OPTICAL MORPHOLOGY EVOLUTION OF INFRARED LUMINOUS GALAXIES IN GOODS-N

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Received 2005 June 19; accepted 2005 September 13; published 2005 October 10

ABSTRACT

We combine optical morphologies and photometry from HST, redshifts from Keck, and mid-infrared luminosities from Spitzer for an optically selected sample of ~800 galaxies in GOODS-N to track the morphology evolution of luminous infrared galaxies (LIRGs) since redshift z = 1. We find a 50% decline in the number of LIRGs from z = 1 to lower redshift, in agreement with previous studies. In addition, there is evidence for a morphological evolution of the populations of LIRGs. Above z = 0.5, roughly half of all LIRGs are spiral, the peculiar/irregular-to-spiral ratio is ~0.7, and both classes span a similar range of L_100 and M_100. At low z, spirals account for one-third of the LIRGs, the peculiar-to-spiral fraction rises to 1.3, and for a given M_100 spirals tend to have lower IR luminosity than peculiars. Only a few percent of LIRGs at any redshift are red early-type galaxies. For blue galaxies (U - B < 0.2), M_100 is well correlated with log L_100 with an rms scatter (about a bivariate linear fit) of ~0.25 dex in IR luminosity. Among blue galaxies that are brighter than M_100 = −21, 75% are LIRGs, regardless of redshift. These results can be explained by a scenario in which at high z, most large spirals experience an elevated star formation rate as LIRGs. Gas consumption results in a decline of LIRGs, especially in spirals, to lower redshifts.

Subject headings: galaxies: evolution — infrared: galaxies

1. INTRODUCTION

Aussel et al. (1999) demonstrated that the large density of mid-IR (MIR) sources detected in deep ISOCAM (Cesarsky et al. 1996) data are dominated by galaxies at intermediate redshifts. Luminous infrared galaxies (LIRGs), though rare locally, are common in the past and suggest a previously overlooked site of significant star formation: dust enshrouded starbursts. Zheng et al. (2004) analyzed Hubble Space Telescope (HST) Wide Field Planetary Camera 2 images of 36 distant (0.4 < z < 1.2) ISOCAM-detected LIRGs. They classified 36% of their objects as disk galaxies, 22% as irregulars, 17% as obvious mergers, and 25% as compact sources. They found a size-color relationship for the cores of their galaxies. Compact sources tend toward blue cores, while the larger disk galaxies tend to have redder cores. This suggested to the authors an evolutionary sequence of disk galaxy formation, with compact blue bulges forming first, followed by inside-out disk growth while the core reddens. This theme was elaborated by Hammer et al. (2005, hereafter H05), who suggested that disk mergers are driving the evolution of both LIRGs and star formation over the last 8 Gyr. In their picture, disk mergers and rebuilding account for the various morphological stages seen in LIRGs at intermediate redshifts. For instance, a brief peculiar phase of heightened star formation is followed by a compact phase with dust and gas funneled into the center, growing the bulge. Subsequent settling of gas into the potential well regrows the disk from the inside out. The authors suggest that this scenario may have occurred in 75% of intermediate-mass spirals since z = 1.

ISOCAM data are only sensitive to the brightest MIR sources at intermediate redshifts. With the launch of the Spitzer Space Telescope (Werner et al. 2004), much deeper IR data have become available. Using the Multiband Imaging Photometer for Spitzer (MIPS; Rieke et al. 2004) 24 μm observations, Bell et al. (2005, hereafter BELLO5) study 1500 z ~ 0.7 galaxies with photometric redshifts in the Chandra Deep Field–South. They found a somewhat different morphological makeup of LIRGs than the Zheng et al. (2004) and H05 studies and drew different conclusions. BELLO5 found more than half of LIRGS are undisturbed, massive (M_* > 2 × 10^10 M_⊙) spirals and less than a third strongly interacting. They conclude that major mergers are not the primary factor in LIRG production or of the rapid decline of star formation since z ~ 0.7. They suggest instead a combination of gas depletion and minor mergers.

