Astrophys Space Sci (2008) 313: 297–302
DOI 10.1007/s10509-007-9618-1

ORIGINAL ARTICLE

Luminous infrared galaxies with the submillimeter array: probing the extremes of star formation

C.D. Wilson · G.R. Petitpas · D. Iono · A. Peck · M. Krips · B.E. Warren · A.J. Baker · M.S. Yun · Y. Pihlstrom · C. Mihos · S. Matsushita · M. Juvela · P.T.P. Ho · T.J. Cox · L. Armus

Received: 30 January 2007 / Accepted: 26 July 2007 / Published online: 11 September 2007
© Springer Science+Business Media B.V. 2007

Abstract Luminous and Ultraluminous infrared galaxies (ULIRGs) contain the most intense regions of star formation in the local universe. Because molecular gas is the fuel for current and future star formation, the physical properties and distribution of the warm, dense molecular gas are key components for understanding the processes and timescales controlling star formation in these merger and merger remnant galaxies. We present new results from a legacy project on the Submillimeter Array which is producing high resolution images of a representative sample of galaxies with $\log L_{FIR} > 11.4$ and $D < 200$ Mpc.

Keywords Galaxies: infrared · Galaxies: ISM · Galaxies: individual (Mrk231, Mrk273, UGC5101, IRAS10565+2448)

C.D. Wilson (✉) · B.E. Warren
Dept. of Physics & Astronomy, McMaster University, Hamilton, Ontario L8S 4M1, Canada
e-mail: wilson@physics.mcmaster.ca

G.R. Petitpas · A. Peck · M. Krips
Smithsonian Astrophysical Observatory, Hilo, USA

D. Iono
National Astronomical Observatories of Japan, Tokyo, Japan

A.J. Baker
State University of New Jersey, Piscataway, USA

M.S. Yun
University of Massachusetts, Amherst, USA

Y. Pihlstrom
University of New Mexico, Albuquerque, USA

1 Introduction

Ultra-luminous infrared galaxies (ULIRGs) contain the regions of most intense star formation in the local universe. Although their high rates of star formation and accretion appear to be triggered by the merger of two gas-rich galaxies (Sanders et al. 1988; Veilleux et al. 2002), the detailed physical connection between galaxy mergers and star formation and, in particular, the time evolution of this process, is not well understood. Relating numerical hydrodynamical models (Mihos and Hernquist 1996; Cox et al. 2004) to observations is complicated by the difficulty in identifying the precise stage of the merger (Murphy et al. 2001). In addition, while high resolution imaging has found that most ULIRGs have nuclear separation from <0.3 kpc to 48 kpc (Murphy et al. 1996), other merging galaxies with these nuclear separations which are *not* ULIRGs have also been found (Braine et al. 2004). These observations suggest that the onset of the intense star formation and accretion which produces a ULIRG is not a simple function of the age of the merger and leaves open the question of whether all luminous infrared

C. Mihos
Case Western Reserve University, Cleveland, USA

S. Matsushita · P.T.P. Ho
Institute of Astronomy & Astrophysics, Academia Sinica, Taipei, Taiwan

M. Juvela
University of Helsinki Observatory, Helsinki, Finland

T.J. Cox
Center for Astrophysics, Cambridge, USA

L. Armus
Infrared Processing and Analysis Center, Pasadena, USA

galaxies (LIRGs; $11 \le \log(L_{FIR}/L_{\odot}) < 12$) will undergo a ULIRG phase ($12 \ge \log(L_{FIR}/L_{\odot})$) at some point in their evolution.

Local ULIRGs are also important as the closest analogs to the high-redshift submillimeter galaxies (Blain et al. 2002): both populations have high infrared luminosities, large amounts of molecular gas (Frayer et al. 1998, 1999; Neri et al. 2003; Greve et al. 2005; Tacconi et al. 2006) and display morphological evidence of past or ongoing mergers (Veilleux et al. 2002; Conselice et al. 2003). Since galaxy merger rates are substantially higher in the early universe (Le Fèvre et al. 2000; Gottlöber et al. 2001), understanding the physical and dynamical properties of nearby ULIRGs is also important for understanding the processes in the early universe which give rise to the very luminous submillimeter galaxy population.

In this paper, we present some first results obtained with the Submillimeter Array (SMA) for a sample of 14 luminous and ultraluminous infrared galaxies. The galaxies have all been observed in the CO J = 3-2 lines and in continuum emission at 880 μm, which allows us to compare the dust and gas properties in the central kiloparsec.

