ABSTRACT

We present the results of a Spitzer IRAC and MIPS 24 μm study of extended Lyman-α clouds (or Lyman-α Blobs, LABs) within the SSA22 filamentary structure at z = 3.09. We detect 6/26 LABs in all IRAC filters, four of which are also detected at 24 μm, and find good correspondence with the 850 μm measurements of Geach et al. An analysis of the rest-frame ultraviolet, optical, near- and mid-infrared colors reveals that these six systems exhibit signs of nuclear activity (active galactic nucleus (AGN)) and/or extreme star formation. Notably, they have properties that bridge galaxies dominated by star formation (Lyman-break galaxies (LBGs)) and those with AGNs (LBGs classified as QSOs). The LAB systems not detected in all four IRAC bands, on the other hand, are, as a group, consistent with pure star-forming systems, similar to the majority of the LBGs within the filament. These results indicate that the galaxies within LABs do not comprise a homogeneous population, though they are also consistent with scenarios in which the gas halos are ionized through a common mechanism such as galaxy-scale winds driven by the galaxies within them, or gravitational heating of the collapsing cloud itself.

1. INTRODUCTION

Understanding the complex physics of galaxy formation is one of the key goals of astronomy today. Observations at high redshift show that the young universe was strikingly different than it is locally and while many high-redshift galaxy populations have low-redshift analogs, significant evolution is seen in their global properties such as their clustering strength (Coil et al. 2004; Le Fèvre et al. 2005), the shape of their luminosity function (e.g., Cirasuolo et al. 2008) and their overall contribution to the integrated background light (e.g., Cirasuolo et al. 2008) and their overall contribution to the integrated background light (e.g., Cirasuolo et al. 2008) and their overall contribution to the integrated background light (e.g., Cirasuolo et al. 2008) and their overall contribution to the integrated background light (e.g., Cirasuolo et al. 2008). Individually, the galaxies themselves are generally more violent and dynamic objects than typical galaxies today. They are more gas-rich, show higher levels of star-formation and nucleic activity (Chapman et al. 2005; Fine et al. 2006), experience increased rates of major mergers (Patton et al. 2002), and exhibit signs of energetic outflows (Shapley et al. 2003). The role that these processes play in building and shaping galaxies is still poorly understood, as is the link between different evolutionary phases and the importance of properties such as mass and the local environment in driving evolution.

Hierarchical structure formation models predict, and observations confirm, that the first objects to form in the early universe will have been highly clustered (e.g., Kaiser 1984; Giavalisco et al. 1998). For this reason, many studies of galaxy evolution focus on single large structures at high redshift which, in addition to isolating the most active sites of structure formation at early times, provides large samples of equidistant galaxies over a range in mass, luminosity, and evolutionary stages. Such studies of high-density environments have recently detected a new population of extended Lyman-α (Lyα) emitting nebulae at high redshift (Pynbo et al. 1999; Keel et al. 1999; Steidel et al. 2000; Francis et al. 2001; Matsuda et al. 2004; Palunas et al. 2004; Dey et al. 2005). The properties of these so-called Lyα Blobs (LABs) indicate they are energetic phases in the formation of galaxies: they have projected physical extents of tens to several hundreds of kpc, Lyα luminosities of $10^{44}$ erg s$^{-1}$, and the Lyα emission is often morphologically irregular and dynamically complex. They are prevalent in high-density regions which exhibit other signs of intense star-formation and active galactic nuclei (AGNs) activity, though the extent to which this is a selection effect has not been adequately explored through unbiased studies (e.g., Prescott et al. 2008).

One of the largest samples of extended LABs is presented in Matsuda et al. (2004, hereafter M04), within the SSA22 structure at z = 3.09 (see also Saito et al. 2006, 2008). Originally discovered as an overdensity of Lyman-break galaxies (LBGs; Steidel et al. 1998), subsequent narrowband imaging of the SSA22 field (Steidel et al. 2000) revealed two giant LABs within the concentration with sizes > 100 kpc. Narrowband imaging over a larger area by M04 assembled a sample of 35 LABs with sizes above a few tens of kpc and luminosities of $10^{42–44}$ erg s$^{-1}$. They are imbedded within a large (>$ 60$ Mpc) structure, traced by the fainter and smaller Lyα emitter (LAE) population (Hayashino et al. 2004; Matsuda et al. 2005) consisting of at least three dynamically distinct filaments. The two brightest LABs are located at the filamentary intersection.

Clearly, the SSA22 structure is a concentration of evolutionary activity and the large number of LABs within it provides us with an opportunity to conduct a more systematic study of these enigmatic systems than has been done before. The primary outstanding question concerns the mechanism responsible for their intense Lyα luminosities and supergalactic sizes. While an obvious explanation is photoionization by an embedded source, many LABs do not contain UV-bright galaxies of...
sufficient luminosity (M04). Neither are they powered by interactions between radio jets and the ambient intergalactic medium as they are radio-quiet, unlike the similar Ly$\alpha$ halos surrounding high-redshift radio galaxies (Reuland et al. 2003). Alternative scenarios hold that these systems are powered by shock heating from galaxy-wide superwinds (Geach et al. 2005; Colbert et al. 2006; Taniguchi et al. 2001; Taniguchi & Shioya 2000), driven by intense starbursts or AGNs (Keel et al. 1999), or through gravitational heating during the collapse of a large primordial cloud (e.g., Smith et al. 2007; Nilsson et al. 2006).

