mass gas-rich spirals.

In this paper we discuss the morphological and color properties of high-redshift ($0.8 < z < 1.0$) (U)LIRGs selected at 70μm in the COSMOS field. The 70μm selection ensures an accurate estimate of the total infrared luminosity for each of our sources. Even with this selection, the large area of the COSMOS field allows us to select a large number of sources (1074 at all redshifts and 110 in the redshift range discussed here).

2. Observations

The optical imaging data used for this study were obtained as part of the HST-COSMOS project (Scoville et al. 2007). COSMOS originated as an *HST* Treasury program imaging an ~ 2 deg^2 equatorial field with the Advanced Camera for Surveys (ACS), using the F814W filter (I-band). This is the largest contiguous field ever observed by *HST*. Details of the ACS images, including their calibration and reduction, are given in Koekemoer et al. (2007). To supplement the ACS coverage, followup observations have been obtained across the entire spectrum using both space- and ground-based facilities. A complete description of the COSMOS datasets can be found in Scoville et al. 2007 and Capak et al. 2007.

S-COSMOS (Sanders et al. 2007) is a *Spitzer* legacy survey designed to cover the entire 2 deg^2 COSMOS field with both the MIPS and IRAC instruments. The data were taken in Jan 2006 and Jan–May 2007 for cycle 2 and cycle 3, respectively. A complete description of the data reduction and catalogs for the IRAC 3.6–8 μm and the MIPS 24μm, 70μm, and 160μm data sets is given in Sanders et al. 2007, Le Floc'h et al. 2009, and Frayer et al. 2009.

3. The 70μm Sample

The full 70 μm catalog used for this study consists of 1417 sources detected with S/N > 4 across the full COSMOS field with ACS coverage. This roughly corresponds to a flux limit of 6 mJy across the entire field. Spurious sources detected around bright objects were removed by eye, bringing the total sample size to 1317 sources.

3.1. Identifying Counterparts

We identified the optical counterpart for each 70 μm source by first matching to the 24 μm catalog positions. 701 of the sources have a single isolated 24 μm source within the 18$''$ (FWHM) 70 μm beam. 26 sources have no 24 μm counterpart within the beam, all of which are near the flux limit and thus likely spurious. The remaining 625 sources have more than one source in the beam, but we were able to identify the most likely counterpart for all but 35. We removed these 35 sources from our sample because we were unable to unambiguously identify the correct counterpart.

All of the remaining 1256 sources with a 24 μm counterpart were also detected by IRAC. We then matched the IRAC positions to the optical photometric catalog and removed masked sources near bright objects in the optical and IRAC images, resulting in a final sample of 1074 objects. Of these, 181 sources are also detected at 160 μm.

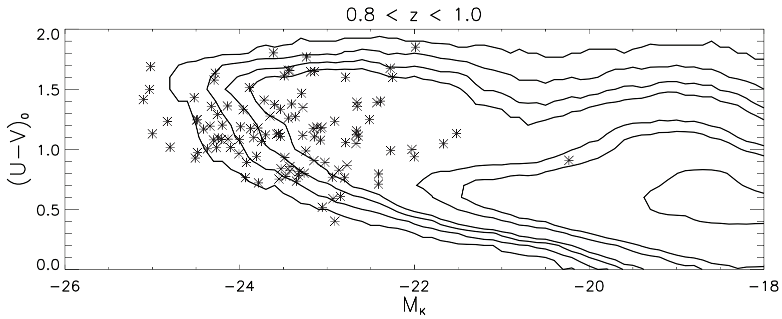

Figure 1. Rest frame $U - V$ vs. M_K color-magnitude diagram for the $0.8 < z < 1.0$ redshift bin. The optically selected sample for the full field is shown by the contours and the asterisks mark the 70 μm selected sources.

3.2. Properties of the Sample

Photometric redshifts (Ilbert et al. 2009) are available for all of the 1074 galaxies in the sample. 112 of these sources are detected as AGN in the xray by the *XMM-Newton* satellite (Hassinger et al. 2007). For these 112 sources, the photometric redshifts determined by Salvato et al. 2009 with AGN templates are used. Spectroscopic redshifts are available for 444 ($\sim$ 40%) of the sample. For the analysis discussed in these proceedings, we adopt the spectroscopic redshift for those sources with reliable spectroscopy and the photometric redshift (using the galaxy or AGN templates as appropriate) for the rest of the sample.

4. Results

In order to estimate the total infrared luminosity ($L_{\rm IR}$) of our sample, we chose the best-fit template to the infrared spectral energy distribution from several empirical and model template libraries (Chary & Elbaz 2001, Dale & Helou 2002, Lagache et al. 2008, and Siebenmorgen & Krugel 2008). In the following analysis, we focus on the 110 70 μm sources in the $0.8 < z < 1.0$ redshift bin only. All of the sources in this bin are LIRGs and ULIRGs and provide an excellent high redshift sample to compare to LIRGs and ULIRGs observed locally.

