The Astrophysical Journal, 532:L21–L24, 2000 March 20

THE MID-INFRARED SPECTRA OF NORMAL GALAXIES

G. Helou,[1] Nanyao Y. Lu,[1] M. W. Werner,[1,2] S. Malhotra,[1] and N. Silbermann[1]
Received 1998 September 30; accepted 2000 January 31; published 2000 March 2

ABSTRACT

The mid-infrared spectra (2.5–5 and 5.7–11.6 μm) obtained by ISOPHOT reveal the interstellar medium emission from galaxies powered by star formation to be strongly dominated by the aromatic features at 6.2, 7.7, 8.6, and 11.3 μm. Additional emission appears in between the features, and an underlying continuum is clearly evident at 3–5 μm. This continuum would contribute about a third of the luminosity in the 3–13 μm range. The features together carry 5%–30% of the 40–120 μm far-infrared (FIR) luminosity. The relative fluxes in individual features depend very weakly on galaxy parameters such as the far-infrared colors, direct evidence that the emitting particles are not in thermal equilibrium. The dip at 10 μm is unlikely to result from silicate absorption since its shape is invariant among galaxies. The continuum component has a $f_\nu \propto \nu^{+0.65}$ shape between 3 and 5 μm and carries 1%–4% of the FIR luminosity; its extrapolation to longer wavelengths falls well below the spectrum in the 6–12 μm range. This continuum component is almost certainly of nonstellar origin and is probably due to fluctuating grains without aromatic features. The spectra reported here typify the integrated emission from the interstellar medium of the majority of star-forming galaxies and could thus be used to obtain redshifts of highly extincted galaxies up to $z = 3$ with *SIRTF*.

Subject headings: galaxies: ISM — infrared: ISM: lines and bands

1. INTRODUCTION

The *Infrared Space Observatory* (*ISO*; Kessler et al. 1996) has provided a unique opportunity for infrared spectroscopy at wavelengths and sensitivities inaccessible to suborbital platforms. Mid-infrared spectroscopy has been an important tool in characterizing star formation and the interstellar medium (ISM) in galaxies since the mid-1970s (Willner et al. 1977; Roche et al. 1991), and it has taken a major leap forward thanks to the sensitivity and unimpeded spectral coverage of *ISO*.

This is a first report on the mid-infrared spectroscopy of galaxies using ISOPHOT (Lemke et al. 1996), using data obtained as part of the *ISO* Key Project under NASA Guaranteed Time on the ISM of normal galaxies (Helou et al. 1996). This Key Project used *ISO* to derive the physical properties of the interstellar gas, dust, and radiation field in a broad sample of "normal" galaxies, defined as systems whose luminosity is derived from stars. This sample includes 60 objects comprising all morphological types, with visible-light luminosities ranging from 10^8 to 10^{11} $L_\odot$, infrared-to-blue ratios from 0.1 to 100, and *IRAS* colors $R(60/100) = f_\nu(60)/f_\nu(100)$ between 0.3 and 1.2. The sample is not statistically complete but is designed to capture the great diversity among galaxies, especially in terms of the ratio of current to long-term average star formation rate.

2. THE SPECTRA

The PHT-S module of the ISOPHOT instrument (Lemke et al. 1996) has a $24'' \times 24''$ aperture on the sky, pointed with an accuracy $\leq 2''$ (Kessler et al. 1996). The instrument has two 64-element linear Si:Ga detector arrays covering the 2.5–4.9 μm range with $\Delta\lambda = 0.04$ μm per element and the 5.9–11.7 μm range with 0.1 μm per element. The elements are sized to match the image of the entrance aperture, thereby determining the spectral resolution. The FWHM of an unresolved line varies between 1.5 and 2 elements depending on the centering of the line with respect to pixel boundary. Each galaxy was observed for a total of 512 s, split evenly between galaxy and sky, using a double-sided chopping scheme for sky subtraction. The PHT-S spectra were derived from the edited raw data using the ISOPHOT Interactive Analysis (PIA) V.7 in a standard way. The flux calibration was done using a mean, signal-dependent "detector response function" derived directly from chopped observations of standard stars with known spectra. Our final spectra are the integrals under the PHT-S beam profile of the surface brightness distribution of each source, expressed as flux densities. The combined uncertainties of the relative calibration across the spectrum and the absolute flux scale should be $\lesssim$30% according to the PHT-S calibration report as well as our own cross calibration with the CAM photometry at 6.75 μm in D. Dale et al. (2000, in preparation).