Although exceptional UV and radio sources are not in general found within LABs, recent observations have shown that many (but not necessarily all) LABs are associated with infrared-luminous (IL) galaxies (Champan et al. 2001; Geach et al. 2005; Colbert et al. 2006; Beelen et al. 2008). The work of Champan et al. (2001) and Geach et al. (2005) detected five of the M04 LABs at 850 $\mu$m ($>3\sigma$ significance). It is notable that the Smithsonian Astrophysical Observatory Submillimeter Array (SMA) has failed to detect the most luminous of these, LAB01 ($S_{850\mu m} = 17$ mJy; Steidel et al. 2000) indicating either extended submillimeter emission ($>4''$) or multiple submillimeter emitters confused within the beam (Matsuda et al. 2007), a point we will return to in Section 4.2. Work with the MIPS camera on board Spitzer has also revealed IL counterparts to a number of LABs including the largest currently known (Dey et al. 2005; Colbert et al. 2006). These results all imply classifications of ultra-/hyperluminous infrared galaxies (ULIRGs/HyLIRGs), with infrared luminosities of $\sim10^{12-13}$ $L_\odot$. The relationship between the IL systems and their respective LABs is unclear, but a weak correlation between the counterpart bolometric luminosity and the Ly$\alpha$ luminosity suggests that the size and luminosity of the LAB is controlled by global, galactic-sized processes such as superwinds.

In this paper, we present the first mid-infrared (MIR) study of a large sample of LABs within the SSA22 filament with IRAC (Fazio et al. 2004) and MIPS (Rieke et al. 2004) on
board the Spitzer Space Telescope (Werner et al. 2004). We use these observations, along with supplementary data from the literature, archives, and our own optical observations, to identify the galaxies which are associated with the LABs and to investigate their nature and relation to the clouds. At $z = 3.09$ these data sample the rest-frame near-infrared (NIR) and MIR, and are sensitive to stellar emission, thermally radiating hot dust, and polycyclic aromatic hydrocarbon features (PAHs). The broad shape of the spectral energy distribution (SED) in this region provides a useful diagnostic of the energy production mechanism within each galaxy that is complementary to the optical/UV and far-infrared observations.

The paper is organized as follows: Section 2 describes the observations and data analysis techniques of the NIR, optical, and archival X-ray data; in Section 3 we present the infrared counterparts to the LABs; and Section 4 contains a discussion of the constraints on the nature of the counterparts, comparisons to previous studies, and implications for our understanding of the LABs and their relation to galaxy formation.

2. OBSERVATIONS AND ANALYSIS

2.1. The IRAC and MIPS Observations

The Spitzer IRAC (3.6, 4.5, 5.8, and 8.0 μm) and MIPS (24 μm) data are part of two GTO programmes, PID 64 and 30328 (PI.: Giovanni Fazio). The former obtained single pointing data while the latter obtained images over most of the LABs; and Section 4 contains a discussion of the constraints on the nature of the counterparts, comparisons to previous studies, and implications for our understanding of the LABs and their relation to galaxy formation.

The IRAC data were combined using MOPEX in tandem with the IRAProc package (Schuster et al. 2006) version 4.2.1. The pixels in the final mosaics were chosen to be 0.′86 on a side so that the area subtended by each pixel was exactly half that of the native IRAC pixels. The MIPS data were reduced and mosaicked with the MIPS Data Analysis Tool (DAT) as described in Gordon et al. (2005). The 24 μm images were resampled and mosaicked with half of the original instrument pixel scale (1′′/2).

Figure 1 illustrates the varying IRAC and MIPS coverage of the field. Of the 35 LABs discovered by M04, 32 are covered by all four IRAC filters (not covered are LAB17, LAB10, LAB 28). Of these, six are confused or contaminated by nearby bright objects (LAB03, LAB04, LAB13, LAB21, LAB30, LAB32). This yields a working sample of 26 LABs, of which 20 lie within the 225 arcmin$^2$ covered by MIPS and by all four IRAC filters to a uniform depth, except in the region of the single deep pointing. Figure 1 also shows the location of the ∼200 LBGs from Steidel et al. (2003), which constitute a comparison sample throughout the paper.

Photometry on the IRAC and MIPS images was performed using 3′′4 and 6′′ diameter apertures, respectively, and aperture corrections were applied to correct to total fluxes. Uncertainties were determined through the variance in the sky background within an aperture area, measured within an 80′′ box surrounding each object, and the variation in depth seen in Figure 1 is reflected in the uncertainty variation in Table 1. Table 1 lists the IRAC, MIPS flux measurements or upper limits for the LABs with coverage at all four IRAC filters; we also include the SCUBA measurements of Champman et al. (2001) and Geach et al. (2005) for reference.

