

EVIDENCE THAT FeLoBALs MAY SIGNIFY THE TRANSITION BETWEEN AN ULTRALUMINOUS INFRARED GALAXY AND A QUASAR

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ABSTRACT

We present mid/far-infrared photometry of nine FeLoBAL QSOs, taken using the *Spitzer Space Telescope*. All nine objects are extremely bright in the infrared, with rest-frame 1–1000 μm luminosities comparable to those of ultraluminous infrared galaxies. Furthermore, a significant fraction of the infrared emission from many, and possibly all, of the sample is likely to arise from star formation, with star formation rates of the order of several hundred solar masses per year. We combine these results with previous work to propose that FeLoBALs mark galaxies and QSOs in which an extremely luminous starburst is approaching its end, and in which a rapidly accreting supermassive black hole is in the last stages of casting off its dust cocoon. FeLoBAL signatures in high-redshift QSOs and galaxies may thus be an efficient way of selecting sources at a critical point in their evolution.

Subject headings: galaxies: active — galaxies: evolution — infrared: galaxies — quasars: absorption lines

1. INTRODUCTION

First seen in 1967 (Lynds 1967), broad absorption line (BAL) QSOs are those objects that show broad, deep troughs in their UV and optical spectra, arising from resonance line absorption in gas outflowing with velocities of $\geq 0.1c$ (Weymann et al. 1991; Arav et al. 2001; Hall et al. 2002; Reichard et al. 2003). BAL QSOs come in three subtypes, depending on which absorption features are seen. High-ionization BAL QSOs (HiBALs) show absorption in $\text{Ly}\alpha$, $\text{N v } \lambda 1240$, $\text{Si iv } \lambda 1394$, and $\text{C iv } \lambda 1549$, and comprise about 85% of the BAL population. Low-ionization BAL QSOs (LoBALs) contain all the absorption features seen in HiBALs, and also show absorption in $\text{Mg II } \lambda 2799$ and other low-ionization species, and comprise $\sim 15\%$ of the BAL population. Finally, a rare class of BAL QSO, in addition to showing all the absorption lines seen in LoBALs, also show absorption features arising from metastable excited levels of iron. These are termed FeLoBAL QSOs (Hazard et al. 1987; Becker et al. 1997; Branch et al. 2002; Lacy et al. 2002).

Efforts to explain the origin of BALs in QSOs have been ongoing since their discovery. Broadly, there are two possibilities. The first is that BAL QSOs are normal QSOs viewed along a particular line of sight; in this case the absorption features arise when an accretion disk wind encounters a high column density, ionized gas outside the broad-line region (Murray & Chiang 1998; Proga et al. 2000). The gas is driven outwards via resonance line absorption, but the high column density of the gas shields it from higher energy photons that would otherwise completely ionize it. In this case, BAL QSOs are those QSOs viewed along a line of sight that coincides with the outflowing gas (Elvis 2000). The second possibility is that BAL QSOs are youthful objects, still surrounded by gas and dust in which the absorption takes place; in this case the BALs do not arise due to a particular line of sight (Voit et al. 1993; Becker et al. 1997; Williams et al. 1999).

There has been significant debate over the years as to the best

method for finding young QSOs (e.g., Sanders et al. 1988; Kawakatu et al. 2006), so the idea that some BAL QSOs may be such objects is particularly intriguing. Most attention has focused on the LoBALs as candidate young QSOs (Lipari et al. 1994; Canalizo & Stockton 2001), as the differences between the line properties of LoBAL QSOs and those of ordinary QSOs are hard to explain solely in terms of different relative orientations (Sprayberry & Foltz 1992). Nevertheless, the picture of LoBALs being young QSOs is controversial; for example, submillimeter observations (Lewis et al. 2003; Willott et al. 2003; Priddey et al. 2007) show no differences between BAL QSOs and ordinary QSOs. Furthermore, Voit et al. (1993) propose a scenario in which LoBALs form via ablation of dust by UV photons in outflows arranged either as a thick disk or as an isotropic distribution of clouds; in this case LoBALs do fit within AGN orientation schemes, and this scenario is consistent with polarimetric observations (Schmidt & Hines 1999; Ogle et al. 1999; Hutsemékers & Lamy 2000).

