The Astrophysical Journal Supplement Series, 154:103–106, 2004 September

REST-FRAME MID-INFRARED DETECTION OF AN EXTREMELY LUMINOUS LYMAN BREAK GALAXY WITH THE *SPITZER* INFRARED SPECTROGRAPH (IRS)[1,2]

H. I. Teplitz,[3] V. Charmandaris,[4,5] L. Armus,[3] P. N. Appleton,[3] J. R. Houck,[4] B. T. Soifer,[3]
D. Weedman,[4] B. R. Brandl,[6] J. van Cleve,[7] C. Grillmair,[3] and K. I. Uchida[4]
Received 2004 March 26; accepted 2004 April 26

ABSTRACT

We present the first rest-frame ~4 μm detection of a Lyman break galaxy. The data were obtained using the 16 μm 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 (SDSS) spectra (as reported by Bentz et al.). The source is strongly detected with a flux of 0.94 ± 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 mid-infrared source. We find no evidence of a strong lens among the mid-infrared sources.

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

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 that 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 that 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; $L_{\rm IR} > 10^{12}\ L_\odot$) are so highly extincted that they would be missed in rest-frame UV-selected surveys for high-redshift galaxies such as 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 et al. 2004, hereafter BOW04). 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 mag brighter than the most luminous LBGs in the Steidel et al. (2003) sample. Most of the six do not show spectral features that would be expected for active galactic nuclei (AGNs), such as broad or high-ionization emission lines. BOW04 find no morphological or environmental indicators that suggest lensing. By contrast, the only comparably bright known LBG is MS 1512−cB58 (hereafter cB58; Yee et al. 1996); it is strongly lensed by a dense foreground cluster (Seitz et al. 1998) and has an obvious arclike shape that is discernible from the ground.

In this paper we present the first *Spitzer* detection of an LBG at 16 μm with the *Spitzer* Infrared Spectrograph (IRS; Houck et al. 2004) "blue" peak-up filter, which is centered at 16 μm. 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 adopt a flat, Λ-dominated universe ($H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_M = 0.3$, and $\Omega_\Lambda = 0.7$).

2. OBSERVATIONS

We obtained 16 μm imaging of S-LBG-1 on 2003 November 14 with the Infrared Spectrograph (IRS) on board *Spitzer*. 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 1 minute each.

The data were reduced using the IRS pipeline at the *Spitzer* Science Center.[8] 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 mosaicking. 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 peak-up observations prior to our program.

Photometric calibration utilized routine observations of a bright standard. We measured the flux in 16 μm images of

[1] Based on observations obtained with the *Spitzer Space Telescope*, which is operated by JPL, California Institute of Technology, for the National Aeronautics and Space Administration.

[2] The IRS is a collaborative venture between Cornell University and Ball Aerospace Corporation that was funded by NASA through JPL.

[3] *Spitzer* Science Center, MC 220-6, California Institute of Technology, Pasadena, CA 91125; hit@ipac.caltech.edu.

[4] Astronomy Department, Cornell University, Ithaca, NY 14853.

[5] Chercheur Associé, Observatoire de Paris, F-75014 Paris, France.

[6] Leiden University, 2300 RA Leiden, Netherlands.

[7] Ball Aerospace and Technologies Corporation, 1600 Commerce Street, Boulder, CO 80301.

[8] See chapter 7 of the *Spitzer* Observer's Manual, available at http://ssc.spitzer.caltech.edu/documents/som.

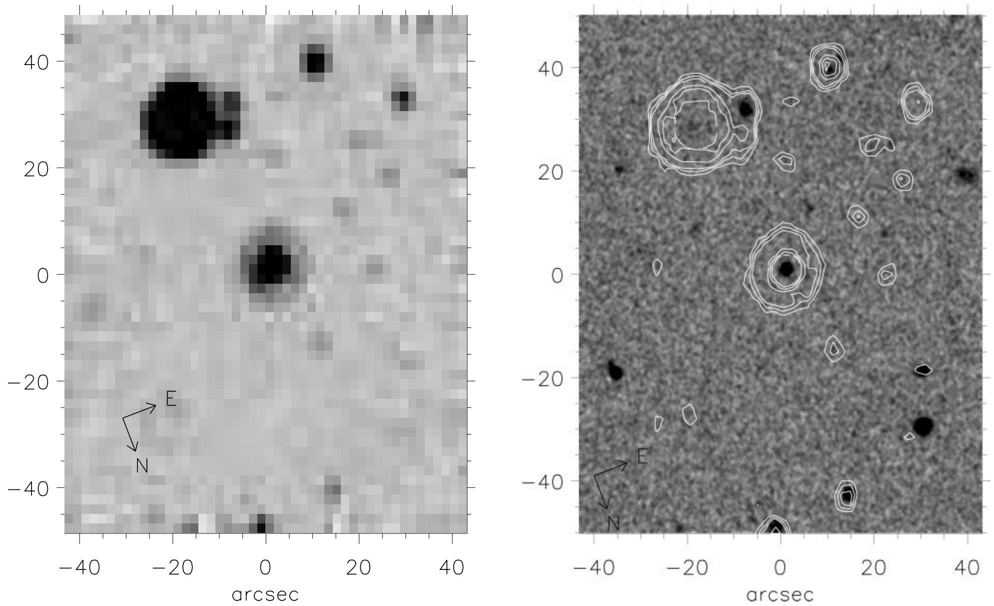

FIG. 1.—*Left:* IRS 16 μm *Spitzer* image of the field. S-LBG-1 is the object at the center. Spatial offsets are indicated relative to S-LBG-1. *Right:* Contours of detected and marginal objects in the *Spitzer* data overplotted on the SDSS *i*-band image. The SDSS image has been rotated to match the 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.

