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NORMAL GALAXIES IN THE LOCAL UNIVERSE

G. Helou

SIRTF Science Center, California Institute of Technology, Pasadena, CA 91125

Abstract. ISO studies of normal galaxies in the local Universe have revealed basic new properties with significant implications for the star formation process and cosmology. This article will describe prominent ISO surveys, and review some general statistical results, grouping them by wavelength range. First the mid-infrared low-resolution spectroscopy and broad-band imaging and photometry, then far-infrared photometry and spectrocopy of the fine-structure lines. A glimpse of the profusion of exciting results on individual objects will also be included.

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1. INTRODUCTION

Nucleosynthesis in stars is the main evolutionary process affecting the chemical make-up and energy balance of the Universe. Most star formation in the local Universe takes place in the ``normal'' disk galaxies, those whose sizes and luminosities are not extreme (cf. the luminosity function in Kim & Sanders (1999) for instance), but whose other properties span wide ranges on many axes such as density, intensity, metallicity, extinction, or light-to-mass ratios. This great diversity in properties, and the complex mix of physical conditions within each system, have frustrated attempts at deriving simple models for the behavior of these ``unremarkable'' galaxies. Surveys of galaxies in the local Universe have thus become particularly valuable for codifying the empirical evidence. Infrared surveys are well suited to pursuing questions related to star formation, since current and recent star formation is preferentially expressed in the infrared.

This review will highlight recent advances derived from infrared surveys using primarily the Infrared Space Observatory (ISO; Kessler et al. 1996) in understanding normal galaxies, defined as those powered by nucleosynthesis with negligible contributions by an active galactic nucleus. Because of the diversity in properties and of the ease of detecting normal galaxies out to several hundred Mpc, survey design and sample selection determine what questions can be addressed with a given survey. Conversely, statistical results can only be interpreted in the context of the sample they are based on.

2. OBSERVATIONS

While ISO was an observatory rather than a survey mission, many surveys were carried out using various capabilities of the versatile payload. Some prominent surveys that concern normal galaxies either directly or indirectly are listed below. This is by no means an exhaustive list, especially since most ISO data have yet to be published.

1. Mid-infrared maps of nearby galaxies were obtained under the ISO-CAM (Césarsky et al. 1996) guaranteed time (GT) program, targeting large angular-size galaxies in various categories, such as early-type, spirals barred and non-barred, dwarf irregulars, and active (Vigroux 1997). There were also surveys of galaxies in Virgo and other clusters. All galaxies were surveyed in the LW2 (6.75μm) and LW3 (15μm) filters, and some in other filters within the 3 to 18μm wavelength range of ISO-CAM. In addition, several were observed with the Circular Variable Filter (CVF), which yields images at a spectral resolution of about 20 over most of the same wavelength range. These data were taken with 3" pixels, with an effective resolution of 7 to 9" half-maximum width.

2. Far-infrared spectral surveys of a few samples of galaxies were carried out under the GT program of the ISO-LWS (Clegg et al. 1996), most notably for infrared-bright galaxies, meaning those with a flux density greater than 50Jy at 60μm, and of ultra-luminous galaxies (Fischer et al., 1999; Luhman et al. 1999). Most objects were observed with a LWS low-resolution full spectral scan covering 45 to 195μm.

3. Far-infrared maps of well-resolved nearby galaxies were obtained under the ISO-PHOT (Lemke et al. 1996) GT program at 60, 100 and 175μm, most notably of M31, M33 and M101.

4. Photometry at $\lambda \geq$ 60μm was also carried out under the ISO-PHOT GT program for several samples, including 75 bright (B < 12mag) galaxies from the Revised Shapley-Ames Catalog, and selected objects in the Virgo Cluster. These samples were observed (Joseph et al.) at 60, 100 and 175μm, as well as 12μm (ISO-CAM filter LW10), with additional data collected from the ground in the near-infrared and the submm.

5. Open time projects included several galaxy surveys, such as the Knapp et al. (1996) study of early type galaxies, the Lu et al. study of infrared-cold galaxies, and the Metcalfe et al. (1996) BCD/Irr survey.