Recently, however, evidence has mounted that FeLoBAL QSOs may be the strongest candidates for youthful QSOs. Based on UV and optical spectra, Hall et al. (2002) suggest that FeLoBALs are young objects still surrounded by a dust cocoon. Similar conclusions are reached by Gregg et al. (2002), who also postulate that FeLoBALs may be associated with galaxy interactions. Further evidence comes from observations of the only two known FeLoBALs at $z < 0.15$, both of which are associated with ultraluminous infrared galaxies (ULIRGs; e.g., Farrah et al. 2005). Finally, the presence of winds with large spatial extents (≥ 100 pc) in some FeLoBAL QSOs (de Kool et al. 2002) provides a plausible mechanism for an emerging QSO to directly affect the star formation. Although selection effects may play a role, this lends weight to the idea that FeLoBALs and ULIRGs are linked in some way.

It is plausible, therefore, that the Fe absorption seen in FeLoBALs arises from iron injected into the ISM by an ongoing or recent starburst; marking the FeLoBAL phenomenon as a transition stage in a ULIRG when the starburst is at or near its end, and the central QSO is starting to throw off its dust cocoon. In this Letter we examine the validity of this speculation, by observing a sample of nine FeLoBAL QSOs using MIPS (Rieke et al. 2004) on board *Spitzer* (Werner et al. 2004). We assume a spatially flat cosmology, with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega = 1$, and $\Omega_\Lambda = 0.7$. Unless otherwise stated, the term “IR lumi-

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TABLE 1
FeLoBAL QSO SAMPLE, AND INFRARED PHOTOMETRY

Galaxy	R.A.	Decl.	z	m_i	f_{15}	f_{24}	f_{70}	f_{160}	f_{450}^a	f_{850}^a
ISO J005645.1–273816	00 56 45.15	–27 38 15.6	1.78	20.95 ^b	1.33 ^c	1.56	<7.0	<50	...	...
LBQS 0059–2735	01 02 17.02	–27 19 48.8	1.59	17.39 ^b	...	7.83	19.9	29.0 ^d	<168.9	10.3
SDSS J033810.85+005617.6	03 38 10.85	+00 56 17.6	1.63	18.33	...	2.02	8.4	55.5 ^e	...	...
SDSS J115436.60+030006.3	11 54 36.60	+03 00 06.4	1.46	17.74	...	7.59	17.9	<50	...	...
SDSS J121441.42–000137.8	12 14 41.43	–00 01 37.9	1.05	18.77	...	4.69	38.3	78.9	...	...
FBQS J142703.6+270940	14 27 03.64	+27 09 40.3	1.17	18.11	...	4.76	32.6	68.1	...	...
SDSS J155633.78+351757.3	15 56 33.80	+35 17 58.0	1.50	18.01	8.30 ^f	13.93	24.7	<50	<86.1	<3.6
SDSS J221511.93–004549.9	22 15 11.94	–00 45 49.9	1.48	16.49	...	10.4	27.2	<50	...	...
SDSS J233646.20–010732.6B	23 36 45.10	–01 07 32.4	1.29	21.73	...	0.48	<7.0	<50	...	...

NOTES.— All fluxes are quoted in mJy; R.A./Decl. are J2000. The “small” field size was used for all three channels, using the default pixel scale at 70 μm . Exposure times per cycle and number of cycles for all sources except LBQS 0059–2735 were 30, 10, and 10 s, and 5, 7 and 4 respectively, giving on-source exposure times of 2260, 755, and 85 s. For LBQS 0059–2735, the exposure times were shorter: 3, 10, and 10 s with 1, 1, and 3 cycles, respectively. Errors are typically 10% on the 24 μm fluxes, 20% on the 70 μm fluxes, and 25% on the 160 μm fluxes. Limits are 3 σ .

^a Lewis et al. (2003).

^b R-band magnitude.

^c Duc et al. (2002).

