Molecular Gas Distribution in Double-Nucleus Ultraluminous Infrared Galaxies

A. S. Evans

Dept. of Physics & Astronomy, SUNY, Stony Brook, NY 11794-3800

J. A. Surace & J. M. Mazzarella

IPAC, Caltech MS 100-22, Pasadena CA 91125

and D. B. Sanders

Institute for Astronomy, 2680 Woodlawn Dr., Honolulu, HI 96822

Abstract.

Millimeter (CO) observations of 5 double-nucleus ultraluminous infrared galaxy (ULIG) mergers are presented. With nuclear separations of \(3 \sim 5\) kpc, these galaxies are in the “intermediate” stages of the merger process. A preliminary comparison of the distribution of molecular gas (the likely fuel source for both starbursts and active galactic nuclei: AGN) shows a tendency for molecular gas to be associated with the AGN nucleus of ULIGs with “warm”, Seyfert-like infrared colors (\(f_{25\mu m}/f_{60\mu m} \geq 0.20\)) and associated with both stellar nuclei of ULIGs with “cool” infrared colors (\(f_{25\mu m}/f_{60\mu m} < 0.2\)). Studies of ULIGs with a wide range of nuclear separations using the high resolution and increased sensitivity of ALMA will provide a larger statistical sample with which the gas distribution, molecular gas masses, and densities can be determined as a function of the evolutionary stage, starburst and AGN activity, and lookback time.

1. Introduction

The availability of ground and space-based instruments sensitive to radiation redward of 1\(\mu\)m has resulted in a flurry of activity in the study of ultraluminous infrared galaxies (ULIG: \(L_{IR}(8 - 1000\mu m) \geq 10^{12} L_\odot\), assuming \(H_0 = 75\) km \(s^{-1}\) Mpc\(^{-1}\)). Much of the present research on these dusty merger by-products has focussed on two issues - (i) the nature of the embedded energy sources, and (ii) the cosmological significance of dust enshrouded star formation and AGN activity relative to that observed in optically selected galaxies. The former issue has been addressed with extensive high-resolution (0.1\(^{\prime\prime} - 0.2\)\(^{\prime\prime}\)), near-infrared imaging with the Hubble Space Telescope (HST: Scoville et al. 2000), ground-based spectroscopy at near-infrared wavelengths (e.g. Veilleux, Sanders, & Kim 1999), and mid-infrared spectroscopy with the Infrared Space Observatory (Genzel et al. 1998; Lutz et al. 1998). The data show that at least 30% of local ULIGs (i.e., primarily the “warm” ULIGs) appear to have AGN as the domi-
nant energy sources, and that the tendency for the energy source to be an AGN increases with increasing luminosity. The latter issue has been investigated via surveys with the Submillimeter Common User Bolometer Array (SCUBA). Not only has SCUBA enabled the systematic detection of ULIGs at cosmological distances (Smail et al. 1997; Hughes et al. 1998; Barger et al. 1998), but compelling arguments infer that ULIGs may represent a significant fraction of the star formation and AGN activity occurring in the early universe.

Of equal importance to the question of what ULIGs are is the question of what their progenitors were. Specifically, it is clear that ULIGs result primarily from the interaction/merger of gas-rich spiral galaxies and that they are powered by starbursts and AGN, but what properties of their progenitor galaxies determine the dominant energy source, the star formation rate, and the infrared luminosity? One possible way of answering this is to select a sample of ULIGs in which the progenitor galaxies are close enough to be under the gravitational influence of each other, but far enough apart to still possess distinguishable features. Such a selection criteria has the benefit of selecting objects which are likely to remain ultraluminous well into the coalescence of the nuclei, but misses objects that (if they exist) have similar nuclear separations, but have yet to reach the ultraluminous phase. Features which may yield important diagnostics are the star-forming molecular gas content, the optical or near-infrared morphologies, and the bulge-to-disk (or perhaps more appropriately, bulge-to-tidal tail) ratios of the progenitors.

In this conference article, we focus on millimeter (CO) interferometry of a sample of 5 double-nucleus ULIGs in the redshift range $z \sim 0.05 - 0.12$ and which have projected nuclear separations of $\sim 3 - 5$ kpc ($2'' - 6''$). The results presented here were obtained with the Owens Valley Millimeter Array (OVRO) at a resolution of $\sim 2''$, and are discussed at length in Evans et al. (1999), Evans, Surace, & Mazzarella (2000), and Evans et al. (2000).

