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WESTPHAL-MMD 11: AN INTERACTING, SUBMILLIMETER LUMINOUS LYMAN BREAK GALAXY

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ABSTRACT

We present new *Hubble Space Telescope*, high-resolution optical imaging of the submillimeter luminous Lyman break galaxy (LBG), Westphal-MMD 11, an interacting starburst at $z = 2.979$. The new imaging data, in conjunction with reanalysis of Keck optical and near-IR spectra, demonstrate MMD 11 to be an interacting system of at least three components: a luminous blue source, a fainter blue source, and an extremely red object (ERO) with $R-K \gtrsim 6$. The separations between components are ∼8 kpc ($\Lambda = 0.7$, $\Omega_M = 0.3$, $h = 0.65$), similar to some of the local ultraluminous infrared galaxies (ULIGs). The lack of obvious active galactic nucleus in MMD 11, along with the fragmented, early-stage merger morphology, suggest a young forming environment. While we cannot unambiguously identify the location of the far-IR emission within the system, analogy to similar ULIGs suggests the ERO as the likely far-IR source. The greater than $10^{12}\ L_\odot$ bolometric luminosity of MMD 11 can be predicted reasonably from its rest-frame UV properties once all components are taken into account; however, this is not typically the case for local galaxies of similar luminosities. While LBGs as red in $g-R$ and $R-K$ as MMD 11 are rare, they can only be found over the restricted $2.7 < z < 3.0$ range. Therefore, a substantial number of MMD 11–*like* galaxies ($\simeq$0.62 arcmin^{-2}) may exist when integrated over the likely redshift range of Submillimeter Common-User Bolometric Array (SCUBA) sources ($z = 1$–5), suggesting that SCUBA sources should not necessarily be seen as completely orthogonal to optically selected galaxies.

Subject headings: cosmology: observations — galaxies: evolution — galaxies: formation — galaxies: starburst

1. INTRODUCTION

Our understanding of the blank-field submillimeter sources, their diversity, and their connection to optically selected galaxies has had a slow progression since their discovery by Smail, Ivison, & Blain (1997). The few sources with well-studied properties come mostly from the lensed surveys of Smail et al. (2002) and have been restricted to the small fraction with relatively bright and obvious optical counterparts. Only one of these does not contain the signatures of an active galactic nucleus (AGN; SMM J14011+0252; Ivison et al. 2000, 2001). While the identification of submillimeter sources has thus far only been successful for the brightest optical counterparts and the strongest emission-line spectra, none of the emission lines are all that strong compared to purely star-forming objects, and it is as yet unclear what the relative proportion of AGN is for submillimeter sources. This bright counterpart bias also manifests itself in the redshift distribution of submillimeter sources. While photometric studies place the median redshift for the submillimeter sample at $\langle z \rangle \sim 3$ (Smail et al. 2000; Archibald et al. 2001), no submillimeter-selected galaxy has yet been spectroscopically identified with redshift higher than 2.8.

Westphal-MMD 11 (hereafter MMD 11) remains among the highest spectroscopically confirmed redshift submillimeter sources ($z = 2.979$), which are thought to be exclusively starbursting galaxies. Targeted submillimeter observations of rare, luminous AGNs at $z > 3$ have, however, yielded detections since early single-bolometer observations (Hughes, Dunlop, & Rawlings 1997 summarize the state of submillimeter detections with pre–Submillimeter Common-User Bolometric Array [SCUBA] instruments; Archibald et al. 2001, Carilli et al. 2001, and Willott et al. 2002 have demonstrated the high frequency of high-z AGN detection in the submillimeter). Ironically, MMD 11 was discovered originally not through its copious submillimeter emission but as a Lyman break galaxy (LBG; Steidel, Pettini, & Hamilton 1995). MMD 11 was isolated as a candidate LBG with a very high star formation rate (SFR), its rest-frame UV properties suggesting several hundred $M_\odot$ yr^{-1}, and its $R-K = 4.54$ is the reddest color for the observed LBG sample (Shapley et al. 2001). The submillimeter detection validated the UV-based predictions, showing that this is an ultraluminous IR galaxy (ULIG) with a far-IR luminosity of $L_{\rm FIR} \sim 6.6 \times 10^{12}\ L_\odot$, implying an SFR $\sim 10^3\ M_\odot$ yr^{-1}. The detailed properties of this source have prompted successful submillimeter detection of other LBGs (Chapman et al. 2000a).