2.2. MMT Optical Imaging

The SSA22 field was imaged at r′ and i′ (bands that approximate, but are not identical to, Sloan Digital Sky Survey (SDSS) r and i) during the nights of 2006 September 25, 26, and 27 with the Megacam camera (McLeod et al. 2006) on the MMT atop Mount Hopkins under conditions of stable sub-arcsecond seeing at a variety of position angles. The 500 s 36-chip exposures were reduced using standard methods and the custom IRAF reduction package Megared. Individual exposures were first bias-subtracted and trimmed before correcting bad pixels by nearest-neighbor interpolation and flattening with evening twilight flats. The coordinate system for each exposure was refined using the USNO-B1 catalog and a priori knowledge of the relative orientations of the detector arrays; absolute accuracy in the positions of objects that are well detected in single exposures should be better than 0′′.2.

Using photometry of stars common to the set of exposures, illumination corrections were computed to account for the contribution of OH skyglow to the twilight flats (B. Mcleod 2007, private communication). These two corrections (one at r′, the other at i′) were applied to all exposures in the appropriate bands. Sky templates were then created by median-filtering the object-masked science frames; these sky templates were used to fit and subtract large-scale gradients in the background of the individual exposures on a chip-by-chip basis. The utility SWarp was then used to project all 36 chips from each exposure to a common coordinate grid with pixels 0′/32 on a side (four times the Megacam pixel size) and simultaneously to fit and remove large-scale (>82′′) structure from the backgrounds. Using co-extensive SDSS photometry, the individual exposures were individually flux-calibrated and then correspondingly scaled/weighted when subsequently co-added to construct the final mosaics. The approximate 3σ depths of the final mosaics, after removal of artifacts, are roughly 27.1 and 25.9 AB mag at r′ and i′, respectively.

2.3. Archival X-Ray Data

2.4. Chandra

The SSA22 field was observed with Chandra on 2001 July 10. After downloading from the archive, the data were reduced and analyzed using standard recipes with the CIAO package version 3.3.0. The observation was performed continuously with no significant increase in background and a total live time of 77.8 ks. The sources associated with the SSA22 LABs fall throughout the ACIS-S3 and ACIS-S2 chips. Exposure maps were computed for both chips and the resulting fluxes corrected accordingly.

2.5. XMM-Newton

XMM-Newton observations were taken on 2002 November 10 and 2002 December 15. After downloading from the archive, the data were reduced and analyzed using standard techniques and
SAS version 7.0.0. Periods of high background were excluded from the data. During both observations, the EPIC MOS1/MOS2 and planetary nebula (PN) detectors were operated in full-window mode using the thin filter. In order to increase the signal to noise, we combined the individual MOS1 + 2 (i.e., one total MOS) and PN data set for each observation. The total observing times were 256 and 110 ks for the MOS and PN detectors, respectively. Exposure maps were averaged and the resulting fluxes corrected accordingly.

2.6. X-Ray Analysis

The Chandra and XMM-Newton data sets were searched for LAB counterparts using source detection algorithms such as celldetect, wavdetect, and e wavedet. We detect two systems: LAB02, which has a previously published X-ray detection (Basu-Zych & Scharf 2004), is marginally detected by systems: LAB02-a which has a previously published X-ray from the data. During both observations, the EPIC MOS1

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detectors, respectively. Exposure maps were averaged and the full-window mode using the thin filter. In order to increase the intrinsic photon energy power-law slope of \[ \Gamma \]

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by Champan et al. (2001) reveals four faint optical components with much lower spatial resolution, in the central region of LAB01 and we recover these structures, despite the poor spatial resolution of the submillimeter imaging.

The IRAC/MIPS photometry of LAB01-a and -b are very similar; both are detected in all four IRAC filters and MIPS-24 μm at roughly the same flux levels. As discussed in Section 4, their infrared colors are indicative of z ~ 3 galaxies and we here conclude that both systems are associated with the SSA22 filament and LAB01. As already noted by Geach et al., the projected separation is ~30 kpc and hence this may be an interacting system within the LAB, though no clear evidence of this is seen in the deep optical imaging.

LAB01 has now been observed with a number of different submillimeter facilities. The original SCUBA detection (Champan et al. 2001) is the strongest and most significant at S_{850} = 16.8 ± 2.9 mJy, but the large beam (FWHM ~ 15″) of the JCMT at 850 μm makes the positional uncertainty significant, and it is possible that more than one source within the LAB is contributing to the submillimeter flux. Such a scenario would explain both the very high submillimeter emission measured by the JCMT and the recent nondetection of this LAB with SMA (Matsuda et al. 2007). The SMA observations should have detected the source, unless it was extended beyond 4″ or composed of multiple fainter systems, confused within the JCMT beam, in which case the emission would be resolved by the SMA below the detection threshold. The 24 μm detections of both LAB01-a and -b mark them both as strong infrared emitters and thus possible submillimeter sources, and their separation of ~5 arcsec is certainly well below the resolution limit of SCUBA at 850 μm.