Of the 45 galaxies eventually observed in total with PHT-S, Figure 1 shows spectra for seven galaxies selected so that most of their flux is contained within the PHT-S aperture (Table 1). This selection is based on broadband images at 6.75 μm ($\Delta\lambda \simeq 3$ μm) obtained with ISOCAM (Césarsky et al. 1996a) and described elsewhere (N. Silbermann et al. 2000, in preparation). Table 1 lists the galaxies and illustrates the large spread in their basic properties. Column (1) gives the name, column (2) the *IRAS* color ratio $R(60/100)$, column (3) the optical morphology, column (4) the fraction of 6.75 μm flux within the PHT-S aperture, column (5) the infrared-to-blue ratio, column (6) the luminosity in solar units within the far-infrared (FIR) synthetic band (42.5–122.5 μm) defined in Helou et al. (1988), and column (7) the mid-infrared morphology from Silbermann et al. (1996) and D. Dale et al. (2000, in preparation).

The mid-infrared spectra of all these galaxies are dominated by emission features that appear in two main groups, one stretching from 5.5 to 9 μm and the other starting at 11 μm and extending beyond the spectral range of these data (see Boulanger et al. 1996 for a similar spectrum at longer wavelengths of a molecular cloud region). The shape and relative

[1] Infrared Processing and Analysis Center, California Institute of Technology, MS 100-22, 770 South Wilson Avenue, Pasadena, CA 91125; gxh@ipac.caltech.edu, lu@ipac.caltech.edu, mww@ipac.caltech.edu, san@ipac.caltech.edu, nancys@ipac.caltech.edu.

[2] Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109.

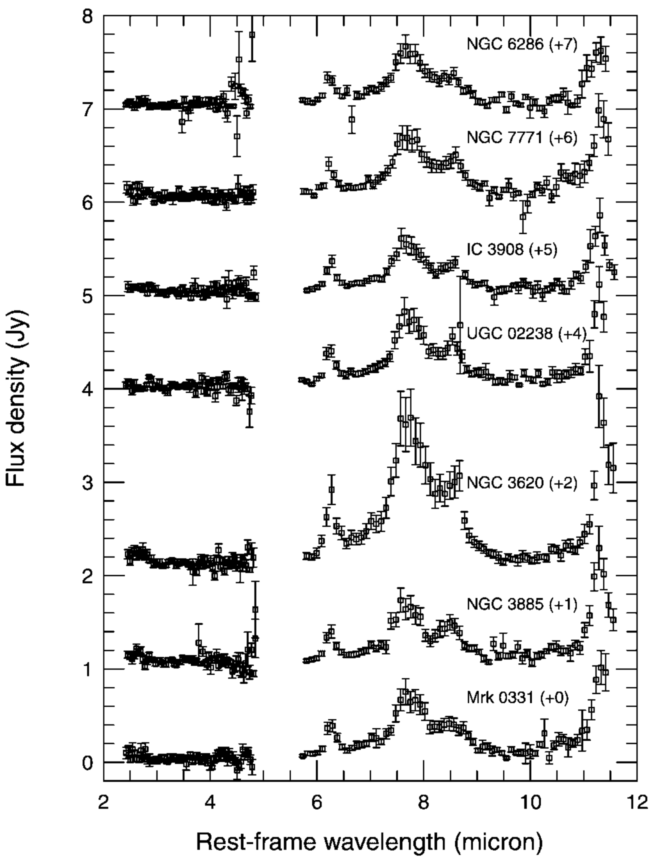

FIG. 1.—*ISO* Mid-IR spectra of the seven galaxies listed in Table 1. The ordinate is the flux density within the PHT-S aperture of 24″ × 24″, and the abscissa is the rest-frame wavelength in units of microns. Each spectrum has been vertically shifted by a constant given in the parentheses next to the name of the galaxy.

