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EVIDENCE FOR A MAJOR MERGER ORIGIN OF HIGH-REDSHIFT SUBMILLIMETER GALAXIES

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ABSTRACT

Submillimeter-detected galaxies located at redshifts $z > 1$ host a major fraction of the bolometric luminosity at high redshifts due to thermal emission from heated dust grains, yet the nature of these objects remains a mystery. The major problem in understanding their origin is whether the dust-heating mechanism is predominantly caused by star formation or active galactic nuclei and what triggered this activity. We address this issue by examining the structures of 11 submillimeter galaxies imaged with STIS on the *Hubble Space Telescope*. We argue that ~61% ± 21% of these submillimeter sources are undergoing an active major merger using the CAS (concentration, asymmetry, clumpiness) quantitative morphological system. We rule out at ~5 σ confidence that these submillimeter galaxies are normal Hubble types at high redshift. This merger fraction appears to be higher than for Lyman break galaxies undergoing mergers at similar redshifts. Using reasonable constraints on the stellar masses of Lyman break galaxies and these submillimeter sources, we further argue that at redshifts $z \sim 2$–3, systems with high stellar masses are more likely than lower mass galaxies to be involved in major mergers.

Subject headings: galaxies: evolution — galaxies: formation — galaxies: high-redshift — galaxies: interactions

1. INTRODUCTION

Faint submillimeter (submm) galaxies were discovered with the first generation of multielement detecting devices working at submm wavelengths, most notably the SCUBA array (Smail, Ivison, & Blain 1997). The nature of these galaxies has however remained a mystery, despite a considerable amount of observing time spent obtaining ~300 detections in the field and behind lensing clusters (Blain et al. 2002). The generally accepted working idea is that these submm galaxies are distant $z > 1$ systems that emit in the rest-frame far-infrared due to thermal emission from dust grains heated by star formation and/or active galactic nuclei (AGNs). These objects are also thought to be analogs of nearby ultraluminous infrared galaxies (ULIRGs), although it is debated whether the heating is by the UV continuum of massive stars or an active nucleus. As submm galaxies are 400 times more common at $z \sim 2$ than at $z \sim 0$, they constitute a significant fraction of the bolometric luminosity density at high redshift (Chapman et al. 2003a); thus understanding their origin and relationship to nearby galaxies is of central importance.

Answering fundamental questions concerning submm galaxies by studying them at multiple wavelengths has remained very difficult because of the low-resolution of SCUBA and other submm instruments. One approach to this problem has been to identify submm galaxies through their emission in the radio (Ivison et al. 1998; Chapman et al. 2002a), utilizing the fact that submm/far-infrared luminosities correlate in nearby galaxies (Helou et al. 1985). Through these identifications, we are able to determine submm source positions to within a subarcsecond, from which optical follow-up can be done. A subset of these submm galaxies whose positions were located using the radio have been imaged with the *Hubble Space Telescope* using STIS (see also a companion paper, Chapman et al. 2003b). Previous studies have been largely qualitative and often contain misidentifications (e.g., Smail et al. 1998; Ivison et al. 2001; Chapman et al. 2002b). On the basis of our analysis we conclude that 40%–80% of these submm sources are consistent with undergoing major mergers and statistically rule out at 5 σ confidence that these systems are normal galaxies at high redshift. We further demonstrate, through comparisons with artificially redshifted nearby ULIRGs and normal (non-ULIRG) galaxies, that high-redshift submm galaxies appear qualitatively similar to ULIRGs and are potentially forming into massive spheroids.

2. IMAGING AND ANALYSIS METHOD

Our sample consists of 11 submm sources selected in the radio. The full sample selection for these galaxies is described in Chapman et al. (2003b). Although there are some selection issues, these objects were not chosen on the basis of optical properties, and they span a wide range of optical magnitudes (Chapman et al. 2003b). Each of the submm sources (Fig. 1) we study was imaged in the 50CD clear filter in one to three orbits, in two separate exposures per orbit, resulting in a total exposure time of 1–3 ks (see Chapman et al. 2003b for further details).

