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SUBMILLIMETER OBSERVATIONS OF THE ULTRALUMINOUS BROAD ABSORPTION LINE QUASAR APM 08279+5255

GERAINT F. LEWIS,[1] SCOTT C. CHAPMAN,[2] RODRIGO A. IBATA,[3] MICHAEL J. IRWIN,[4] AND EDWARD J. TOTTEN[5]
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ABSTRACT

With an inferred bolometric luminosity of $5 \times 10^{15}\ L_{\odot}$, the recently identified $z = 3.87$, broad absorption line quasar APM 08279+5255 is apparently the most luminous object currently known. Since half of its prodigious emission occurs in the infrared, APM 08279+5255 also represents the most extreme example of an ultraluminous infrared galaxy. Here we present new submillimeter observations of this phenomenal object; while indicating that a vast quantity of dust is present, these data prove to be incompatible with the current models of emission and reprocessing mechanisms in ultraluminous systems. The influence of gravitational lensing on these models is considered, and we find that while the emission from the central continuum-emitting region may be significantly enhanced, lensing-induced magnification cannot easily reconcile the models with the observations. We conclude that further modeling, including the effects of any differential magnification, is required to explain the observed emission from APM 08279+5255.

Subject headings: gravitational lensing — infrared: galaxies — quasars: individual (APM 08279+5255)

1. INTRODUCTION

With bolometric luminosities exceeding $10^{12}\ L_{\odot}$, ultraluminous infrared galaxies (ULIRGs) represent an extreme class of objects whose spectra are dominated by emission in the far-infrared (for a review of their properties, see Sanders & Mirabel 1996). The source of their prodigious output is thought to arise in a thick, cool ($T \sim 100$ K) nuclear dust structure that reprocesses emission from an obscured active galactic nucleus (AGN)–like core, a massive star formation region, or possibly both (Genzel et al. 1998). The funneling of fuel into the nucleus and the resultant activity may be triggered by a violent interaction between gas-rich galaxies (Barnes & Hernquist 1996; Taniguchi & Shioya 1998); this appears to be the case observationally, with ~90% of ULIRGs displaying disturbed or merging morphology (Clements & Baker 1996).

Recently identified in a survey of halo carbon stars, the $z = 3.87$, broad absorption line (BAL) quasar APM 08279+5255 was found to be positionally coincident with a source in the *IRAS* Faint Source Catalog (Irwin et al. 1998). With a flux of 0.9 Jy at 100 μm, this $m_r = 15.2$ object possesses an inferred bolometric luminosity of $5 \times 10^{15}\ L_{\odot}$ ($\Omega_0 = 1$ and $H_0 = 50$ km s^{-1} Mpc^{-1} throughout), making APM 08279+5255 apparently the most luminous object currently known. However, ground-based images taken in ~0″.9 seeing reveal that the source is slightly elongated, suggesting that APM 08279+5255 consists of a pair of subcomponents separated by ~0″.3, which is consistent with the merger-driven hypothesis but also with the action of gravitational lensing. In several extreme ULIRGs, the morphology of the subcomponents directly reveals the action of gravitational lensing, the magnification effect of which can significantly enhance the intrinsic properties of a system; this is the case in both H1413+117 (the "Cloverleaf quasar"; Magain et al. 1988; Kneib et al. 1998) and the hyperluminous galaxy IRAS F10214+4724 (Rowan-Robinson et al. 1991; Broadhurst & Lehar 1995; Eisenhardt et al. 1996), where the lensing-induced amplification is estimated to be ~30–100. Since APM 08279+5255 is apparently so extremely luminous, the possibility that gravitational lensing is influencing the observed properties is highly likely.

Given the cool temperature of the dust region, photometric and spectroscopic observations at submillimeter wavelengths have proved to be an important probe of ULIRG systems, revealing details of the physical properties and processes underway in these energetic objects (see, e.g., Ivison et al. 1998a, 1998b; Hughes & Dunlop 1998). In this Letter, we present new submillimeter photometry of APM 08279+5255, from which an estimate of the total mass of dust, and its temperature, is derived. Combining these data with previous observations, we compare the total spectral energy distribution with popular models of ULIRG galaxies, while taking into account the potential effects that gravitational lensing may be playing in distorting our view of this system.