^d 2 σ detection.

^e 2.7 σ detection.

^f Clavel (1998).

nosity” refers to the total luminosity integrated over 1–1000 μm in the rest frame.

2. OBSERVATIONS

Due to their rarity, assembling a homogenous sample of FeLoBAL QSOs is not trivial. At the time of writing this Letter, a few hundred FeLoBALs are known (Trump et al. 2006), but when the proposal was being written only 40 or so FeLoBAL QSOs were known over the whole sky, most of which lay at $z > 1$. We therefore aimed to select a sample that spanned a relatively narrow redshift range, and gave a reasonable sampling of the properties of FeLoBAL QSOs, at the expense of homogeneity, with the broader goal of obtaining a qualitative idea of the range of their infrared properties. We imposed an upper redshift cutoff of $z = 1.8$ and a lower redshift cutoff of $z = 1.0$. We then randomly selected nine objects. Six of these objects were found via spectroscopic observations of the Sloan Digital Sky Survey (Hall et al. 2002), one (ISO J0056–2738) was discovered serendipitously from follow-up of distant clusters that had been surveyed with *ISO* (Duc et al. 2002), one (FBQS J1427+2709) was discovered during spectroscopic follow-up of radio loud quasar candidates from the FIRST survey (Becker et al. 1997), and one is the “archetype” FeLoBAL QSO LBQS 0059–2735 (Hazard et al. 1987). The full sample is listed in Table 1.

Seven of the sample were observed in 2006 July, one (SDSS J0338+0056) was observed in 2007 February, and one (LBQS

0059–2735) was observed in 2004 March, using MIPS at 24, 70, and 160 μm (PIDs 30299 and 82). Following observation, the raw data were processed automatically with the MIPS data reduction pipeline at the *Spitzer* Science Center, which performs standard tasks such as image co-addition, sky and dark subtraction, and bias removal. We inspected the output frames from this pipeline, and determined that they were of sufficient quality for reasonably accurate ($\sim 10\%$) photometry of our targets, so no further reduction steps were performed. Photometry was carried out using the *digiphot* package within IRAF. We used apertures of 2.45, 2.0 and 2.5 pixels at 24, 70, and 160 μm to measure the fluxes of our objects, resulting in aperture corrections of 1.698, 3.900, and 3.215, respectively.

3. RESULTS

The MIPS fluxes are presented in Table 1, along with any available archival IR photometry. Four objects are detected in all three MIPS bands, although two of these four are detected only weakly at 160 μm . Three objects are detected at 24 and 70 μm . The remaining two objects are detected only at 24 μm .

In the absence of IR spectroscopy, detailed measurements of the properties of IR-luminous AGNs or starbursts in our sample are not possible. We can, however, constrain both the total IR luminosities and the contribution from star formation and/or an AGN by fitting the IR photometry simultaneously with the library of model spectral energy distributions (SEDs) for the emission from a starburst (Efstathiou et al. 2000) and an AGN (Rowan-Robinson 1995), following the methods described in Farrah et al. (2003). These model libraries span a large number of free parameters (e.g., torus opening angle and line of sight for the AGN, burst lifetime and UV opacity for the starbursts) but we here use the complete model libraries solely to estimate the likely range in total, starburst, and AGN luminosities that are consistent with the available data. The results are presented in Table 2.

The four objects with detections in all three MIPS bands are all extremely luminous, with IR luminosities exceeding $10^{12.7} L_{\odot}$. In all four objects, a starburst is required to explain the 160 μm emission while remaining consistent with the 24 and 70 μm points (for LBQS 0059–2735, an AGN model is consistent with the MIPS data, but the detection at 850 μm requires a starburst component). The predicted starburst luminosities exceed $10^{12.4} L_{\odot}$ in

TABLE 2
INFRARED LUMINOSITIES

Galaxy	L_{tot}	L_{AGN}	L_{SB}
ISO J0056–2738	12.48–13.00	12.40–13.00	<12.90
LBQS 0059–2735	12.95–13.20	12.80–13.00	12.44–12.82
SDSS J0338+0056	12.90–13.40	<12.40	12.60–13.40
SDSS J1154+0300	12.89–13.10	12.70–12.95	<12.98
SDSS J1214–0001	12.70–12.88	<12.44	12.68–12.84
FBQS J1427+2709	12.81–13.01	<12.70	12.70–13.00
SDSS J1556+3517	13.10–13.30	12.90–13.23	<12.50
SDSS J2215–0045	13.00–13.40	12.50–13.40	<12.80
SDSS J2336–0107	11.70–12.90	...	...