strengths of the features are quite similar to "type A sources," which are the most common nonstellar objects in the Milky Way: reflection nebulae, planetary nebulae, molecular clouds, diffuse atomic clouds, and H II regions (see Geballe 1996, Tokunaga 1996, and references therein). While there is good evidence to link these features to polycyclic aromatic hydrocarbons or similar compounds, there is no rigorous spectral identification (Puget & Léger 1989; Allamandola, Tielens, & Barker 1989). It is generally agreed, however, that the emitters are small structures, ~100 atoms typically, transiently excited to high internal energy levels by single photons. The identification issue will not be discussed further here, and the spectral features will be referred to as "aromatic features in emission" (AFE). Quantitatively similar spectra have been reported from spectroscopic observations with the PHT-S, the ISOCAM circular variable filter, and the *ISO* short-wavelength spectrometer (SWS) on a variety of Galactic sources and a number of galaxies (see Tielens 1999 for a review; Vigroux et al. 1996; Metcalfe et al. 1996). However, interstellar dust can manifest mid-infrared spectra of a fundamentally different appearance in environments such as the Galactic center (Lutz et al. 1996), supernova remnants (R. Tuffs 2000, in preparation), compact H II regions (Césarsky et al. 1996b), and active galactic nuclei (AGNs; Lutz et al. 1998; Roche et al. 1984). Such sources are thus obviously not major contributors to the integrated spectra of normal galaxies.

ISO SWS spectra with greater spectral resolution show AFE with the same shape, a clear indication that they are spectrally resolved in our PHT-S data. The nondetection of the 3.3 μm feature in individual spectra is not surprising since it is known to amount to 1% or less of the luminosity carried by the mid-infrared AFE in type A sources (Tokunaga 1996; Willner et al. 1977 for M82) and would therefore be below the 1 σ level in our individual spectra.

Finally, an important consequence of the invariant shape of the spectrum up to 11 μm is that the 10 μm trough is best interpreted as a gap between AFE rather than a silicate absorption feature. An absorption feature would become more pronounced in galaxies with larger infrared-to-blue ratios, and that is not observed (see also Sturm et al. 2000).

3. THE AVERAGE SPECTRUM

The seven objects in Table 1 are among the 45 galaxies observed by *ISO* for the Key Project, most of which display similar spectra, regardless of the relative sizes of aperture and galaxy. The only significant exceptions are NGC 4418, which is known to harbor an AGN, and NGC 5866, an early-type galaxy discussed in detail in N. Y. Lu et al. (2000, in preparation). Thus, the mid-infrared spectral shape varies little or only weakly with galaxy attributes. Relative to each other, various feature luminosities are constant to within the signal-to-noise ratio, or ~20%. One exception is the relative strength of the 11.3 μm feature, which varies among galaxies by as much as 40% and will be discussed in more detail elsewhere (Lu et al. 1996; N. Y. Lu et al. 2000, in preparation). Figure 2 shows a composite spectrum obtained by averaging the data from 28 galaxies, including the seven in Figure 1, after normalizing each spectrum to the integrated flux between 6 and 6.6 μm. The 28 galaxies are a random subset of the Key Project sample with diverse properties, ranging for instance from 0.28 to 0.88 in *R*(60/100). This composite spectrum should be a reliable representation of the emission from the ISM of normal galaxies.

