SUBMILLIMETER IMAGING OF THE LUMINOUS INFRARED GALAXY PAIR VV 114
D. T. Frayer,1 R. J. Ivison,2 I. Smail,3 M. S. Yun,4 and L. Armus5

Received 1999 January 20; accepted 1999 March 22

ABSTRACT

We report on 450 and 850 µm observations of the interacting galaxy pair VV 114 E + W (IC 1623), taken with the SCUBA camera on the James Clerk Maxwell Telescope, and near-infrared observations taken with the UKIRT Fast-Track Imager on the UK Infrared Telescope. The system VV 114 is in an early stage of a gas-rich merger. We detect submillimeter emission extended over 30'' (12 kpc) and find a good correlation between the spatial distribution of the submillimeter and CO emission. Both the CO and submillimeter emission peak near the reddest region of VV 114 E and extend toward VV 114 W. The bulk of the submillimeter emission resides in the central region showing the largest CO velocity gradients, which is thought to mark the kinematic centroid of the merger remnant. We derived a total dust mass of 1.2 × 10^8 M_☉, assuming a power-law distribution of dust temperatures. The submillimeter observations suggest that the majority of the dust is relatively cool (T_d ~ 20–25 K), and the total dust mass is about 4 times higher than that inferred from the IRAS data alone. The system will likely evolve into a compact starburst similar to Arp 220.

Key words: galaxies: evolution — galaxies: individual (VV 114) — galaxies: interactions — galaxies: starburst

1. INTRODUCTION

Many extremely luminous infrared starbursts (L_IR > 10^{11} L_☉) are merging systems, containing large reservoirs of molecular gas and dust (Sanders & Mirabel 1996 and references therein). To understand the evolution of the interstellar medium (ISM) and star formation in these systems, we require imaging observations of the molecular gas and dust reservoirs associated with the star-forming regions. Much of what is known about these systems has been inferred from interferometric CO observations (e.g., Scoville, Yun, & Bryant 1997; Downes & Solomon 1998). Our knowledge of the distribution of thermal dust emission in merging systems is lacking because of the limited spatial resolution of the Infrared Astronomical Satellite (IRAS). With the commissioning of the new Submillimeter Common-User Bolometer Array (SCUBA; Holland et al. 1999) camera on the James Clerk Maxwell Telescope (JCMT), we can now directly image the thermal dust emission at relatively high (~ 8'–15') spatial resolution.

The interacting galaxy pair VV 114 is only 80 Mpc away (H_0 = 75 km s^{-1} Mpc^{-1}) and is composed of two stellar components separated by 15' (6 kpc in projection), designated VV 114 E and VV 114 W (Knop et al. 1994). The extreme infrared colors of VV 114 E indicate the presence of a large concentration of dust, while VV 114 W is relatively unobscured at optical wavelengths (Knop et al. 1994). The CO emission is distributed along a bar-like structure located between the optical components (Yun et al. 1994). The extended nature of the CO emission, as well as the non-circular gas kinematics, suggests that VV 114 is in an early stage of a gas-rich merger (Yun et al. 1994). The gas in VV 114 has already begun to flow into its central regions, while the stellar components are still well separated. This is consistent with theoretical models of young mergers (Barnes & Hernquist 1991, 1996).

In addition to the capability of SCUBA to resolve the VV 114 system, the submillimeter observations at 450 and 850 µm allow us to constrain the amount of cool material present (T_d ≤ 30 K). Preliminary evidence for the existence of cold dust in galaxies comes from the gas-to-dust ratios estimated using the warm dust masses derived from IRAS. The typical gas-to-dust ratios found for the bright IRAS galaxies are about an order of magnitude larger than the Galactic value derived from extinction studies, which includes dust at all temperatures (Devereux & Young 1990). A simple explanation for this discrepancy is that the majority of the dust in bright IRAS galaxies is cooler (T_d ≤ 30 K) than the warm material observed by IRAS. Observations with SCUBA can directly search for this component and provide a test of this hypothesis.