NOTES.— Quoted luminosities are the logarithm of the rest-frame 1–1000 μm luminosity, in units of solar luminosities ($3.826 \times 10^{26} \text{ W}$), derived from the SED fits. Limits and ranges are 3 σ .

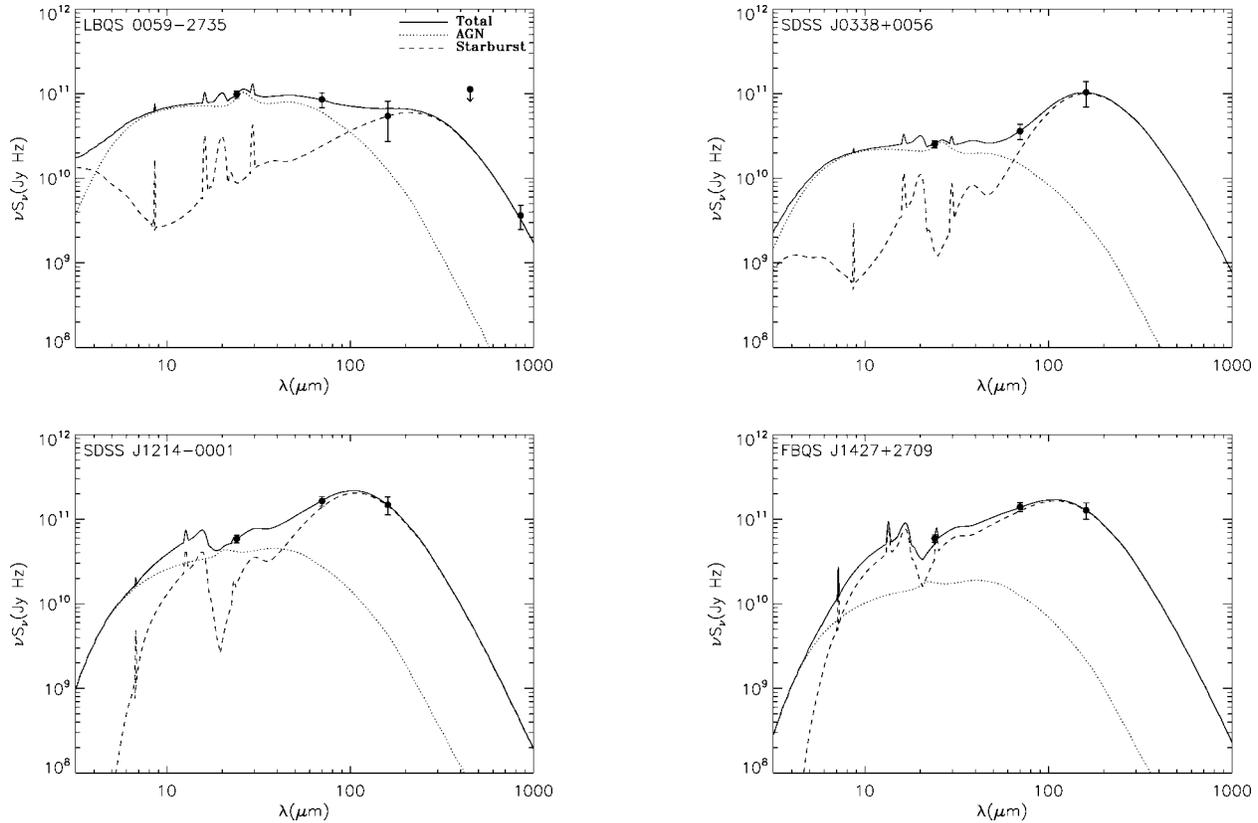


FIG. 1.—Best-fit observed-frame SEDs for the four objects with detections in all three MIPS bands. The best fits have a starburst and an AGN component in all four cases, although an AGN contribution to the IR emission is required only in LBQS 0059–2735. The fits do not provide any constraints on the contribution from a starburst or an AGN in the near/mid-IR, or on spectral features (e.g., PAH luminosities). The fits do, however, illustrate that a starburst is required to explain the emission at longer wavelengths, while remaining consistent with the 24 and 70 μm fluxes. Error bars are 1σ , while upper limits are 3σ .

all cases, with inferred star formation rates of several hundred solar masses per year. The best-fit SEDs for these four objects are given in Figure 1. An example of a pure AGN fit to one of these four objects is shown in Figure 2.

The remaining five objects are not detected at 160 μm , so the constraints on their luminosities and power sources are cruder. For these five objects we do not present best-fit SEDs, but merely summarize the results. Three of these five objects are detected at 24 and 70 μm , and all have IR luminosities exceeding $10^{12.9} L_{\odot}$.

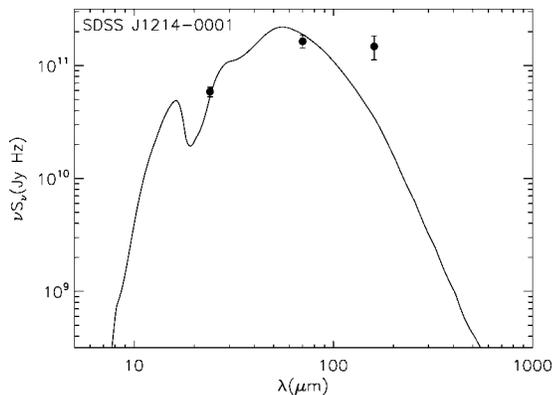


FIG. 2.—Example of an observed-frame pure AGN fit to one of the four objects in our sample with detections at longer wavelengths, in this case the best possible pure AGN fit to SDSS J1214–0001. Here the AGN model differs from that in the lower left panel of Fig. 1; the torus is viewed nearly edge-on, leading to a very high inferred obscuration and a strong absorption feature at rest-frame 9.7 μm . Even with such a model, however, the fit misses the 160 μm point by a wide margin.