2 Sample and observations

For this survey, we selected a sample of luminous and ultraluminous infrared galaxies with redshifts $z < 0.045$ (distances $D_L < 200$ Mpc, adopting $H_o = 70$ km s^{-1} Mpc^{-1}, $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$) and far-infrared luminosities $\log L_{FIR} > 11.4$. The distance limit was chosen so as to be able to achieve spatial resolutions of order 1 kpc or better in all the target galaxies. The luminosity cutoff was chosen to allow us to span a wide range of merger properties and luminosities while still concentrating on the most infrared luminous nearby galaxies. Out of a total of 39 galaxies above declination −20° (Sanders et al. 2003) which meet these two criteria, we selected 14 galaxies with previous interferometric observations in the CO J = 1-0 transition to be observed in this survey.

The observations discussed here were obtained between 2005 May 16 and 2006 April 22 using either the compact or extended configuration of the SMA. The configuration was chosen so as to achieve a spatial resolution of 0.7–1 kpc in the CO J = 3-2 line; the typical angular resolution in the extended configuration is 0.7″. The correlator was configured to have a spectral resolution of 0.8125 MHz (∼0.7 km s^{-1} for CO J = 3-2) with a bandwidth of 2 GHz in each of the upper and lower sidebands. Each galaxy was observed with the ^{12}CO J = 3-2 transition in the lower sideband of the receiver and the adjacent continuum in the upper sideband, 10 GHz away. All galaxies were detected strongly in the CO J = 3-2 line, and also in the continuum with a signal to noise of four or better; examples of the CO J = 3-2 integrated emission are shown in Figs. 1 and 2.

3 The gas to dust mass ratio

We can use our new CO J = 3-2 and 880 μm data to estimate the gas to dust mass ratio in the central regions of these luminous infrared galaxies. The gas to dust ratio is interesting because it allows us to probe the physical properties of the interstellar medium on kiloparsec scales in regions of galaxies with intense heating from starburst activity and possibly an active galactic nucleus.

We have calculated the dust mass from the 880 μm flux assuming a dust emissivity at 880 μm, κ, of 1 cm^2 g^{-1} (Henning et al. 1995; Johnstone et al. 2000). With this assumption, the dust mass is given by

$$M_{dust} = 74220 S_{880} D_L^2 (\exp(17/T_D) - 1)/\kappa \ (\mathrm{M}_\odot)$$

where S_{880} is the 880 μm flux in Jy and D_L is the luminosity distance in Mpc. We calculated the dust temperature, T_D, from the 60 and 100 μm fluxes (Sanders et al. 2003) assuming the emission at these wavelengths is optically thick (Solomon et al. 1997).

To calculate the H_2 gas mass, we adopt the revised CO-to H_2 conversion factor advocated by (Downes and Solomon 1998),

$$M_{H_2} = 0.8 L'_{CO}(1-0)$$

where M_{H_2} is the H_2 gas mass in $\mathrm{M}_\odot$ and L_{CO}(1-0) is the luminosity of the CO J = 1-0 line in K km s^{-1} pc^2. (This equation corresponds to a CO-to-H_2 conversion factor of 0.5×10^{20} H_2 cm^{-2} (K km s^{-1})$^{-1}$.) We adopt an average CO J = 3-2/J = 1-0 line ratio of 0.5, which is consistent with single dish and interferometric measurements of Mrk231 and Mrk273 (Wilson et al. 2007) in calculating the H_2 gas mass.

We focus here on the gas-to-dust mass ratio determined in the central beam to probe the extreme central region of each galaxy or galaxy component. Thus, we compare the H_2 mass calculated from the integrated CO J = 3-2 intensity in a single beam at the peak of the emission with the dust mass calculated from the peak 880 μm continuum intensity. This analysis gives an average gas to dust ratio including all 13 galaxies or galaxy components analyzed to date of 207 ± 49 (standard deviation 177). Thus, our new SMA data suggest that the gas to dust mass ratio in the central kiloparsec of these luminous and ultraluminous infrared galaxies is very similar to the gas to dust ratio measured in the Milky Way. This result is somewhat surprising given that the dust in these nuclear regions is subject to more intense heating (as well as perhaps processing due to shocks) compared to typical regions in the Milky Way.