This picture is confused however by two other data sets, which call into question the submillimeter measurements. The Owens Valley Radio Observatory (OVRO) CO(4–3) observations (Chapman et al. 2004) detected a single object 2″N of the ERO, which implies only a single submillimeter emitter; however the detection is only at a 3.2σ significance and thus a second source of similar flux could lie just below the detection limit of these data. Recent observations taken with the AzTeC camera on the Atacama Submillimeter Telescope Experiment at 1 mm (Kohno et al. 2008) however failed to detect any submillimeter emission, to a 5σ limit of ~10 mJy (Kohno et al. 2008). Given the large beamsize of ~38″ at 1 mm, the existence of multiple submillimeter emitters cannot explain this nondetection.

LAB02: LAB02 is the second of three LABs in this sample with multiple objects within its large extent. Although this object has been identified as a possible submillimeter emitter, the 850 μm detection (Champan et al. 2001) is of significance (2.75σ) and we consider this an unreliable detection. As first reported by Geach et al. (2007), and seen in Figure 2, there are a number of systems detected in the IRAC imaging with very different observed optical and infrared colors. The brightest object in the group, object c in Geach et al., is a bright radio source and has S_{3.6 μm}/S_{3.6 μm} < 1 and S_{24 μm}/S_{3.6 μm} < 1 with a foreground galaxy at z < 1. Source d (not discussed in Geach et al.) is also consistent with a low-redshift galaxy: it is detected in the optical through to 4.5 μm, with

(\text{S_{850 μm} ~ 17 mJy}) and a radio source at 1.4 GHz (Champan et al. 2001); these may be the same object, though the uncertainty on the submillimeter position is substantial and is spatially consistent with other counterparts. Deep HST STIS imaging by Champan et al. (2001) reveals four faint optical components in the central region of LAB01 and we recover these structures, with much lower spatial resolution, in the r′-band MMT image (Figure 2). One of these (J2 in Chapman et al.) is an extremely red object (ERO) and is a second possible counterpart to the submillimeter source, but is offset from the radio position.

Geach et al. (2007) investigated the MIR properties (rest-frame NIR) of LAB01 (and LAB02) using a subset of the data presented here. For clarity we have adopted the counterpart labels of that paper in Figure 2 for LAB01 and LAB02. There are five objects detected at 3.6 μm within the extent of the Lyα emission which Geach et al. have denoted a, b, c, d, e. Sources e and d are only detected at 3.6 and 4.5 μm and have blue colors (S_{3.6 μm} > S_{5 μm}) consistent with z < 1 galaxies. Source c is the LBG C11 (Steidel et al. 2000) which is a member of the filament and therefore possibly physically associated with the LAB, though as noted by Geach et al. and Bower et al. (2004) it appears kinematically distinct from the Lyα emission.

Sources a and b are detected in all four IRAC bands as well as MIPS 24 μm. LAB01-a is located in the central region of the cloud, close to a peak in the Lyα emission, but its counterpart at shorter wavelengths remains unclear. For the remainder of the paper we have adopted the ERO mentioned above as it is the closest object to the 3.6 and 24 μm centroids and is optically red, though a second possibility is the radio source. We note however that the similar r′-band flux of the ERO and radio source means none of our key results are strongly dependent on this assumption.

LAB01-b has not received much attention thus far, perhaps because it lies in the outer region of the Lyα cloud and ~7″ from the submillimeter centroid. The optical and NIR imaging reveals two objects separated by 2″, one of which is substantially brighter than the other and coincident with the center of the 3.6 μm emission; hereafter we take this brighter system to be the IRAC source.

Figure 2. Postage stamps of the 8 μm-detected LABs at r′, 3.6, 8.0, and 24 μm with the Lyα contours overlaid in red (Matsuda et al. 2004). North is up and east to the left. The distance between large tick marks corresponds to 5″, and each image is 25″×25″ in size.
is poorly constrained; for that reason although its photometry is with $8 \mu m$ (e.g., Alonso-Herrero et al. 1980). Tracks run from $\nu_\alpha$ and $b$. LAB02-a however is detected with a significance of only $\sim 2\sigma$; this may also be the case at the longer wavelengths, $>8.0 \mu m$, but the centroid is poorly determined because of the lower S/N and the larger PSF.

LAB16: A counterpart is detected in all four IRAC filters, as well as MIPS $24 \mu m$. The peak $Ly\alpha$ flux is offset from the $r'$ and $3.6 \mu m/4.5 \mu m$ counterpart by $\sim 2''$; this may also be the case with the long at the longer wavelengths, $>8.0 \mu m$, but the centroid is poorly determined because of the lower S/N and the larger PSF.

LAB18: This LAB is detected at all infrared wavelengths, though is slightly confused by a foreground neighbor at $24 \mu m$. LAB18 has no obvious single $r'$-band counterpart, but diffuse emission along the extent of the LAB is clearly visible. In Figure 2, we see two additional objects south of the main LAB emission which are detected at all four IRAC wavelengths, though not in the $r'$ image, nor at $24 \mu m$. The southernmost object is coincident with another $Ly\alpha$ peak and has IRAC colors similar to the main LAB counterpart and consistent with a $z \sim 3$ galaxy (see Section 4.1). The fainter, middle source, however, shows no $Ly\alpha$ flux and its color is contaminated by the main LAB counterpart, and we therefore have not included it as an LAB counterpart, although these three objects may form a single interacting system. This LAB has a submillimeter detection of $S_{250 \mu m} = 11 mJy$, and with a separation of $7''$, both IRAC sources could contribute to the measured submillimeter flux, as may be the case with LAB01.