2. OBSERVATIONS

The observations were conducted with the Submillimeter Common-User Bolometer Array (SCUBA; Gear & Cunningham 1995) on the James Clerk Maxwell Telescope (JCMT).[6] SCUBA contains a number of detectors and detector arrays cooled to 0.1 K that cover the atmospheric windows from 350 to 2000 μm. For our photometric observations, we operated the 91-element short-wavelength array at 450 μm, the 37-element long-wavelength array at 850 μm, and the single photometry pixel at 1350 μm, giving half-power beamwidths of 7″.5, 14″.7, and 21″, respectively. A nine-point jiggle pattern was

[1] Fellow of the Pacific Institute for Mathematical Sciences 1998–1999; Department of Physics and Astronomy, University of Victoria, P.O. Box 3055, Victoria, BC V8W 3P6, Canada; and Department of Astronomy, University of Washington, Box 351580, Seattle WA 98195-1580; gfl@uvastro.phys.uvic.ca; gfl@astro.washington.edu.

[2] Department of Geophysics and Astronomy, University of British Columbia, 129-2219 Main Mall, Vancouver, BC V6T 1Z4, Canada; schapman@geop.ubc.ca.

[3] European Southern Observatory, Karl-Schwarzschild-Strasse 2, 85748 Garching bei München, Germany; ribata@eso.org.

[4] Royal Greenwich Observatory, Madingley Road, Cambridge CB3 0EZ, England, UK; mike@ast.cam.ac.uk.

[5] Department of Physics, Keele University, Keele, Staffordshire ST5 5BG, England, UK; ejt@astro.keele.ac.uk.

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TABLE 1
SUBMILLIMETER PHOTOMETRY OF APM 08279+5255

Date	1350 μm	850 μm	450 μm
Apr 4 (mJy)	…	75 ± 4	203 ± 51
Apr 18 (mJy)	26 ± 4	74 ± 9	260 ± 130
Apr 19 (mJy)	23 ± 3	…	…
Variance-weighted mean (mJy)	24 ± 2	75 ± 4	211 ± 47

employed to reduce the impact of pointing errors. The source was centered on the central pixel of the arrays with the outer pixels being used for subtraction of the sky variations. While jiggling, the secondary was chopped at 7.8125 Hz by 60″ in azimuth. The pointing stability was checked every hour, and regular sky dips were performed to measure the atmospheric opacity. The rms pointing errors were below 2″.

The observations were conducted over three nights in 1998 April. The first night had stable atmospheric zenith opacities at 450 and 850 μm, with τ being 1.47 and 0.29, but extremely high winds that forced dome closure. Firm detections were obtained at both wavelengths. Sky conditions were reasonably good on the second night, and observations at both 850 μm/450 μm (τ = 0.58/3.7) and 1350 μm were carried out. On the third night, conditions were less favorable [τ(225 GHz) around 0.1 and variable], and only 1350 μm observations were done.[7]

On the first and second nights, both CRL 618 and IRC +10216 were observed as calibrators, while only IRC +10216 was observed on the third night. The latter is variable on a timescale of 2 yr, and all observations were referenced to CRL 618, which has well-determined flux densities with SCUBA at 850 and 450 μm but nothing yet published for SCUBA at 1350 μm. In the latter case, the CRL 618 flux density published by Sandell (1994) was used, and it resulted in a sensible value for IRC +10216. The values derived for IRC +10216 at 450 μm/850 μm from CRL 618 were also well within the quoted errors.

[7] Observations on days 2 and 3 were undertaken as part of the CANSERV program operated by the Herzberg Institute for Astrophysics.

The dedicated SCUBA data reduction software (Jenness & Lightfoot 1998) was used to reduce the observations. All nonnoisy bolometers beyond 40″ of the central pixel were used to compensate for spatially correlated sky emission in the 850 μm/450 μm arrays. The 1350 μm pixel currently has no provision for subtracting sky variations using the other wavelength pixels. The results of these observations, as well as variance-weighted mean values, are listed in Table 1.