2. OBSERVATIONS

2.1. Submillimeter Imaging

Fully sampled images of VV 114 were obtained using the SCUBA submillimeter camera during 1997 July and 1998 May. We used the 91-element short-wave array at 450 µm (7.8 FWHM beam) and the 37-element long-wave array at 850 µm (14.7 FWHM beam) during excellent conditions. Typical 850 µm zenith opacities were approximately 0.2, determined from hourly sky dips. We obtained 7.7 ks of useful on-source integration time at 850 µm and 5.1 ks at 450 µm.

Fluxes were calibrated against Uranus, and the flux densities determined for VV 114 at 450 and 850 µm are accurate to ±18% and ±14%, respectively, including errors induced by opacity uncertainties and the absolute flux uncertainty of Uranus. The uncertainty in the 450 µm/850 µm flux ratio is approximately ±7%, which represents the full dispersion in the measurements made on the separate nights. The error in the 450 µm/850 µm flux ratio is less than total uncer-

---

1 Department of Astronomy, California Institute of Technology, 105-24, Pasadena, CA 91125.
2 Department of Physics and Astronomy, University College London, Gower Street, London, WC1E 6BT, UK.
3 Department of Physics, University of Durham, South Road, Durham DH1 3LE, UK.
4 National Radio Astronomy Observatory, P.O. Box O, Socorro, NM 87801.
5 SIRTF Science Center, California Institute of Technology, 100-22, Pasadena, CA 91125.
Table 1: Submillimeter Observational Results

| Parameter       | 450 μm [1] | 450 μm [2] | 850 μm |
|-----------------|------------|------------|--------|
| α (J2000)       | 01h07m47s  | 01h07m47s  | 01h07m47s |
| δ (J2000)       | -17°30'32" | -17°30'32" | 27'2   |
| Beam (FWHM)     | 7.8        | 7.8        | 14.7   |
| Flux (Jy)       | 2.43 ± 0.44| 0.273 ± 0.038|

* Positional uncertainty is ±2".
* Derived from a Gaussian fit to the peak.
* Total integrated flux.

Fig. 1.—(a, b) SCUBA 450 μm and 850 μm maps. The 1 σ rms levels are 75 and 4.4 mJy beam⁻¹ for the 450 and 850 μm data, respectively. Contour levels are plotted at -2, 2, 3, 4, 5, 6, 8, 10, and 12 σ for the 450 μm map and 3, 4, 5, 6, 8, 10, 12, 15, 20, 25, 30, and 35 σ for the 850 μm map. The 2 μm NIR peaks, signifying the positions of VV 114 E + W, are shown by crosses and plus signs (Knop et al. 1994). The 8.4 GHz radio peak is shown by the triangle (Condon et al. 1991); the diamonds show peaks in the optical R-band emission (Knop et al. 1994). (c) Integrated CO (1→0) emission (Yun et al. 1994). Contour levels are plotted at 5, 10, 15, 30, 50, and 70 Jy km s⁻¹ beam⁻¹. For (a), (b), and (c), the beam sizes are shown in the bottom left of each panel. (d) NIR J−K color map, where lighter pixels indicate redder colors and darker pixels represent bluer colors. The color map ranges from $J - K = 0.9$ for the blue regions of VV 114 W to the very red compact region in VV 114 E, which has a color of $J - K = 3.0$ at the observed resolution (0.7). [See the electronic edition of the Journal for a color version of this figure.]

Near-infrared (NIR), J- and K-band, imaging of VV 114 was obtained during the night of 1998 October 19 using the new UKIRT Fast-Track Imager (UFTI) mounted on the 3.8 m UK Infrared Telescope (UKIRT) on Mauna Kea.
UFTI comprises a 1024$^2$ HgCdTe HAWAII array cooled to 77 K and sensitive from 0.8 to 2.5 μm. The pixel scale is 0.091, allowing Nyquist sampling of the best seeing experienced on UKIRT, and the field of view is 92″. The observations of VV 114 consisted of three sets of nine exposures, two in K (2.2 μm) and one in J (1.2 μm), each of 30 s, dithered on a 3 × 3 grid with 9.1″ spacing. These were interspersed by similar-length observations of an offset sky region and dark exposures to allow the removal of the sky and instrumental backgrounds. The final stacked exposures represent 270 s in J and 540 s in K. The tip-tilt secondary on UKIRT was used to provide standard adaptive correction within our field, although the conditions were non-photometric and the seeing achieved was only mediocre, ~0″.7. Nevertheless, these images represent a substantial improvement in resolution over those presented by Knop et al. (1994).

