1995ApJ...450L..41B

THE ASTROPHYSICAL JOURNAL, 450:L41–L44, 1995 September 10
© 1995. The American Astronomical Society. All rights reserved. Printed in U.S.A.

A GRAVITATIONAL LENS SOLUTION FOR THE *IRAS* GALAXY FSC 10214+4724

TOM BROADHURST
Department of Physics and Astronomy, Johns Hopkins University, Baltimore, MD 21218

AND

JOSEPH LEHÁR
Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, MS-78, Cambridge, MA 02138
Received 1995 May 3; accepted 1995 July 6

ABSTRACT

We show that the $z = 2.3$ *IRAS* source FSC 10214+4724 is gravitationally lensed by an intervening elliptical galaxy. Its many anomalous properties can be explained if the active galactic nucleus (AGN) region of the source is much more magnified than its outer regions. We uncover a small counterimage to the arc adjacent to the lensing galaxy, as predicted by our lens model. A redshift of unity for the lens is suggested by a red component in the observed spectrum, yielding a lensing mass interior to the critical radius of $M(r < 3 \text{ kpc}) \approx 10^{11}\ M_\odot$, consistent with an ordinary massive galaxy. We present new high-resolution optical images which show a thin arc of emission, implying that the optical source is compact (less than 0.5 kpc) and highly magnified (more than 20 times). Since the optical emission is known to be strongly polarized and Seyfert 2, we propose that the optical arc is a highly magnified image of the inner "mirror" region of an obscured AGN. The central obscuring "torus" will be similarly magnified, naturally accounting for the large IR flux. We propose that cases like F10214 represent the obscured AGN counterparts to the lensed QSO population, and find that the probability of finding objects like F10214 in *IRAS* redshift surveys is reasonably large.

Subject headings: galaxies: individual (FSC 10214+4724) — gravitational lensing

1. INTRODUCTION

The *IRAS* galaxy FSC 10214+4724 (hereafter referred to as F10214) is unusual even by *IRAS* standards. It was discovered in a redshift survey of 1400 *IRAS* sources (Broadhurst et al. 1995) selected from the *IRAS* Faint Source Catalog (Moshir et al. 1989). At $z = 2.3$, F10214 has by far the largest redshift in the survey (Rowan-Robinson et al. 1991). The identification of the far-IR flux with this redshift rests on the near-coincidence between a millijansky radio source and the high-redshift optical object. Subsequently, CO line emission at $z = 2.3$ was found in this direction for several transitions (Brown & Vanden Bout 1991; Solomon, Downes, & Radford 1992). This suggested a high molecular content, which, together with the inferred large IR luminosity of $\sim 3 \times 10^{13}\ h^{-2}\ L_\odot$ ($h = H_0/100$ km s^{-1} Mpc^{-1}), led to much speculation about the nature of F10214. It is now clear that Seyfert 2 activity, not star formation, dominates the UV-optical emission from high-excitation narrow lines and a strong polarization (Lawrence et al. 1993; Elston et al. 1994). Lawrence et al. (1994) also report nondetection of any significant X-ray emission, refuting the hypothesis that F10214 is powered solely by a modestly extinguished QSO.

In this letter, we show how F10214 can be an ordinary obscured active galactic nucleus (AGN) which has been gravitationally lensed by a foreground elliptical galaxy. Matthews et al. (1994) did suggest that F10214 could be lensed, but observed that the arc is very different at various wavelengths. Despite their mentioning that it could result from source structure, they were discouraged by this achromaticity, and strongly favored a merger scenario. However, a characteristic of lensing is that the magnification can depend sensitively on the source size. We show that this allows us to completely understand the many unusual properties of F10214.

2. F10214 AS A GRAVITATIONAL LENS

In the lensing interpretation, the light from the distant *IRAS* source is magnified by the gravitational field of an intervening galaxy. As in Matthews et al. (1994), we identify the *IRAS* source with the arc-shaped object (source 1), and the lensing galaxy with the central object (source 2). The arc is focused on the lensing galaxy at a radius of 1″.2, and contains a bright "core" which is dominated by Hα emission. Sources 3 and 4 cannot be additional lensed images of the *IRAS* source, and we take it that these are just other galaxies close to the line of sight.