6. The ISO Key Project on the Interstellar Medium of Normal Galaxies (Helou et al. 1996) under NASA GT collected data on a set of sixty galaxies that explore the full range of morphology,

luminosity, infrared-to-blue ratio and far-infrared color among star-forming galaxies. These sixty objects were selected to be small in their IRAS emission size compared to the 80" LWS beam and the 3' ISO-CAM field of view, so as to allow studies of their global properties. In addition, nine nearby galaxies were mapped to the extent possible, including NGC 6946, NGC 1313, IC 10, and parts of M101. For most galaxies, maps were obtained at 7 and 15μm with ISO-CAM, spectro-photometry was obtained with ISO-PHOT-S between 3 and 12μm, and far-infrared fine-structure lines were targeted with ISO-LWS, attempting to measure as many as possible of the following lines, in the order listed: [CII] λ 157.7 μm, [OI] λ 63.2 μm, [NII] λ 121.9 μm, [OIII] λ 88.4 μm, [NIII] λ 57.3 μm, [OIII] λ 51.8 μm.

7. The ISO-PHOT Serendipity Survey collected data during satellite slews between target observations with the 170μm channel. By the end of the mission, data had been collected over 150,000° of slew track, with an estimated 4,000 galaxies detected (Stickel et al. 1998). This data set will be a unique source of far-infrared fluxes for thousands of galaxies with IRAS detections at $f\nu \gtrsim$ 1.5Jy.

8. By its nature as an observatory-class mission, ISO has generated a rich archive containing all the observations of individual galaxies, groups, or clusters of galaxies investigated by various observers for specific interests. This collection constitutes a *de-facto* survey of unique or peculiar objects from which one could learn much about the less exotic cases (e.g. Smith 1998; Smith & Madden 1997; Lu et al. 1996; Jarrett et al. 1999; Valentijn et al. 1996; Xu et al. 1999). Many useful survey samples could be constructed after the fact by selecting objects out of the ISO archive once it becomes available in the summer of 1999.

9. Ground-based infrared surveys: There is no question that the 2MASS and DENIS surveys will be making fundamental contributions to our view of normal galaxies, though their results are not reviewed here. Apart from these, several near-infrared imaging surveys of nearby galaxies are already revealing some surprising results. Grauer & Rieke (1998) for instance demonstrate that spiral arms are almost as contrasted in the K band as they are in the B band. See also Terndrup et al. (1994).

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3. NORMAL GALAXIES IN THE MID-INFRARED

Based on IRAS data, the mid-infrared spectral range was thought to be the domain of small fluctuating grains and Aromatic Features in Emission (AFE) as far as the interstellar medium (ISM) was concerned (Beichman 1987; Puget & Léger 1989). Since the integrated emission from normal galaxies is dominated by the ISM in this range, ISO has been able to address quantitatively the energy budget of the ISM across various emission components, to investigate the variation of this budget among galaxies, and to contrast these properties with those of galaxies illuminated by Active Nuclei. This section will expand on the first two of these three areas.

3.1 Mid-Infrared Spectroscopy

Spectroscopic data on normal galaxies in the mid-infrared range were acquired with ISO-PHOT from 2.5 to 5 and from 5.7 to 11.6μm (Lemke et al. 1996); with ISO-CAM in the CVF mode from 5 to 16.5 (Césarsky et al. 1996); and to some extent with SWS from 2.5 to 45μm (de Graauw et al. 1996).

The interstellar medium emission from galaxies powered by star formation is strongly dominated by AFE (Figure 1). These appear in two main groups, one stretching from 5.5 to 9μm, with peaks at 6.3, 7.7 and 8.6, and the other one starting at 11μm and extending to 12.5μm (Helou et al. 1999). There is good evidence linking these features to Polycyclic Aromatic Hydrocarbons (PAH), but no rigorous spectral identification of specific molecules (Puget & Léger 1989; Allamandola et al. 1989). It is generally agreed that the emitters are small structures, no more than a few hundred atoms, transiently excited to high energy levels by single photons.