The nondetection at 160 μm combined with the detection at 70 μm sets an upper limit on any starburst contribution such that an AGN must supply at least some of the 24 and 70 μm emission. Indeed, it is possible to explain the 24 and 70 μm emission in all three objects purely with an AGN model, although a significant starburst contribution is not ruled out. The final two objects are only detected at 24 μm . For one of these (ISO J0056–2738), we also have a 15 μm flux from *ISO* (Duc et al. 2002), allowing us to conclude that the bulk of the IR emission likely arises from an AGN. For SDSS J2336–0107, however, we have only a 24 μm flux, and hence cannot set any meaningful constraints on its IR emission.

4. DISCUSSION

Starting with the results in this Letter, we examine the conjecture that FeLoBAL QSOs represent a specific point in an evolutionary sequence between a ULIRG and a “classical” QSO. We initially only consider the total IR luminosities, listed in Table 2. All of our sample are extremely IR-luminous, with luminosities comparable to those of both local ULIRGs (Farrah et al. 2003; Lonsdale et al. 2006) and high-redshift submillimeter bright sources (SMGs, e.g., Blain et al. 2002; Borys et al. 2004). In most cases, the upper limits on the IR luminosities exceed $10^{13} L_{\odot}$, making them potentially comparable in luminosity to high-redshift hyperluminous infrared galaxies (Rowan-Robinson 2000; Farrah et al. 2002). At time of writing, there exists no classical QSO sample for which direct comparisons to our sample are valid (i.e., one at $1.0 < z < 1.8$, matched in optical magnitude and observed with MIPS), but it is notable that the IR luminosities of our sample substantially

exceed those of nearly all the Palomar-Green QSOs presented by Haas et al. (2003).