3. RESULTS

Figures 1a and 1b show the 450 and 850 μm images of VV 114 taken with SCUBA. The integrated flux densities summed over the emission regions are 2.43 ± 0.44 and 0.273 ± 0.038 Jy at 450 and 850 μm, respectively (Table 1). At 850 μm, we detect emission extended in the east-west direction, while at 450 μm we appear to resolve the central emission into two peaks (450 μm [1] and 450 μm [2] in Table 1). Given that the separation of the two 450 μm peaks is near the resolving limit of SCUBA, observations at higher resolution are required to confirm this double-peaked morphology. When the 450 μm data are convolved to the resolution of the 850 μm map, the data at both wavelengths show a similar shape, size, and position. At this resolution (14″:7), we fail to detect any significant variations in the $S(450 \mu m)/S(850 \mu m)$ flux ratio. Integrating over all emission regions, we find a flux ratio of 8.9 ± 0.6, which is also the ratio measured for the peak of the submillimeter emission (at a resolution of 14″:7). The consistencies in the 450 and 850 μm data would be expected if the bulk of the submillimeter emission was on the blackbody tail of spectral energy distribution with dust temperatures $T \gtrsim 10$ K. Observations at higher resolution are required to search for possible variations in the $S(450 \mu m)/S(850 \mu m)$ ratio on smaller spatial scales.

The submillimeter emission lies along the CO barlike structure (Fig. 1c) extending east-west between the two optical components. Both the CO and submillimeter emission peak near the brightest K-band source of VV 114, which is by far the reddest part of the VV 114 system, as indicated by the J − K color map (Fig. 1d). Although the NIR data were not taken in photometric conditions, an approximate J − K magnitude scale was derived by matching the data with the previously determined J − K color of VV 114 W (Knop et al. 1994). The higher resolution data presented here suggests a color of $J − K \approx 3$ for the bright compact red component in VV 114 E. These results are consistent with those found for the Near Infrared Camera and Multi-Object Spectrometer (NICMOS) data taken with the Hubble Space Telescope (Scoville et al. 1999).

4. DISCUSSION

4.1. Comparison of the Submillimeter Maps with Data at Other Wavelengths

The submillimeter, radio continuum, and CO emission from VV 114 all have roughly the same spatial extent. However, there are significant differences in their detailed structure. In particular, the radio sources (Condon et al. 1990, 1991) are located near the NIR emission peaks (Knop et al. 1994), suggesting that these regions are responsible for the majority of the ongoing star formation. The submillimeter and CO peaks do not appear to be correlated with the radio and NIR peaks but tend to lie primary in between VV 114 E + W.

The CO peak lies approximately 2″ from the submillimeter peak, which is consistent within the positional uncertainties of the data sets. The general similarities of the CO and submillimeter maps suggest that both the CO (1→0) and submillimeter emission probe the same material: the molecular gas and dust reservoir associated with the merger event. Despite these consistencies, there are differences in their detailed structure, which may indicate optical depth or excitation effects in the CO emission. The CO emission is distributed more smoothly along the barlike structure between VV 114 E and VV 114 W, while the submillimeter emission is more strongly peaked near VV 114 E. The tidal tails are also more apparent in the CO map, while the 450 μm emission is more extended in the east and southwest directions. The excess submillimeter emission in the east and southwest directions may be associated with H I tidal debris infalling into the central regions (Hibbard & Yun 1999).