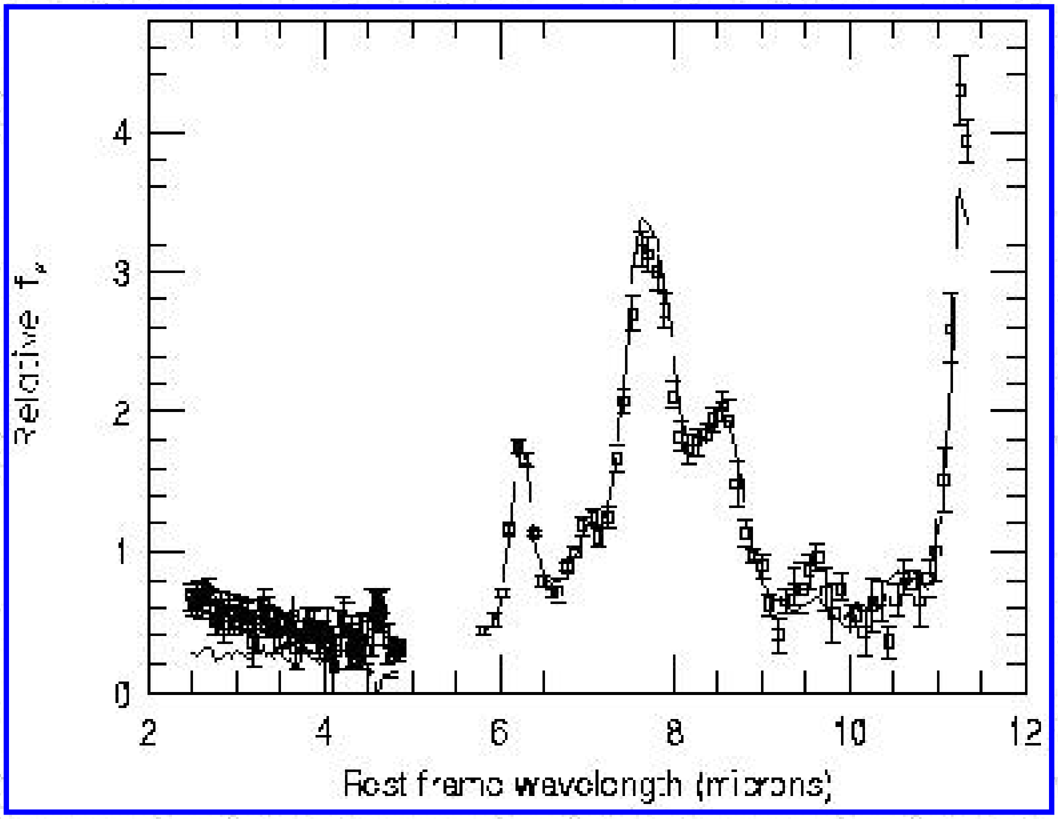

Figure 1. Two composite mid-infrared spectra, one for twelve FIR-cold galaxies (squares), and one for twelve FIR-warm ones (connected dots). Spectra were averaged after normalization to the 6.3μm peak.

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. Figure 1 shows that the difference between the galaxies coldest and warmest in the far infrared is very small in relative terms. In addition to the AFE, there is a continuum component with a slope close to zero in f_ν vs. ν between 3 and 5μm, and whose extrapolation to longer wavelengths would place it below the observed flux density even at 9-10μm. This continuum component is almost certainly of non-stellar origin, and is probably due to fluctuating grains without aromatic features.

ISO-CAM CVF studies targeting the shape of the continuum emission and ionic fine-structure lines between 5 and 16.5μm are turning out to be powerful diagnostics of the radiation field in the disks of nearby galaxies, allowing us to disentangle the variations in heating intensity and hardness of interstellar radiation (Tran 1998; Contursi 1998).