4.1. Morphology

We classified each galaxy in our sample visually into several morphological types, including spiral, elliptical, minor, and major mergers. The major merger class was then broken into several interaction classes based on the prescription of Veilleux, Kim, and Sanders (2002), where I and II are galaxy pairs before and at first contact, respectively, III are physically interacting pairs, IV are mergers where the two separate galaxies have coalesced, and V is the merger remnant with visible debris but no obvious tidal features. For comparison, we then chose an optically selected sample in this same redshift bin by selecting 220 galaxies chosen randomly across the entire field spanning the same stellar mass range as our 70 μm sources. A summary of the classification of both the 70 μm and comparison samples is shown in table 1.

Table 1. Summary of morphological classifications for 70 μm selected sources and a comparison sample of optically selected galaxies

Morphological Classification*	70 μm selected %	Optically selected %
Spirals	12.7	37.7
E/S0	10	23.5
Minor Mergers	4.5	10.5
Class I	7.3	10.5
Class II	0	2.3
Class III	47.3	5
Class IV	16.4	3.2
Class V	0	0.5
Unknown	1.8	6.8

See §4.1 for a description of interaction classes I–V

4.2. Color-Magnitude Diagrams

Figure 1 shows the distribution of the 70 μm sample in color-magnitude (rest-frame $U-V$ versus absolute K magnitude) space relative to the optically selected galaxy sample (illustrated by the contours). The optically selected sample clearly shows the color bi-modality often seen in optical samples, separating into a well-defined "red sequence" of quiescent galaxies and a "blue cloud" of star forming galaxies. The absolute K magnitude was chosen for the x-axis because it roughly corresponds to stellar mass.

5. Discussion

Locally, all ultraluminous infrared galaxies are strongly interacting/merging systems (Kim, Veilleux, & Sanders 2002) and exhibit the presence of tidal tails, disturbed morphology, or multiple nuclei. For the less luminous LIRGs ($10^{11}L_{\odot} < L_{\rm IR} < 10^{12}L_{\odot}$), there seems to be a variety of morphologies, from major gas-rich mergers at the high luminosity end, to minor interactions and morphologically normal gas-rich spirals at lower luminosities (Ishida 2004). Presently, there is much disagreement as to whether or not this trend holds as one looks at IR luminous sources at higher redshift (e.g., Melbourne et al. 2008; Bridge et al. 2007; Shi et al. 2006; Dasyra et al. 2008).

The results summarized in table 1 provide a large high-redshift sample for comparison. This redshift bin is also low enough that morphological k-corrections are not necessary and visual classification is still possible. As for local LIRGs and ULIRGs, these galaxies are dominated by interacting and merging galaxies (71% if all interaction stages are included versus 21.5% for the optically selected comparison sample). Normal spiral and elliptical galaxies make up a small fraction (12.7% and 10%, respectively) of (U)LIRGs whereas they represent a significant portion (37.7% and 23.6%) of the optically selected population.

Figure 2 shows a histogram of the rest-frame $U-V$ colors for the 70 μm selected sources coded by morphology. The dotted line represents the opti-

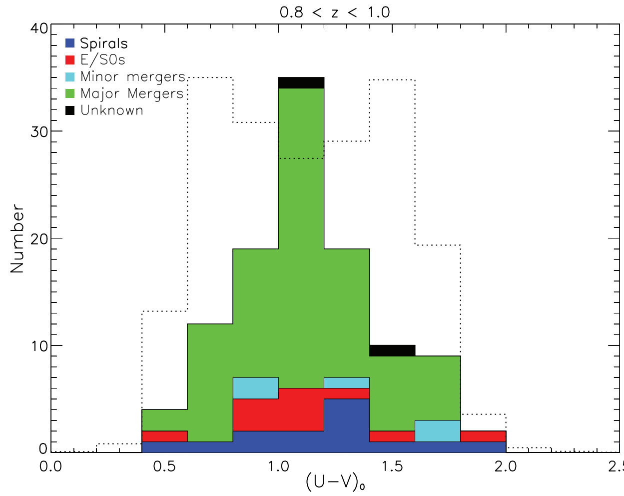

Figure 2. $U-V$ histogram for the 70 μm sample across all M_K values in the $0.8 < z < 1.0$ redshift bin olor coded by morphology. The $U-V$ distribution for the entire optically selected sample over the same M_K range is shown as the dotted line.

cally selected population, scaled down to match. Not only does this illustration confirm that COSMOS (U)LIRGs are dominated by major mergers (shown in green), but it also shows that these sources peak in the green valley, in between the blue cloud and red sequence of the normal galaxy population.

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