The spectrum in Figure 2 is consistent with earlier data in this spectral range, including early M82 spectra by Willner et al. (1977), ground-based surveys (Roche et al. 1991), and *IRAS*

TABLE 1
GALAXIES WITH MID-IR SPECTRA[a]

Galaxy (1)	*R*(60/100) (2)	Morphology (3)	f_{aper} (4)	L(FIR)/L(B) (5)	log [L(FIR)/$L_\odot$] (6)	Mid-IR Morphology (7)
NGC 6286	0.32	Sb	0.69	9	10.3	Inclined disk
NGC 7771	0.47	SBa	0.52	7	10.4	Warped disk
IC 3908	0.52	SBd	0.53	5	9.0	Inclined disk
UGC 02238	0.52	Im?	0.80	11	10.4	Just resolved ~15″
NGC 3620	0.68	SBab	0.75	100	10.0	Faint disk, central peak
NGC 3885	0.75	S0/a	0.82	3	9.4	Just resolved ~15″
Mrk 0331	0.81	S?	0.76	27	10.5	Just resolved ~15″

[a] Shown in Fig. 1.

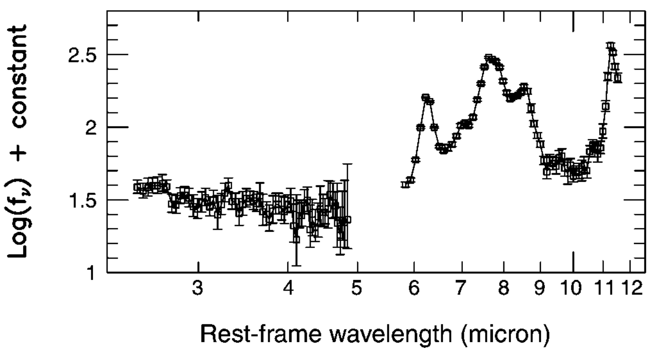

FIG. 2.—Average spectrum obtained from a set of 28 galaxies, including the galaxies in Fig. 1 (§ 3). The quantities plotted are the same as those in Fig. 1, except for the use of logarithmic scales on both axes. Error bars indicate the dispersion among the averaged spectra when they are all normalized, as described in the text.

low-resolution spectrometer data (Cohen & Volk 1989). However, it reveals new details and establishes the universality of the AFE. A striking aspect of the composite spectrum is the smooth continuum stretching from 3 to 5 μm and apparently underlying the AFE at longer wavelengths (see § 5).

Madden, Vigroux, & Sauvage (1997) and Boselli, Lequeux, & Contursi (1997) show spectra of elliptical galaxies dominated by stellar photospheric emission, which drop off between 2 and 5 μm like $f_\nu \propto \lambda^{-2.5} \propto \nu^{2.5}$. This component appears negligible in the composite spectrum at $\lambda \geq 3$ μm since the continuum has $f_\nu \propto \nu^{0.65}$ at 3 μm $\leq \lambda \leq$ 5 μm. The well-known 3.3 μm aromatic feature is detected at the expected wavelength, carrying about 0.5% of the power in the AFE longward of 5 μm, a significantly smaller fraction than observed in M82 (Willner et al. 1977).

The small bump at 7 μm is a significant signal, carrying about 0.65% of the total AFE power, and might include the [Ar II] 6.985 μm and the S(5) pure rotational line (v = 0–0) of H_2 6.910 μm. In well-resolved *ISO* SWS spectra, e.g., M82 or the line of sight to the Galactic center (Lutz et al. 1996), [Ar II] clearly dominates. The 0.65% fraction of AFE power, or about 0.1% of the FIR luminosity, approaches the most luminous lines in the far-infrared, [O I] and [C II] (Malhotra et al. 1997). Although no dust-related feature has been reliably identified at this wavelength, the high luminosity suggests that such a feature may also contribute to the [Ar II] + H_2 blend. The smaller bump at 9.6 μm coincides with the S(3) pure rotational line (v = 0–0) of H_2 9.665 μm, but it is too luminous to be the result of that line alone, as scaled from galaxies studied by Valentijn et al. (1996).