3. SPECTRAL ENERGY DISTRIBUTION

The submillimeter photometry presented in Table 1 is combined with previous data (Irwin et al. 1998) in Figure 1, which shows the spectral energy distribution (SED) of APM 08279+5255. The new data reveals that, in the submillimeter regime, the SED possesses a slope of 3.1 ± 0.2 in νF_ν, consistent with Rayleigh-Jeans blackbody emission. The curves superposed on Figure 1 show pure blackbody spectra of a source of temperature $T = 120$ K (*dot-dashed line*) and $T = 220$ K (*solid line*); such temperatures are representative of the temperature range of the regions of the source that emit in the submillimeter/far-infrared region of the SED. These values are slightly higher than those determined for the far-infrared emission in other ULIRG systems, which are typically $T \lesssim 100$ K (Eales & Edmunds 1996). The implied radius of such a blackbody is ~650 pc (assuming the emission region is spherical),

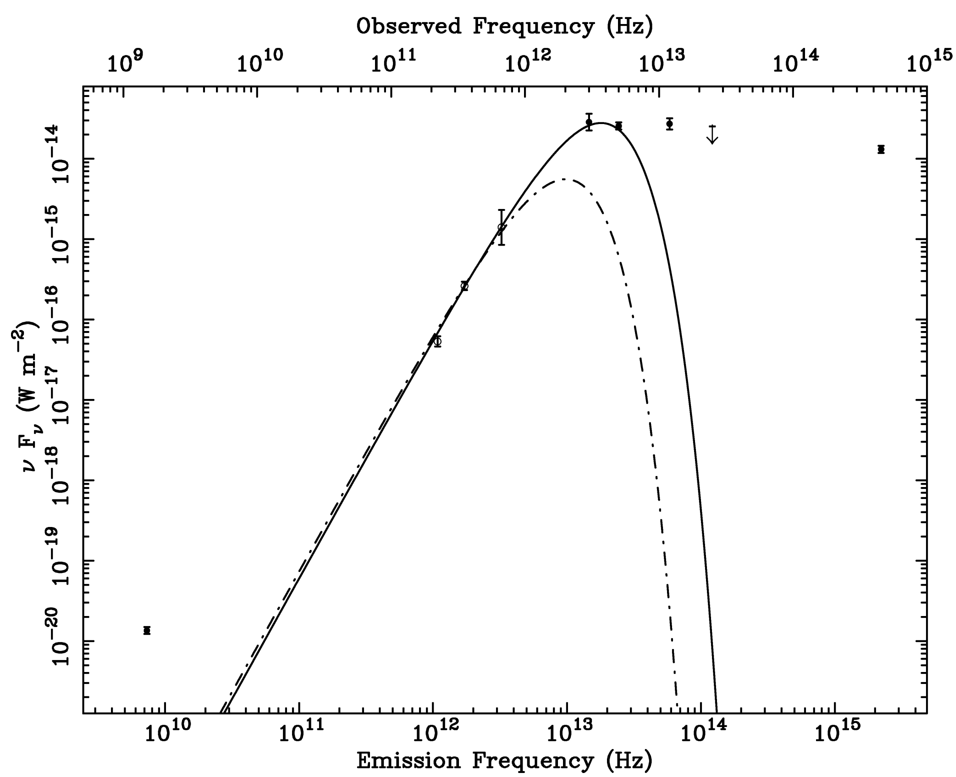

FIG. 1.—SED for APM 08279+5255. The open circles represent the data presented in this Letter. The filled circles are detailed in Irwin et al. 1998, with the arrow indicating an upper limit. The two curves are the SED for pure blackbody emitters, the solid curve the SED for a system of temperature $T = 220$ K, and the dot-dashed curve the SED for $T = 120$ K. The curves have been normalized to the submillimeter observations presented in this Letter.