### 4. DISCUSSION

#### 4.1. Observed Mid-Infrared Colors: Constraints on the Nature of the LAB Counterparts

At $z \sim 3$ the IRAC filters sample the rest-frame NIR. In this region pure stellar populations are characterized by the stellar bump at $1.6 \mu m$, with decreasing emission toward longer wavelengths. If cold dust is present within a galaxy, band emission from PAHs becomes important over the range of $6-11 \mu m$ while warm dust produces emission that continues to rise as a power law longward of $1.6 \mu m$ (e.g., Alonso-Herrero et al. 2006). These distinctly different SED shapes can, in principle, be exploited to diagnose the dominant power source of a galaxy (e.g., Lacy et al. 2004; Stern et al. 2005), but do suffer from important ambiguities and limitations, in particular beyond $z \sim 2$. In particular, red rest-frame NIR colors only indicate the presence of warm dust, and cannot discriminate between an AGN with a nuclear warm dust component and an extreme IL starburst whose warm dust is associated with H ii regions (e.g., Yun et al. 2008). Moreover, the separation of IL galaxies into AGN and starbursting systems is regardless an oversimplification, since the most luminous ULIRGs at low and high redshifts show evidence for both AGN activity and intense star formation and the optical/NIR emission will contain contributions from both processes. Nevertheless, an investigation of the rest-frame NIR–MIR SED shapes can provide basic clues to the nature of the galaxies residing within LABs.

In Figure 3, we show an IRAC color–color diagram for LAB counterparts detected in all four IRAC filters (e.g., Lacy et al. 2004). As discussed above, infrared power-law galaxies at low and high redshift inhabit a specific region of the diagram that is generally distinct from galaxies dominated by stellar emission in the optical/infrared, but which overlaps with the location of high-redshift star-forming ULIRGs. To illustrate this we plot the observed infrared colors of two representative SEDs with...
redshift from $z = 0$ to $z = 3.09$: the ULIRG Arp 220 and a typical irregular starburst galaxy from Coleman et al. (1980). Also shown are the observed infrared colors of 8 $\mu$m bright LBGs within the SSA22 structure (Steidel et al. 2003) and the general 8 $\mu$m-selected population in the SSA22 field.

The LBGs exhibit rest-frame optical/NIR colors spanning almost an order of magnitude; while the bulk of the objects have colors consistent with a $z = -3$ blue starburst galaxy, a number extend into the region of the diagram inhabited by ULIRGs and AGNs. The LAB counterparts on the other hand are found without exception in the region of the redder LBGs and AGN/ULIRG templates and are not well described by a low-extinction starburst. In addition to the ULIRG/AGN ambiguity, it is also difficult to constrain the redshifts using the observed NIR colors; pure power-law systems in particular have a flat color–redshift relation. Nevertheless, one can see from Figure 3 that among the 8 $\mu$m-selected population power-law (and power-law-like) galaxies are rare ($\sim10\%$) and thus the likelihood that all five LABs have a randomly aligned unassociated power-law galaxy (and two in the case of LAB01) within the extent of the Ly$\alpha$ emission is remote ($\lesssim1\%$ assuming a generous alignment distance of 5$''$), and we therefore conclude that all seven systems have $z = 3$ and are associated with their parent LAB.

Although the majority of the LABs were not detected in all four IRAC filters, nor MIPS 24 $\mu$m, we can still place constraints on their average properties through a stacking analysis of their infrared emission. For this exercise we take as the source position the coordinates of the 3.6 $\mu$m counterpart when available (the majority of the LABs) or if no counterpart exists at 3.6 $\mu$m we simply take the peak of the Ly$\alpha$ emission; only one LAB is too extended to identify a clear peak/center and has no clear counterpart (LAB27), resulting in a sample of 20 systems, including LAB02-a. We detect stacked emission at $>3\sigma$ in all four IRAC filters and show the average color of the infrared-faint (IF) LAB systems in Figure 3. As we see, they are not simply lower luminosity versions of the 8 $\mu$m-detected LABs, but rather are similar in color to the blue 8 $\mu$m-detected LBG population, implying they are more moderate starburst systems.

Returning to the infrared-bright LABs, the observed NIR colors require the presence of hot dust, heated by either extreme dust-enshrouded star formation or feedback from a central AGN. As we now discuss, however, the X-ray and MIR data indicate that AGNs are present in some of these systems. First, turning to the X-ray results, two of the 10 LBGs in this region are previously known optically confirmed QSOs (Steidel et al. 2003) which are strong X-ray emitters, and two of the seven LAB counterparts have weak X-ray emission (see Section 3). Here we use the Bauer et al. (2004) AGN/starburst classification scheme where a galaxy is considered an AGN if it satisfies any one of five X-ray or spectral conditions. Two of these conditions are $L_X > 3 \times 10^{42}$ erg s$^{-1}$ and $f_{0.5-8.0\text{keV}}/f_R > 0.1$ which are satisfied by the two X-ray-detected LABs ($L_X \sim 4 \times 10^{42}$ erg s$^{-1}$ and $f_{0.5-8.0\text{keV}}/f_R \sim 1.5$). The individual and stacked X-ray limits for the remaining LABs are generous ($L_X < 8 \times 10^{42}$ erg s$^{-1}$ and $L_X < 6 \times 10^{42}$ erg s$^{-1}$, respectively) and are consistent with AGN according to these criteria. Deeper X-ray studies (J. E. Geach et al. 2009, in preparation) will clarify this issue.

