Rest-Frame MIR Detection of an Extremely Luminous Lyman Break Galaxy with the Spitzer IRS

H. I. Teplitz, V. Charmandaris, L. Armus, P.N. Appleton, J.R. Houck, B.T. Soifer, D. Weedman, B.R. Brandl, J. van Cleve, C. Grillmair, K.I. Uchida

ABSTRACT

We present the first rest-frame $\sim 4\mu m$ detection of a Lyman break galaxy. The data were obtained using the $16\mu m$ imaging capability of the Spitzer Infrared Spectrograph. The target object, J134026.44+634433.2, is an extremely luminous Lyman break galaxy at $z=2.79$ first identified in Sloan Digital Sky Survey spectra (Bentz, Osmer, & Weinberg 2004). The source is strongly detected with a flux of $0.94 \pm 0.02$ mJy. Combining Spitzer and SDSS photometry with supporting ground-based J- and K-band data, we show that the spectral energy distribution is consistent with an actively star-forming galaxy. We also detect other objects in the Spitzer field of view, including a very red MIR source. We find no evidence of a strong lens amongst the MIR sources.

Subject headings: cosmology: observations — galaxies: evolution — galaxies: high-redshift — galaxies: individual (J134026.44+634433.2)

1. Introduction

Two types of galaxies account for the vast majority of star formation at $z > 2$: the Lyman Break galaxies (LBGs; Steidel et al. 1996, 2003), and the ultra/hyperluminous infrared
galaxies detected at submillimeter and millimeter wavelengths (Blain et al. 2002 and references therein; Bertoldi et al. 2000). As both selections identify strong star formation, it is tempting to assume they are sampling a common population. However, current observations do not show a large overlap between the two samples. Only a small percentage of LBGs are detected with SCUBA, even though their high star formation rates predict they should be far-infrared (FIR) luminous (Chapman et al. 2000; Peacock et al. 2000). The reverse is true as well – the majority of ultraluminous infrared sources (ULIRGs; $L_{IR} > 10^{12} L_{\odot}$) are so highly extincted that they would be missed in rest-frame UV-selected surveys for high redshift galaxies like the LBGs (Meurer et al. 1999; Goldader et al. 2002). This difference may imply that the two methods select galaxies at different stages of evolution, or with intrinsically different physical characteristics. The Spitzer Space Telescope gives us the first opportunity to study both populations across a wide range of mid-infrared (MIR) wavelengths.

Recently, six extremely bright LBGs were discovered in Sloan Digital Sky Survey (SDSS) spectra (Bentz, Osmer, & Weinberg 2004; hereafter BOW). The spectra of the six sources are typical of LBGs, with bright rest-frame UV continua and clearly detected stellar and interstellar absorption lines. They appear 2-3 magnitudes brighter than the most luminous LBGs in the Steidel et al. sample. None of the six show spectral features that would be expected for AGN, such as broad or high ionization emission lines. BOW find no morphological or environmental indicators which suggest lensing. By contrast, the only comparably bright known LBG is MS1512-cB58 (Yee et al. 1996; hereafter cB58); it is strongly lensed by a dense foreground cluster (Seitz et al. 1998), and has an obvious arclike shape which is discernible from the ground.

In this paper, we present the first Spitzer detection of an LBG at 16$\mu$m with the Spitzer Infrared Spectrograph (IRS; Houck et al. 2004) “blue” Peak Up filter which is centered at 16$\mu$m. “blue” peak up array. One of the SDSS LBGs, J134026.44+634433.2 (hereafter S-LBG-1), was selected as a Science Verification target for Spitzer. The object has a spectroscopic redshift of $z=2.79$. Throughout the paper, we will adopt a flat, $\Lambda$-dominated universe ($H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.7$, $\Omega_\Lambda = 0.7$).

2. Observations

We obtained 16$\mu$m imaging of S-LBG-1 on 14 November 2003 with the IRS onboard the Spitzer Space Telescope. Between exposures, we moved the telescope in a four point dither pattern, with separations of 4". At each point in the pattern, two nod positions were observed, and two cycles were taken at each nod position. A total of 16 exposures were
taken, with integration times of one minute each.