4. THE ENERGETICS

The fraction of starlight processed through AFE has been under debate since the *IRAS* mission (Helou, Ryter, & Soifer 1991) and can now be directly estimated using the new *ISO* data for the sample described above. The various AFE are measured by integrating the spectrum in the intervals 6–6.5, 7–9, and 11–11.5 μm. The contribution from an extrapolation of the 4 μm continuum is completely negligible, below the 1% level. The 11.3 μm feature merges into a complex that extends to about 13 μm. We estimate the total power of this complex by extending our composite spectrum using the mean, continuum-subtracted spectrum from Boulanger et al. (1996) and Césarsky et al. (1996c). This extension amounts to a 12% adjustment to the AFE within the PHT-S range. The result is that AFE account for about 65% of the total power between 3 and 13 μm and about 90% of the power between 6 and 13 μm. The AFE carry 25%–30% of L(FIR) in quiescent galaxies in our sample. This fraction gradually drops to less than 10% in the most actively star-forming galaxies, i.e., those with the greatest L(IR)/L(B) ratio or R(60/100), following the trend already noted in Helou et al. (1991). In a typical quiescent galaxy, AFE might carry 12% of the total infrared dust luminosity between 3 μm and 1 mm, whereas all the dust emission at $\lambda < 13$ μm comes up to ~18% of the total dust luminosity.

In the individual galaxy spectra, the power integrated between 7 and 9 μm runs at 2.5–3 times that between 6 and 7 μm; these integrals include the plateau between the features. From the composite spectrum, we find that the integrals from 5.8 to 6.6, 7.2 to 8.2, and 8.2 to 9.3 μm are in the ratio of 1 : 2 : 1.

5. THE 4 MICRON CONTINUUM

Even though it lies an order of magnitude below the AFE peaks, the continuum level shortward of 5 μm is unexpectedly strong (see, for instance, the model of Désert, Boulanger, & Puget 1990). The reliability of this continuum is not in question since it was detected in several individual galaxies with the same relative strength and was confirmed by *ISO* PHT-S staring (rather than chopping) observations of a few galaxies. However, the calibration of such weak signals may be uncertain by more than the nominal 30%; a comparison with ISOCAM data shows a 30% difference, with PHT-S on the high side.

The 4 μm continuum flux density is positively correlated with the AFE flux, which is strong evidence linking the continuum to dust rather than to stellar photospheres. It appears to follow a power law $f_\nu \propto \nu^{+0.65}$ between 3 and 5 μm, with an uncertainty of 0.15 on the power-law index. Its extrapolation runs 3 times weaker than the observed f_ν(10 μm), leaving open the nature of the connection between the 4 μm continuum and the carriers of the AFE. Bernard et al. (1994) have reported evidence for continuum emission from the Milky Way ISM in *COBE*-DIRBE broadband data at these wavelengths, with comparable amplitude.

Extrapolating the 4 μm continuum to longer wavelengths and assuming the AFE are superposed on it, one finds that the continuum contributes about a third of the luminosity between 3 and 13 μm, the balance being due to AFE. In the range between 6 and 13 μm, that fraction drops to about 10%. Against this extrapolated continuum, the AFE, defined again as the emission from 5.8 to 6.6, 7.2 to 8.2, and 8.2 to 9.3 μm, would have equivalent widths of about 4 μm or 3.4×10^{13} Hz, 18 μm or 9.2×10^{13} Hz, and 13 μm or 4.9×10^{13} Hz, respectively.

The natural explanation for the 4 μm continuum is that it is due to a population of small grains transiently heated by single photons to apparent temperatures of ~1000 K. Such a population was invoked by Sellgren (1984) to explain the 3 μm emission in reflection nebulae and by other authors to explain the *IRAS* 12 μm emission in the diffuse medium (e.g., Boulanger et al. 1988). Small particles with 10–100 atoms have sufficiently small heat capacities that a single UV photon can easily propel them to a 1000 K equivalent temperature (Draine & Anderson 1985). Such a population is a natural extension of the AFE carriers, although it is not clear from these data whether it is truly distinct or whether the smooth continuum is simply the nonresonant emission from the AFE carriers.

