A MOLECULAR GAS SURVEY OF $Z < 0.2$
INFRARED EXCESS, OPTICAL QSOS

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Abstract

Millimeter-wave (CO) observations of optically-selected QSOs are potentially a powerful tool for studying the properties of both the QSOs and their host galaxies. We summarize here a recent molecular gas survey of $z < 0.17$ optical QSOs with infrared (IR) excess, $L_{IR}(8 – 1000\mu m)/L_{bol}(0.1 – 1.0\mu m) > 0.36$. Eight of these QSOs have been detected to date in CO($1 \rightarrow 0$), and the derived molecular gas masses are in the range $1.7 – 35 \times 10^9 M_\odot$. The high $L_{IR}/L_{CO}$ of QSOs relative to the bulk of the local ($z < 0.2$) IR luminous galaxy merger population is indicative of significant heating of dust ($L_{IR}$) by the QSO nucleus and/or by massive stars created in the host galaxy with high efficiency (i.e., per unit molecular gas, $L'_{CO}$).

1. INTRODUCTION

Millimeter-wave (CO) observations of QSOs have not been a traditional means of studying the underlying QSO host galaxies. This is partially due to the fact that millimeter-wave telescopes and arrays with large ($\geq 500$ m$^2$) collecting areas and sensitive, low-noise receivers have only been available within approximately the last decade; prior to this time, single-dish and interferometric CO($1 \rightarrow 0$) observations of “distant” sources with faint mid- and far-IR flux densities, such as the $z < 0.16$ QSO Mrk 1014 (= PG 0157+001: Sanders et al. 1988a), were time-consuming ventures. As a result, it is not surprising that most of the advances in our understanding of QSOs have been achieved via observations obtained at other wavelengths (primarily optical and radio). The situation today is significantly different from what it was circa 1990 – millimeter arrays operated by Caltech, the Berkeley-Illinois-Maryland (BIMA) consortium, Nobeyama, and IRAM have five to six 10–15m diameter dishes with state-of-the-art receivers, and upcoming facilities such as the Smithsonian SubMillimeter Array (SMA), the Large...
Millimeter Telescope (LMT), the Combined Array for Research in Millimeter Astronomy (CARMA), and the Atacama Large Millimeter Array (ALMA) will provide additional telescope availability and sensitivity with which to conduct routine, large millimeter-wave surveys of distant galaxies in a variety of different molecular tracers (e.g., CO, HCN).

For the past few years, we have made use of the Owens Valley Millimeter Array (OVRO) to conduct a CO(1 → 0) survey of QSOs from the Palomar-Green (PG) Bright Quasar Survey (Schmidt & Green 1983). In the context of this meeting, the motivation for undertaking such a survey is three-fold: First, the rotational transitions of CO are tracers of star-forming molecular gas, thus strong CO emission from QSOs is an indication that their host galaxies have a significant cold molecular component to their interstellar medium (ISM). Massive galaxies that are known to contain such an ISM are spiral galaxies and ongoing IR-selected mergers, which typically have molecular gas masses in excess of $10^9 \, M_\odot$. In contrast, optically-selected, massive elliptical galaxies are intrinsically poor in molecular gas and dust, with typical molecular gas masses $< 10^8 \, M_\odot$. Second, in addition to fueling star formation, molecular gas in the host galaxy is a potential source of fuel for QSO activity. Thus, correlations between the distribution, kinematics and amount of molecular gas and the level of QSO activity may eventually aid in understanding the nature of mass accretion processes of QSOs. Third, there exists the possibility that some ultraluminous IR galaxy mergers (ULIGs: defined as having IR luminosities, $L_{IR}[8-1000\mu m] \geq 10^{12} \, L_\odot$) are the evolutionary precursors of QSOs (Sanders et al. 1988b). In such a scenario, ULIGs evolve from a molecular gas-rich, dust-enshrouded cool (i.e., 25$\mu$m to 60$\mu$m flux density ratio, $f_{25}/f_{60} < 0.2$) ultraluminous phase where vigorous star formation and accretion of significant amounts of mass unto the supermassive nuclear black hole have commenced, to a warm ($f_{25}/f_{60} \geq 0.2$) phase in which AGN signatures are visible (i.e., bright nuclei with near-IR colors consistent with a reddened QSO nucleus and Seyfert-like emission-line spectrum), then finally to an UV-excess QSO. This latter stage can only occur after significant consumption or clearing of molecular gas and dust from the nuclear region has occured, thus revealing the optical QSO nucleus. Given this, CO(1 → 0) observations of QSOs designed to search for residual amounts of molecular gas from an earlier ULIG phase may enable a direct comparison with the molecular gas content of IR luminous galaxy mergers.
2. IR-EXCESS, OPTICAL QSOS

In order to better facilitate comparisons with IR luminous galaxies, it was necessary to select a QSO sample for which accurate determinations of $L_{\text{IR}}$ could be made (i.e., QSOs that have IRAS\(^1\) detections at mid and far-IR wavelengths). The sample was thus chosen from a $z < 0.17$ IR-excess (i.e. IR to “big blue bump” luminosity ratio, $L_{\text{IR}}/L_{\text{bbb}}[0.10 - 1\mu m] > 0.36$) sample of 18 PG QSOs compiled by Surace & Sanders (2001).\(^2\) The IR-excess criteria of the sample thus selects the most likely “transition” candidates between the dust-enshrouded ULIG phase and the optical, UV-excess QSO phase.