However, LBGs have been difficult to consistently detect in the submillimeter. Work by Chapman et al. (2000b), Peacock et al. (2000), Eales et al. (2000), van der Werf et al. (2000), Sawicki (2001), Baker et al. (2001), and Webb et al. (2002) has suggested that the direct overlap between the SCUBA and LBG populations is small and that potential overlap may be difficult to predict from knowledge of UV characteristics. Therefore, an unresolved issue is the overlap between submillimeter-selected and optically selected galaxy populations, with MMD 11 remaining an enigmatic bridge since its discovery as a submillimeter source (Chapman et al. 2000b). Attempts to model the properties of MMD 11 led to apparently contradictory pictures. The galaxy shows an unremarkable optical spectrum for a ULIG with 3 times the bolometric luminosity of Arp 220 (Chapman et al. 2000b). In the near-IR, it shows narrower nebular line widths than the median LBG (Pettini et al. 2001) but is not unusual in the line ratio diagnostics. MMD 11 has broadband colors that cannot be simultaneously fitted in both the UV/optical and near-IR with synthetic spectral templates; adding sufficient dust to the template to match the J, H, K_s photometry produces an increased extinction at shorter wavelengths, resulting in an underestimate of the UV/optical bands. The broadband photometry is therefore best fitted by the superposition of a blue, relatively unobscured galaxy coupled with a young, dusty galaxy (Shapley et al. 2001).

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In this Letter, we present new *Hubble Space Telescope* (*HST*) optical imaging of MMD 11, using existing Keck spectroscopy and near-IR imaging to elucidate the high-resolution *HST* data. All calculations assume a $\Lambda = 0.7$, $\Omega_M = 0.3$ cosmology, with $h = 0.65$ providing a scale of $1'' = 8.31$ kpc at $z = 2.979$.

2. OBSERVATIONS AND RESULTS

2.1. *HST Visible and Keck Near-IR Observations*

HST imaging was obtained through a Cycle 10 program with the Space Telescope Imaging Spectrograph (STIS) to study the morphologies of submillimeter luminous galaxies. One orbit of integration time, giving 1170 s of LOW SKY observation, was split between two exposures, using the 50CCD clear filter. The pipeline-processed frames were calibrated, aligned, and cosmic-ray–rejected, using standard IRAF/STSDAS routines. The pixel size in the STIS image is $0\farcs0508$ pixel^{-1}. The sensitivity limit reached is 50CCD ~ 27 ($5\ \sigma$), corresponding to $R \sim 28$ for a point source with a late-type spiral galaxy spectral energy distribution (SED). The 50CCD clear filter is roughly a Gaussian with 1840 Å half-width and a pivot wavelength of 5733.3 Å, and we refer to the associated AB magnitude as $R'(573)$. Near-IR observations in $0\farcs4$ *K*-band seeing were obtained with the Near-InfraRed Camera (NIRC) on the Keck I telescope in the *J*, *H*, and K_s bands, as described originally in Shapley et al. (2001). The STIS image is presented in Figure 1*a* with K_s-band contours overlaid. The K_s limiting magnitude in a $1\farcs5$ aperture is 22.1, $5\ \sigma$.

The relative astrometry was ascertained in the images by smoothing the STIS image to the K_s resolution and matching all sources greater than $5\ \sigma$ except MMD 11. After maximizing the cross-correlation signal between frames, the rms of the match between the optical and infrared sources is $0\farcs16$. While ground-based optical imaging with $\sim1''$ seeing identified only an $R_s = 24.05$ unresolved source (Shapley et al. 2001), our STIS imaging uncovers three distinct components with intervening low surface brightness emission in the MMD 11 region, identified as *B*1, *B*2, and *R*3. The component separations are $B1-B2 = 1\farcs13$, $B1-R3 = 0\farcs71$, $B2-R3 = 0\farcs74$. A $2\farcs5$ aperture subsuming all three components and intervening structure measures $R'(573) = 24.03$, whereas the sum of the three component measurements in $0\farcs4$ apertures amounts to $R'(573) = 24.54$, or 63% of the total flux ($R_{B1} = 25.28$, $R_{B1} = 26.11$, $R_{R3} = 25.75$). We therefore see a significant portion of the total flux from MMD 11 is emitted in low surface brightness regions between the compact components. Component *B*1 has close to half the $R'(573) = 24.54$ measurement for the triplet, with *B*2 and *R*3 having, respectively, $\frac{1}{6}$ and $\frac{1}{3}$. The *R*3 component is resolved by STIS but is quite compact and isolated with a half-light radius of $0\farcs2$. *B*1, on the other hand, is morphologically complex, with low surface brightness emission extending to relatively large radius.