The spectra reported here typify the integrated emission from the interstellar medium of the majority of star-forming galaxies, and could thus be used as a template to obtain redshifts of highly extincted galaxies with SIRTF. For instance, a galaxy at a redshift z = 3 with a flux density average of 0.5 mJy in the range 19-27μm and a total infrared luminosity comparable to Mkn 231 at ~3 x 10^{12} $L_\odot$ would be detected by SIRTF's IRS (Infrared Spectrometer; Roellig et al. 1998) in roughly 1000 seconds of integration (Weedman 1998).

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3.2 Mid-Infrared Photometry

ISO-CAM (Césarsky et al. 1996) has obtained striking images of galaxies between 4 and 18μm, showing dust emission in nuclear regions, outlining the spiral arms, and tracing the disk out to the Holmberg radius and beyond (Malhotra et al. 1996, Sauvage et al. 1996, Vigroux 1997, Boselli & Lequeux 1997, Smith 1998). There are clear color variations within spiral galaxies, some of which have not yet found satisfactory explanations (Helou et al. 1996; Tran 1998). Mid-infrared colors derived from ISO-CAM are effective discriminants between stellar photospheres and dust as sources of emission. Lenticular galaxies often have contributions from both of those sources (Madden et al. 1997; Boselli et al. 1998). Rouan et al. (1996), Block et al. (1997) and Smith (1998) have combined mid-infrared and Brγ images with other broad-band and line images to estimate star formation rates, ISM parameters, obscuration and dust properties. These studies again point to Aromatic Feature carriers as a ubiquitous component of interstellar dust, to the likely destruction of these carriers by ionizing UV, and to dust heating being derived from both old stars and OB stars in non-starburst disk galaxies.

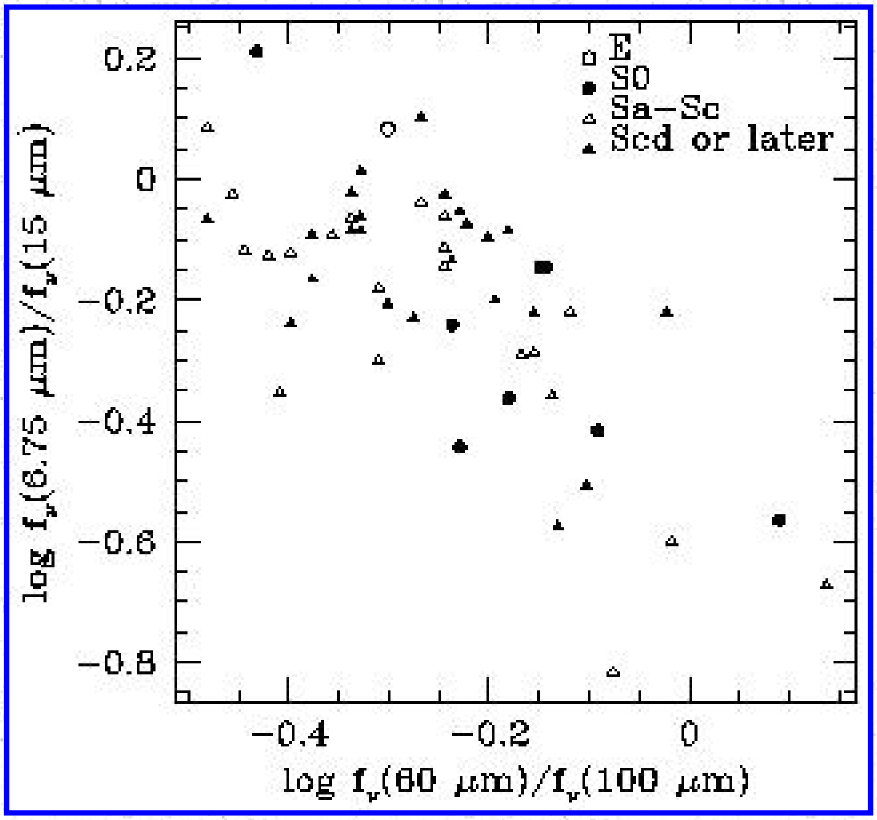

Figure 2. The ISO-IRAS color-color diagram for galaxies in the ISO Key Project on normal galaxies (Helou et al. 1996). The progression of colors can be readily explained by a simple two-component model similar to that of Helou (1986).