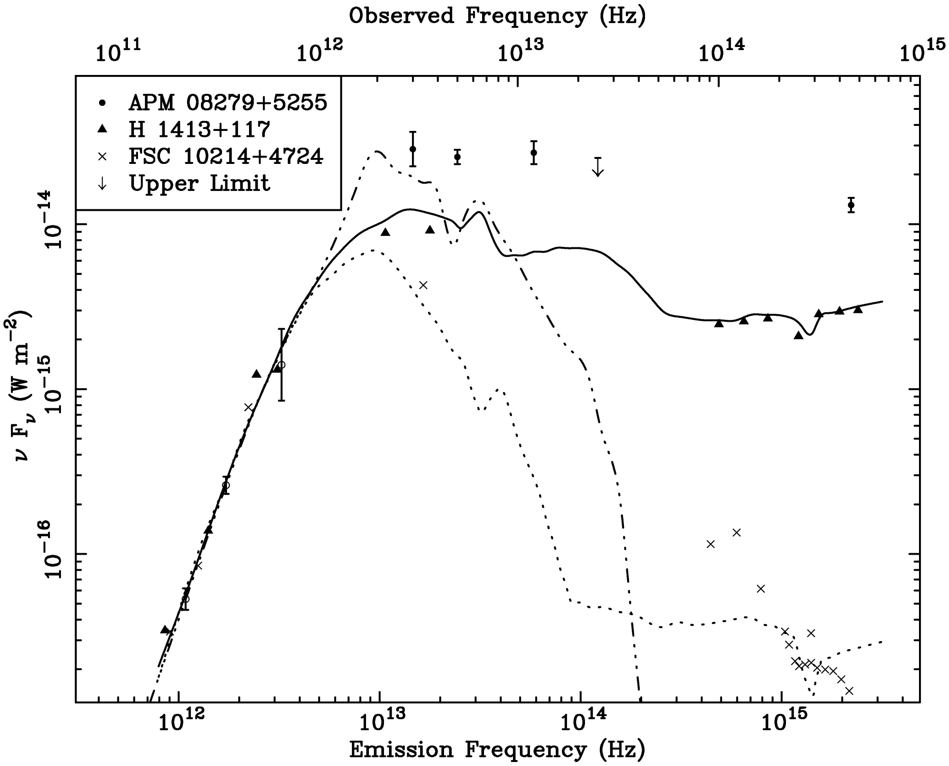

FIG. 2.—Submillimeter-to-optical SED of APM 08279+5255. The dash-dotted curve represents the SED for a quasar source embedded within a spherical distribution dust (Efstathiou & Rowan-Robinson 1995), while the solid curve represents a face-on view of a quasar at the center of a dusty torus (Granato et al. 1996). The dotted line represents this latter model viewed in the equatorial plane. The curves have been normalized to the submillimeter observations presented in this Letter. The emission-frame SEDs for H1413+117 (*triangles*) and IRAS FSC 10214+4724 (*crosses*) are also included, normalized to the submillimeter SED of APM 08279+5255. As can be seen, none of the models adequately represent the SED of APM 08279+5255, while those of Granato et al. describe SEDs of the other ultraluminous systems.

a factor of 2 smaller than the cooler (80 K) region responsible for the emission in IRAS F10214+4724 (Downes et al. 1992).

As outlined in Hildebrand (1983), observations in the submillimeter can be used to determine the mass in dust of ULIRGs (see, e.g., Clements et al. 1992; Downes et al. 1992; Eales & Edmunds 1996). Typically, the dust emission in these systems appears to be optically thin, as is inferred from their steep SED slope (the blackbody spectrum is modified by a dust absorption coefficient, $\kappa_d \propto \nu^n$, where $n = 1$–2; in the Rayleigh-Jeans regime, this is apparent as a steepening of the slope to at least 4 in νF_ν). The SED of APM 08279+5255 does not show such a steep slope; instead, it is consistent with emission from an optically thick blackbody. The dust mass obtained from the application of the optically thin treatment can be treated therefore as a lower bound on the total dust mass in the system. Assuming that the dust has a temperature of 220 K, the resulting dust mass from the three submillimeter data points presented here is $(3.7 \pm 0.3) \times 10^9\ M_\odot$ (assuming a constant dust absorption coefficient of $\kappa_d = 0.1$ m^2 kg^{-1}; Hughes & Dunlop 1998). If gravitational lensing plays a role, this value could be overestimated by a factor of ∼30, although it does indicate that APM 08279+5255 possesses copious amounts of dust, equivalent to that inferred for IRAS F10214+4724 (Downes et al. 1992) and other ULIRGs (Eales & Edmunds 1996).

The complex form of the SED in ULIRGs suggests that a single-temperature blackbody source for the far-infrared flux represents a gross simplification of the underlying processes, and several multicomponent models have been developed to better model these systems (Rowan-Robinson et al. 1993; Efstathiou & Rowan-Robinson 1995; Green & Rowan-Robinson 1996; Granato, Danese, & Franceschini 1996). Generally, these models are used to consider a powerful source of continuum radiation embedded in a thick distribution of dust that possesses grains of varying composition (Rowan-Robinson 1986). Radiative transfer techniques are then employed to calculate the reprocessing and reemission of the central continuum radiation.

Three such models are superposed on the submillimeter-optical region of the SED in Figure 2. The dash-dotted curve represents the “embedded quasar model” of Rowan-Robinson et al. (1993) (their model C); this model possesses a power-law continuum source at the center of a spherically symmetric dust distribution. Since the dust obscures a direct view of the illuminating source, all observed emission has been reprocessed. This model spectrum is normalized to the submillimeter data points presented here. Such a “pure dust emission” spectrum provides a poor fit to APM 08279+5255 and other ultraluminous systems, thus severely underestimating the optical flux. Spherical models with a lower optical depth allow some continuum flux through the dust region, but such models cannot account for the far-infrared/submillimeter flux (Rowan-Robinson et al. 1993).