In Figure 4, we look at the constraints placed by the 24 $\mu$m data through an investigation of the IRAC/MIPS colors. Here we are limited to the LAB and LBG comparison systems which are also detected at 24 $\mu$m. AGN-dominated systems generally inhabit the lower right of this diagram: hot dust enhances their observed 8 $\mu$m flux (2 $\mu$m in the rest frame) over the shorter wavelength stellar emission, but the lack of strong PAH features results in blue 24–8 $\mu$m colors, with some variation due to the steepness of the power law. Star-forming systems, on the other hand, have less enhanced observed 8 $\mu$m (rest-frame 2$\mu$m) emission, and thus blue 8.0–4.5 $\mu$m colors, but exhibit a wide variety of PAH strengths and therefore a range in 24–8 $\mu$m colors. Such a diagram has been used by other authors to attempt to identify the power sources within the very luminous SMG population (e.g., Egami et al. 2004; Pope et al. 2006) which contain AGNs and star-formation contributions, sometimes within the same objects, and, as seen in Figure 4, tend to populate the entire color space.

We see a clear separation of AGN and star-forming systems within the 24 $\mu$m bright LBG population. It is interesting to see that the LAB counterparts occupy a small region of the color space, and transition between these two populations. Thus while smoking-gun evidence of AGNs in these systems is lacking, they appear distinct from the presumably pure star-forming LBGs, but are also exhibit bluer NIR colors than AGNs. We again perform a stacking analysis on the IF LABs, this time restricting the sample to those which fall on the MIPS image. No MIPS flux is detected from these systems as a whole and we place an upper limit on their observed 24 $\mu$m/8 $\mu$m color on Figure 4. Here the separation between the infrared-bright and -faint LABs is less clear, though the IF LABs again lie bluerward of the infrared-bright systems, toward the star-forming region of the diagram.

4.2. Agreement with Submillimeter Results

Geach et al. (2005) observed 25 of the 35 LABs from Matsuda et al. (2004) at 850 $\mu$m and detected 5 at $>3\sigma$ significance. One
of these, LAB10, lies outside of our imaged region. We find an almost one-to-one correspondence between the 8 and 24 μm detections presented here and the submillimeter detections. We recover all four of the 850 μm sources (for which we have data) at 8 μm. At 24 μm we fail to detect only LAB05 (limits are given in Table 1).

The 24–850 μm flux ratios or limits are in good agreement with those measured for z ~ 3 SMGs (<0.02) by Pope et al. (2006). As extensively discussed by Pope et al. (2006) such low values are consistent with galaxies such as Arp 220 and Mrk 273, which are not typical ULIRGs, and indicate higher levels of extinction and/or cooler dust temperatures than generally seen for ULIRGs. Cooler dust temperatures may be reached if the dust is spatially extended compared to local compact ULIRGs. This explanation is particularly interesting for LAB01: recent observations with the SMA (Matsuda et al. 2007) have failed to detect the $S_{850 \mu m} \sim 17$ μJy source in the blob and this places a lower limit on its spatial extent of >4″ in the submillimeter (assuming it is signal dust-enshrouded system). Such an explanation however cannot account for the failure of recent ASTE-AzTeC observations to detect this source with a 5σ limit of ~10 mJy (Kohno et al. 2008).

As we showed in the previous section the 8 μm flux of the 8 μm-detected systems cannot be due only to stellar emission, but must be enhanced by the presence of hot dust, associated with prodigious star formation, or due to central dust-enshrouded AGNs. We have not detected any 8 μm source within a LAB which is not also detected at 850 μm, with the exception of LAB16, whose 850 μm limit is four times higher than the four other 850 μm sources.

Adopting the average 850–8 μm color for the infrared-bright LABs, a nondetection at 850 μm of <3 mJy (the approximate depth of Geach et al.) would lie below our 8 μm detection limit and therefore, based on this color alone, the IF LABs could simply be lower luminosity versions of the same kinds of systems. A nondetection at 850 μm (Geach et al. 2005) and 24 μm (this work) does not place very stringent limits on the bolometric luminosities of these systems, however, and they remain compatible with ULIRG-level luminosities. Alternatively, the IF systems could be starburst galaxies with low extinction levels and correspondingly lower 850–8 μm ratios. This scenario is in agreement with the stacked measurement on Figure 3 and with the additional color results discussed in the following sections. We can rule out with certainty, however, dust-enshrouded QSOs of similar rest-frame 2 μm luminosities, but which lack an extended cold dust component.