HD 46190 to calculate the zero point 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 Wide-Field Infrared Camera (WIRC) instrument (Wilson et al. 2003) on the Hale 5 m telescope. The observations were taken on 2004 January 27. The field was observed for five dithered exposures in each filter. *J*-band exposures were two co-additions of 1 minute each, and *K*-band exposures were two co-adds of 30 s each. The night was not photometric, but conditions were stable over the few minutes of the observations. The WIRC field of view contains ~20 Two Micron All Sky Survey stars, which we used to calibrate the photometry and estimate the extinction.

3. RESULTS

The final, registered 16 μm image (Fig. 1) has an rms noise of 15 μJy in an aperture of 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 (5 σ 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 § 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 16 μm imaging is diffraction limited, and the point-spread function (PSF) has a FWHM of 4″. S-LBG-1 is compact in both the SDSS and WIRC imaging, which have FWHMs of ~0.75 and ~1″, respectively. At the redshift of S-LBG-1, $z = 2.79$, 1″ corresponds to ~8 kpc.

4. DISCUSSION

The 16 μm filter extends from 13.3 to 18.6 μm at FWHM, or 3.5–4.9 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 (Fig. 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

TABLE 1
PHOTOMETRY

Object	AB Magnitude							16 μm
	u	*g*	*r*	*i*	*z*	*J*	*K*	(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 BOW04.

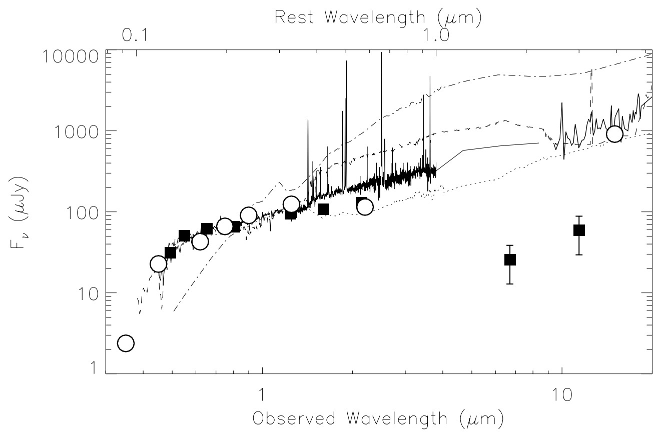

FIG. 2.—We show the observed optical/IR SED of S-LBG-1 (*circles*) at 0.3–16 μm. Error bars are comparable to or smaller than the symbol size. We plot for comparison the spectral templates for an ultraluminous starburst galaxy (Arp 220; *dashed line* [Silva et al. 1998]), two Seyfert 1 galaxies (NGC 3227, *dot-dashed line* [Edelson & Malkan 1986] and NGC 5548, *dotted line* [Krolik et al. 1991]), and the starburst galaxy NGC 5253 reddened by an additional $A_v = 1$ (*solid line*; Wu et al. 2002 and references therein). We also compare the SEDs of cB58 (*squares*; Ellingson et al. 1996; Bechtold et al. 1998) The spectral templates and cB58 photometry have been scaled to match S-LBG-1 in the rest-frame UV.

star formation in the last 100 Myr (see Calzetti et al. 1997 and the references 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 that of NGC 5253 in the UV, but the two match quite well if 1 mag of additional extinction is applied. The rest-frame optical color of S-LBG-1 (the observed *J* and *K* bands) 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 fitted with a recent (10 Myr) secondary burst of star formation added to a large (85% by mass) stellar population with an age of $\lesssim$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) star formation rate of cB58 is $\sim$20 $M_\odot$ yr^{-1} (Teplitz et al. 2000), compared with the $\sim$1000 $M_\odot$ yr^{-1} 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 (Fig. 2). However, BOW04 see no high excitation lines in the UV. It is also possible that the observed 16 μm flux of S-LBG-1 indicates a "buried" AGN that is not seen in the UV. BOW04 discuss the possibility that the S-LBGs are broad absorption line QSOs but conclude that they would be unique among 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 μm 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 μm range. This has been attributed to hot dust emission heated to near sublimation temperatures ($\sim$1000 K for silicates and $\sim$1500 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 NGC 1068 and NGC 4151 (Le Floc'h et al. 2001; 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 μm 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 et al. 1999; Tran et al. 2001).