VV 114 E is located near a peak of the submillimeter emission, which is consistent with the high level of dust obscuration inferred from its extremely red NIR colors (Fig. 1d; also see Knop et al. 1994). VV 114 W, on the other hand, lies along a line of sight that is nearly free of submillimeter emission (Fig. 1a) and is consistent with the low level of extinction estimated at NIR wavelengths (Knop et al. 1994). The NIR data show that the star formation is occurring globally throughout the system, but the most active site is in the nucleus of VV 114 E, which is associated with the brightest radio sources in the 8.4 GHz subarcsecond-resolution map (Condon et al. 1991). The Infrared Space Observatory 15 μm continuum also peaks strongly on the eastern nucleus of VV 114 (Yun et al. 1999). VV 114 E itself is composed of two bright nuclear sources in the NIR (Knop et al. 1994). The northeast component of VV 114 E is strongest in J and is associated with the brightest compact radio source (Fig. 1, triangle) in the high-resolution radio map (Condon et al. 1991). The red southwest component of VV 114 E is strongest in K (Fig. 1, cross) and is associated with a region containing several bright, compact radio sources. This red southwest component of VV 114 E is nearest to the position of the peaks in the submillimeter and CO emission but is still offset by 3″5−5″. This positional offset is larger than the positional errors in the data sets and hence may be significant.

Although most of the current star formation is occurring in and around the stellar components seen in the NIR (Knop et al. 1994), the central submillimeter and CO emission regions between the optical components may mark the location of a future major starburst, given that these regions show the largest CO velocity gradients (Yun et al. 1994) and contain the bulk of the molecular gas and dust in the system. The apparent displacement of the submillimeter and CO emission from the most active regions of star formation is consistent with the low HCN/CO ratio observed in VV 114 (Gao 1996). Typical infrared-luminous galaxies show enhanced HCN/CO ratios, presumably due to the
high density of the molecular gas in the starburst regions (Gao 1996). The low HCN/CO ratio in VV 114 may indicate that the bulk of the molecular gas is in regions of lower density and is displaced from the most active star-forming regions. Although the submillimetre emission of VV 114 is currently extended over 12 kpc, it is likely to evolve into a more compact starburst system similar to that seen for Arp 220 (Downes & Solomon 1998; Sakamoto et al. 1999). In the context of the numerical models for merging galaxies (Barnes & Hernquist 1996), VV 114 is an early-stage merger where the gas is accumulating within the central regions in advance of the stars. The system has yet to trigger a strong compact starburst at the dynamical centroid as seen for Arp 220 and other compact ultraluminous galaxies (Downes & Solomon 1998).

4.2. Estimating the Total Dust Mass

Observations at submillimetre wavelengths provide a better estimate of the total dust mass than that inferred from the IRAS data alone, since IRAS was not sensitive to cool dust. Assuming optically thin dust emission, the dust temperature is the blackbody function for a frequency $v$ and a temperature $T_d$, $D$ is the distance, and $k_d$ is the dust absorption coefficient. We adopt $k_d = 10{\lambda/(250 \text{ mm})}^{-\beta} \text{ g}^{-1} \text{ cm}^2$, where $\beta = 1$ for $\lambda < 250 \text{ mm}$ (Hildebrand 1983). At longer wavelengths ($\lambda > 250 \text{ mm}$), the typical values for $\beta$ range between 1 and 2. Empirically, at long wavelengths the Galactic cirrus is well fitted by $\beta \approx 1.5$ (Masi et al. 1995), while Galactic star-forming regions have $\beta \approx 2$ (Chini, Krügel, & Kreysa 1986; Lis et al. 1998).

From the submillimetre measurements, we can directly estimate the value of $\beta$ appropriate for VV 114 as a function of temperature. The integrated submillimetre flux density ratio is $S(450 \text{ mm})/S(850 \text{ mm}) = 8.9 \pm 0.6$. The value for $\beta$ is calculated from $S(450 \text{ mm})/S(850 \text{ mm}) = (450/850)^{-\beta}B(666 \text{ GHz}, T_d)/B(353 \text{ GHz}, T_d)$. At $T_d = 20 \text{ K}$, the data imply $\beta = 2.15 \pm 0.11$. At the temperature of $T_d = 41 \text{ K}$ inferred from the IRAS data (Soifer et al. 1989), the submillimetre data imply $\beta = 1.76 \pm 0.11$. Since the mass-weighted average temperature of the dust is expected to be less than or equal to the IRAS dust temperature, the lower limit for $\beta$ in VV 114 is $\beta \geq 1.65$. In fact, we find (see below) that most of the dust is relatively cool in VV 114 ($T \approx 20–25 \text{ K}$), suggesting that $\beta \approx 2$, which is similar to that observed for Galactic star-forming regions (Chini et al. 1986).