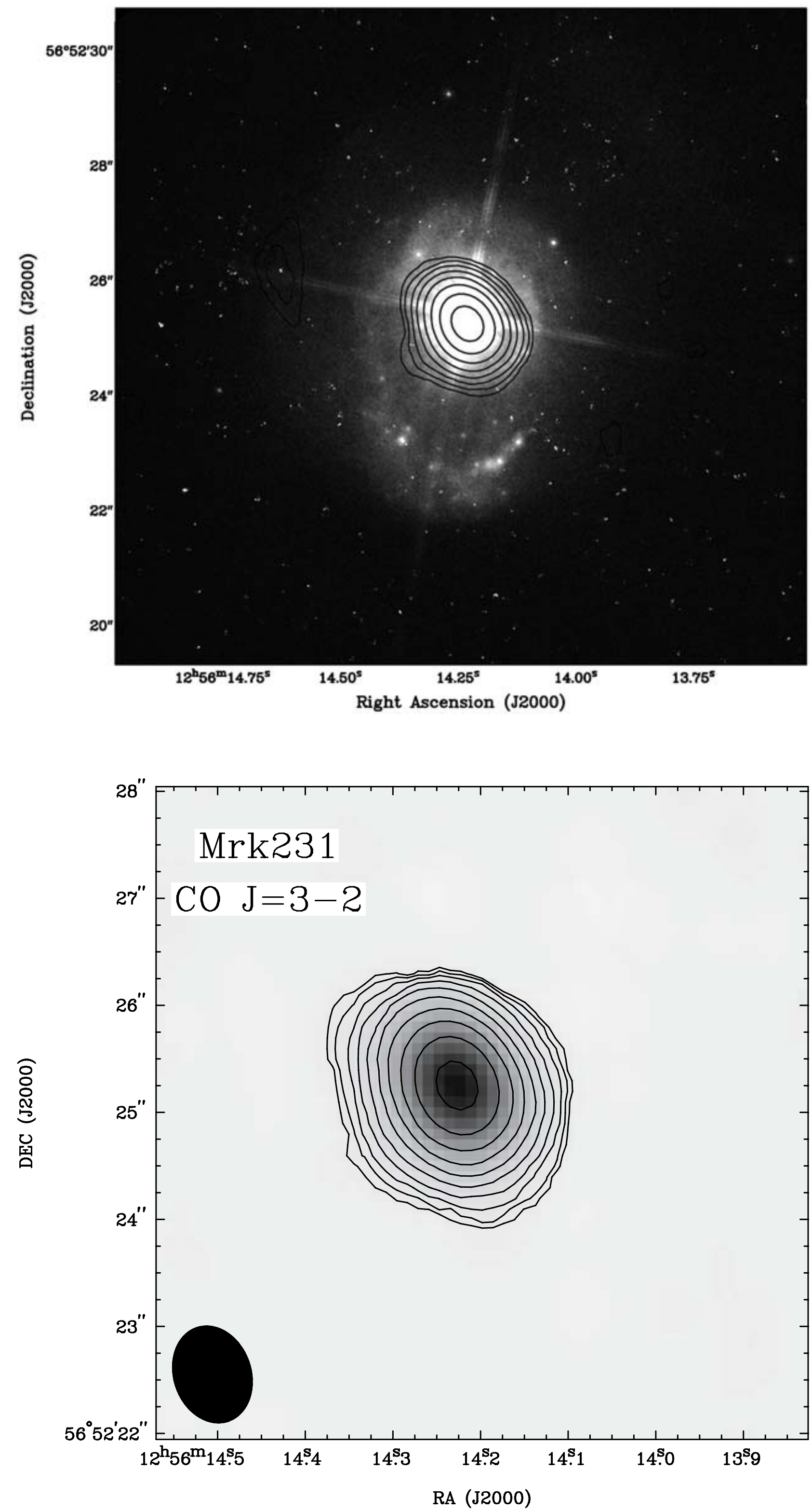

Fig. 1 (*Top*) CO J = 3-2 integrated intensity map for Mrk 231 overlaid on an I band image from the Hubble Space Telescope. Note that the coordinate alignment between the optical and radio images is only approximate. (*Bottom*) Closer view of the CO J = 3-2 integrated intensity map. The lowest contour is 2σ (5.2 Jy/beam km/s) contours increase by factors of 1.5. The $\sim 0.8''$ beam is indicated in the lower left corner