A natural extension of such a model is to remove the assumption of spherical symmetry and to consider instead an axisymmetric distribution of absorbing dust, which represents a torus about the nuclear region (Rowan-Robinson et al. 1993; Efstathiou & Rowan-Robinson 1995; Green & Rowan-Robinson 1996). As well as scaling with total luminosity, the emergent spectrum is also then a function of orientation with respect to the observer; when viewing a system from the equatorial plane, the dusty torus obscures the view of the continuum source, and the SED is dominated by infrared dust emission. When viewing from the pole, however, an observer can look directly onto the central continuum source, and the SED can possess both significant infrared and optical components. Such a model was recently applied to several extreme ultraluminous systems and, considering only orientation and total luminosity, was found to reproduce the gross characteristics of the observed SEDs (Granato et al. 1996). In Figure 2, the solid line represents this model as viewed from the pole, while the dotted line is an equatorial view. The rest-frame SEDs for the ultraluminous Cloverleaf quasar, H1413+117 (*filled triangles*), and IRAS FSC 10214+4752 (*crosses*), both normalized to the submillimeter observations of APM 08279+5255, are also plotted. While adequately describing these spectra, it is apparent that the models of Granato et al. underestimate the infrared-to-optical flux by a factor of $\gtrsim 5$, even at the extreme polar viewing orientation, and provide a poor fit of the SED of APM 08279+5255. Extrapolating this model to the data presented in this system, the implied dust mass is $\sim 3 \times 10^8 M_\odot$, but again it likely underestimates the true mass of dust in this system and is dependent on the degree of gravitational lensing.

4. INFLUENCE OF GRAVITATIONAL LENSING

The degree to which the flux from a source is enhanced by the action of gravitational lensing is dependent on the scale size of the source, which leads to pronounced differential magnification effects (Schneider, Ehlers, & Falco 1992); in IRAS F10214+4724, the optical emission is thought to be magnified by a factor of ∼100, while the flux from the more extended far-infrared region undergoes a magnification of ∼30 (Eisenhardt et al. 1996). If gravitational lensing influences APM 08279+5255, can such effects account for the discrepancy between these models and the observed SED? In "typical" quasars, the optical-to-infrared continuum ratios are seen (in νF_ν) to be ∼2 (Saunders et al. 1989; Elvis et al. 1994). All this emission arises in the central accretion disk, whose scale is similar to both emission regimes; gravitational lensing would uniformly magnify such a source, by simply scaling its contribution to the total spectrum. Normalizing the (magnified) quasar SED to the observed *R*-band magnitude, it can be seen that the quasar continuum source, even if highly magnified in this system, can contribute little to the submillimeter-infrared SED. It should be noted, however, that if the quasar continuum source does intrinsically possess significant emission into the far-infrared, differential magnification effects may reconcile the data with the current models.

5. CONCLUSIONS

This Letter has presented new submillimeter observations of the ultraluminous BAL quasar APM 08279+5255; the data are consistent with emission from a warm (120–220 K), massive, optically thick distribution of dust that is heated by a quasar central continuum source. A simple model for the emission region of ULIRGs, which consists of an AGN-like continuum embedded within a spherical distribution, fails, when normalized to the submillimeter data, to reproduce the observed SED, underestimating the flux in the infrared and, because of a highly obscured view onto the quasar source, predicts no optical flux. Axisymmetric models, where the dust is distributed in a torus, do allow relatively unobscured views of the quasar core, thus allowing unprocessed optical flux to escape. Even at the most extreme viewing angles, however, current models still underestimate both the infrared and optical flux by several factors.

Further modeling of the geometry and physics of the emission region in APM 08279+5255, coupled with the effects of possible differential magnification due to gravitational lensing, is therefore required. Such modeling will provide a more accurate determination of the dust mass in APM 08279+5255, which, when coupled with spectroscopic observations of warm molecular gas tracers such as CO, will shed light on the interaction between star formation, warm dust, and the AGN core in explaining the observed properties of this phenomenal system.