Only a very simple lens model is required to reproduce the observed *K*-band morphology. We use a singular isothermal ellipsoid potential (Blandford & Kochanek 1987), whose model parameters are the lens center; a characteristic deflection angle or "ring radius," β; the ellipticity, ε; and the position angle, ϕ. We have placed a small source with a compact core just outside a cusp of the diamond caustic (see Fig. 1). Two images of this source are formed: an arc-shaped image "A" to the south, and a smaller counterimage "B," just north of the lensing galaxy "G." The compact core gives rise to the bright point at the middle of the arc.

In our model, the magnification m depends strongly on the source size r (see Fig. 1). For small sources $m(r)$ is dominated by the tangential stretching of A, so the arc length is $\approx 2rm(r)$. The *K*-band arc is $\sim 2''$ across, suggesting a source with $r \sim 0''.2$ and only a moderate magnification, $m \sim 5$. The 8 GHz radio source is coincident with the *K*-band core, and both are $\sim 0''.5$ across (Lawrence et al. 1993). This is much shorter than the *K*-band arc, and corresponds to a source with $r \sim 0''.01$ and a much stronger magnification, $m \sim 50$. A large central magnification for the radio emission would imply that the far-IR luminosity may also be highly magnified, thereby reducing the

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1995ApJ...450L..41B

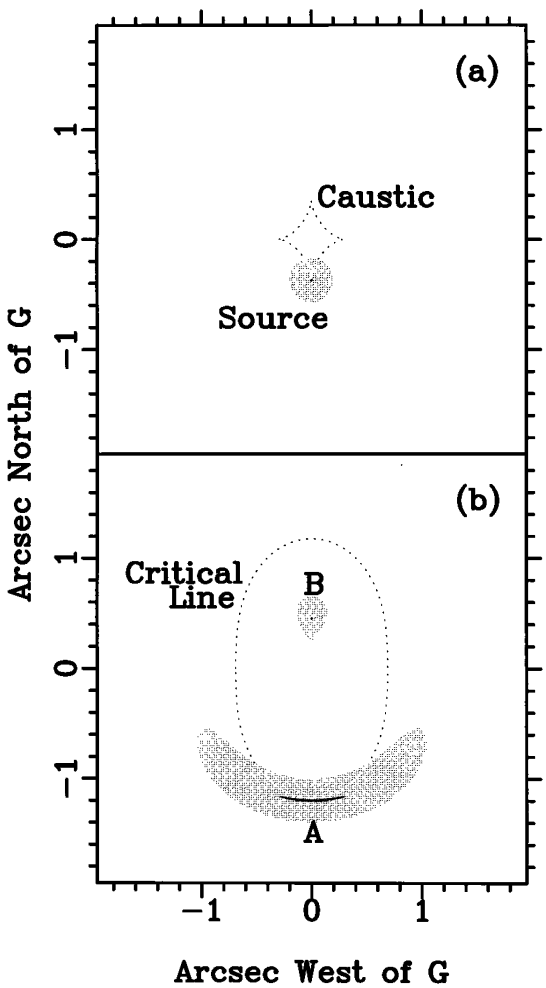

FIG. 1.—Gravitational lens model for F10214. Panel *a* shows how the source would appear in the absence of the lens, and panel *b* shows the distorted images seen through the lens. Sources outside the caustic produce two images, and those inside produce four. The lens is centered on G, with $\beta = 0''.91$, $\varepsilon = 0.18$, and $\phi = 0°$ (CCW from north). The source has two components: a small region ($r = 0''.2$) which gives rise to the moderately magnified *K*-band arc ($m \sim 5$) and a compact core ($r = 0''.01$) which corresponds to the highly magnified radio and Hα emission ($m \sim 50$). Both components are offset by $b = 0''.024$ from a cusp in the caustic.