We analyzed these images using the CAS (concentration, asymmetry, and clumpiness) morphological system (Conselice 2003). In the CAS system, the asymmetry index (A) is used to determine whether a galaxy is involved in a major merger (Conselice et al. 2000a, 2000b, 2003; Conselice 2003). The value of A is calculated by rotating a galaxy through 180° and subtracting this rotated galaxy from the original and comparing the absolute value of the residuals of this subtraction to the original galaxy flux (Conselice et al. 2000b). We placed our initial guess for the center on the brightest portion of each submm galaxy and ran the CAS program to determine their asymmetries and light concentrations.

To understand the systematics that are due to a lowered resolution and signal-to-noise ratio, we artificially redshifted 50 nearby ULIRGs (from Farrah et al. 2001 and Conselice 2003) and 82 normal Hubble types (Frei et al. 1996; Conselice 2003) to how they would appear in our STIS images at $z \sim 2$–3, the spectroscopic redshift range of these sources (S. C. Chapman et al., in preparation). These simulations are performed by reducing the resolution and surface brightness of a

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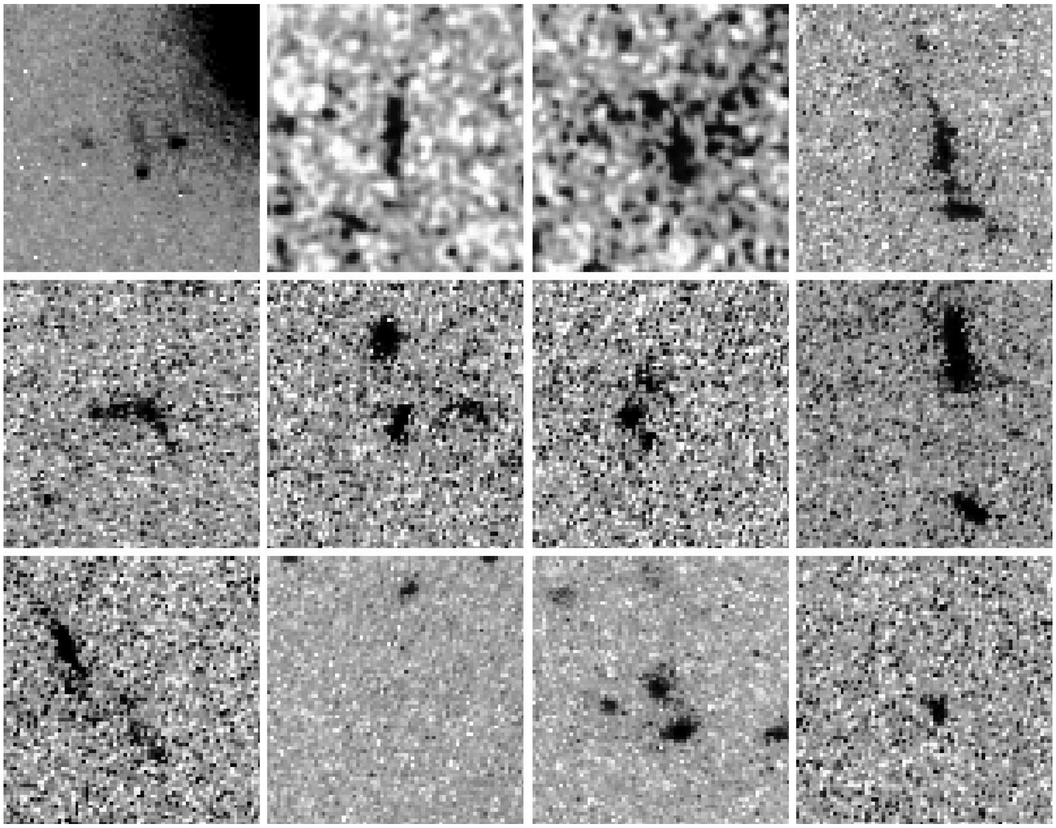