In this Letter, we focus on one of the deepest MIR survey fields yet taken, the MIPS 24 μm image (M. Dickinson 2005, in preparation) of the Great Observatories Origins Deep Survey (GOODS; Giavalisco et al. 2004) north field. Very deep optical HST imaging (~0.5 mag deeper than BELLO5) are used as well as spectroscopic redshifts from the Team Keck Redshift Survey (TKRS; Wirth et al. 2004). We compare optical morphologies and luminosities with IR luminosities of ~800 optically selected galaxies to trace the morphological evolution of star-forming galaxies since z = 1. The optically selected sample is less biased against low-IR luminosity objects than the previous studies. In addition, the deeper HST data allow for more accurate morphological typing, especially of fainter tidal features from mergers. Our sample contains 3 times the number of LIRGs as the Zheng et al. (2004) and H05 sample and spans a wide range in redshift encompassing the BELLO5 narrow redshift slice. Section 3 explores the relationship between optical and IR luminosity, and its dependence on optical color, morphology, and redshift. Specifically, we (1) look for evolution in the number density and morphological makeup of LIRGs since z = 1 and (2) investigate the utility of optical color and luminosity as a predictor of IR luminosity. Section 4 synthesizes the results into a picture of LIRG evolution over the last 8 Gyr, similar to that of BELLO5.

We adopt Vega magnitudes and a flat, h = 0.7, Ω_m = 0.3 cosmology throughout.

2. THE DATA

2.1. Optical

Galaxies are identified in the GOODS-N field (Giavalisco et al. 2004) using the B, V, i, and z HST images. Spectroscopic
redshifts are from TKRS (Wirth et al. 2004), a magnitude-limited ($R_{AB} \leq 24.4$) survey of 2018 objects in GOODS-N. TKRS is 53\% complete at its limiting magnitude (Wirth et al. 2004). Elliptical aperture photometry from the STSDAS program ELLIPSE was generated from the four HST hands for all objects in TKRS (J. Melbourne 2005, in preparation). Total magnitudes were calculated from the ELLIPSE measurements using a curve-of-growth technique. Following the prescription in Willmer et al. (2005), $k$-corrections convert apparent magnitudes to absolute $M_B$ and rest-frame color ($U - B$). Our sample contains the 789 TKRS galaxies brighter than $M_B < -19.0$ grouped into three equal volume bins between 0.1 < $z$ < 1.0. This introduces a slight bias for redshifts $z > 0.9$, where the TKRS limiting rest-frame magnitude is greater than $M_B \sim -19.0$. This should not have a major impact on the LIRG detection as the majority of LIRGs are brighter than this limit (see, for instance, Fig. 10 in Le Floc’h et al. 2005).

Galaxies are typed into one of four morphological categories: spiral, peculiar/irregular, compact, and early types (E/S0). Spirals exhibit symmetry, signs of bulge, and disk components and spiral arms. Peculiars are characterized by asymmetry, tidal features, or obvious mergers. Ellipticals are picked out as smooth, symmetric, and red and lacking an obvious disk component. Compacts are selected by having half-light radii smaller than 3 kpc. At low and intermediate redshifts ($z < 0.8$), the typing is done with the very deep $V$- and $i$-band images. At higher redshift, the $z$-band image (rest-frame $M_z$) is used to account for the morphological $k$-correction. The typing was done by three independent researchers with 70\% full agreement and 100\% agreement between at least two of three classifications. A final classification was assigned by majority. As a check of our typing, we classify the 27 noncompact objects in Zheng et al. (2004) and agree with all but one of the classifications. Furthermore, we clone our low-redshift LIRGs to the pixel scale and signal-to-noise ratio of the $z = 0.95$ LIRGs and find that the classifications are not affected.

2.2. 24 $\mu$m Fluxes

Twenty-four micron fluxes are measured from the publicly released MIPS mosaic image of the GOODS-N field (GOODS DR1+ data release; M. Dickinson 2005, in preparation). The image is flux-calibrated and aligned to the astrometry of the Infrared Array Camera images of the same region (Chary et al. 2004). The MIPS 24 $\mu$m point-spread function (PSF) has an FWHM of ~6\arcsec, meaning virtually every source on the image is pointlike. As a result, our photometry techniques are borrowed from those used in crowded star fields (see, for instance, Stetson 1987). First we generate a PSF for the image by median combining 10 flux-scaled isolated sources. Then for each TKRS galaxy position, we (1) subtract all neighbors with centroids separated by more than 2\" and less than 75\" from the location of interest; (2) measure the flux in a 9\" aperture at the location of interest; (3) apply an aperture correction of 1.34 to the flux measurement (taken from the MIPS Data Handbook ver. 2.1), to account for the large amount of flux in the wings of the MIPS PSF; and (4) apply an additional correction to the flux such that image $-$ (scaled PSF) is within 0.5\% of the sky value.