We fitted thermal dust spectral energy distributions (SEDs) to the observational data in order to estimate the total dust mass in VV 114. Figure 2a shows models appropriate for a temperature of $T_d = 41 \pm 4 \text{ K}$, derived from the IRAS $60 \mu \text{m}/100 \mu \text{m}$ flux density ratio (Soifer et al. 1989). The dust mass inferred for this temperature is $3^{+2}_{-1} \times 10^7 M_\odot$ (Table 2). The uncertainty in $k_d$ provides an additional uncertainty of about a factor of 2 in the dust mass. None of the single-component temperature models fit the submillimetre data. The low-$\beta$ models are inconsistent with the $S(450 \mu\text{m})/S(850 \mu\text{m})$ flux density ratio, and for $\beta \approx 2$ the submillimetre fluxes are significantly higher than those expected from the IRAS data. A simple interpretation of the data is the presence of cooler material that was not detected by IRAS. Figure 2b shows a three-component fit to the data, assuming $\beta = 2$ at $\lambda > 250 \mu$m. The mass of dust residing in the cool component ($T_c = 20 \text{ K}$) is $(1–2) \times 10^8 M_\odot$, which is significantly larger than that found in the warm IRAS component ($T_d = 41 \text{ K}$, $0.3 \times 10^8 M_\odot$). By varying the allowed dust temperatures, the relative amount of dust in the warm (37–45 K) and cool ($\sim 15–25 \text{ K}$) components can be modified by factors of 2–3. The amount of dust in the hot component ($T_h = 150 \text{ K}$), constrained by the 12 and 25 $\mu$m data, is negligible (Table 2).

More complicated models, which include several different grain types, cool cirrus, and warm starburst components, could also be fitted to the data (Rowan-Robinson 1992; Andreani & Franceschini 1996). Although such models may be more realistic, the number of model parameters exceeds the number of observational data points for VV 114. For the model with three temperature components (Fig. 2b), there are six free parameters (mass and temperature of each component) for only six data points. In reality, there is likely to be a continuous range of dust temperatures.

A simple approach is to adopt a power-law distribution of dust temperatures: $dM_d/dT \propto T^{-\alpha}$. (Xie, Goldsmith, & Zhou 1991). The total dust mass is determined by integrating the distribution function over a range of temperatures from $T_{low}$ to $T_{high}$. The upper limit to the dust temperature has little effect on the total dust mass (see, e.g., de Muizon & Rouan 1985). We assume $T_{high} = 200 \text{ K}$. Figure 2c shows dust SEDs computed for several different temperature distributions. Considering the small number of free parameters [$x$, $T_{low}$, and $M_d$(total)], the shape of the computed SEDs match the observational data remarkably well. The best fit to the $60–850 \mu\text{m}$ observational data occurs for $T_{low} = 22 \text{ K}$ and $x \approx 6$. The $12–25 \mu\text{m}$ data are not fitted well with a single power-law distribution, but these data have little effect on the total dust mass. Since $M_d \propto T_d^{-5}$ for dust in thermal equilibrium (Soifer et al. 1989), we expect $x \approx 6$. With this piece of theoretical insight, the SED is effectively fitted by only $T_{low}$ and $x$. We assume $x = 6$.

| Model                  | Fitted Data ($\mu$m) | $T_d$ (K) | $M_d$ ($10^8 M_\odot$) | Notes       |
|-----------------------|----------------------|-----------|-------------------------|-------------|
| Single-component      | 60–100               | 41        | 3.0                     | Fig. 2a     |
| Three-component       | 12–850               | 20        | 13                      | Fig. 2b     |
|                       | 41                   | 2.7       |                         | Fig. 2b     |
|                       | 150                  | 0.0018    |                         |             |
| Temperature distribution | 450–850              | 15        | 21                      | $T_d = T_{low}$, $x = 6$; Fig. 2c |
|                       | 450–850              | 30        | 8                       | $T_d = T_{low}$, $x = 6$; Fig. 2c |
|                       | 60–850               | 22        | 12                      | $T_d = T_{low}$, $x = 6$; Fig. 2c |
4.3. Implications for Cool Dust in Luminous IRAS Galaxies