FIG. 1.—Montage images of the 12 submm galaxies imaged with STIS on the *Hubble Space Telescope.* In this Letter, we examine the quantitative morphological properties of all but one of these systems whose structure is too faint for an analysis.

galaxy to how it would appear at high redshifts. The amount of noise matching that expected in the STIS observations is then added in. Once these new images are created, on the basis of these simulations, we remeasure the CAS parameters of the simulated galaxies, in the same manner as for the original submm sources. Note that we are taking a very conservative approach by including these two types of nearby galaxies to account for redshift effects. The apparent morphology of the submm sources is very peculiar, and therefore the likewise peculiar nearby ULIRGs are a better population for making this correction. Normal galaxies also do not become significantly more irregular in the rest-frame ultraviolet (Windhorst et al. 2002). We use the nearby normal sample as an extreme lower limit to what these corrections could be.

3. RESULTS

3.1. *Evidence for a Merger Origin*

Concentration-asymmetry diagrams (e.g., Conselice et al. 2000a; Bershady, Jagren, & Conselice 2000) for our sample of submm galaxies are shown in Figure 2. The asymmetry and concentration values for these galaxies have been corrected for redshift effects assuming that they have morphologies intrinsically similar to ULIRGs (Figs. 2*a* and 2*c*) and nearby normal galaxies (Figs. 2*b* and 2*d*) (Conselice et al. 2000b). We also plot in Figures 2*a* and 2*b* the average values and 1 σ variations of measured concentrations and asymmetries for nearby galaxy populations, including ULIRGs, as observed in the rest-frame optical (Conselice 2003). Although we view these submm galaxies in the near- to mid-UV, the morphological appearance of ULIRGs and other star-forming galaxies does not significantly differ between optical and near-UV wavelengths (e.g., Conselice et al. 2000c; Surace & Sanders 2000). Figures 2*c* and 2*d* show the location of the submm galaxies in reference to the actual *C*-*A* values found for nearby normal galaxies, including separately labeled elliptical galaxies and ULIRGs.

We can use Figure 2 to determine which population the submm galaxies are most similar to morphologically. As can be seen in Figure 2, the dominant morphological feature of the submm galaxies is their high asymmetries. The distribution of the submm sources in *C*-*A* space is also most similar to the ULIRGs and does not overlap much with any normal galaxy type. Using the major merger criteria calibrated in Conselice (2003), on the basis of nearby ULIRGs, we find that a galaxy is likely a major merger if $A > A_{\rm merger} = 0.35$. Using the ULIRG $z \sim 2$ correction, we find that the merger fraction for the submm sources is 0.82, which is the same fraction found when correcting by the $z \sim 3$ simulations. The normal galaxy correction still reveals a large merger fraction of ~0.4, which is certainly a lower limit to the actual fraction of galaxies involved in mergers. This lower limit is as high as the largest merger fractions found for any Lyman break galaxy population (Conselice et al. 2003) (§ 3.2).

There are naturally uncertainties in this merger fraction calculation. First, the sample size is small, only 11 galaxies. Second, it is based on a correction that necessarily has some uncertainty in it, since the submm galaxies may be a mix of normal and merger/ULIRG systems. To circumvent this problem we performed a series of Monte Carlo simulations using our normal and ULIRG galaxy samples after they were simulated to $z \sim 2$. Sources of error accounted for in this simulation are our small sample size, resolution, surface brightness dimming, noise from STIS, and background light, as well as the range in possible intrinsic morphology. To carry out these simulations