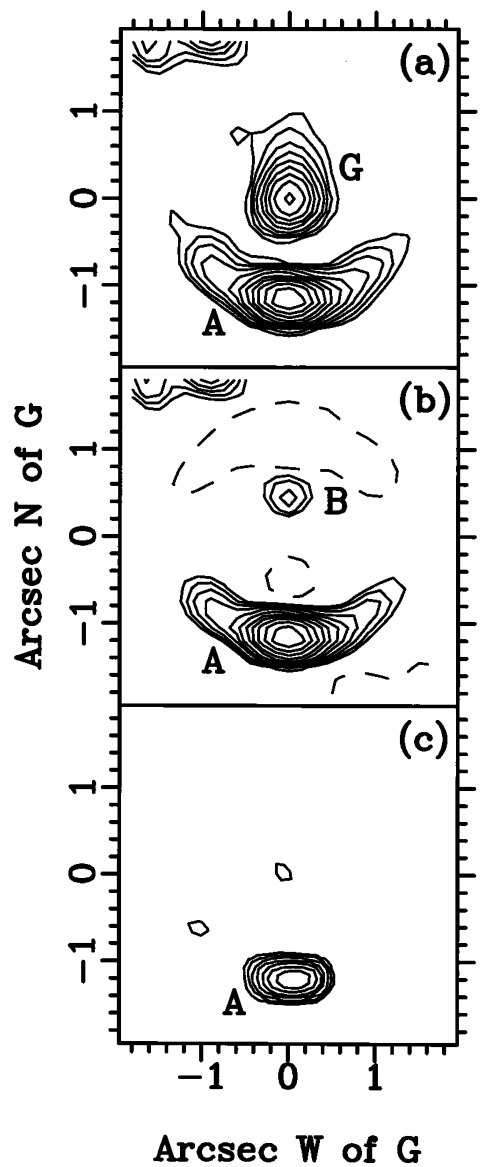

FIG. 2.—Near-IR and optical images of F10214. The contours mark fractional intervals of $\sqrt{2}$ in intensity, stepping down from the map maximum. (*a*) *K*-band image from the data of Matthews et al. (1994). The image is sharpened to $0''.3$ resolution, showing the arc A and the central galaxy G. (*b*) The same image, rotated by 180° around G, and subtracted from the image in (*a*), to remove symmetric emission from G. The arc counterimage B is visible $\sim 0''.45$ north of G. (*c*) New *B*-band image, sharpened to $0''.2$ resolution. Only the central part of the arc is detected, and it is similar in size to the *K*-band core. Since the counterimage is not detected, the core region must be magnified by more than 20 times.

bolometric luminosity of F10214 to within the range more typical of *IRAS* sources. It is worth noting that unless the far-IR emission is magnified by at least a factor of 10, F10214 remains the most luminous object in the universe. So, if the magnification is only comparable to that of the *K*-band arc, the introduction of gravitational lensing just makes F10214 unique in a second sense!

If F10214 is lensed, the lensing galaxy must be at a lower redshift than the source. We have examined the published spectra of F10214, looking for evidence of the lensing galaxy. The spectra are too noisy for any absorption lines to be identified. However, a distinctive red continuum component is visible (Rowan-Robinson et al. 1991, Fig. 2; Soifer et al. 1995, Fig. 2) at wavelengths longer than ~8000 Å, similar to the spectrum of early-type galaxies at $z \sim 1$. We note that lensing galaxies are most likely to be early type, given their larger central densities (Turner, Ostriker, & Gott 1984).

Finally, the lens model predicts an opposing counterimage to the *K*-band arc, as illustrated in Figure 1. With this in mind, we have reanalyzed the *K*-band data of Matthews et al. (1994), kindly provided to us by the authors. Figure 2*a* shows the image, sharpened using the procedure described in § 3. Both the arc A and the central galaxy G are present, but a tail of emission extends northward from G. Figure 2*b* shows the same map after removing G. A distinct source B is visible $\sim 0''.45$ north of G, providing a striking confirmation of the lensing interpretation.

3. NEW OPTICAL IMAGES OF F10214

We have imaged F10214 at high resolution in the optical *B* band with the William Herschel Telescope in 1994 April. Two

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1995ApJ...450L..41B

10 minute exposures were taken which cover the source and two nearby bright stars. The seeing was 0″.6, and the images are oversampled, with 0″.1 pixels. The stars are both unsaturated. We deconvolved the images using the Lucy-Richardson algorithm, choosing the number of iterations to minimize the difference between the original and deconvolved images, after reconvolving with the stellar point-spread function. Virtually identical results were obtained using both template stars and between 50 and 500 iterations. Figure 2*c* shows the co-added deconvolved image of F10214.

A single bright arc is visible, coincident with the "core" of the *K*-band arc. Like the radio source, this arc is oriented east-west, with most of its flux toward the western end. The arc is ~1″ long (0″.5 FWHM), so its inferred magnification from our model is ~50. The arc is unresolved in the north-south direction at 0″.2 resolution, setting an upper limit on the source size of $r < 0.5\ h^{-1}$ kpc at $z = 2.3$. The arc's magnitude is $B \approx 21.5$, and no counterimage is detected to a 3 σ level of $B \sim 25$. This limits the optical magnification to $m > 20$, which is consistent with the arc length constraint. The lensing galaxy G is also not detected, so it must be very red ($B - K > 7.3$), consistent with an early-type galaxy at $z > 0.5$ (Mobasher, Sharples, & Ellis 1993).