### 4.3. The Rest-Frame UV/Optical/NIR Properties

The bulk of the LAB sample is not detected longward of 4.5 μm, and in addition to the stacking analysis of the previous sections we can also look to the combination of 3.6 and/or 4.5 μm data with the NIR and optical imaging. In Figure 5, we show a rest-frame UV/optical/NIR color–color diagram for the LBGs and LABs. Here again, we see a clear separation between 8 μm detected and nondetected systems, be they LABs or LBGs. The infrared-bright galaxies continue to show red colors into the rest-frame UV, indicating either older stellar populations and/or high levels of extinction. Notably, as seen in Figure 3 the IF LABs are well separated in color from the infrared-bright systems, and are very similar to the general IF LBGs. The exceptions are the two infrared-bright LBG–QSOs, which show extremely blue UV/optical colors.

In Figure 6, we show the observed 8.0 μm/3.6 μm flux ratio as a function of observed 8.0 μm and, alternately, 3.6 μm flux. Again we compare to the LBG population, and add to the analysis the SMGs and QSOs as in Figure 4. In Figure 6(a), we see a correlation between the rest-frame 2.0 μm and the rest-frame NIR/optical colors, in the sense that galaxies which are more luminous at 2.0 μm exhibit redder colors, and the stacking analysis confirms that this relation continues to fainter levels. Visually, the slope of the relation appears to lie between a flat color–luminosity relation and that of the line representing constant 3.6 μm flux; that is, the relation results from an overall increase in luminosity and an enhancement of the 2.0 μm flux over the rest-frame optical. The rest-frame ~2.0 μm is often taken as a proxy for stellar mass; however we have already argued that this wavelength is contaminated by AGN or intense star formation in many of these systems. Indeed, the most luminous systems at observed 8.0 μm are the confirmed QSOs, followed by the LABs and then the infrared-bright LBG population. Though clearly not a complete comparison sample this does again hint that the LABs are transition objects between pure AGN and star-formation dominated systems.

In Figure 6(b), we plot the same color, but now against observed 3.6 μm flux. In addition to illustrating the spread in 3.6 μm luminosities, this allows us to probe the observed 8 μm flux of the comparison LBG population as a function of 3.6 μm flux. The statistical detection of the 8 μm faint LABs fits within the general behavior of the LBGs, which become markedly bluer in the optical/NIR with decreasing 3.6 μm luminosity. Thus, the fainter, presumably less massive systems contain lower levels of dust, star-formation and AGN activity.

### 4.4. Lyα Excitation Mechanisms and Implications for Galaxy Evolution within the SSA22 Structure

The two central questions concerning LABs are: what drives the extended Lyα emission and, more generally, how are
these structures related to galaxy formation? There are two basic scenarios for the relationship between the LABs and their counterpart galaxies. In the first, the embedded object is the excitation power source through processes such as photoionization by a strong UV emitter or by shock heating due to supergalactic scale winds from a very strong starburst or a central AGN. In the second scenario, the Lyα emission could be due to heating through gravitational collapse; in such a picture, the LAB and counterpart have no causal relationship (that is, the galaxy is not driving the Lyα emission), but rather both mark sites of galaxy formation activity. In either case we might expect a correlation between the properties of the counterpart and the Lyα halo; in the first case the correlation is obvious and causal while in the second case we might, for example, expect the most massive and luminous LABs to trace regions of correspondingly massive galaxy formation activity such as major mergers, AGNs, and extreme infrared starbursts.

Much work has been done to attempt to separate these different scenarios, but no common picture which works for all LABs has yet emerged. M04 extensively discussed the possible excitation mechanisms of the 35 LABs in SSA22. Using simple assumptions, such as a Salpeter IMF and an unhindered line of sight, they showed that ~1/3 of the LABs do not contain galaxies which are sufficiently UV-luminous to power the LABs. Of the six 8 μm-detected LABs discussed here, four (LAB01, LAB02, LAB05, LAB14) are not sufficiently bright in the rest-frame UV unless the bulk of the ionizing radiation is emitted away from our line of sight. This is not an unreasonable explanation since all six objects are dusty and IR-luminous, as evidenced by their 8, 24, and/or 850 μm emission. The remaining LABs, however, have UV/optical/IR colors which imply lower levels of dust extinction and are therefore unlikely to be highly obscured, but still lack obvious UV emitters.

By probing both hot and cold dust emission a number of authors (Dey et al. 2005; Geach et al. 2005; Colbert et al. 2006) have shown that a small fraction of LABs host infrared-bright systems of ULIRG and HyLIRG luminosity levels and, importantly, that the inferred bolometric luminosity of these systems is weakly correlated with the Lyα luminosity, though roughly three orders of magnitude larger. To the infrared-bright sample of Geach et al. (2005) we add LAB16; although not detected at 850 μm we may extrapolate from the 24 μm flux (assuming a similar SED as the other infrared-bright LABs) and find that LAB16 follows roughly the same L_{Lyα}–L_{bol} relation. As argued by Geach et al. (2005), this suggests that the process which heats the dust, i.e., a powerful AGN or intense star formation, is also responsible for exciting the gas halo, and a natural mechanism for this is galaxy-scale winds; however, this relation could simply indicate a natural noncausal correlation between the size of the collapsing gas cloud and the galaxy formation activity occurring within it.