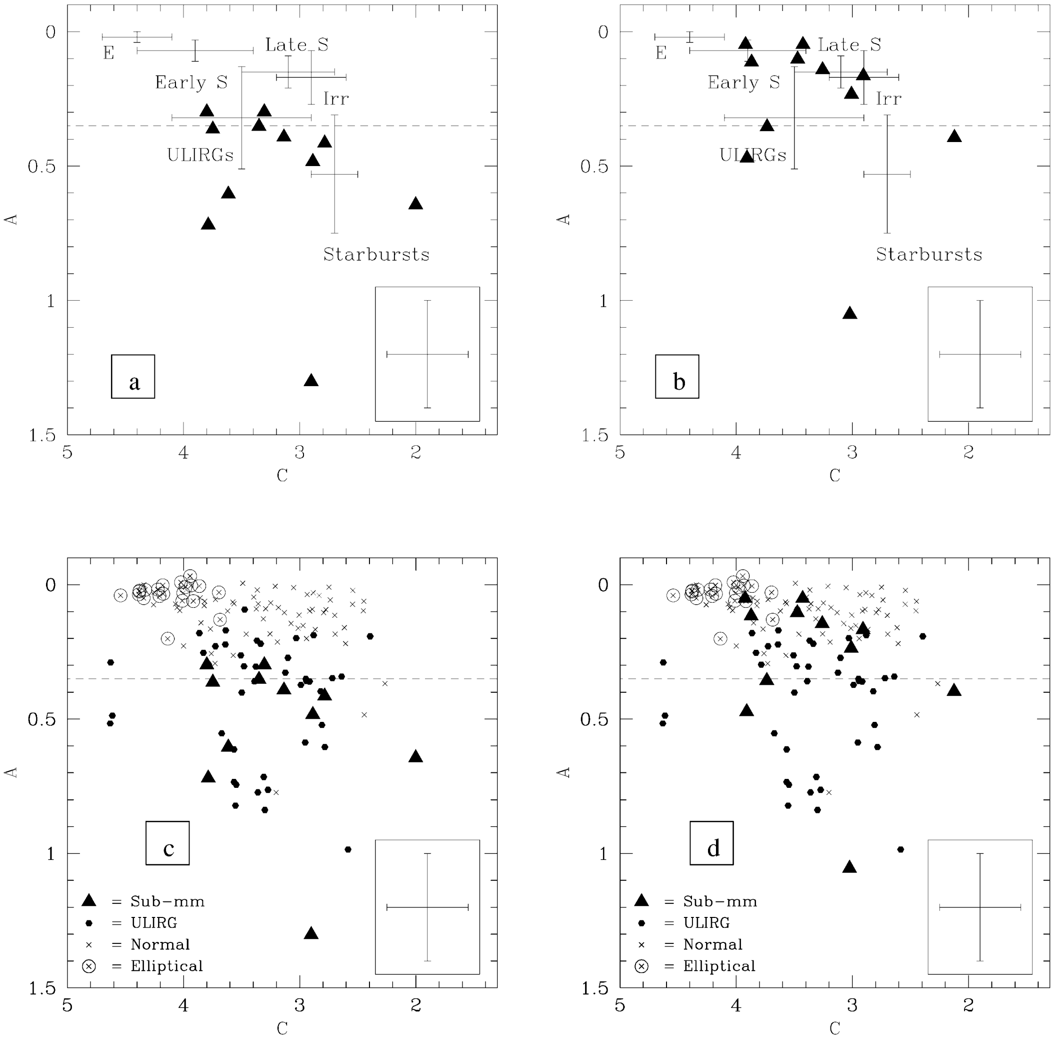

FIG. 2.—Concentration-asymmetry (*C-A*) diagram for the submm galaxies studied in this paper. The triangles show the locations of the submm sources on these diagrams after (*a*, *c*) correcting their measured values using $z \sim 0$ ULIRGs simulated to $z = 2$ and (*b*, *d*) correcting values using $z \sim 0$ normal galaxies simulated to $z \sim 2$. The various crosses in (*a*, *b*) show where average nearby galaxy populations fall in this space and their 1 σ variations. Plotted in (*c*, *d*) are the individual *C-A* values for nearby ULIRGs and normal galaxies, with the elliptical galaxies shown as circles. The horizontal dashed line is the asymmetry limit for major mergers, such that a galaxy is likely undergoing a merger if $A > A_{\rm merger} = 0.35$.