For bright objects ($>200 \mu Jy$), this technique reproduces the results in the DR1+ bright source catalog (R. Chary 2005, in preparation) to within 5\%. For fainter sources (100 $\mu Jy < f < 200 \mu Jy$), the results vary with an rms of 15\%. While the DR1+ catalog supplies measurements of objects brighter than 100 $\mu Jy$, the measurement strategy outlined above provides flux estimates of faint sources to 25 $\mu Jy$. In addition, because we select galaxies in the optical, we measure 24 $\mu$m fluxes for objects that may not have been identified by the standard DAOPHOT source-finding routines.

Elbaz et al. (2002) demonstrate that the MIR is well correlated with total IR luminosity, even at cosmological distances. We estimate the total IR luminosity, $L_{100}$ ($8$–$1000$ $\mu$m), from the MIPS 24 $\mu$m flux following the prescription in Le Floc’h et al. (2005). For each redshift and 24 $\mu$m flux, this method derives the monochromatic luminosity at the corresponding rest-frame wavelength, which is then translated into a total IR luminosity ($8$–$1000$ $\mu$m) according to libraries of IR spectral energy distributions (SEDs). The SEDs considered in this work were taken from Chary & Elbaz (2001). Other templates give consistent results within 0.3 dex, which is also considered to be the accuracy of our estimates. Following the convention established in Sanders & Mirabel (1996), LIRGs are defined as $log (L_{100}/L_{\odot}) > 11$. Using the conversion to star formation rates (SFRs) given in Kennicutt (1998), LIRGs have SFR > $17 M_{\odot}$ yr$^{-1}$. Starbursts are defined as $10 < log (L_{100}/L_{\odot}) < 11$ and have SFRs of $2$–$17 M_{\odot}$ yr$^{-1}$, while normal blue galaxies, log ($L_{100}/L_{\odot}$) < 10, have SFRs less than $2 M_{\odot}$ yr$^{-1}$.

3. RESULTS

Figure 1 shows ACS three-color images of sample galaxies from the intermediate-redshift bin ($z \sim 0.7$). Galaxies are placed into four morphological categories: spiral, peculiar/irregular, compact, and early types (E/S0 not shown on image). For each morphological category, the figure shows a LIRG, a starburst galaxy, and a normal galaxy. Aside from the dearth of red early-type LIRGs (only five of the 119 LIRGs are classified as ellipticals), morphology is not a good predictor of IR luminosity.

Table 1 reports the morphological typing of the 119 LIRGs binned into three equal volume bins (low, intermediate, and
high redshift) and one additional low-redshift bin to highlight morphology evolution of the sample. Two major conclusions can be drawn from these numbers. First, the number density of LIRGs has dropped by 50% from the high-redshift bin to the intermediate-redshift bin and continues to drop in the low-redshift bins. Second, the morphological fraction of the LIRGs has changed. Above $z = 0.5$, the peculiar-to-spiral ratio for LIRGs is $p/s \sim 0.7$, whereas below $z = 0.5$ the peculiar-to-spiral ratio is $p/s = 9/7 = 1.3$. A quick Monte Carlo simulation indicates that drawing such a skewed sample from a distribution with $p/s = 0.7$ is unlikely at the 84% level, for this small sample size. We caution that the reclassification of four low-$z$ objects would be enough to change these fractions to match the higher $z$ results. Therefore, larger samples of low-$z$ LIRGs will be helpful in verifying if this trend is real. While the result is marginal, Figure 2, a plot of IR luminosity versus $M_B$ for the entire sample of galaxies, provides additional evidence for a change in LIRG population with redshift.

Figure 2 plots IR luminosity versus $M_B$, in low-, intermediate-, and high-redshift equal volume bins. The red horizontal line divides starburst galaxies (below the line) and LIRG luminosity (above the line). Objects with MIPS 24 $\mu$m measurements below 25 $\mu$J are shown as black circles and are designated “normal” galaxies. The morphologies of the starburst and LIRG samples are indicated: spiral galaxies are blue circles, peculiar/irregular are green squares, compact galaxies are yellow stars, and ellipticals are red triangles. Filled symbols are blue galaxies, $(U - B) < 0.2$, and open symbols are galaxies redder than this limit. This plot illustrates the morphological evolution hinted at in the previous analysis. In the high-redshift bin, spirals and peculiars are well mixed, spanning similar and high-redshift equal volume bins. The red horizontal line divides starburst galaxies (below the line) and LIRG luminosity (above the line). Objects with MIPS 24 $\mu$m measurements below 25 $\mu$J are shown as black circles and are designated “normal” galaxies. The morphologies of the starburst and LIRG samples are indicated: spiral galaxies are blue circles, peculiar/irregular are green squares, compact galaxies are yellow stars, and ellipticals are red triangles. Filled symbols are blue galaxies, $(U - B) < 0.2$, and open symbols are galaxies redder than this limit. This plot illustrates the morphological evolution hinted at in the previous analysis. In the high-redshift bin, spirals and peculiars are well mixed, spanning similar $M_B$ and $L_{IR}$ ranges. In the low-redshift bin, the two populations segregate with the peculiars systematically at higher IR luminosity than the spirals. This results in a change of the LIRG peculiar-to-spiral ratio.