4. PROPERTIES OF THE LENSING GALAXY

The near-IR geometry constrains the model of the lensing mass. The mass must be elongated in order to produce both a long arc and a small counterimage. Since the arc is very symmetric, and since source B is closer to G than to A, the mass must be oriented with its major axis within a few degrees of the north-south axis. The positions of A, B, and G then constrain the ring radius to $\beta = 0''.91$, and the intrinsic source position to 0″.38 south of G. The ellipticity ε is determined by the requirement that the core of A be strongly magnified. The size of the caustic increases with ε, reaching the source center when $\varepsilon = 0.18$ (or isophotal axial ratio ~0.6). After removing B, G shows no obvious elongation in the *K*-band image, but this is probably due to limited angular resolution.

The model can be used to estimate the lensing mass. For a lens at $z_L \sim 1$ and a source at $z_S = 2.3$, the ring size $\beta = 0''.91$ gives an isothermal velocity dispersion of ≈320 km s^{-1} (assuming $\Omega = 1$). This corresponds to a mass of $\sim 3 \times 10^{11}\ h^{-1}\ M_\odot$ within β ($\sim 4\ h^{-1}$ kpc). This mass estimate is insensitive to assumptions about the mass model profile and the lens ellipticity, but varies by 30% for a lens redshift range of $0.8 < z_L < 1.2$.

The mass estimate can be compared with the luminosity of G. After removing the counterimage, the near-IR magnitude is $K_S = 17.65$ (Matthews et al. 1994), and this converts to a standard B_T magnitude if we assume an early-type galaxy spectrum. We use $B_T = K_S - \Delta K + (B_T - K) - E_{\rm corr}$, where $B_T - K = 3.7$ is the present-date rest-frame color of luminous early-type galaxies (Mobasher et al. 1993), and $\Delta K = 0.15(H - K) = 0.05$ is the correction between the standard *K* band and the short K_S band (J. Graham 1995, private communication). The *K*-corrected evolution in the redshifted *K* band is small ($0.07 < E_{\rm corr} < 0.12$ for early-type galaxies at $z \sim 1$, $0.5 < h < 1$, $\Omega = 1$; Bruzual & Charlot 1993). The resulting rest-frame luminosity is then $M_{B_T} = -20.0 \pm 0.2$ for $0.5 < z_L < 1.5$, and the central mass-to-light ratio is 25.0 ± 5.0 h in solar units. This is larger than for most local elliptical galaxies (Lauer 1985), but not surprising. A further check comes from the Faber-Jackson relation as expressed by Fukugita & Turner (1991). The expected velocity dispersion, $\sigma \approx 255\ h^{0.5}$ km s^{-1}, is consistent with the lens dispersion, if a factor of $\sqrt{1.5}$ is included to account for the stellar brightness profile (Gott 1977).

5. THE NATURE OF THE BACKGROUND SOURCE

Gravitational lensing places severe constraints on the nature of the source. If a small source is offset by $b \ll \beta$ from the caustic, we find empirically that the magnification is $\sim 2\beta/b$. To achieve the high magnifications in our model, the source radius r cannot exceed b, so $r < 2\beta/m$. There is also a lower limit to the source size if the far-IR source is thermal. About half of the bolometric flux can be fitted by an 80 K thermal IR component (Downes et al. 1992). In this case, the apparent luminosity is magnified, so that $L \propto mR^2T^4$. Hence, the minimum blackbody radius of the IR emission is $R_{BB} \approx 560 m^{-0.5}\ h^{-1}$ pc, corresponding to $r > 0''.14 m^{-0.5}$ at $z = 2.3$. So the allowed range of source size is $0''.14 m^{-0.5} < r < 1.8 m^{-1}$, which limits the magnification to $m < 170$. For $m = 50$, the range is $0''.02 < r < 0''.04$, corresponding to a source diameter of only $\sim 100\ h^{-1}$ pc at $z = 2.3$. Thus, if the lens magnification can reduce the intrinsic luminosity of F10214 to within the observed *IRAS* range, the IR source must be very small, and also optically thick if it is thermal.