The data were reduced using the IRS pipeline at the Spitzer Science Center (see chapter 7 of the Spitzer Observer’s Manual\(^3\)). Individual frames were registered based on the reconstructed pointing (accurate to better than 1″) and refined with centroiding of objects. Bad pixels were masked before mosaicing. We have not removed the small (< 2%) geometric distortion in the images. We have several times redundancy for each pixel on the sky, and we remove faint latent images caused by bright sources in PU observations prior to our program.

Photometric calibration utilized routine observations of a bright standard. We measured the flux in 16μm images of HD 46190 to calculate the zeropoint by comparison with template spectra based on normalized Kurucz (1993) models (Cohen et al. 2003). A curve of growth was used to estimate total flux for a point source from aperture photometry.

We also obtained supporting near-infrared (NIR) data in the J- and K-bands with the WIRC instrument (Wilson et al. 2003) on the Hale 200-inch telescope. The observations were taken on 27 January 2004. The field was observed for five dithered exposures in each filter. J-band exposures were two coadds of one minute each, and K-band were two coadds of 30 seconds each. The night was not photometric, but conditions were stable over the few minutes of the observations. The WIRC field of view contains ∼ 20 2MASS stars, which we used to calibrate the photometry and estimate the extinction.

3. Results

The final, registered 16μm image (Figure 1) has an RMS noise of 15 μJy in an aperture with 5″ radius, and 25 μJy in an aperture of 9″ radius. S-LBG-1 is detected, with a flux of 0.94 ± 0.02 mJy. Seven other objects are detected (5σ or more) in the field, one of which is very bright in the MIR and quite faint at optical wavelengths. Of these, two have no counterpart in the SDSS or WIRC imaging. Five additional sources are marginally detected (2 – 3 σ), without optical counterparts. However, given the faintness of these sources it is not surprising that deeper optical/NIR data will be needed to identify them. The reddest object, J134025.02+634358.3 (hereafter RED-1), is discussed further in section 4.3. Photometric data from IRS and WIRC are given in Table 1. The WIRC imaging shows no objects in the field that were not detected in SDSS.

There is no indication that S-LBG-1 is resolved, but it is not expected to be. The 16μm imaging is diffraction limited, and the point spread function (PSF) has a full width at

\(^3\)http://ssc.spitzer.caltech.edu/documents/som/
half maximum (FWHM) of 4″. S-LBG-1 is compact in both the SDSS and WIRC imaging, which have FWHM of ∼ 0.75 and ∼ 1″, respectively. At the redshift of S-LBG-1, z=2.79, one arcsecond corresponds to ∼ 8 kpc.

4. Discussion

The 16μm filter extends from 13.3 to 18.6 μm at FWHM, or 3.5 to 4.9 μm in the rest frame. This wavelength range encompasses Brα but does not include the polycyclic aromatic hydrocarbon (PAH) feature centered at 3.3 μm (Tokunaga et al. 1991). The filter samples the Rayleigh-Jeans tail of the stellar photospheric continuum emission, which can be considerable if the galaxy contains a substantial population of old stars. Alternatively, 4 μm marks the beginning of the rise in emission from warm dust, heated either by very young stars or by an active nucleus.

The spectral energy distribution (SED) of S-LBG-1 is consistent with a strongly starbursting galaxy (Figure 2). In the figure we show a direct comparison with the spectrum of NGC 5253 (Wu et al. 2002), a “benchmark starburst” (Calzetti et al. 1999) with regions that have undergone intense star formation in the last 100 Myr (see Calzetti et al. 1997 and the reference therein), and a substantial older stellar population. It has MIR emission from dust heated by massive, young stars (Crowther et al. 1999). The SED of S-LBG-1 is redder than NGC 5253 in the UV, but the two match quite well if one magnitude of additional extinction is applied. The rest-frame optical color of S-LBG-1 (the observed J- and K-band) is bluer than that of NGC 5253, perhaps implying a lower fraction of old stars.