we take 11 objects at random from the ULIRG and normal galaxy distributions and compare their asymmetry distributions to those of the submm sources. Doing this, we find at 5 σ confidence that normal galaxies at $z \sim 2$ cannot reproduce the high asymmetries of the submm sources through a comparison of their resulting mean A values. The simulated ULIRGs are also slightly less asymmetric than the submm sources but have asymmetry values distributions consistent to within 1.9 σ.

3.2. *Submm and Lyman Break Galaxies*

The implied merger fraction of these submm galaxies appears to be slightly larger than what is found for UV-bright galaxies in the Hubble Deep Field (HDF) (Conselice et al. 2003) at similar redshifts. Lyman break galaxies at $z \sim 2.5$ found in the HDF all have implied merger fractions lower than our derived submm values (Conselice et al. 2003). For example, UV-bright galaxies at $2 < z < 3$ with magnitudes $M_B < -20$ and stellar masses greater than $10^{9.5}\ M_\odot$ have a merger fraction of ∼0.18 (Fig. 3). The brightest and most massive galaxies seen in the HDF, with $M_B < -21$ and $M_* > 10^{10}\ M_\odot$, have merger fractions of ∼0.4–0.5, which is lower than the implied merger fractions of our submm sample. From this it appears that the submm galaxies are actively undergoing mergers in a greater abundance than Lyman break galaxies. This may be the result of higher mass systems undergoing more mergers at higher redshifts (Fig. 3). Submm galaxies as a population appear to be dominated by systems involved in major mergers, while the Lyman break galaxies are more likely to be in various phases of evolution. In Figure 3 we plot the merger fraction of the submm sources at a stellar mass of $10^{11}\ M_\odot$. This estimate is likely roughly correct as submm galaxies have dynamical and gas masses greater than $10^{11}\ M_\odot$ (e.g., Frayer et al. 1998).

3.3. *Comparison to z ∼ 0 Galaxies: ULIRGs and Spheroids*

Although we are in the regime of small number statistics, we can argue that the submm galaxies are similar to nearby ULIRGs in terms of their structural properties, in addition to their already well-established similarities in producing rest-frame far-infrared light (e.g., Dey et al. 1999). We have already argued this through the high asymmetries and implied high merger fraction for the submm galaxies and the low probability that these submm sources are morphological similar to normal

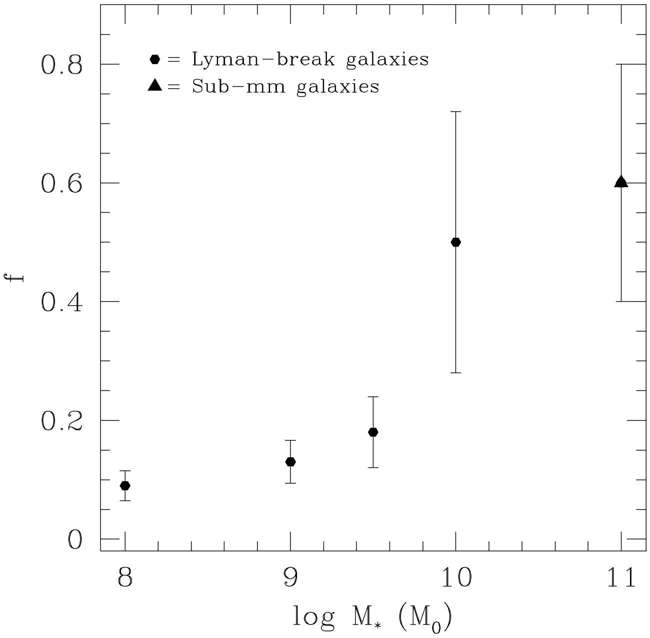

FIG. 3.—Fraction of galaxies between $2 < z < 4$ consistent with undergoing a major merger (f), as a function of stellar mass lower limit. The stellar masses of the Lyman break galaxies (LBGs) were obtained through fits to spectral energy distributions acquired by Papovich et al. (2001) and whose merger properties are discussed in detail in Conselice et al. (2003). The stellar mass lower limit of $10^{11}\ M_\odot$ for the submm galaxies is estimated on the basis of the large gas and dynamical mass measurements of these galaxies.