These restrictions can be met if the source is an AGN. We know that the optical/IR spectrum is clearly Seyfert 2–like, and is polarized by ≈15% (Lawrence et al. 1993; Elston et al. 1994) and that such high levels of polarization are found in the central "mirror" region of local Seyfert galaxies (Antonucci 1993). The scale of local AGN mirrors is ≈50–100 pc. This is consistent with the above limits, and for $m \sim 50$ it would produce a ~1″ long optical arc. Therefore, we suggest that our observed optical arc is a highly magnified image of the central region of an obscured AGN.

If the central region of the AGN is so highly magnified, then we must naturally expect the central obscuring "torus" to be similarly magnified. The torus would radiate predominantly in the IR, peaking at ~10–20 μm, on a size scale of 10–100 pc (Pier & Krolik 1993). This region is small enough and optically thick enough to satisfy the above blackbody constraint. Furthermore, such torus models can be constructed to agree well with the overall IR spectra of luminous *IRAS* galaxies for only modest dust masses $M_{\rm dust} \sim 10^4$–$10^5\ M_\odot$, and also reproduce well the spectrum of F10214 when redshifted (e.g., Granato & Danese 1994, Fig. 6). If the AGN in F10214 is similar to the local Seyfert 2 galaxy NGC 1028, with a total IR luminosity of $\sim 5 \times 10^{11}\ L_\odot$ (Rieke & Low 1975), then $m \sim 50$ brings this close to the apparent luminosity of F10214.

The view that F10214 is a lensed AGN solves several other problems associated with this source. (1) This source is very "red" in the IR, in that its apparent far-IR to near-IR flux ratio is much higher than for local Seyfert 2 nuclei (Lawrence et al. 1994). This is easily explained if the core is preferentially magnified. (2) High magnification can explain the unusually bright CO emission. The high temperature deduced from the CO transitions (Solomon et al. 1992) and the observed velocity profile are consistent with conditions in AGN centers (Meixner et al. 1990). (3) If the AGN narrow-line region has any ionization structure, the spectral lines will be magnified by different amounts. This may explain the anomalously large high-ionization lines, like N v in F10214, compared with other

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1995ApJ...450L..41B

Seyfert 2 galaxies. (4) The unexpected polarization angle is also explained. The $\boldsymbol{E}$ vector of polarized optical emission is usually perpendicular to the radio elongation in Seyfert 2 sources. However, in the case of F10214 the polarization is only ~35° from the radio source major axis (Lawrence et al. 1993). In our model, the radio source is stretched by a factor of more than 20 by lensing, so the observed elongation is unrelated to any intrinsic structure.

6. PROBABILITY OF FINDING SOURCES LIKE F10214

One might ask how likely such a lensing event is, given what is known about the *IRAS* luminosities and the intervening galaxy population. This is easy to quantify because the *IRAS* redshift survey in which F10214 was found has a pure flux limit of 0.2 Jy at 60 μm, and angular coverage of 0.20 sr (Broadhurst et al. 1995).

We determine the total cross section to lensing in the limit of compact sources following Turner et al. (1984), and include the extra boost to the high-magnification tail from the diamond caustics of elliptical lenses (Wallington & Narayan 1993).

The cross section is sensitive to the choice of *IRAS* galaxy evolution, the form of which is constrained by the survey from which F10214 was selected, albeit at lower redshift $z < 0.4$ (Broadhurst et al. 1995). Pure density evolution at a rate of $(1 + z)^5$ provides a good fit to the redshift survey luminosities. For this case we expect 0.3 lensed *IRAS* sources in the survey with an expected source redshift of $< z_S > \approx 1.2$. The expected *IRAS* magnification is $m \sim 40$, in the small source-size limit. Pure luminosity evolution at a rate of $(1 + z)^{2.5}$ also fits well, and yields 1.2 expected lensed sources, with $<z_S> \approx 2.0$ and $m \sim 25$. The expected lens redshift depends only on the source redshift, and we find $<z_L> = 0.7 \pm 0.2$ for both cases. Thus the a priori probability of finding systems like F10214 in a flux-limited IR survey is encouragingly large.

7. CONCLUDING REMARKS

We believe that systems like F10214 represent those lensed AGNs whose central engines are obscured. If they are as common as we predict, obscured AGNs could be more useful than QSOs for probing the lens galaxy mass distributions, since their background emission is measurably extended. Other such cases may already be known. The *IRAS* source with the next highest inferred luminosity is F15307+3252, at $z = 0.93$ (Cutri et al. 1994), and it is probably another case like F10214. The lensed QSO 2237+030 ($z_S = 2.5$) is a strong CO emitter (Barvainis et al. 1994) and may be a face-on version of F10214.