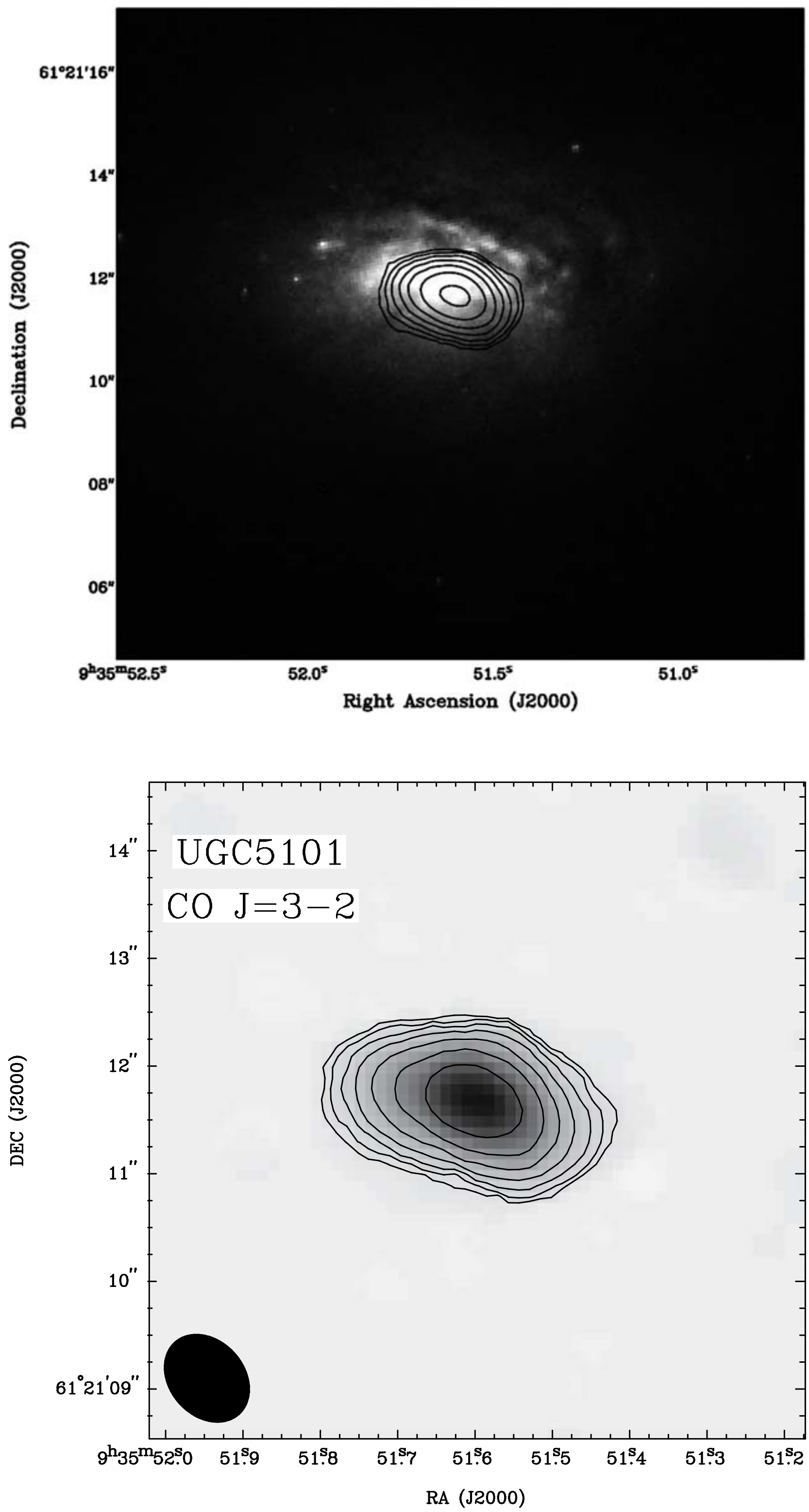

Fig. 2 (*Top*) CO J = 3-2 integrated intensity map for UGC 5101 overlaid on an I band image from the Hubble Space Telescope. Note that the coordinate alignment between the optical and radio images is only approximate. (*Bottom*) Closer view of the CO J = 3-2 integrated intensity map. The lowest contour is 2σ (7.6 Jy/beam km/s) contours increase by factors of 1.5. The $\sim 0.8''$ beam is indicated in the lower left corner

4 Comparing ULIRGs at low and high redshift

We have compared four of the brightest and most compact galaxies in our sample (Mrk 231, Mrk 273, UGC 5101, and IRAS 10565+2448) with eight high-redshift submillimeter galaxies that have been observed in the CO J = 3-2 line (Downes and Solomon 2003; Genzel et al. 2003; Weiss et al. 2003; Tacconi et al. 2006). By choosing this high-redshift sample that was observed in exactly the same CO line, we do not have to worry that CO excitation effects may bias our results.