Ellingson et al. (1996) showed that the optical/NIR SED of cB58 could be fit with a recent (10 Myr) secondary burst of star-formation added to a large (85% by mass) stellar population with an age of < 1 Gyr. The young age of the source was later confirmed by UV absorption line studies (Pettini et al. 2002). A marginal detection of cB58 with ISOCAM (Bechtold et al. 1998), at rest-frame 1.8 and 3 μm, favored a higher percentage of younger stars. Taken at face value, the cB58 SED is not consistent with S-LBG-1 unless cB58 rises steeply beyond the rest-frame K-band. The inconsistency could result from a higher dust content in S-LBG-1 and likely a dissimilar spatial distribution of dust, which may not be surprising given the different star formation states of the sources. The intrinsic (corrected for lensing magnification) SFR of cB58 is ∼ 20 M⊙/yr (Teplitz et al. 2000), compared to the ∼ 1000 M⊙/yr in S-LBG-1 (without correcting for extinction).
4.1. Possible AGN Contribution

The S-LBG-1 SED is also consistent with a relatively dust-free Seyfert galaxy (Figure 2). However, BOW see no high excitation lines in the UV. It is also possible that the observed 16\(\mu\)m flux of S-LBG-1 indicates a “buried” AGN that is not seen in the UV. BOW discuss the possibility that the S-LBG’s are BAL QSO’s, but conclude that they would be unique amongst that class of objects if they were. Nonetheless, the luminosity of S-LBG-1 may favor the possibility of AGN activity dominating the MIR flux. In addition, shorter wavelength Spitzer observations of S-LBG-1 are needed to conclusively rule out a very steep MIR slope, given the low rest-frame 3 \(\mu\)m flux of cB58.

Laurent et al. (2000) show that the presence of an AGN is revealed in the MIR by an excess of emission in the 3-6 \(\mu\)m range. This has been attributed to hot dust emission heated to near sublimation temperatures (\(\sim 1000 \text{ K for silicates and } \sim 1500 \text{ K for graphite}\)) by the accretion disk. The presence of this continuum has been detected in a number of nearby galaxies hosting an active AGN including NGC1068 and NGC4151 (Le Floc’h et al. 2000, Alonso-Hererro et al. 2003), as well as Centaurus A (Mirabel et al. 1999). However, such excess usually has a positive slope in the 3-6 \(\mu\)m range, making it challenging to identify in distant systems because the old stellar population of the bulge of the galaxy may be misinterpreted as an excess of thermal emission. Furthermore, there has been evidence that as the luminosity of dust enshrouded IR galaxies increases beyond \(10^{12.3} L_\odot\), so does the probability that an AGN contributes substantially to the heating of the dust (Sanders et al. 1988; Veilleux, Kim, & Sanders 1999; Tran et al. 2001).

If the brightest LBGs harbor buried AGN, it might indicate that the typical percentage of AGN in LBG searches, \(\sim 10\%\) (Steidel et al. 2002), is underestimated. In that case, the inferred \(L_{IR}\) of LBG systems, and thus the large correction to their inferred contribution to the global density of star formation, would be overestimated.

4.2. Comparison with Ultraluminious IR sources

The prodigious star formation rates of S-LBG-1 (\(\gtrsim 1000 M_\odot/yr;\) BOW) implies that it must be generating enough UV radiation to put it in the same luminosity class as ULIRGs (\(L_{IR} > 10^{12} L_\odot\)) and perhaps enough to be comparable to the hyper-LIRGs found among the SCUBA galaxies (\(L > 10^{13} L_\odot;\) Blain et al. 2002). It is not certain, however, how much of this radiation is absorbed and reradiated by dust. The optical to mid-infrared SED of S-LBG-1 is not consistent with Arp 220, given the latter’s high extinction in the UV. However, the SED over our sampled wavelength provides only a tenuous indication of the bolometric
luminosity.