The 6.75-to-15μm color ratio formed from ISO-CAM bands remain relatively constant and near unity as the ISM of galaxies proceeds from quiescent to mildly active (Figure 2). As dust heating increases further, the 15μm flux increases steeply compared to 6.75μm, pointing to a significant contribution by dust at color temperature 100 K < T_{MIR} < 200 K, typical of a heating intensity up to 10^4 times that of the diffuse interstellar radiation field in the local Milky Way (Helou et al. 1997). While such a temperature could result from classical dust heated within or just outside HII regions, it is probably more accurate to associate this component empirically with the observed emission spectrum of HII regions and their immediate surroundings (Tran 1998; Contursi 1998). This emission has severely depressed AFE, and is dominated by a steeply rising though not quite a blackbody continuum, consistent with mild fluctuations in grain temperatures, $\delta T/T \sim 0.5$. This HII region hot dust component becomes detectable when the color temperature from the 60-to-100μm ratio is half T_{MIR}, demonstrating the broad distribution of dust temperatures within any galaxy (Helou 1986).

At the other end of the spectrum, photometry at 120-200μm using ISO-PHOT is starting to constrain the distribution of dust temperatures at low heating levels, especially in nearby well resolved galaxies such as M31 (Haas et al. 1998), M51 or M101 (Hippelein et al. 1996), where cold dust dominates the luminosity. Similar analysis on more active galaxies is also under way (e.g. Klaas et al. 1997).

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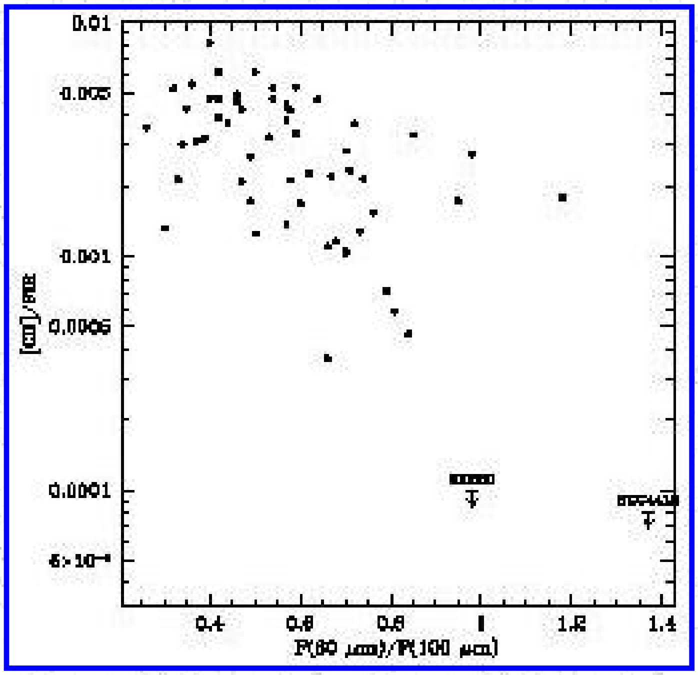
4. FAR-INFRARED LINE SPECTROSCOPY

Far-infrared fine structure lines, especially [CII] λ 157.7μm and [OI] λ 63.2 μm, have long been used for estimating density and radiation intensity in photo-dissociation regions (PDR) (e.g. Hollenbach & Tielens 1997). ISO has provided for this topic a wealth of data, whose interpretation is creating controversy and challenging theoretical models. Malhotra et al. (1997) showed that while two thirds of normal galaxies have ℓ(CII) / ℓ(FIR) in the range 2-7 x 10^{-3}, this ratio decreases on average as the 60-to-100 or the ℓ(FIR) / ℓ(B) ratios increase, both indicating more active star formation (Figure 3). They linked this decrease to elevated heating intensities, which ionize grains and thereby reduce the photo-electric yield.