Compared to the local ULIRGs, the high-redshift galaxies are at least an order of magnitude more luminous in the CO J = 3-2 line; this result was already known from single dish observations of both sets of galaxies. We also see that the high redshift galaxies have somewhat broader line widths on average (560 ± 90 km/s) compared to the local ULIRGs (370 ± 90 km/s), which suggests that the high redshift galaxies are more massive systems. Finally, the high redshift galaxies that have been spatially resolved have much larger diameters (5 kpc full width half maximum) compared to 0.6 kpc for the local galaxies. If this result is robust, it suggests that the CO surface brightness (or equivalently, the molecular gas surface density) may be up to an order of magnitude *lower* in the high redshift galaxies than in the local ULIRG sample. However, this conclusion remains to be confirmed by an analysis of our complete local sample (Iono et al. 2007) and perhaps higher resolution observations of the high redshift galaxies to confirm their diameters.

5 Future work

This SMA legacy survey aims to address five broad scientific questions:

1. *What are the distributions, kinematics, and physical conditions of dense molecular gas in U/LIRGs?* By combining our new SMA data with published and archival CO J = 1-0 and J = 2-1 data and radiative transfer models (Juvela 1997), we will be able to determine the physical properties of the cool, warm, and dense molecular gas components which feed the starburst and any AGN activity.
2. *What is the distribution of the dust in U/LIRGs?* High-resolution 340 GHz continuum images from the SMA can be combined with Spitzer IRS spectra to estimate the dust temperature via the mid-infrared to submillimeter spectral energy distribution (SED) and the dust mass (including both small and large grains).
3. *Do the gas properties change as the interaction progresses?* This data set covering a range of mergers from mid to late stages will allow us to determine how the distribution and kinematics of the gas change as a function of physical conditions such as density and temperature, and to correlate those changes with the stage of the merger.
4. *How do the properties of the dense gas in local U/LIRGs compare to those of the high-redshift submillimeter galaxies?* Armed with a robust local sample of 14 U/LIRGs, we can make a rigorous comparison of the properties of the gas with those in higher redshift galaxies (Greve et al. 2005; Tacconi et al. 2006).
5. *What is the origin of nuclear OH megamasers?* Our sample, which contains galaxies with and without OH megamasers, is well suited for identifying any unique nuclear conditions (physical, chemical, kinematical) that produce OH megamasers.

This survey should give us a good understanding of the kiloparsec-scale properties of the interstellar medium in these very luminous and active galaxies. In the future, with ALMA we will be able to probe much smaller spatial and mass scales in many of these same galaxies. For example, ALMA will be able to detect giant molecular clouds with masses of 5×10^6 $M_\odot$ (3σ) out to the distance limit of our survey (200 Mpc) in just one hour of integration. Thus, ALMA will let us search for and study giant molecular clouds, the fundamental star forming unit in galaxies, in a much wider range of environments than is possible with current telescopes.

References

Blain, A.W., Smail, I., Ivison, R.J., Kneib, J.-P., Frayer, D.T.: Submillimeter galaxies. Phys. Rep. **369**, 111–176 (2002)

Braine, J., Lisenfeld, U., Duc, P.-A., et al.: Colliding molecular clouds in head-on galaxy collisions. Astron. Astrophys. **418**, 419–428 (2004)

Conselice, C.J., Chapman, S.C., Windhorst, R.A.: Evidence for a major merger origin of high-redshift submillimeter galaxies. Astrophys. J. **596**, L5–L8 (2003)

Cox, T.J., Primack, J., Jonsson, P., Somerville, R.S.: Generating hot gas in simulations of disk-galaxy major mergers. Astrophys. J. **607**, L87–L90 (2004)

Downes, D., Solomon, P.M.: Rotating nuclear rings and extreme starbursts in ultraluminous galaxies. Astrophys. J. **507**, 615–654 (1998)