While the current data cannot rule out other contributions, the shape does rule out a simple extension of the photospheric emission from main-sequence stars. Red supergiants and asymptotic giant branch stars may contribute, although the level would have to be fortuitously comparable to the dust emission at 10 μm, and the superposition of emission spectra would have to mimic a $f_\nu \propto \nu^{+0.65}$ spectrum.

6. SUMMARY AND DISCUSSION

The mid-infrared spectra of normal star-forming galaxies are dominated by interstellar dust emission. They are well described between 3 and 13 μm as a combination of aromatic features and plateaus and an underlying $f_\nu \propto \nu^{+0.65}$ continuum, with the features carrying about 65% of the luminosity between 3 and 13 μm. One can reliably assume that this is a universal spectral signature of dust.

The fact that the spectral shape is constant against the changing heating conditions from galaxy to galaxy is strong evidence that particles are transiently excited by individual photons rather than being maintained in thermal equilibrium. This explanation is especially compelling because it accounts for both the aromatic features and the continuum. Transient heating obtains only within a finite range of ISM phases, namely, from the translucent molecular regions, through the atomic regions, and up to the weakly ionized regions. In denser regions, AFE carriers may be insufficiently illuminated (Beichman et al. 1988; Boulanger et al. 1990) or condensed onto larger grains (Draine 1985), whereas in H II regions, they would be destroyed by ionizing radiation (Césarsky et al. 1996c). Therefore, the AFE flux may be approximated as the integral over the appropriate ISM phases in each galaxy of the product of the AFE carrier cross section and the heating intensity. Helou et al. (1991) show that the mid-infrared carries a diminishing fraction of the dust luminosity as the star formation activity increases in a galaxy. While this has been interpreted as being the result of the generally depressed AFE carrier abundance throughout the whole galaxy, it is more likely to result primarily from relatively smaller AFE carrier niches, presumably overtaken by H II regions where harder and more intense radiation destroys AFE carriers.

The mid-infrared spectral shape is sufficiently uniform among galaxies that it can be used for redshift determinations using, for instance, the *SIRTF* Infrared Spectrometer (Roellig et al. 1998): $L(\mathrm{FIR}) = 10^9\ L_\odot$ galaxies can be readily detected out to $z = 0.1$ in about an hour of integration time, whereas ultraluminous galaxies may be detectable out to $z = 3$ in a comparable amount of time depending on the AFE-to-FIR ratio that is assumed (D. Weedman 1999, private communication). For galaxies with known redshifts, AFE detection would be an unmistakable dust signature, and thus it would help us to distinguish instantly between thermal and nonthermal mid-infrared emission or to quantify their relative importance (Lutz et al. 1998).

We would like to thank L. Vigroux, X. Désert, F. Boulanger, and B. T. Soifer for interesting discussions. The anonymous referee's comments were helpful in improving this Letter. G. H. acknowledges the hospitality of the IAS (Université Paris Sud) and of Delta Airlines during part of this work. The *ISO* is an ESA project with instruments funded by ESA Member States (especially the PI countries: France, Germany, the Netherlands, and the UK) and with participation of NASA and ISAS. The ISOPHOT data presented in this Letter were reduced using PIA, which is a joint development by the ESA Astrophysics Division and the ISOPHOT consortium. This work was supported in part by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