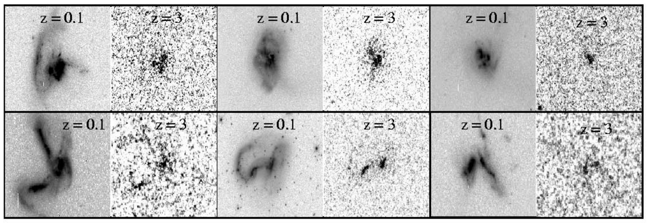

FIG. 4.—Nearby ULIRGs at $z \sim 0.1$, and images of the same galaxies after they have been simulated to $z \sim 3$ and viewed under the same conditions as the submm galaxies.

galaxies. This can be shown qualitatively as well.Figure 4 shows nearby ULIRGs at $z \sim 0.1$ and the same galaxies after they have been simulated at $z \sim 3$. These are the same simulations used in § 2 to determine the correction to the concentration and asymmetry values. The simulated ULIRGs appear very similar to the submm galaxies (Fig. 1), although the separation between components in nearby ULIRGs and the submm sources differs (Chapman et al. 2003b). Nearby normal galaxies, such as disk and elliptical galaxies, do not appear in a similar manner when redshifted out to these same redshifts.

We can further test how similar the ULIRGs and submm galaxies are in terms of their morphologies by performing Kolmogorov-Smirnov (K-S) tests. The probability that the submm source asymmetries are taken from the ULIRG population asymmetries is 21% after correcting by the ULIRG simulation results and 2% when correcting by the normal galaxy simulations. The probability of association with the normal galaxies is less than 0.001% when using the ULIRG correction and 1% when using the normal galaxy simulation correction. The concentration index probabilities of association with ULIRGs are 96% for the ULIRG correction and 78% for the normal galaxy correction. The corresponding probabilities for a normal galaxy association are 12% and 32%, respectively. Although these K-S tests are not conclusive, they again rule out that the submm asymmetry distribution is similar to the asymmetry distribution of normal galaxies.

If submm sources are analogs of nearby ULIRGs, then they are perhaps forming into modern elliptical galaxies. Elliptical galaxies can be uniquely identified in the CAS system by their high light concentrations and low asymmetries. The only galaxies that have light concentrations as high as elliptical galaxies are the ULIRGs (Conselice 2003), suggesting a causal connection. From Figure 2 it can also be seen that some of the submm sources have light concentrations as high as elliptical galaxies, suggesting that at least some of these systems are forming into spheroidal galaxies. We can conclusively rule out that all of these systems are spiral galaxies, as four (36%) have light concentrations too high to be forming into disks.

4. DISCUSSION AND CONCLUSIONS

Submm galaxies and ULIRGs have comparable rest-frame far-infrared luminosities and large masses, suggesting that submm sources result from a similar merger origin. However, direct quantitative evidence has been lacking. We argue in this Letter that a significant fraction of submm sources are galaxies actively engaged in major mergers by using the CAS morphological system (Conselice 2003). We find that 40%–80% of our submm galaxies show consistent evidence for undergoing major mergers. These results have important implications for the nature of massive galaxy formation. Submm sources constitute a significant galaxy population at high redshift, undergoing mergers, that likely later evolve into the massive galaxies seen in the nearby universe. These massive galaxies therefore appear to be forming their stars through merger-induced starbursts rather than collapses.

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