The near-IR images of MMD 11 are all nearly unresolved and of high enough resolution to identify their location among the STIS components. The peaks of the bright *J*, *H*, and K_s sources all align to within $0\farcs2$ with the component labeled *R*3, and all three bands show an extension toward the STIS-identified blue component, *B*1. The K_s-band image has the best seeing ($\sim0\farcs45$), and a faint source is visible at the position of *B*1. A point-source fit to the bright *R*3 component is subtracted (Fig. 1*b*), and an aperture measurement at *B*1 with matched $0\farcs5$ diameter shows $K_s = 21.9$, suggesting a plausible infrared counterpart to the bright optical LBG with $R-K = 2.7$, close to the median for the LBG sample of $R-K = 2.85$ (Shapley et al. 2001). We conclude that the optically bright component and the near-IR bright component (Shapley et al. 2001) are two distinct parts of an interacting system. We note that MMD 11 displays a striking difference between its rest-frame UV and visible emission (a *morphological k-correction*), seen only rarely in more local galaxies (Hibbard & Vacca 1997; Abraham et al. 1999; Kuchinski et al. 2001; Windhorst et al. 2002).

2.2. *Spectroscopic Observations*

Keck, Low-Resolution Imaging Spectrometer (LRIS), and NIRSPEC observations were obtained for MMD 11. By chance, the slit alignments on both LRIS and NIRSPEC were such that we find evidence for redshifts of the three components labeled in Figure 1. The reductions of the spectra are described in Pettini et al. (2001). With NIRSPEC, the derotator was not functioning during the observation, and the slit rotates in time, starting at 0° (north) and rotating through to $-30°$ (west of north). While a source with a strong continuum is always present in the two-dimensional spectra, a second source appears to rotate in and out of the $1''$ slit with time, having a strong [O III] λ5007 emission line at the same redshift as the bright *K*-band source but no detected continuum (Fig. 2). The separation of the two components is $0\farcs7$, similar to the separation of either *B*1/*R*3 or *B*2/*R*3 seen in the STIS image. There remains some ambiguity as to whether the second source lacking continuum is *B*1 or *B*2, or both at different times. Analysis of the two components in the NIRSPEC spectrum indicates that they have roughly equal $[\mathrm{O\ III}]_{5007}$ flux. While Hβ and $[\mathrm{O\ III}]_{4959}$ are also visible in the bright *K*-band source, there are no other lines visible for the off-continuum component. $[\mathrm{O\ III}]_{4959}$ in particular lies in a much noisier region of the *H*-band window than $[\mathrm{O\ III}]_{5007}$ and is only just detected in the brighter *R*3 component.

The LRIS slit was aligned with the brightest *R*-band peak, which we now identify as STIS-*B*1. Close inspection of the LRIS image suggests that a spatially extended or double Lyα line lies on the slit, with an apparent extension of $\sim1''$. The slit is aligned north/south, and the extension of the line has no continuum associated. We conclude that the red source, STIS-*R*3, was also present on the slit with detected Lyα.

2.3. *Submillimeter and Radio Observations*

SCUBA observations at 850 and 450 μm were taken during an observing runs in 1998. Reductions and measurements from the data were presented in Chapman et al. (2000b). The photometry detection at 850 μm measured 5.5 ± 1.4 mJy. MMD 11 has also been detected at 1200 μm at IRAM (A. Baker 2002, private communication). Very Large Array (VLA) radio observations were obtained in the A configuration at 1.4 GHz. These observations were made available to us to search for a radio counterpart to the submillimeter source in order to pinpoint the location of the far-IR emission. The reductions and details are described elsewhere (M. Yun et al. 2002, in preparation). No significant emission is detected at the optical source position, or within the SCUBA beam, and we place a $3\ \sigma = 75\ \mu$Jy limit on the 1.4 GHz flux.