We next consider the power source behind the IR emission. In 5/9 objects, the SED fits predict that the IR emission arises at least in part, and possibly entirely, from an AGN, perhaps accompanied by a starburst. In 4/9 objects however, those with detections at longer wavelengths, the SED fits demand that a substantial fraction of the total IR emission arises from star formation, with implied star formation rates of the order of a few hundred solar masses per year. This implies that FeLoBAL QSOs are preferentially associated with obscured, luminous starbursts comparable to the starbursts that are thought to power the majority of the IR emission from both local ULIRGs and distant SMGs. There is the caveat that our sample is heterogeneous, but if we restrict our attention to only the six QSOs selected from the SDSS, then the fraction of sources with starbursts, 2/6, remains equivalent within the errors, although the small sample sizes render these conclusions tentative at best.

A potentially more serious caveat, however, is that the results in Table 2 are dependent on the assumption that the SED libraries used in the fitting span the range in SED shapes of observed IR-luminous starbursts and AGNs. This assumption is a reasonable one, given that these same SED libraries give good fits to the SEDs of local ULIRGs, and predict starburst and AGN luminosities that are consistent with results from other wavelengths (Farrah et al. 2003). There is, however, one scenario we cannot test for. Although we find that a luminous starburst must be present in the four objects detected at 160 μm , there do exist models for the dust distributions around AGNs where the dust is so extended (several tens of parsecs) that its outer regions are cold enough to emit significantly at wavelengths longward of 100 μm . Such an extended dust distribution could account for some or all of the 160 μm emission in these four objects. We cannot formally exclude this scenario, but note that interferometric observations of local AGNs have found no evidence supporting such extended dust distributions (e.g., Jaffe et al. 2004). We therefore do not consider this possibility to be likely.

Finally, we consider our results together with those from previous work. Prior evidence suggesting links between FeLoBAL QSOs and ULIRGs includes: (1) the only two systems at low redshifts known to contain FeLoBALs are both ULIRGs (e.g., Farrah et al. 2005), (2) FeLoBAL QSOs at high redshifts may be involved in interactions (Gregg et al. 2002), and (3) large-scale winds in FeLoBAL QSOs may provide a mechanism for the emerging AGN to affect star formation in the host galaxy (de Kool et al. 2002). To these we add (4) FeLoBAL QSOs are, as a class, extremely IR-luminous, with IR luminosities comparable to those of ULIRGs at low and high redshifts, and (5) star formation powers a significant fraction of the IR emission in many, and possibly all, FeLoBAL QSOs, with implied star formation rates comparable to those inferred for local and high-redshift ULIRGs. Overall, therefore, our results combine with those from previous work to construe strong, albeit indirect, evidence for evolutionary links between FeLoBAL QSOs and ULIRGs. We therefore propose that FeLoBALs mark galaxies and QSOs in which an extremely luminous starburst is approaching its end, and in which a rapidly accreting supermassive black hole is in the last stages of casting off its dust cocoon. FeLoBAL signatures in high-redshift QSOs and galaxies may thus be an efficient way of selecting sources at a critical point in their evolution.