If the brightest LBGs harbor buried AGNs, it might indicate that the typical percentage of AGNs in LBG searches, $\sim$10% (Steidel et al. 2002), is underestimated. In that case, the inferred $L_{\rm IR}$ 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 rate of S-LBG-1 ($\gtrsim$1000 $M_\odot$ yr^{-1}; BOW04) implies that it must be generating enough UV radiation to put it in the same luminosity class as ULIRGs ($L_{\rm IR} > 10^{12}$ $L_\odot$) 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 from ULIRGs, then one must ask why their large UV luminosity is notabsorbed 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 H II regions. If the LBGs have a less homogeneous distribution of dust, more UV radiation may escape. Another possibility is that the extreme UV radiation fields of the most luminous LBGs heat 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—the result of either extremely low metallicity or the destruction of grains by the UV radiation field (as suggested by BOW04)—would allow greater UV brightness.

4.3. *Lensing and the Extremely Red Object*

In the SDSS image, BOW04 find no evidence to suggest strong lensing. One might expect that if the lens were highly extincted, it could be detected in the NIR or MIR. 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 μm 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 μm but is faint in the optical ($r_{AB} = 23.3$). The surface density of such sources is quite low. *Infrared Space Observatory* observations of the ELAIS field detected 14 ± 3 sources down to 3 mJy deg^{-2}, or one per $\sim$200 peak-up fields (La Franca et al. 2004). Down to 1 mJy, the source counts are only 10 times higher (Elbaz et al. 1999 and the references therein). Few 3 mJy sources are as red as RED-1. La Franca et al. find only 18% of 15 μm 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 $\sim$12 μm PAH feature and very small grain continuum emission at $z \sim 0.3$ and the $\sim$7 μm PAH features at $z \sim 1$. At a higher redshift, RED-1 would fall into the hyper-LIRG luminosity class, but at $z \sim 0.3$ it would be only $10^{11}\ L_{\odot}$ (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 LBG in the first *Spitzer* 16 μm 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 the Infrared Array Camera (Fazio et al. 2004) and the Multiband Imaging Photometer (Rieke et al. 2004) will potentially detect moderate-luminosity LBGs. The 16 μm 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

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, L37
Bechtold, J., Elston, R., Yee, H. K. C., Ellingson, E., & Cutri, R. M. 1998, in ASP Conf. Ser. 146, The Young Universe: Galaxy Formation and Evolution at Intermediate and High Redshift, ed. S. D'Odorico, A. Fontana, & E. Giallongo (San Francisco: ASP), 241
Bentz, M. C., Osmer, P. S., & Weinberg, D. H. 2004, ApJ, 600, L19 (BOW04)
Bertoldi, F., et al. 2000, A&A, 360, 92
Blain, A. W., Smail, I., Ivison, R. J., Kneib, J.-P., & Frayer, D. T. 2002, Phys. Rep., 369, 111
Blandford, R. D., & Narayan, R. 1992, ARA&A, 30, 311
Calzetti, D., Conselice, C. J., Gallagher, J. S., III, & Kinney, A. L. 1999, AJ, 118, 797
Calzetti, D., Meurer, G. R., Bohlin, R. C., Garnett, D. R., Kinney, A. L., Leitherer, K., & Storchi-Bergmann, T. 1997, AJ, 114, 1834
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, 351, L37
Ellingson, E., Yee, H. K. C, Bechtold, J., & Elston, R. 1996, ApJ, 466, L71
Fazio, G. G., et al. 2004, ApJS, 154, 10
Flores, H., et al. 1999, ApJ, 517, 148
Goldader, J. D., et al. 2002, ApJ, 568, 651
Houck, J., et al. 2004, ApJS, 154, 18
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: SAO)
La Franca, F., et al. 2004, AJ, 127, 3075
Laurent, O., Mirabel, I. F., Charmandaris, V., Gallais, P., Madden, S. C, Sauvage, M., Vigroux, L., & Cesarsky, C. 2000, A&A, 359, 887
Le Floc'h, E., Mirabel, I. F., Laurent, O., Charmandaris, V., Gallais, P., Sauvage, M., Vigroux, 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
Rieke, G., et al. 2004, ApJS, 154, 25
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
Silva, L., 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. 2002, ApJ, 576, 653
———. 2003, ApJ, 592, 728
Steidel, C. C., Giavalisco, M., Pettini, M., Dickinson, M., & Adelberger, K. L. 1996, ApJ, 462, L17
Teplitz, H. I., et al. 2000, ApJ, 533, L65
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, 552, 527
van der Werf, P. P., Knudsen, K. K., Labbe, I., & Franx, M. 2001, preprint (astro-ph/0011217)
Veilleux, S., Kim, D.-C., & Sanders, D.B. 1999, ApJ, 522, 113
Wilson, J. C., et al. 2003, Proc. SPIE, 4841, 451
Wu, W., Clayton, G. C., Gordon, K. D., Misselt, K. A., Smith, T. L., & Calzetti, D. 2002, ApJS, 143, 377
Yee, H. K. C., Ellingson, E., Bechtold, R. G., Carlberg, R. G., Cuillandre, J.-C. 1996, AJ, 111, 1783