We can use the data presented here to add to these studies by directly probing the nature of the LAB counterparts, though as with the earlier work this cannot prove a causal connection between the embedded galaxy and the gas emission. Throughout the paper however we have included similar analyses on the LAB population within the SSA22 structure, with the motivation that a comparative study of those systems which do not exhibit extended Lyα emission might further elucidate the processes responsible for the LABs.

We can divide the sample into two distinct groups: those systems, be they LBGs or LABs, which are detected at 8 μm, hereafter referred to as IL, and galaxies which are not detected at 8 μm, or IF. Let us first discuss the IL sample. The MIR/NIR colors of the LBGs and LABs within this group are similar and are best described by either a dusty AGN power law or an intense starburst ULIRG. Some of these have been detected in the X-ray with emission levels consistent with though not uniquely indicative of AGNs. Differences begin to arise when we look at the UV/optical colors or include the rest-frame 6 μm in the analysis (Figures 5 and 4). The bulk of the LAB population is systematically bluer in UV/optical color than the LBGs, while in MIR color there is a clear continuum of colors between the bulk of the LBGs, the LABs, and the LBG–QSOs. Finally, in Figure 6 we see hints of a similar gradient in rest-frame 2 μm luminosity, such that the LABs lie between the confirmed LBG–QSO and the remainder of the LBG population. This hints that, like the SMG population, IL–LABs may harbor deeply enshrouded AGNs, in addition to intense star formation.

The following toy model might therefore be proposed for these systems. The most luminous LABs are powered through galaxy-scale superwinds driven by intense star-formation and AGN activity. As the AGN grows it eventually becomes powerful enough to completely blow out the gas cloud and enshrouding dust and emerges as a naked AGN, still luminous at the shorter IR wavelengths but no longer an LAB. It is not clear from these data how the IL–LABs fit into this picture. As suggested by Dey et al. (2005), one might speculate that the brightest LBGs are older systems whose AGN has turned off, hence their lower 8 μm fluxes, but whether a LAB phase is common to all LBGs is not yet clear. This scenario could however account for the

Figure 6. (a) Optical/NIR color as a function of rest-frame ~2 μm. The vertical dotted line denotes the approximate 5σ limit of the 8 μm data. The diagonal dotted line corresponds to the 8 μm/3.6 μm flux ratio, at the 3.6 μm detection limit. Points are the same as in Figure 4. The filled black circles are the 8 μm-detected LAB counterparts; the filled blue triangles are the 8 μm-detected LBGs, with the two solid red stars corresponding to the confirmed QSOs, and the solid green squares are SMGs (Egami et al. 2004; Pope et al. 2006) for comparison. The open black circle and blue triangle below the 8 μm detection limit correspond to stacked measurements for the 8 μm faint LABs and LBGs, respectively. (b) The optical/NIR color as a function of rest-frame ~0.9 μm. The dotted line shows the color limit at the 8 μm depth. The points are as in (a); however the LBG stacked detections include both 8 μm faint and 8 μm bright objects.
variety of morphologies of the LABs and the location of the galaxies within them. Take for example the three largest LABs, LAB01, LAB02 and the LAB of Dey et al. (2005); all have likely AGN counterparts near the edge of the Ly(α) emission, and these may be systems caught in the process of emerging from their parent cloud.

One might posit that an AGN is required to power the intense Ly(α) emission, and this is the root of the difference between the LBG without extended Ly(α) emission and LAB populations. This seems at odds, however, with the IF systems. Though the data are sparse for these groups, we see no difference between the properties of the IF LAB counterparts and the IF LBGs; both appear to be pure star-forming systems with roughly similar mass. The presence of a Ly(α) halo for one group but not the other be explained by obvious differences in their counterpart properties.

It seems more likely therefore that the difference is in an evolutionary phase over a cross section of masses; those galaxies with extended Ly(α) emission are in earlier phases of formation than the older LBGs. In this case the Ly(α) emission could be powered by superwinds, as discussed above, or may be unrelated to (but still correlated with) the embedded galaxies and driven instead by gravitational heating, as suggested, for example, by Dey et al. (2005) and Smith et al. (2007). Again, however, such a scenario would seem to imply that a LAB phase is common to all systems, unless secondary factors such as morphology play a role.

4.5. Conclusions

We have used MIR imaging from Spitzer IRAC and MIPS 24 μm to investigate the nature of a large sample of LAB systems within the SSA22 filament at z = 3.09. We have detected 6/26 of the objects in all four IRAC filters, with four also detected with MIPS 24 μm, and find excellent correspondence with the 850 μm detections of Geach et al. (2005). By analyzing the rest-frame UV, optical, and NIR/MIR/far-infrared colors, and archival X-ray imaging, we show that these six systems exhibit signs of AGN activity and/or intense and dusty star formation; notably, they exhibit colors which bridge the star-forming LBGs within the SSA22 structure and objects optically identified as QSOs. Through a stacking analysis we see that the IF LABs are markedly different than the IL systems, and are older systems than the LABs. A scenario in which the LAB Ly(α) emission is the result of gravitational heating and the galactic activity is not driving the LAB luminosity cannot be ruled out, however.

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