Most of the dust in VV 114 is at a temperature of $T_d = 20$–25 K. Based on the SCUBA data, the total dust mass derived for VV 114 is 4 times larger than that derived from the 60–100 $\mu$m IRAS data. Since the IRAS colors for VV 114 are typical for its infrared luminosity (Soifer & Neugebauer 1991), we could expect to find similar results for other luminous IRAS sources. The existence of cool dust ($T_d < 30$ K) undetected by IRAS is not a surprising result. As stated in § 1, the high gas-to-dust ratios in galaxies derived from the IRAS data of spiral galaxies imply the presence of cool material (Devereux & Young 1990). Millimeter observations of spiral galaxies also suggest massive cool dust reservoirs with $T_d \sim 10$–20 K (Guélin et al. 1993, 1995; Franceschini & Andreani 1995). Recent SCUBA observations of NGC 891 support these results with the detection of a cool dust reservoir that is over an order of magnitude more massive than its warm dust component (Alton et al. 1998).

The results for VV 114 indicate that even very luminous IRAS galaxies can have cool dust reservoirs. Based solely on the IRAS data, the gas-to-dust ratio for VV 114 is $M(H_2)/M_d = 1100$ (Sanders, Scoville, & Soifer 1991), which is much higher than the Galactic value of about 100 (Devereux & Young 1990). By using the dust mass implied by the submillimeter data, we find a more realistic value of $M(H_2)/M_d \approx 300$. These gas-to-dust ratios assume the Galactic CO-to-H$_2$ conversion factor. If the Galactic value is not applicable for ultraluminous galaxies (Solomon et al. 1997), then the gas-to-dust ratio for VV 114 could be reduced further by a factor of 2–4. Observations of other luminous IRAS galaxies will test the generality of these results.

The cool dust temperature for VV 114 may be related to its early-merger evolutionary phase. More evolved, luminous mergers have warm dust emission associated with a compact starburst and/or an active galactic nucleus (Mazzarella, Bothun, & Boroson 1991). For example, the submillimeter data for the evolved, compact starburst Arp 220 (Rigopoulou, Lawrence, & Rowan-Robinson 1996) show no evidence for excess submillimeter emission associated with cool dust and can be fitted with a single-temperature, warm dust model of $T_d = 47$ K (Klaas et al. 1997). The dust may be cooler in VV 114 because the majority of the dust is displaced from the star-forming regions traced by the NIR and radio emission peaks. Given the radio–to–far-IR relationship (Helou, Soifer, & Rowan-Robinson 1985), we expect to find warm dust within the star-forming regions, especially near the most active region, VV 114 E. As VV 114 evolves into a compact gaseous system similar to Arp 220, the star formation is expected to increase in the central regions and the dust temperature should rise accordingly.

5. Conclusions

We present submillimeter maps of the young merger system VV 114. We detect submillimeter emission in excess of that expected from the IRAS data. This submillimeter excess suggests the presence of a cool, massive component of dust. By fitting a variety of dust models to the SED of VV 114, we derive a total dust mass of approximately $1 \times 10^8 M_\odot$, a temperature of $T_d \approx 20$–25 K, and $\beta \approx 2$. The major-
ity of the dust is located in between the optical components, VV 114 E + W, near the suspected dynamical center of the merger remnant. The submillimeter emission regions correlate well with the CO emission regions but do not correlate well with the peaks in the radio and NIR emission regions, which are thought to trace the star formation activity. The fact that the submillimeter emission is displaced from the most active regions of star formation may explain the cool temperature for the majority of the dust. Given the extremely large reservoir of gas and dust available in the central regions, VV 114 is expected to evolve into a more luminous central starburst, similar to that seen for Arp 220.