3. ANALYSIS AND DISCUSSION

While early modeling efforts for MMD 11 did not result in any conclusive picture, our deep STIS imaging in conjunction with the Keck spectra and near-IR imaging have revealed the source to be composed of at least three distinct components (Figs. 1 and 2) lying at the same redshift. The *R*3 component

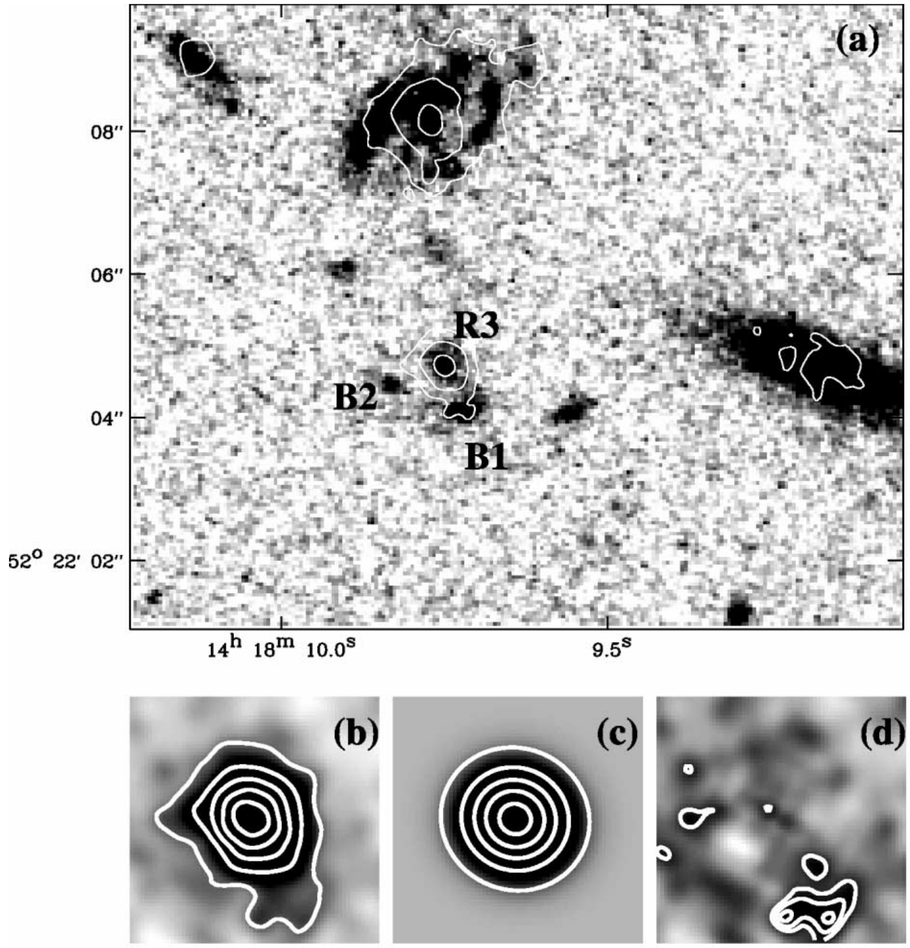

FIG. 1.—(*a*) MMD 11 observed with STIS 50CCD and the K_s band (Keck/NIRC) in contours. North is up and east is left, with a 9″ × 11″ frame centered near the red *R3* component. Note the faint K_s extension from *R3* to *B1*. In the other three panels, we present (*b*) a close-up view of the red *R3* component, (*c*) a Gaussian fit to *R3*, and (*d*) the residuals after subtraction. A faint *K* source is present at the position of the blue source, *B1*.

represents an extremely red object (ERO) with $R'(573)-K_s = 6.15$, generating the bulk of the near-IR emission, and can naturally be fitted with a dusty template SED. By subtracting a point-source fit to the K_s-band *R*3, we have also measured the *K* flux from *B*1, resulting in $R'(573)-K_s = 2.7$, a value fairly typical of LBGs. However, a template SED fit to an ERO at $z \sim 3$ requires a large amount of extinction using the Calzetti dust law (Calzetti 1997), as found even for the average properties of LBGs like MMD 11 in Shapley et al. (2001). For MMD 11 in particular, this would imply an unphysically large SFR, dwarfing the submillimeter-implied 600 $M_\odot$ yr^{-1} (Chapman et al. 2000b), as even the ERO component *R*3 has one-fifth the total system flux at the *R* band (translating to an uncorrected SFR of ∼4 $M_\odot$ yr^{-1}). In addition, the large bandwidth of the STIS 50CCD filter precludes accurate constraints on the optical SED for the various components. We simply conclude that the majority of the near-IR emission emanates from the *R*3 component.