If the S-LBGs in general are not fundamentally different than ULIRGs, then one must ask why isn’t their large UV luminosity absorbed and reradiated by dust. LBGs are found to be 5-20 times underluminous (less dusty) in the IR for their UV slopes (Baker et al. 2001; van der Werf et al. 2001), while ULIRGs are equally overluminous (Goldader et al. 2002). One possibility is that they are at a different stage of evolution. Star formation in $z < 1$ ULIRGs is triggered by merger activity (Flores et al. 1999). In such systems, the dust is dynamically mixed throughout and can easily absorb most of the UV radiation emitted from actively star-forming HII regions. If the LBGs have a less homogeneous distribution of dust, more UV radiation may escape. Another possibility is that the extreme UV radiation field of the most luminous LBGs heats the dust to higher temperatures than in typical starbursts, suppressing the FIR emission relative to the UV (Baker et al. 2001). This would have the effect of shifting the peak of the reradiated luminosity closer to the Spitzer wavelengths. Finally, a significantly lower dust content – either the result of extremely low metallicity, or the destruction of grains by the UV radiation field (as suggested by BOW) – would allow greater UV brightness.

4.3. Lensing and the extremely red object

In the SDSS image, BOW find no evidence to suggest strong lensing. One might expect that if the lens were highly extincted, it could be detected in the near- or mid-IR. However, we find no evidence of a massive source close in projection to S-LBG-1 that could be identified as a gravitational lens. The 16$\mu$m PSF does not allow us to identify close ($\lesssim 3''$) companions, but such objects would likely have been seen in the K-band if they were present. The critical radius is a few arcseconds even for a massive elliptical (Blandford & Narayan 1992; Eisenhardt et al. 1996). The brightest MIR source in the field, RED-1, lies 30'' away.

RED-1 is somewhat unusual in both brightness and color. It has a flux density of 3 mJy at 16$\mu$m, but is faint in the optical ($r_{AB} = 23.3$). The surface density of such sources is quite low. ISO observations of the ELAIS field detected 14 ± 3 sources down to 3 mJy per square degree, or one per ~ 200 PU fields (La Franca et al. 2004). Down to 1 mJy, the source counts are only ten times higher (Elbaz et al. 1999 and the reference therein). Few 3 mJy sources are as red as RED-1. La Franca et al. find only 18% of 15 $\mu$m sources brighter than 1 mJy have $R$ magnitudes fainter than 23.

The morphology of RED-1 is hard to quantify. It is faint and has low surface brightness in both the optical and NIR. It is detected only at the limit of the WIRC and SDSS images.
It shows no central concentration and is clearly extended, covering several square arcseconds.

The 16 µm filter samples the ~ 12 µm PAH feature and very small grain continuum emission at \( z \sim 0.3 \) and the ~ 7 µm PAH features at \( z \sim 1 \). At the higher redshift, RED-1 would fall into the hyper-LIRG luminosity class, but at \( z \sim 0.3 \) it would be only \( 10^{11} \) L⊙ (Chary & Elbaz 2001). In addition, the object is not extremely red in R-K as would be expected for a \( z \sim 1 \) ULIRG.

5. Summary

We have detected an extremely luminous Lyman break galaxy in the first Spitzer 16µm image of a UV-selected source at high redshift. The MIR data point is consistent with the large star formation rate inferred from the UV continuum. The SED confirms that the star formation is likely not extincted enough for the object to be considered a ULIRG. We find no evidence for a strong lens in the field.

Future Spitzer observations will be crucial to understanding the connection between vigorously star forming LBGs and ULIRGs. Deep imaging with IRAC (Fazio et al. 2004) and MIPS (Rieke et al. 2004) will potentially detect moderate luminosities LBGs. The 16µm imaging capability of the IRS is a powerful additional mode for the study of these objects. The detection of MIR emission in S-LBG-1 demonstrates that the brightest LBGs will be observable by IRS spectroscopy, allowing more detailed studies of their dust properties. Such observations will open a new window onto a class of objects that may be different from the infrared luminous sources that will be more commonly studied with Spitzer.