REFERENCES

Allamandola, L. J., Tielens, A. G. G. M., & Barker, J. R. 1989, ApJS, 71, 733
Beichman, C. A., Wilson, R. W., Langer, W. D., & Goldsmith, P. F. 1988, ApJ, 332, L81
Bernard, J.-P., Boulanger, F., Désert, F. X., Giard, M., Helou, G., & Puget, J.-L. 1994, A&A, 291, L5
Boselli, A., Lequeux, J., & Contursi, A. 1997, A&A, 324, L13
Boulanger, F., Beichman, C., Désert, F. X., Helou, G., Perault, M., & Ryter, C. 1988, ApJ, 332, 328
Boulanger, F., Falgarone, E., Puget, J.-L., & Helou, G. 1990, ApJ, 364, 136
Boulanger, F. et al. 1996, A&A, 315, L325
Césarsky, C. J., et al. 1996a, A&A, 315, L32
Césarsky, D., Lequeux, J., Abergel, A., Perault, M., Palazzi, E., Madden, S., & Tran, D. 1996b, A&A, 315, L305
———. 1996c, A&A, 315, L309
Cohen, M., & Volk, K. 1989, AJ, 98, 1563
Désert, F. X., Boulanger, F., & Puget, J. L. 1990, A&A, 237, 215
Draine, B. T. 1985, in Protostars and Planets II, ed. D. C. Black & M. S. Matthews (Tucson: Univ. Arizona Press), 621
Draine, B. T., & Anderson, N. 1985, ApJ, 292, 494
Geballe, T. R. 1996, in From Stardust to Planetesimals: Contributed Papers, ed. M. E. Kress, A. G. G. M. Tielens, & Y. J. Pendleton (NASA Publ. 3343; Moffett Field: NASA ARC), 119
Helou, G., Khan, I., Malek, L., & Boehmer, L. 1988, ApJS, 68, 151
Helou, G., et al. 1996, A&A, 315, L157
Helou, G., Ryter, C., & Soifer, B. T. 1991, ApJ, 376, 505
Kessler, M. F., et al. 1996, A&A, 315, L27
Lemke, D., et al. 1996, A&A, 315, L64
Lu, N., et al. 1996, BAAS, 28, 1356
Lutz, D., et al. 1996, A&A, 315, L269
Lutz, D., Spoon, H. W. W., Rigopoulou, D., Moorwood, A. F. M., & Genzel, R. 1998, ApJ, 505, L103
Madden, S. C., Vigroux, L., & Sauvage, M. 1997, in Extragalactic Astronomy in the Infrared, ed. G. A. Mamon, T. X. Thuan, & J. T. T. Van (Paris: Editions Frontières), 229
Malhotra, S., et al. 1997, ApJ, 491, L27
Metcalfe, L., et al. 1996, A&A, 315, L105
Puget, J.-L., & Léger, A. 1989, ARA&A, 27, 161
Roche, P. F., Aitken, D. K., Smith, C. H., & Ward, M. J. 1991, MNRAS, 248, 606
Roche, P. F., Whitmore, B., Aitken, D. K., & Phillips, M. M. 1984, MNRAS, 207, 35
Roellig, T. L., et al. 1998, Proc. SPIE, 3354, 1192
Sellgren, K. 1984, ApJ, 277, 623
Silbermann, N., et al. 1996, AAS Meeting, 189, 6701
Sturm, E., Lutz, D., Tran, D., Feuchtgruber, H., Genzel, R., Moorwood, A. F. M., & Thornley, M. D. 2000, A&A, in press
Tielens, A. G. G. M. 1999, in The Universe as Seen by *ISO*, ed. P. Cox & M. F. Kessler (ESA SP-47; Noordwijk: ESA), 579
Tokunaga, A. T. 1996, in From Stardust to Planetesimals: Contributed Papers, ed. M. E. Kress, A. G. G. M. Tielens, & Y. J. Pendleton (NASA Publ. 3343; Moffett Field: NASA ARC)
Valentijn, E. A., van der Werf, P. P., de Graauw, T., & de Jong, T. 1996, A&A, 315, L145
Vigroux, L., et al. 1996, A&A, 315, L93
Willner, S., Soifer, B., Russell, R., Joyce, R., & Gillett, F. 1977, ApJ, 217, L121