With such disparate broadband and morphological properties between components, it is surprising that the [O III]$_{\lambda 5007}$ from different components are roughly equal in intensity (EW$_\lambda$ is, of course, very different). We assume that the similarities occur only by chance.

While we have elucidated the optical and near-IR structure of MMD 11 significantly with our high-resolution imaging and spectroscopy, we would like to identify precisely the location and nature of the intense far-IR emission within the system. Our radio data are not deep enough to pinpoint the far-IR emission within MMD 11, although it should have detected a buried AGN component if present. The upper limit ($S_{1.4\,\mathrm{GHz}} < 75$ μJy) is still within the error bounds of the median expected flux relation for the submillimeter measurement (30 μJy; using Carilli & Yun 2000). The luminosity limit (2.00×10^{22} W Hz^{-1}, assuming a radio spectral index of $\alpha = -0.75$) is a factor of 10–100 less than $z \sim 0.1$ radio-quiet quasars studied by Kukula et al. (1998). The LRIS spectrum of MMD 11 shows no evidence for narrow (type II AGN) or broad (type I AGN) emission lines. The Lyα profile, known for both *B*1 and *R*3, has a total equivalent width of zero considering both the emission and absorption. The Lyα emission line EWλ is only 6 Å in the rest frame, which is weak compared with the Lyα emission EWλ distribution of LBGs (Steidel et al. 1999). For component *R*3, the Hβ line is narrow, and the [O III]/Hβ ratio is consistent with a starburst. Therefore, the spectroscopic data can be used to place strong limits on the AGN contribution to MMD 11.

While we have no way to directly assess the location or extent of the far-IR emission, other ULIG systems often show submillimeter emission arising in the ERO galaxy component, while the bulk of the optical emission remains relatively unobscured in bluer companions. The only submillimeter-selected source identified with a pure starburst nature is SMM 14011−0252. This galaxy was recently characterized with a similar multicomponent structure (Ivison et al. 2001), encompassing an ERO separated by ∼1″.5 from each of two luminous bluer sources, the far-IR emission apparently localized near the ERO from the radio

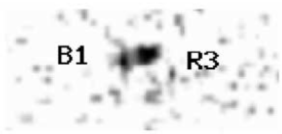

FIG. 2.—Spatially extended spectra of the [O III] λ5007 line from NIRSPEC, identifying redshifts for two of the three components labeled in Fig. 1: STIS-B1 and R3 (separation ∼0″.7). The image has been smoothed with a 0″.4 Gaussian. The dispersion direction is vertical.

and CO gas (Frayer et al. 1999; Ivison et al. 2000). MMD 11 has a similar far-IR luminosity to SMM 14011−0252, which has a cluster lensing-corrected SCUBA flux of 5.0 mJy and a redshift of $z = 2.56$, although the CO (3–2) measurement would not have been possible without the 2.5 times lensing factor. A similar multicomponent configuration with the radio/far-IR identified to an ERO is also seen in two $z \lesssim 1$ SCUBA-detected ULIGs from the *Infrared Space Observatory*/FIRBACK survey (Chapman et al. 2002b).

Both MMD 11 and SMM 14011−0252 appear morphologically to be examples of the *early-stage merger* type of ULIG (Goldader et al. 2002), prevalent in ∼25% of the local ULIG population whereby luminous components are separated by greater than 10 kpc. These sources are in some sense equally well identified from their submillimeter/far-IR or UV properties. While this class of system appears relatively common in SCUBA identifications, it is as yet unclear whether this is because these sources were the easiest to identify of the submillimeter population or because submillimeter galaxies are typically made in different ways than local ULIGs, such early-stage mergers being much more common at high z. Recent work with *HST* has suggested the merger rate in the past being higher by a factor of $(1 + z)^{2.5}$ (Le Fèvre et al. 2000).