We thank L. Yan, D. Frayer, and J. Colbert for helpful suggestions. This work is based in part on observations made with the Spitzer Space Telescope, which is operated by the Jet Propulsion Laboratory, California Institute of Technology under NASA contract 1407. Support for this work was provided by NASA through an award issued by JPL/Caltech.

REFERENCES

Adelberger, K.L. & Steidel, C.C. 2000, ApJ, 544, 218

Alonso-Herrero, A., Quillen, A. C., Rieke, G. H., Ivanov, V. D., Efstathiou, A., 2003, AJ, 126, 81
Baker, A. J., Lutz, D., Genzel, R., Tacconi, L. J., & Lehnert, M. D. 2001, A&A, 372, 37
Bechtold, J., Elston, R., Yee, H. K. C., Ellingson, E., & Cutri, R. M. 1998, in “The Young
Universe: Galaxy Formation and Evolution at Intermediate and High Redshift”. Eds
S. D’Odorico, A. Fontana, and E. Giallongo. ASP Conference Series; Vol. 146, p.241
Bentz, M.C., Osmer, P.S., & Weinberg, D.H. 2004, ApJL, 600, 19 (BOW)
Bertoldi, F., et al. 2000, A&A,360,92
Blain, A. W., Smail, I., Ivison, R. J., Kneib, J.-P., Frayer, D. T. 2002, PhR, 369, 111
Blandford, R. D. & Narayan, R. 1992, ARA&A, 30, 311
Bruzual, G. & Charlot, S. 2003, MNRAS, 344, 1000
Calzetti, D., Conselice, C.J., Gallagher, J.S., III, Kinney, A.,L. 1999, AJ, 118, 797
Chapman, S.C., et al. 2000, MNRAS, 319, 318
Chary, R. & Elbaz, D. 2001, ApJ, 556, 562
Cohen, M., Megeath, T.G., Hammersley, P.L., Martin-Luis, F., & Stauffer, J. 2003, AJ, 125,
2645
Crowther, P.A., Beck, S.C., Willis, A.J., Conti, P.S., Morris, P.W., Sutherland, R.S. 1999,
MNRAS, 304, 654
Edelson, R. A. & Malkan, M. A. 1986, ApJ, 308, 59
Eisenhardt, P.R., Armus, L., Hogg, D.W., Soifer, B.T., Neugebauer, G., & Werner, Michael
W. 1996, ApJ, 461, 72
Elbaz, D., & et al. 1999, A&A, 351L, 37
Ellingson, E., Yee, H.K.C, Bechtold, J., & Elston, R. 1996, ApJL 466, 71
Fazio, G., et al. 2004, ApJS, this volume
Flores, H., et al. 1999, ApJ, 517, 148
Goldader, J.D., et al. 2002, ApJ, 568, 651
Houck, J. et al. 2004, ApJS, this volume
Krolik, J. H., Horne, K., Kallman, T. R., Malkan, M. A., Edelson, R. A., & Kriss, G. A.
1991, ApJ, 371, 541
Kurucz, R. L. 1993, CD-ROM 13, ATLAS9 Stellar Atmosphere Programs and 2 km/s Grid
(Cambridge: Smithsonian Astrophys. Obs.)
La Franca, F., et al. 2004, AJ, in press; astro-ph/0403211
Laurent, O., Mirabel, I.F., Charmandaris, V., Gallais, P., Madden, S.C, Sauvage, M., Vignroux, L., & Cesarsky, C. 2000, A&A, 359, 887
Le Floc'h, E., Mirabel, I.F., Laurent, O., Charmandaris, V., Gallais, P., Sauvage, M., Vignroux, L., & Cesarsky, C. 2001, A&A, 367, 487
Meurer, G.R., Heckman, T.M., & Calzetti, D. 1999, ApJ, 521, 64
Mirabel, I.F. et al. 1999, A&A, 341, 667
Peacock, J.A., et al. 2000, MNRAS, 318, 535
Pettini, M., Rix, S.A., Steidel, C.C., Adelberger, K.L., Hunt, M.P., & Shapley, A.E. 2002, ApJ, 569, 742
Ricke, G. et al. 2004, ApJS, this volume
Sanders, D. B., Soifer, B. T., Elias, J. H., Madore, B. F., Matthews, K., Neugebauer, G., & Scoville, N. Z., 1988, ApJ, 325, 74
Seitz, S., Saglia, R.P., Bender, R., Hopp, U., Belloni, P., & Ziegler, B. 1998, MNRAS 298, 945
Shapley, A.E., Steidel, C.C., Pettini, M., & Adelberger, K.L. 2003, ApJ, 588, 65
Silva,Ll, Granato, G.L., Bressan, A., & Danese, L. 1998, ApJ, 509, 103
Steidel, C. C., Adelberger, K. L., Shapley, A. E., Pettini, M.,Dickinson, M., & Giavalisco, M. 2003, ApJ, 592, 728
Steidel, C.C., et al. 2002, ApJ, 576, 653
Steidel, C.C., Adelberger, K.L., Giavalisco, M., Dickinson, M. & Pettini, M. 1999, ApJ, 519, 1
Teplitz, H.I. et al. 2000b, ApJLetters, 533, 65
Tokunaga, A. T., Sellgren, K., Smith, R. G., Nagata, T., Sakata, A., & Nakada, Y. 1991, ApJ, 380, 452
Tran, Q.D., et al. 2001, ApJ, 522, 527
van der Werf, P.P., Knudsen, K.K., Labbe, I., & Franx, M. 2001, astro-ph/0011217
Veilleux, S., Kim, D.-C., Sanders, D.B. 1999, ApJ, 522, 113
Yee, H.K.C., Ellingson, E., Bechtold, R.G., Carlberg,R.G., Cuillandre, J.-C. 1996, AJ, 111, 1783
Wilson, J.C., et al. 2003, SPIE, 4841, 451
Wu, W., Clayton, G.C., Gordon, K.D., Misselt, K.A., Smith, T.L., Calzetti, D. 2002, ApJS, 143, 377
Table 1. Photometry