Current searches for lensing have used optical QSOs and active radio sources, which are only a subset of the full AGN population. Selection by far-IR allows a fuller coverage of AGNs but is presently limited by the relatively bright *IRAS* flux limit. In the future, lensed AGNs may be efficiently selected by correlating hard X-ray, radio, and far-IR sky surveys with the multicolor Sloan Digital Sky Survey, selecting out hybrid red + blue identifications for detailed *Hubble Space Telescope* (*HST*) follow-up.

More work is clearly needed on F10214 itself. Deep optical images should detect the counterimage, and recent observations confirm this (Graham & Liu 1995; Eisenhardt et al. 1995). The *HST* images will place tighter limits on the source size from the radial width of the main arc. Since they are highly magnified, any structures in the arc could give very detailed information on the background galaxy and better constraints on the mass distribution of the lensing galaxy.

If the lens is a luminous early-type galaxy at $z_L \sim 1$ as we suggest, obtaining its redshift should be relatively straightforward. The lens redshift would improve the mass estimate, and of course would provide conclusive confirmation of lensing.

The authors are grateful to Keith Matthews, Tom Soifer, and Lee Armus for providing us with their *K*-band Keck image. We also thank Tim Heckman, Julian Krolik, and Ed Turner for useful suggestions, and Dave Carter and Karl Glazebrook for help with the WHT observations. J. L. acknowledges support from NSF grant AST93-03527.

REFERENCES

Antonucci, R. 1993, ARA&A, 31, 473
Barvainis, R., Tacconi, L., Antonucci, R., Alloin, D., & Coleman, P. 1994, Nature, 371, 586
Blandford, R. D., & Kochanek, C. S. 1987, ApJ, 321, 658
Broadhurst, T. J., et al. 1995, in preparation
Brown, R. L., & Vanden Bout, P. A. 1991, AJ, 102, 1956
Bruzual, G., & Charlot, S. 1993, ApJ, 405, 538
Cutri, R. M., Huchra, J. P., Low, F. J., Brown, R. L., & Vanden Bout, P. A. 1994, ApJ, 424, L65
Downes, D., Radford, S. J. E., Greve, A., Thum, C., Solomon, P. M., & Wink, J. E. 1992, ApJ, 398, L25
Eisenhardt, P., Armus, L., Soifer, B. T., Hogg, D., Neugebauer, G., & Werner, M. 1995, in preparation
Elston, R., McCarthy, P. J., Eisenhardt, P., Dickinson, M., Spinrad, H., Jannuzi, B. T., & Maloney, P. 1994, AJ, 107, 910
Fukugita, M., & Turner, E. L. 1991, MNRAS, 253, 99
Gott, J. R., III. 1977, ARA&A, 15, 258
Graham, J. R., & Liu, M. C. 1995, ApJ, in press
Granato, G. L., & Danese, L. 1994, MNRAS, 268, 235
Lauer, T. 1985, ApJ, 292, 104
Lawrence, A., Rigopoulou, D., Rowan-Robinson, M., McMahon, R. G., Broadhurst, T. J., & Lonsdale, C. L. 1994, MNRAS, 266, 41P
Lawrence, A., et al. 1993, MNRAS, 260, 28
Matthews, K., et al. 1994, ApJ, 420, L13
Meixner, M., Puchalsky, R., Blitz, L., Wright, M., & Heckman, T. 1990, ApJ, 354, 158
Mobasher, B., Sharples, R. M., & Ellis, R. S. 1993, MNRAS, 263, 560
Moshir, M., et al. 1989, Explanatory Supplement to the *IRAS* Faint Source Survey (Pasadena: JPL)
Pier, E. A., & Krolik, J. H. 1993, ApJ, 418, 673
Rowan-Robinson, M., et al. 1991, Nature, 351, 719
Rieke, G. H., & Low, F. J. 1975, ApJ, 199, L13
Solomon, P. M., Downes, D., & Radford, S. J. E. 1992, ApJ, 398, L29
Soifer, B. T., Cohen, L., Armus, K., Matthews, G., Neugebauer, G., & Oke, J. B. 1995, ApJ, 443, L65
Turner, E. L., Ostriker, J. P., & Gott, J. R., III. 1984, ApJ, 284, 1
Wallington, S., & Narayan, R. 1993, ApJ, 403, 517

© American Astronomical Society • Provided by the NASA Astrophysics Data System