Molecular Gas in High-Redshift Submillimeter Galaxies

D. T. Frayer and N. Z. Scoville

California Institute of Technology, Astronomy Dept. 105-24, Pasadena, CA 91125, USA

Abstract.

We present observations of the luminous population of high-redshift sub-mm galaxies taken at the OVRO Millimeter Array. Studies of sub-mm galaxies are vital to our understanding of the formation and early evolution of galaxies since this population could account for a significant fraction of the total amount of star formation and AGN activity at high redshift. We discuss the CO detections for SMM J02399-0136 at $z = 2.8$ and SMM J14011+0252 at $z = 2.6$. The CO data show the presence of massive molecular gas reservoirs ($M(H_2) \sim \text{few} \times 10^{10} - 10^{11} M_{\odot}$) and suggest that the sub-mm galaxies are similar to low-redshift, gas-rich ultraluminous infrared galaxies (ULIGs). These results highlight the importance that future mm/sub-mm interferometric observations will have on our understanding of the high redshift universe.

1. Introduction

Deep surveys of the submillimeter sky using SCUBA on the JCMT have uncovered a population of luminous dusty galaxies at high-redshift (Smail, Ivison & Blain 1997; Barger et al. 1998; Hughes et al. 1998; Eales et al. 1999). Although their redshift distribution is still uncertain, the majority of the sub-mm galaxies are believed to be at high redshifts ($z \geq 2$) based on their radio and near-infrared (NIR) data (Smail et al. 1999a,b; Carilli & Yun 1999). This contrasts somewhat with the early optical studies which argued for lower redshifts for the sub-mm population (Lilly et al. 1999; Barger et al. 1999). Several sub-mm sources are now thought to be undetected at optical wavelengths which makes radio, mm, and NIR follow-up studies crucial, and supports the high-redshift scenario for the sub-mm population.

The relative importance of AGN and starburst activity in powering the high luminosities of the sub-mm population is still open to question. If dominated by AGN activity, the sub-mm galaxies would be responsible for a majority of the X-ray background (Almaini et al. 1999). Alternatively, if the sub-mm galaxies are predominantly powered by starbursts, they would contribute significantly to the total amount of star formation at high redshift (Blain et al. 1999). If the sub-mm galaxies have a significant starburst component, we would expect to detect massive molecular gas reservoirs associated with the star-formation activity.


At the OVRO Millimeter Array, we have been carrying out CO observations of the sub-mm population of galaxies in order to constrain their molecular gas masses, and hence their star-formation activity. We have concentrated on the sub-mm galaxies discovered during a survey toward rich, lensing clusters (Smail et al. 1998). This sub-mm survey has the advantage of having the several candidate counter-parts with accurate redshifts, and the sources are typically brighter than those found in other surveys due to gravitational amplification by factors of 2–3 from the foreground cluster. In addition, the observed flux ratios at different wavelengths should generally represent their intrinsic values since weak gravitational lensing from cluster potentials is independent of the size of the emission regions.
2. Results and Discussion

We have detected CO emission from two sub-mm systems (Fig. 1). The CO emission is coincident in both position and redshift with their optical counterparts, hence confirming their association with the sub-mm sources. The first source, SMMJ02399−0136 at z = 2.8 (SMM J02399), shows an AGN component in its optical spectrum (Ivison et al. 1998), while the second sub-mm galaxy, SMMJ14011+0252 at z = 2.6 (SMM J14011), shows only evidence for starburst activity at optical/NIR wavelengths (Ivison et al. 2000). Although the optical characteristics of these galaxies appear vastly different, their radio, sub-mm, and CO properties are fairly similar and are consistent with a high level of star formation activity (SFRs of a few×10^2 M_⊙ yr^{-1} to more than 10^3 M_⊙ yr^{-1}, depending on the IMF and AGN contamination). After correcting for lensing, we find CO luminosities of 3–4×10^{10} K km s^{-1} pc^2 (H_o = 50 km s^{-1} Mpc^{-1}; q_o = 1/2) in these two systems. These CO luminosities correspond to molecular gas masses of about 5×10^{10}–2×10^{11} M_⊙, depending on the exact value of the CO to H_2 conversion factor (e.g., Solomon et al. 1997). Both SMMJ02399 and SMM J14011 appear to be associated with a merger event. Given that mergers of gas-rich galaxies at low-redshift result in massive starbursts, we expect star-formation to be an important component for powering the far-infrared luminosities in both of these systems. In fact, the large molecular gas masses of SMMJ02399 and SMMJ14011 are sufficient to form the stars of an entire L^* galaxy, which suggests that the sub-mm population may represent the formative phase of massive galaxies.
3. Conclusions

SMM J02399 and SMM J14011 share many of the same properties of the local population of ULIGs, such as high infrared (IR) luminosities, associated with mergers, massive molecular gas reservoirs, comparable CO line widths, and similar IR/radio and IR/CO luminosity ratios. Given that low-redshift ULIGs tend to be comprised of massive starbursts with varying levels of AGN contamination (Sanders & Mirabel 1996; Genzel et al. 1998), we could expect to find similar results for the high-redshift sub-mm galaxies. If this is correct and since the sub-mm galaxies are so numerous (factor of $10^2$–$10^3$ times more numerous per comoving volume than low-z ULIGs), the sub-mm population is expected to contribute significantly ($\gtrsim 30\%$) to both the total amount of star-formation and AGN activity at high redshift. Future studies of this population with ALMA will help elucidate our general understanding of the formation and evolution of galaxies.

Acknowledgments. The observations presented here were done in collaboration with A. Evans, M. Yun, and SCUBA lens survey team of I. Smail, R. Ivison, A. Blain, and J.-P. Kneib. We thank J. Carpenter for assistance in developing the simulation code. We appreciated the efforts of our OVRO colleagues who have helped make these observations a success. The OVRO Millimeter Array is a radio telescope facility operated by the California Institute of Technology and is supported by NSF grant AST 96-13717.

References

Almaini, O., Lawrence, A., & Boyle, B. J. 1999, MNRAS, 305, L59
Barger, A. J., et al. 1998, Nature, 394, 248
Barger, A. J., et al. 1999, AJ, 117, 2656
Blain, A. W., Smail, I., Ivison, R. J., & Kneib, J.-P. 1999, MNRAS, 302, 632
Carilli, C. L., & Yun, M. S. 1999, ApJ, 513, L13
Eales, S. A., et al. 1999, ApJ, 515, 518
Frayer, D. T., et al. 1998, ApJ, 506, L7
Frayer, D. T., et al. 1999, ApJ, 514, L13
Genzel, R., et al. 1998, ApJ, 498, 579
Ivison, R. J., et al. 1998, MNRAS, 298, 583
Ivison, R. J., et al. 2000, MNRAS, in press (astro-ph/9911069)
Hughes, D. H., et al. 1998, Nature, 394, 241
Lilly, S. J., et al. 1999, ApJ, 518, 641
Sanders, D. B., & Mirabel, I. F. 1996, ARA&A, 34, 749
Smail, I., Ivison, R. J., & Blain, A. W. 1997, ApJ, 490, L5
Smail, I., Ivison, R. J., Blain, A., W., & Kneib, J.-P., 1998, ApJ, 507, L21
Smail, I., et al. 1999a, ApJ, in press (astro-ph/9907083)
Smail, I., et al. 1999b, MNRAS, 308, 1061
Solomon, P. M., et al. 1997, ApJ, 478, 144