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REFERENCES

- Arav, N., et al. 2001, *ApJ*, 561, 118
 Becker, R. H., Gregg, M. D., Hook, I. M., McMahon, R. G., White, R. L., & Helfand, D. J. 1997, *ApJ*, 479, L93
 Blain, A. W., Smail, I., Ivison, R. J., Kneib, J.-P., & Frayer, D. T. 2002, *Phys. Rep.*, 369, 111
 Borys, C., Scott, D., Chapman, S., Halpern, M., Nandra, K., & Pope, A. 2004, *MNRAS*, 355, 485
 Branch, D., Leighly, K. M., Thomas, R. C., & Baron, E. 2002, *ApJ*, 578, L37
 Canalizo, G., & Stockton, A. 2001, *ApJ*, 555, 719
 Clavel, J. 1998, *A&A*, 331, 853
 de Kool, M., Becker, R. H., Arav, N., Gregg, M. D., & White, R. L. 2002, *ApJ*, 570, 514
 Duc, P.-A., et al. 2002, *A&A*, 389, L47
 Efstathiou, A., Rowan-Robinson, M., & Siebenmorgen, R. 2000, *MNRAS*, 313, 734
 Elvis, M. 2000, *ApJ*, 545, 63
 Farrah, D., Afonso, J., Efstathiou, A., Rowan-Robinson, M., Fox, M., & Clements, D. 2003, *MNRAS*, 343, 585
 Farrah, D., Serjeant, S., Efstathiou, A., Rowan-Robinson, M., & Verma, A. 2002, *MNRAS*, 335, 1163
 Farrah, D., Surace, J. A., Veilleux, S., Sanders, D. B., & Vacca, W. D. 2005, *ApJ*, 626, 70
 Gregg, M. D., Becker, R. H., White, R. L., Richards, G. T., Chaffee, F. H., & Fan, X. 2002, *ApJ*, 573, L85
 Haas, M., et al. 2003, *A&A*, 402, 87
 Hall, P. B., et al. 2002, *ApJS*, 141, 267
 Hazard, C., McMahon, R. G., Webb, J. K., & Morton, D. C. 1987, *ApJ*, 323, 263
 Hutsemekers, D., & Lamy, H. 2000, *A&A*, 358, 835
 Jaffe, W., et al. 2004, *Nature*, 429, 47
 Kawakatu, N., Anabuki, N., Nagao, T., Umemura, M., & Nakagawa, T. 2006, *ApJ*, 637, 104
 Lacy, M., Gregg, M., Becker, R. H., White, R. L., Glikman, E., Helfand, D., & Winn, J. N. 2002, *AJ*, 123, 2925
 Lewis, G. F., Chapman, S. C., & Kuncic, Z. 2003, *ApJ*, 596, L35
 Lipari, S., Colina, L., & Macchetto, F. 1994, *ApJ*, 427, 174
 Lonsdale, C. J., Farrah, D., & Smith, H. E. 2006, in *Astrophysics Update 2*, ed. J. W. Mason (Heidelberg: Springer), 285
 Lynds, C. R. 1967, *ApJ*, 147, 837
 Murray, N., & Chiang, J. 1998, *ApJ*, 494, 125
 Ogle, P. M., Cohen, M. H., Miller, J. S., Tran, H. D., Goodrich, R. W., & Martel, A. R. 1999, *ApJS*, 125, 1
 Priddey, R. S., Gallagher, S. C., Isaak, K. G., Sharp, R. G., McMahon, R. G., & Butner, H. M. 2007, *MNRAS*, 374, 867
 Proga, D., Stone, J. M., & Kallman, T. R. 2000, *ApJ*, 543, 686
 Reichard, T. A., et al. 2003, *AJ*, 126, 2594
 Rieke, G. H., et al. 2004, *ApJS*, 154, 25
 Rowan-Robinson, M. 1995, *MNRAS*, 272, 737
 ———. 2000, *MNRAS*, 316, 885
 Sanders, D. B., Soifer, B. T., Elias, J. H., Madore, B. F., Matthews, K., Neugebauer, G., & Scoville, N. Z. 1988, *ApJ*, 325, 74
 Schmidt, G. D., & Hines, D. C. 1999, *ApJ*, 512, 125
 Sprayberry, D., & Foltz, C. B. 1992, *ApJ*, 390, 39
 Trump, J. R., et al. 2006, *ApJS*, 165, 1
 Voit, G. M., Weymann, R. J., & Korista, K. T. 1993, *ApJ*, 413, 95
 Werner, M. W., et al. 2004, *ApJS*, 154, 1
 Weymann, R. J., Morris, S. L., Foltz, C. B., & Hewett, P. C. 1991, *ApJ*, 373, 23
 Williams, R. J. R., Baker, A. C., & Perry, J. J. 1999, *MNRAS*, 310, 913
 Willott, C. J., Rawlings, S., & Grimes, J. A. 2003, *ApJ*, 598, 909