The morphological segregation of low-$z$ IR luminous galaxies has been observed by Ishida (2004) in a statistically complete sample of 56 local LIRGs drawn from the Infrared Astronomical Satellite Bright Galaxy Sample (Soifer et al. 1987). The Ishida study finds that 100% of galaxies with $\log L_{IR} > 11.5$ show at least some evidence for tidal features. The majority of galaxies with $11.1 < \log L_{IR} < 11.5$ also tend to be disturbed, but $\sim 30\%$ are bright isolated spirals. The Ishida study indicates that at lower IR luminosities, spirals comprise a larger fraction of the total. The implications of these morphological changes with redshift will be explored in § 4.

While morphology does not appear to be a good indicator of IR luminosity for blue galaxies, $(U - B) < 0.2$, absolute $M_B$ magnitude is. Blue galaxies (filled symbols in Fig. 2) show a clear trend of increasing IR luminosity with $M_B$, regardless of morphology. This trend, shown previously without a color-cut (Chary & Elbaz 2001; Le Floc’h et al. 2005), was found to have a large scatter. With a color-cut, this scatter is significantly reduced. For our sample, the rms scatter in IR luminosity about the best-fit line (black line) is $\sim 0.25$ dex. Brighter than $M_B < -21$ (left of the red vertical line), 75% of galaxies are LIRGs, regardless of redshift. In the highest redshift bin, spirals and peculiars are well mixed. In contrast, at a given $M_B$, in the low-$z$ bin, spirals tend to have lower IR luminosities than peculiars.

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**Table 1**

| Galaxy Type | $0.83 < z < 1.00$ | $0.61 < z < 0.83$ | $0.10 < z < 0.61$ | $0.10 < z < 0.50$ |
|-------------|-------------------|-------------------|-------------------|-------------------|
| Number      | Percent           | Number            | Percent           | Number            | Percent           |
| Total       | 63                | 100               | 30                | 100               | 25                | 100               |
| Spiral      | 29                | 46                | 14                | 47                | 12                | 48                |
| Peculiar    | 20                | 32                | 10                | 33                | 10                | 40                |
| Compact     | 10                | 16                | 6                 | 20                | 2                 | 8                 |
| Elliptical  | 4                 | 6                 | 0                 | 0                 | 1                 | 4                 |

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**Figure 2**—Plot of total IR luminosity (in solar units) vs. rest-frame $B$-band magnitude in three equal volume redshift bins. LIRGs lie above the horizontal red line. Morphology is indicated by color and shape: spirals are blue circles, peculiar/irregular are green squares, compacts are yellow stars, and early types (E/S0) are red triangles. Objects undetected in the MIPS image are shown as small black circles. Filled symbols are blue galaxies, $(U - B) < 0.2$, and open symbols are galaxies redder than this limit. For blue galaxies, there is a clear trend of increasing IR luminosity with $M_B$. The rms scatter in IR luminosity about the bivariate least-squares fit (black line) to the entire sample of blue galaxies is $\sim 0.25$ dex. Brighter than $M_B < -21$ (left of the red vertical line), 75% of galaxies are LIRGs, regardless of redshift. In the highest redshift bin, spirals and peculiars are well mixed. In contrast, at a given $M_B$, in the low-$z$ bin, spirals tend to have lower IR luminosities than peculiars.
LIRGs, regardless of redshift. Only three of the 93 blue galaxies brighter than this limit are undetected in the MIPS image.

