CO OBSERVATIONS OF ULTRALUMINOUS INFRARED GALAXIES, QSOS, AND POWERFUL RADIO GALAXIES WITH THE 12M TELESCOPE

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1. Introduction

During the mid-1980s, the NRAO 12m telescope pioneered the first detections of CO in extragalactic sources at redshifts, $\Delta\lambda/\lambda$, of 0.03–0.2 . These observations strongly suggested that enormous supplies of molecular gas may be directly involved in the genesis of a wide variety of energetic phenomena, including ultraluminous infrared galaxies (ULIGs), quasi-stellar objects (QSOs), and powerful radio galaxies (PRGs). These detections of broad ($\Delta V_{\rm FWZI} \sim 400 - 800$ km s^{-1}), weak ($T_R^* \sim 1 - 3$ mK) lines using integration times typically less than 10 hours were made possible by low-noise, dual-channel receivers in the 80–115 GHz band and switching techniques that allowed extremely stable baselines over a relatively wide detector passband. Continued improvements in receivers have recently allowed the possibility of detecting CO luminosities equivalent to the most luminous objects observed locally ($z < 0.2$) at redshifts above 1. However, the required integration times (~60 hrs at the 12m telescope) may be near the limit of current single-dish performance.

2. The *IRAS* Galaxy Samples

CO observations at the 12m telescope of luminous infrared galaxies in the *IRAS* Bright Galaxy Survey (BGS) provided the first detections of extragalactic objects at $z > 0.03$. Ground-based optical observations of the most luminous BGS objects showed that the trigger for the enormous infrared luminosities was a strong interaction/merger. The most extreme objects (ULIGs), with infrared luminosities equivalent to the bolometric luminosities of QSOs, appeared to be powered by enormous nuclear starbursts

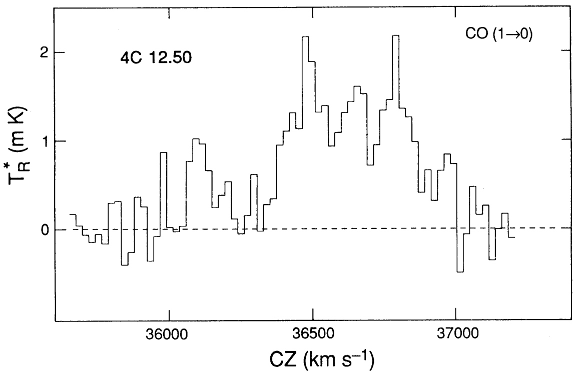

Figure 1. CO(1→0) emission from 4C 12.50 (from Mirabel et al. 1989).

and/or AGN (e.g., Sanders et al. 1988). CO observations suggested that the fuel supply was an enormous reservoir of molecular gas, typically 3–10 times the molecular gas content of the Milky Way (Sanders et al. 1991).

CO observations of a complete sample of ULIGs with 'warm' (S_{60}/S_{100}) infrared colors provided the first CO detections of objects at $z > 0.1$, including the remarkable detections of abundant molecular gas supplies in the optical QSOs Mrk 1014 and I Zw 1, in the infrared selected QSO IRAS 0759+6508, and in the PRG 4C 12.50 (see Figure 1 and refs. in the review of Sanders 1992). These objects display a clear mixture of powerful nuclear starburst and AGN properties, and they appear to represent a class of transition objects where the circumnuclear dust and gas have been dispersed enough to have a clear line of sight to the central AGN.

Further progress in understanding the role of molecular gas in the origin of QSOs and PRGs and the possible evolutionary connection to ULIGs would seem to depend heavily on our ability to obtain sensitive CO observations of a large sample of optically selected QSOs and radio selected PRGs. The recent detections of CO in 3C 48 (Scoville et al. 1993), in several low-z QSOs (e.g., Alloin et al. 1992), and in a sample of low-z PRGs (Mazzarella et al. 1993) show that molecular gas is indeed important in at least some of these objects. Observations of larger samples at higher redshift are clearly needed. There have been spectacular detections of the lensed object H1413+135 and the 'hyperluminous' infrared object IRAS F10214+4724 (which may also be lensed; see elsewhere this volume) at $z > 2$. Observations of additional high-z objects have been severely hampered, however, by both the lack of accurate systemic redshifts and the lack of sensitivity provided by the current generation of millimeterwave telescopes.

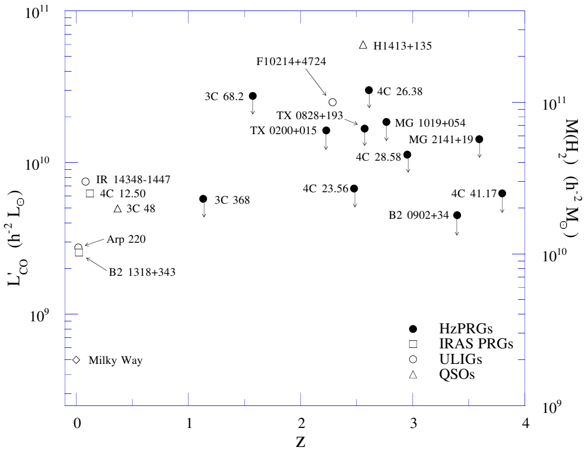

Figure 2. $L'_{\rm CO}$ and $M(\rm H_2)$ vs. z (from Evans et al. 1996). (↓) Upper limits.

3. High-Redshift Powerful Radio Galaxies

The recent availability of accurate redshifts for a substantial number of high-z powerful radio galaxies (HzPRGs) has allowed one of the first sensitive searches for CO at $z > 1$ to be carried out (Figure 2 and Evans et al., these proceedings). Although these observations have not yet yielded any CO detections, they have set meaningful upper limits that show that HzPRGs may contain less molecular gas than the most gas-rich objects observed locally. Further comment seems premature without knowing the relative molecular gas content of ULIGs, QSOs, and PRGs at high redshifts. However, CO observations of PRGs at lower redshift (Mazzarella et al. 1993) have already suggested that FR II sources (e.g. Cygnus A) have less CO luminosity than the most gas-rich FR I and core-dominated PRGs (e.g. 3C 120 and 4C 12.50). Our current CO observations of HzPRGs are consistent with the hypothesis that these objects may represent a terminal stage in the evolution of ULIGs and QSOs, one in which the powerful radio jets have helped to dissipate the gas fueling the central AGN.

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