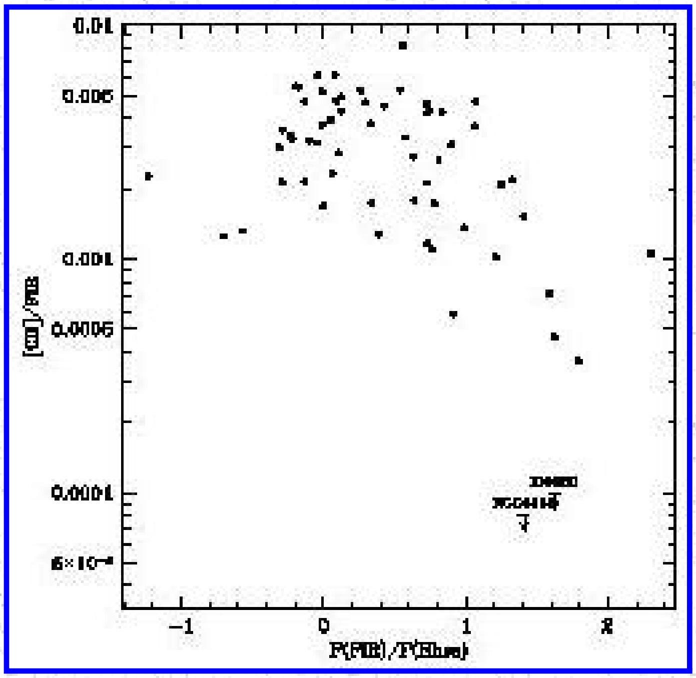


Figure 3. The CII deficiency in active star forming galaxies from Malhotra et al. (1997).

The same CII deficiency is also observed in ultra-luminous infrared galaxies (Fischer et al. 1999; Luhman et al. 1998), who favor optical depth effects as the origin of the effect. This is hard to reconcile however with a similar deficiency effect occurring for [NII] λ 121.9 μm as well, but not for [OI] λ 63.2μm. Detailed discussion is found in Malhotra et al. 1999, Fischer et al. 1999, or Luhman et al. 1999.

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5. CONCLUSIONS

ISO surveys of normal galaxies have already yielded major progress in our grasp of their phenomenology. This progress leads to more informed planning for upcoming surveys or missions, as well as better physical models and understanding of these systems.

Mid-infrared spectral and spatial templates are now available, and the range of variation in these properties is reasonably well characterized. The mid-infrared from the interstellar medium is clearly dominated by emission from particles transiently heated by single-photon events, and most of the emitted energy has the spectral signature of Aromatic compounds. Surveys such as WIRE (Hacking et al. 1999) have already incorporated these data into modeling source signatures, and sorting strategies for identifying the more interesting objects in the 12 and 25μm survey.

Mid-infrared images of galaxies highlight the star forming regions in disk galaxies, but trace the starlight morphology in early-type systems as the interstellar medium drops out. The surface brightness distribution in disk systems could be a major term in detectability with future survey missions at high resolution such as NGST.

The overall spectral energy distribution from 3 to 250μm can now be characterized in a coherent fashion, and its systemtic variations with heating or star forming intensity quantified. There is a definite shift of the luminosity center from 100μm towards 40μm as the intensity increases, and a decrease of the contribution from the mid-infrared and the sub-mm ranges.

The far-infrared cooling lines of the neutral interstellar medium present interesting and complex behavior. Gas cooling via the [CII] line is a smaller fraction of dust cooling in the more active galaxies, whereas the [OI] line seems more constant in relation to dust emission. One obvious implication is that the latter is a better tracer to pursue in high-redshift objects, for which higher luminosity should be associated with higher intensity, and therefore with depressed [CII] emission.