| Object  | u AB mag. | g AB mag. | r AB mag. | i AB mag. | z AB mag. | J AB mag. | K AB mag. | 16µm mJy |
|---------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|----------|
| S-LBG-1 | 22.96     | 20.51     | 19.82     | 19.35     | 19.01     | 18.7±0.1  | 18.8±0.1  | 0.94±0.02 |
| Red-1   | ·         | 23.0±0.4  | 23.3±0.6  | 21.3±0.3  | ·         | 20.5±0.2  | 20.0±0.2  | 3.59±0.07 |

Note. — S-LBG-1 optical magnitudes are from BOW.
Fig. 1.— (left) IRS 16 µm Spitzer image of the field. S-LBG-1 is the object at the center. Spatial offsets are indicated relative to S-LBG-1. (right) Contours of detected and marginal objects in the Spitzer data overplotted on the SDSS $i$-band image. The SDSS image has been rotated to match the orientation of the Spitzer image, and smoothed by the FWHM of its PSF. Contours were plotted after scaling the Spitzer image to the SDSS pixel scale, with bilinear interpolation.
Fig. 2.— We show the observed optical/IR SED of S-LBG-1 (open circles) at 0.3 to 16 μm. Error bars are comparable to or smaller than symbol size. We plot for comparison the spectral templates for an ultraluminous starburst galaxy (Arp 220; dashed line; Silva et al. 1998), two Seyfert 1s (NGC 3227, dot-dash line; NGC 5548, dotted line; Edelson & Malkan 1986; Krolik et al. 1991), and the starburst galaxy NGC 5253 reddened by an additional $A_v = 1$ (solid line; Wu et al. 2002 and the references therein; ). We also compare the SEDs of cB58 (filled squares; Ellingson et al. 1996 and Bechtold et al. 1999) The spectral templates and cB58 photometry have been scaled to match S-LBG-1 in the rest-frame UV.