It is interesting to note that pronounced infrared emission has been observed in a number of Seyfert I and II galaxies in the nearby universe (Bonatto & Pastoriza 1997). Similar to the high-redshift ULIRGs, the source of this emission is thought to be a warm, dusty torus, with the viewing angle–dependent obscuration of the continuum source and the broad emission line region accounting for the difference between the Seyfert classes. The similarity between this model and that proposed for more distant and powerful ULIRGs (Barvainis et al. 1995), especially considering that several Seyfert I systems exhibit absorption features indicating the presence of high-velocity outflows (e.g., Markarian 231; Forster, Rich, & McCarthy 1995), suggests that, rather than being unique objects displaying unusual properties, systems such as APM 08279+5255 and H1413+117 appear to be simply more luminous members of the ULIRG/AGN family.

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REFERENCES

Barnes, J. E., & Hernquist, L. 1996, ApJ, 471, 115
Barvainis, R., Antonucci, R., Hurt, T., Coleman, P., & Reuter, H.-P. 1995, ApJ, 451, 9
Bonatto, C. J., & Pastoriza, M. G. 1997, ApJ, 486, 132
Broadhurst, T., & Lehar, J. 1995, ApJ, 450, 41
Clements, D. L., & Baker, A. C. 1996, A&A, 314, L5
Clements, D. L., Rowan-Robinson, M., Lawrence, A., Broadhurst, T., & McMahon, R. 1992, MNRAS, 256, 35P
Downes, D., Radford, S. J. E., Greve, A., Thum, C., Solomon, P. M., & Wink, E. J. 1992, ApJ, 398, L25
Eales, S. A., & Edmunds, M. G. 1996, MNRAS, 280, 1167
Efstathiou, A., & Rowan-Robinson, M. 1995, MNRAS, 273, 649
Eisenhardt, P. R., Armus, L., Hogg, D. W., Soifer, B. T., Neugebauer, G., & Werner, M. W. 1996, ApJ, 461, 72
Elvis, M., et al. 1994, ApJS, 95, 1
Forster, K., Rich, R. M., & McCarthy, J. K. 1995, ApJ, 450, 74
Gear, W. K., & Cunningham, C. R. 1995, in ASP Conf. Ser. 75, Multifeed Systems for Radio Telescopes, ed. D. T. Emerson & J. M. Payne (San Francisco: ASP), 215
Genzel, R., et al. 1998, ApJ, 498, 579
Granato, G. L., Danese, L., & Franceschini, A. 1996, ApJ, 460, L11
Green, S. M., & Rowan-Robinson, M. 1996, MNRAS, 279, 884
Hildebrand, R. H. 1983, QJRAS, 24, 267
Hughes, D. H., & Dunlop, J. S. 1998, in Highly Redshifted Radio Lines: A Green Bank Science Workshop, ed. C. Carillie (San Francisco: ASP), in press
Irwin, M. J., Ibata, R. A., Lewis, G. F., & Totten, E. J. 1998, ApJ, in press
Ivison, R. J., et al. 1998a, ApJ, 494, 211

Ivison, R. J., Smail, I., Le Borgne, J.-F., Blain, A. W., Kneib, J.-P., Bézzcourt, J., Kerr, T. H., & Davies, J. K. 1998b, preprint (astro-ph/9712161)
Jenness, T., & Lightfoot, J. F. 1998, in ASP Conf. Ser. 145, Astronomical Data Analysis Software and SystemsVII, ed. R. Albrecht, R. N. Hook, & H. A. Bushouse (San Francisco: ASP), 216
Kneib, J.-P., Alloin, D., Mellier, Y., Guilloteau, S., Barvanis, R., & Antonucci, R. 1988, A&A, 329, 827
Magain, P., Surdej, J., Swings, J.-P., Borgeest, U., & Kayser, R. 1988, Nature, 334, 325
Rowan-Robinson, M. 1986, MNRAS, 219, 737
Rowan-Robinson, M., et al. 1991, Nature, 351, 719
Rowan-Robinson, M., et al. 1993, MNRAS, 261, 513
Sandell, G. 1994, MNRAS, 271, 94
Sanders, D. B., & Mirabel, I. F. 1996, ARA&A, 34, 749
Saunders, D. B., Phinney, E. S., Neugebauer, G., Soifer, B. T., & Matthews, K. 1989, ApJ, 347, 29
Schneider, P., Ehlers, J., & Falco, E. E. 1992, Gravitational Lenses (Berlin: Springer)
Taniguchi, Y., & Shioya, Y. 1998, ApJ, 501, L167