2. Results and Discussion

Figure 1 shows the molecular gas distribution of the 5 ULIGs superimposed on near-infrared HST images of the galaxies (except Mrk 463, where an optical HST image is shown). The warm (IR 08572+3915, IR 13451+1232, and Mrk 463) and cool (IR 12112+0305 and IR 14348-1447) ULIGs are shown in the left and right panels, respectively. The most striking feature is the presence of molecular gas on both nuclei of the cool ULIGs, whereas it appears only on the AGN of the warm ULIGs.

The association of molecular gas with the active nucleus of the warm galaxies is consistent with the idea that molecular gas is a major fuel source for their AGN activity. The results are also consistent with their warm, Seyfert-like mid to far-infrared colors; because $\text{H}_2$ forms on the surface of dust grains, it is not surprising to find molecular gas associated with the energy source responsible for heating the dust to such high temperatures.

In the case of the cool ULIGs, the association of molecular gas with both of the stellar nuclei (which has also been observed for the double nuclei in the cool ULIG Arp 220: Sakamoto et al. 1999), combined with the lack of definitive evidence for AGN (i.e., broad, quasar-like or high excitation emission lines),
may be an indication that nuclear starbursts in both progenitors enable them to achieve luminosities in excess of $10^{12} \, L_{\odot}$ at this stage of the merger. There is, however, no reason to believe twin nuclear starbursts should always be necessary to exceed $10^{12} \, L_{\odot}$, and thus a larger sample of ULIGs is required to yield better statistics.

As pointed out by Evans, Surace, and Mazzarella (2000), the morphologies of the lower luminosity luminous infrared galaxies (LIGs: $L_{\text{IR}} = 10^{11.0-11.99} \, L_{\odot}$) with similar nuclear separations have molecular gas predominantly between the two nuclei. This is a possible indication that gas stripping is an important process in LIGs, whereas the bulges of ULIGs may be massive enough such that stripping is minimal. The starburst and AGN luminosities (and thus the fueling rates) of ULIGs require sufficient quantities of high density gas, a condition that can be achieved through dissipative collapse of gas into the deep nuclear potential wells. Off-nuclear star formation induced by gas stripping and compression is unlikely to produce conditions conducive for the ULIG phenomenon.

3. ULIGs and the Atacama Large Millimeter Array

The advantages ALMA will bring to the study of the intermediate stages of the ULIG process is its ability to perform high resolution observations with unparalleled sensitivity. ALMA will be able to resolve the molecular disks of ULIGs with projected nuclear separations as small as $\sim 0.1''$, and will provide a better constraint on the extent (and thus the density) of the gas. This is required to determine statistically whether the properties of molecular gas in more starburst-like ULIGs differ from that of AGN-like ULIGs, and to compare the gas properties of ULIGs with LIGs. ALMA will also aid in determining, in a more statistical sense than possible with present day millimeter arrays, how the general gas properties of ULIGs vary as a function of lookback time.

**Acknowledgments.** We thank the OVRO staff and postdoctoral scholars for their assistance both during and after the acquisition of the data presented here. This research was supported by NASA grant NAG 5-3042 and RF9736D.

**References**

Barger, A. J., Cowie, L. L., Sanders, D. B. et al. 1998, Nature, 394, 248
Evans, A. S., Kim, D. C., Mazzarella, J. M. et al. 1999, ApJ, 521, L107
Evans, A. S., Surace, J. A., & Mazzarella, J. M. 2000, ApJL, 529, in press
Evans, A. S., Surace, J. A., Mazzarella, J. M., & Sanders, D. B. 2000, in prep.
Genzel, R., Lutz, D., Sturm, E. et al. 1998, ApJ, 498, 579
Hughes, D. H., Serjeant, S., Dunlop, J. et al. 1998, Nature, 394, 241
Lutz, D., Spoon, H. W. W., Rigopoulou, D. et al. 1998, ApJ, 505, L103
Sakamoto, K., Scoville, N. Z., Yun, M. S. et al. 1999, ApJ, 514, 68
Scoville, N. Z., Evans, A. S., Thompson, R. et al. 2000, AJ, in press
Smail, I., Ivison, R. J., & Blain, A. W. 1997, ApJ, 490, L5
Veilleux, S., Sanders, D. B., & Kim, D.-C. 1999. ApJ, 522, 139
Figure 1. CO(1 → 0) contours of the 3 warm ULIGs (left panels) and the 2 cool ULIGs (right panels) superimposed on HST images. Extracted CO spectra of each nucleus are also shown. For each image, north is up and east is to the left.
This figure "asefig1.jpg" is available in "jpg" format from:

http://arxiv.org/ps/astro-ph/9912460v1