4. DISCUSSION

Studies of galaxies in the UV and optical have shown that the average comoving SFR density of the universe has declined by a factor of $\sim 10$ since $z = 1$ (Lilly et al. 1996; Madau et al. 1998; Hogg et al. 1998; among others), and observations in the submillimeter wavelengths indicate that it may have peaked around $z = 2$ (Chapman et al. 2005). Because IR luminosity strongly correlates with SFR (Kennicutt 1998), we see a decline, by $\sim 50\%$, in the numbers of LIRGs from the high-redshift bin ($z \sim 0.95$) to the intermediate- ($z \sim 0.7$) and low- ($z \sim 0.4$) redshift bins. This drop in LIRG numbers matches well the results from Le Floc’h et al. (2005), who found that the comoving IR energy density evolves as $(1 + z)^{3.9}$. Assuming the drop in IR energy density is dominated by a reduction in the number of LIRGs, we expect a $50\%$ drop in the number of LIRGs of from $z = 1$ to $z = 0.7$, which is what we find. Despite this decline, $\sim 75\%$ of the brightest $(M_g < -21.0)$, blue $[(U - B) < 0.2]$ galaxies are LIRGs, regardless of redshift. Therefore, it appears that the $B$-band optical and IR luminosities of galaxies are linked, with the SFR as an obvious candidate for the connection.

A large gas supply is required to sustain an elevated SFR at the LIRG level. A LIRG event in the Milky Way lasting only 100 Myr would use up the entire Galactic H I disk gas supply (assuming $2.5 \times 10^7 M_\odot$ of H I gas; Nakanishi & Sofue 2003). However, roughly half of the intermediate- and high-redshift LIRGs in our sample are comprised of large normal-looking spirals like the Milky Way, the difference being that high-$z$ LIRG spirals can be as luminous in the IR as peculiar galaxies. BELL05 finds that LIRG spirals tend to be massive with stellar masses $M_\odot > 2 \times 10^{10} M_\odot$. Figure 4 of BELL05 shows that the specific SFR of a handful of the most massive LIRGs are at or below their past average, indicating that these galaxies experienced multiple LIRG events or have had enough gas to continuously form stars at a LIRG level. Eventually this gas, if not resupplied, will be used up. At low redshift, the makeup of the LIRG population changes. LIRG spirals exhibit lower IR luminosities than their peculiar counterparts and also become more rare. Possible explanations for this include (1) the gas reservoirs in spirals are depleted with time, or (2) gas accretion is reduced with time. With a depleted gas supply, and/or reduced gas accretion, local spirals can still form stars but generally at rates below the LIRG level. One way to build up a large, high-density gas supply at low $z$ is to merge spirals together, an event revealed by peculiar morphology.

This picture of gas depletion differs from that of H05, who suggest that major mergers of spirals are driving the star formation and creation of LIRGs since $z \sim 1$. In the H05 picture, most intermediate-mass spirals undergo at least one major merger since $z \sim 1$, during which the morphology changes from spiral to peculiar (merger) to compact (bulge formation) to spiral again (gas infall reforms the disk). If this scenario is responsible for most LIRGs, the process should maintain a roughly constant peculiar-to-spiral ratio, as each morphological phase leads, proportionally in time, into the next. Such a prediction is hard to reconcile with both the large fraction of undisturbed spirals at high redshift and the evolutionary changes seen in the morphological fractions of LIRGs.

While the changing peculiar-to-spiral ratio may appear at face value to be incompatible with the H05 picture, we would like to caution the reader on several points. First, the evidence against the H05 picture is based on visual morphological classifications and thus somewhat subjective. While identification of major mergers is relatively straightforward at low redshift, tidal features and other indications of peculiar morphology become harder to identify at higher redshift, as the signal-to-noise ratio drops. By using very deep optical imaging and cloning the low-$z$ objects to higher redshift, we have tried to minimize these concerns. In the future, adoption of quantitative morphological indicators such as concentration, asymmetry, clumpiness (Conselice 2003), and Gini/$M_\odot$ (Lotz et al. 2004) may help alleviate these concerns. Second, larger samples preferably in other parts of the sky will help to account for cosmic variance and increase our relatively modest sample of low-redshift LIRGs. Third, gas depletion at low $z$ may itself change the disk rebuilding efficiency in the H05 scenario and result in altered LIRG morphological fractions.

We would like to thank Leonidas Moustakas, Mark Dickinson, Ranga-Ram Chary, Catherine Ishida, and Sandra Faber for helpful comments on the project. This work has been supported in part by the NSF Science and Technology Center for Adaptive Optics managed by the University of California at Santa Cruz under the cooperative agreement AST-9876783.

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