Downes, D., Solomon, P.M.: Molecular gas and dust at z = 2.6 in SMM J14011+0252: a strongly lensed ultraluminous galaxy, not a huge massive disk. Astrophys. J. **582**, 37–48 (2003)

Frayer, D.T., Ivison, R.J., Scoville, N.Z., et al.: Molecular gas in the Z = 2.8 submillimeter galaxy SMM 02399-0136. Astrophys. J. **506**, L7–L10 (1998)

Frayer, D.T., Ivison, R.J., Scoville, N.Z., et al.: Molecular gas in the Z = 2.565 submillimeter galaxy SMM J14011+0252. Astrophys. J. **514**, L13–L16 (1999)

Genzel, R., et al.: Spatially resolved millimeter interferometry of SMM J02399-0136: a very massive galaxy at z = 2.8. Astrophys. J. **584**, 633–642 (2003)

Gottlöber, S., Klypin, A., Kravtsov, A.V.: Merging history as a function of halo environment. Astrophys. J. **546**, 223–233 (2001)

Greve, T.R., Bertoldi, F., Smail, I., et al.: An interferometric CO survey of luminous submillimetre galaxies. Mon. Not. Roy. Astron. Soc. **359**, 1165–1183 (2005)

Henning, Th., Michel, B., Stognienko, R.: Dust opacities in dense regions. Planet. Space Sci. **43**, 1333–1343 (1995)

Iono, D., et al.: in preparation (2007)

Johnstone, D., Wilson, C.D., Moriarty-Schieven, G., Joncas, G., Smith, G., Fich, M.: Large-area mapping at 850 microns. II. Analysis of the clump distribution in the ρ ophiuchi molecular cloud. Astrophys. J. **545**, 327–339 (2000)

Juvela, M.: Non-LTE radiative transfer in clumpy molecular clouds. Astron. Astrophys. **322**, 943–961 (1997)

Le Fèvre, O., Abraham, R., Lilly, S.J., et al.: Hubble space telescope imaging of the CFRS and LDSS redshift surveys—IV. Influence of mergers in the evolution of faint field galaxies from z 1. Mon. Not. Roy. Astron. Soc. **311**, 565–575 (2000)

Mihos, J.C., Hernquist, L.: Gasdynamics and starbursts in major mergers. Astrophys. J. **464**, 641–663 (1996)

Murphy, T.W. Jr., Armus, L., Matthews, K., et al.: Visual and near-infrared imaging of ultraluminous infrared galaxies: the IRAS 2 Jy sample. Astron. J. **111**, 1025–1052 (1996)

Murphy, T.W. Jr., Soifer, B.T., Matthews, K., Armus, L.: Age dating ultraluminous infrared galaxies along the merger sequence. Astrophys. J. **559**, 201–224 (2001)

Neri, R., et al.: Interferometric observations of powerful co emission from three submillimeter galaxies at $z = 2.39$, 2.51, and 3.35. Astrophys. J. **597**, L113–L116 (2003)

Sanders, D.B., Soifer, B.T., Elias, J.H., Madore, B.F., Matthews, K., Neugebauer, G., Scoville, N.Z.: Ultraluminous infrared galaxies and the origin of quasars. Astrophys. J. **325**, 74–91 (1988)

Sanders, D.B., Mazzarella, J.M., Kim, D.-C., Surace, J.A., Soifer, B.T.: The IRAS revised bright galaxy sample. Astron. J. **126**, 1607–1664 (2003)

Solomon, P.M., Downes, D., Radford, S.J.E., Barrett, J.W.: The molecular interstellar medium in ultraluminous infrared galaxies. Astrophys. J. **478**, 144–161 (1997)

Tacconi, L., et al.: High-resolution millimeter imaging of submillimeter galaxies. Astrophys. J. **640**, 228–240 (2006)

Veilleux, S., Kim, D.-C., Sanders, D.B.: Optical and near-infrared imaging of the IRAS 1 Jy sample of ultraluminous infrared galaxies. II. The analysis. Astrophys. J. Suppl. Ser. **143**, 315–376 (2002)

Weiss, A., Henkel, C., Downes, D., Walter, F.: Gas and dust in the Cloverleaf quasar at redshift 2.5. Astron. Astrophys. **409**, L41–L45 (2003)

Wilson, C.D., et al.: in preparation (2007)