We thank the staff at the JCMT and UKIRT who have made these observations possible, and the director of the JAC, Ian Robson, for the provision of discretionary time. D. T. F. acknowledges support from NSF grant AST 96-13717 to the Owens Valley Millimeter Array; R. J. I. and I. S. acknowledge support from a PPARC Advanced Fellowship and a Royal Society Fellowship, respectively.

REFERENCES

Alton, P. B., Bianchi, S., Rand, R. J., Xilouris, E. M., Davies, J. I., & Trewhella, M. 1998, ApJ, 507, L125
Andreani, P., & Franceschini, A. 1996, MNRAS, 283, 85
Barnes, J. E., & Hernquist, L. 1991, ApJ, 370, L65
———. 1996, ApJ, 471, 115
Chini, R., Krügel, E., & Kreyda, E. 1986, A&A, 167, 315
Condon, J. J., Helou, G., Sanders, D. B., & Soifer, B. T. 1990, ApJS, 73, 359
Condon, J. J., Huang, Z.-P., Yin, Q. F., & Thuan, T. X. 1991, ApJ, 378, 65
de Muizon, M., & Rouan, D. 1985, A&A, 143, 160
Devereux, N. A., & Young, J. S. 1990, ApJ, 359, 42
Downes, D., & Solomon, P. M. 1998, ApJ, 507, 615
Franceschini, A., & Andreani, P. 1995, ApJ, 440, L5
Gao, Y. 1996, Ph.D. thesis, State Univ. New York Stony Brook
Guélin, M., Zylka, R., Mezger, P. G., Haslam, C. G. T., & Kreyda, E. 1995, A&A, 298, L29
Guélin, M., Zylka, R., Mezger, P. G., Haslam, C. G. T., Kreyda, E., Lemke, R., & Sievers, A. W. 1993, A&A, 279, L37
Helou, G., Soifer, B. T., & Rowan-Robinson, M. 1985, ApJ, 298, L7
Hibbard, J. E., & Yun, M. S. 1999, in preparation
Hildebrand, R. H. 1983, QJRAS, 24, 267
Holland, W. S., et al. 1999, MNRAS, 303, 659
Hughes, D. H., Dunlop, J. S., & Rawlings, S. 1997, MNRAS, 289, 766
Klaas, U., Haas, M., Heinrichsen, I., & Schulz, B. 1997, A&A, 325, L21
Knop, R. A., Soifer, B. T., Graham, J. R., Matthews, K., Sanders, D. B., & Scoville, N. Z. 1994, AJ, 107, 920
Lis, D. C., Serabyn, E., Keene, J., Dowell, C. D., Benford, D. J., Phillips, T. G., Hunter, T. R., & Wang, N. 1998, ApJ, 509, 299
Masi, S., et al. 1995, ApJ, 452, 253
Mazzarella, J. M., Bothun, G. D., & Boroson, T. A. 1991, AJ, 101, 2034
Rigopoulou, D., Lawrence, A., & Rowan-Robinson, M. 1996, MNRAS, 278, 1049
Rowan-Robinson, M. 1992, MNRAS, 258, 787
Sakamoto, K., Scoville, N. Z., Yun, M. S., Crosas, M., Genzel, R., & Tacconi, L. J. 1999, ApJ, 514, 68
Sanders, D. B., & Mirabel, I. F. 1996, ARA&A, 34, 749
Sanders, D. B., Scoville, N. Z., & Soifer, B. T. 1991, ApJ, 370, 158
Scoville, N. Z., et al. 1999, in preparation
Scoville, N. Z., Yun, M. S., & Bryant, P. M. 1997, ApJ, 484, 702
Soifer, B. T., Boehmer, L., Neugebauer, G., & Sanders, D. B. 1989, AJ, 98, 766
Soifer, B. T., & Neugebauer, G. 1991, AJ, 101, 354
Solomon, P. M., Downes, D., Radford, S. E. J., & Barrett, J. W. 1997, ApJ, 478, 144
Xie, T., Goldsmith, P. F., & Zhou, W. 1991, ApJ, 371, L81
Yun, M. S., et al. 1999, in preparation
Yun, M. S., Scoville, N. Z., & Knop, R. A. 1994, ApJ, 430, L109