While MMD 11 is clearly similar in many respects to ULIG galaxies at more recent cosmic epochs, it remains difficult to relate MMD 11 to the rest of the LBG population. Most of the LBGs can be consistently fitted from the U through K band with a single SED model (Shapley et al. 2001). However, the reddest $R-K$ LBGs have significant far-IR/submillimeter emission as a group, and another $R-K > 4$ LBG has also been detected with SCUBA (Chapman et al. 2000a). It is therefore reasonable to hypothesize that the most bolometrically luminous tail of the LBG population extends into the $z \sim 3$ ULIG/SCUBA population.

When considered as a complete system (all components included), both MMD 11 and SMM J14011 appear to lie roughly on the local far-IR/UV versus UV continuum slope relation for local *IUE* starburst galaxies (FIX/β relation; Meurer, Heckman, & Calzetti 1999). However, we have seen that the regions generating the UV and far-IR are likely to be physically separated by ∼8 kpc, and it might be expected that the predictive qualities of FIX/β are likely to be haphazard and orientation-dependent. We must thus consider why these two $z \sim 3$ galaxies balance in energy output between the UV and far-IR well enough for the prediction to work. MMD 11 is quite luminous, even without any extinction correction; the SFR calculated from $L_{\rm UV}$ is 20 $M_\odot$ yr^{-1}. In addition, the total MMD 11 system is, by UV color, very red, which explains why it was flagged as a submillimeter-bright candidate with a predicted $S_{850\,\mu{\rm m}} \sim 2$ mJy, in the absence of knowledge about the $R-K$ color (MMD 11 would not have been selected for submillimeter follow-up had it been truly unobscured). Systems like MMD 11 and SMM J14011 may therefore suggest that an LBG with a luminous, relatively red, UV component could imply an associated bolometrically luminous system. In other words, the existence of a bright, reddened UV structure makes it causally more likely that there is a bolometrically bright and heavily obscured component lurking nearby. It is not clear that either SMM J14011 or MMD 11 are necessarily *accidents* just because they have multiple components with different amounts of UV attenuation. In this context, the FIX/β relation can be interpreted as mapping bolometrically luminous galaxies to dustier configurations, and even the parts that are able to leak out in the UV will tend to be reddened more so than if the object were dust-free.

The FIX/β relation holds for the local LIG/starburst population ($L_{\rm FIR} \leq 10^{11}\ L_\odot$), despite the UV and far-IR bright components often being spatially distinct. By contrast, this is not a typical property of ULIGs (>10 times more far-IR luminous than the LIGs and *IUE* starbursts) or even the early-stage merger subset of the ULIGs, which are generally many times overluminous in the far-IR compared to the predicted UV energy absorbed. From the ULIG sample of Goldader et al. (2002), only one other galaxy, IRAS 22491, appears to obey the FIX/β relation. However, the $z \sim 3$ LBGs have greater characteristic luminosities for a given far-IR/UV ratio than local galaxies, suggesting that LBGs are less obscured per unit luminosity than lower redshift star-forming galaxies (Adelberger & Steidel 2000; Chapman et al. 2000a). This suggests that LBGs are typically more similar to the less luminous LIG/starburst population locally than the ULIGs.

LBGs as red as MMD 11, in both $g-R$ and $R-K$, are rare (<5% or <0.05 arcmin^{-2}). However, the statistics for such sources are poor since the LBG survey could only have found objects like MMD 11 (i.e., instrinsically red in the UV) over a very restricted redshift range, $\sim 2.7 < z < 3.0$ (at higher redshifts, MMD 11 would have been too red in $g-R$ to have remained in the sample). Therefore, when integrated over the likely redshift range of SCUBA sources ($z = 1$–5), there may be a substantial number of MMD 11–*like* galaxies (<0.62 arcmin^{-2} for our adopted Λ cosmology), suggesting that SCUBA sources should not necessarily be seen as completely orthogonal to optically selected galaxies. While the conclusions extrapolated from MMD 11 may be a misleading effect of small number statistics, the finding is not necessarily inconsistent with the current state of follow-up to blank field and radio-identified submillimeter sources (e.g., Smail et al. 2002; Chapman et al. 2002a; Ivison et al. 2002). These studies reveal a broad range in optical properties for the SCUBA population. At least in part, this may be explained because some of the submillimeter galaxies comprise both obscured and unobscured interacting components like MMD 11 and SMM 14011−0252.

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