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REFERENCES

1. Allamandola, L. J, Tielens, A. G. G. M., & Barker, J. R. 1989, *Ap. J. Suppl.*, 71, 733
2. Beichman, C.A. 1987, *Annu. Rev. Astron. Astrophys.*, 25, 521
3. Block, D.L., Elmegreen, B.G., Stockton, A. & Sauvage, M. 1997, *Ap. J. Lett.*, 486, L95
4. Boselli, A., Lequeux, J. & Contursi, A. 1997, *A&A*, 324, L13
5. Boselli, A. et al. 1998, *A&A*, 335, 53
6. Césarsky, C. et al. 1996, *A&A*, 315, L32
7. Clegg, P. et al. 1996, *A&A*, 315, L38
8. Contursi, A. 1998, *PhD Thesis*, Univ. de Paris
9. de Graauw, T. et al. 1996, *A&A*, 315, L49
10. Fischer, J. 1999, *this conference*
11. Grauer, A.D. & Rieke, M.J. 1998 *Ap. J. Suppl.*, 116, 29
12. Haas, M., Lemke, D., Stickel, M. et al. 1998, *A&A*, 338, L33
13. Hacking, P. et al. 1999, *this conference*
14. Helou, G. 1986, *Ap. J. Lett.*, 311, L33
15. Helou, G. et al. 1988, *Ap. J. Suppl.*, 68, 151
16. Helou, G. et al. 1996, *A&A*, 315, L157
17. Helou, G., Becklin, E., Stencel, R.E. & Wilkes, B. 1997, *ASP Conf Ser* 124, 393
18. Helou, G., Lu, N., Werner, M.W., Malhotra, S. & Silbermann, N. 1999, *Ap. J.*, submitted
19. Hippelein, H. et al. 1996, *A&A*, 315, L79
20. Hollenbach, D.J. & Tielens, A.G.G.M. 1997, *Annu. Rev. Astron. Astrophys.*, 35, 179
21. Jarrett, T., Helou, G., Valjavec, E. & Condon, J. 1999, in preparation
22. Kessler, M.F. et al. 1996, *A&A*, 315, L27
23. Kim, D.-C. & Sanders, D.B. 1998, *Ap. J. Suppl.*, 119, 41
24. Klaas, U., Haas, M., Heinrichsen, I. & Schulz, B. 1997, *A&A*, 325, L21
25. Knapp, G.R., Rupen, M.P., Fich, M., Harper, D.A. & Wynn-Williams, C.G. 1996, *A&A*, 315, L75
26. Lemke, D. et al. 1996, *A&A*, 315, L64
27. Lu, N. et al. 1996, *A&A*, 315, L153
28. Luhman, M.L. et al. 1998, *Ap. J. Lett.*, 504, L11
29. Luhman, M.L. et al. 1999, *this conference*
30. Madden, S.C., Vigroux, L. & Sauvage, M. 1997, in *Extragalactic Astronomy in the Infrared*, ed. Mamon, Thuan & Van (Editions Frontières: Paris)
31. Malhotra, S. et al. 1996, *A&A*, 315, L161
32. Malhotra, S. et al. 1997, *Ap. J.*, 491, L27
33. Metcalfe, L. et al. 1996, *A&A*, 315, L105

34. Puget, J.-L. & Léger, A. 1989, *Annu. Rev. Astron. Astrophys.*, 27, 161.
35. Roellig, T.L., Houck, J.R., Van Cleve, J. et al. 1998, SPIE, 3354, 1192
36. Rouan, D. et al. 1996, *A&A*, 315, L141
37. Sauvage, M. et al. 1996, *A&A*, 315, L89
38. Smith, B. 1998, *Ap. J.*, 500, 181
39. Smith, B.J. & Madden, S. C. 1997, *Astron. J.*, 114, 138
40. Stickel, M. et al. 1998, *A&A*, 336, 116
41. Terndrup, D.M., Davies, R.L., Frogel, J.A., DePoy, D.L., & Wells, L.A. 1994 *Ap. J.*, 432, 518
42. Tran, D. 1998, *PhD Thesis*, Univ. de Paris
43. Valentijn, E.A. et al. 1996, *A&A*, 315, L60
44. Vigroux, L. 1997, in *Extragalactic Astronomy in the Infrared*, ed. G. Mamon, T.X. Thuan & J.T.T. Van (Editions Frontières: Paris)
45. Weedman, D.W. 1998, private communication
46. Xu, C., Sulentic, J.W. & Tuffs, R. 1999, 512, 178

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