While selecting QSOs with IR excesses introduces a bias, it must be remembered that 20–40% of the bolometric luminosity, $L_{\text{bol}}$, of PG QSOs is emitted at IR wavelengths (Sanders et al. 1989), thus the present sample of 18 QSOs simply populate one extreme of a fairly narrow “IR luminosity fraction” distribution.\(^3\) Still, the IRAS detection rate of spiral galaxies and ongoing mergers versus optically-selected elliptical galaxies is very high, and if the host galaxies of QSOs are a mixture of the above galaxy types, the “IR-excess” criteria will be biased towards selecting QSOs hosts that are spiral galaxies and ongoing mergers.

\(^{1}\)I.e., the Infrared Astronomical Satellite \\
\(^{2}\)The sample was selected by Surace and Sanders for the purpose of optical and near-IR imaging and is summarized in the Surace & Surace contribution to this proceedings. \\
\(^{3}\)See the Müller contribution to this proceedings for an updated discussion of PG QSO spectral energy distributions.

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\begin{array}{cccccc}
\text{Source} & z_{\text{phot}} & \log L_{\text{IR}} & \log L_{\text{BB}} & L_{\text{IR}}/L_{\text{MMB}} & z_{\text{CO}} & \Delta v_{\text{WHM}} \\
\text{PG 0807+106} & 0.089 & 11.63 & 12.21 & 0.36 & \cdots & \cdots & < 3.5 \\
\text{PG 0850+124} & 0.061 & 12.00 & 12.32 & 2.01 & 0.061 & 400 & 20 \\
\text{PG 0817+081} & 0.163 & 11.49 & 12.68 & 2.57 & 1.143 & 400 & 35 \\
\text{PG 0838+770} & 0.131 & 11.60 & 12.01 & 0.63 & 0.132 & 90 & 8.4 \\
\text{PG 1110+120} & 0.050 & 11.17 & 11.47 & 1.00 & 0.050 & 260 & 1.7 \\
\text{PG 1126-041} & 0.060 & 11.47 & 11.94 & 0.30 & \cdots & \cdots & < 1.4 \\
\text{PG 1202+291} & 0.165 & 11.78 & 12.07 & 1.05 & \cdots & \cdots & < 9.2 \\
\text{PG 1351+640} & 0.098 & 11.82 & 12.37 & 0.46 & 0.088 & 230 & 5.2 \\
\text{PG 1302+261} & 0.164 & 11.85 & 12.33 & 0.49 & \cdots & \cdots & < 4.9 \\
\text{PG 1415+451} & 0.114 & 11.48 & 11.83 & 0.80 & 0.114 & 50 & 6.1 \\
\text{PG 1440+336} & 0.079 & 11.62 & 11.95 & 0.87 & 0.078 & 370 & 8.0 \\
\text{PG 1613+058} & 0.129 & 11.99 & 12.20 & 1.38 & 0.129 & 490 & 20 \\
\end{array}
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\(^{a}\)Redshifts Based on Optical Emission Lines. \\
\(^{b}\)Calculated assuming $H_0 = 75$ km s\(^{-1}\) Mpc\(^{-1}\) and $q_0 = 0.5$. \\
\(^{c}\)Calculated assuming $\alpha = 4M_\odot$ [K km s\(^{-1}\) pc\(^2\)]\(^{-1}\). 3$\sigma$ root mean square (rms) upper limits are calculated assuming $\Delta v = 260$ km s\(^{-1}\).
Figure 1. CO(1 → 0) spectrum and integrated intensity map of the IR-excess QSO PG 1440+356. For the map, contours are plotted as $1\sigma \times (-2.3, 2.3, 3.3, 4.3, 5.3, 6.3)$; the peak intensity is $0.016 \text{ Jy beam}^{-1}$, and corresponds to the position RA=14:42:07.48 dec=+35:26:22.33 (J2000.0).

The sample of 18 QSOs contains two QSOs (Mrk 1014 = PG 0157+001 and I Zw 1 = PG 0500+124) that have been observed in CO multiple times with different millimeter telescopes, and two QSOs (PG 0838+770 and 1613+658) that have been observed once with the IRAM 30m telescope (e.g. Sanders et al. 1988a; Barvainis et al. 1989; Alloin et al. 1992). Thus far in the survey, PG 0838+770 and 1613+658 have been reobserved, and 8 additional IR-excess QSOs have been searched for CO(1 → 0) emission for the first time (see Table 1). Two transits were typically done per source; in terms of sensitivity, this corresponds to a $3\sigma$ rms molecular gas mass detection limit of $1 \times 10^9 M_\odot$ (assuming $\alpha = 4 M_\odot [\text{K km s}^{-1} \text{ pc}^2]^{-1}$) for a $z \sim 0.1$ galaxy with a CO velocity line width of 280 km s$^{-1}$.

3. MOLECULAR GAS PROPERTIES

Table 1 lists several properties of the 12 IR-excess QSOs observed in CO to date, and a CO(1 → 0) spectrum and integrated intensity map of one QSO (PG 1440+356) is shown in Figure 1. Eight QSOs have been detected thus far, with molecular gas masses in the range $1.7 - 35 \times 10^9 M_\odot$ and velocity line widths ranging from approximately 50 to 500 km s$^{-1}$. The molecular gas mass range of the detected QSOs indicates the
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Figure 2. A plot of $L_{\text{IR}}/L_{\text{CO}}'$ vs. $L_{\text{IR}}$ for the low-$z$ QSO sample, a flux-limited sample ($f_{60\mu\text{m}} > 5.24$ Jy) of IR luminous galaxies and a sample of ultraluminous IR galaxies. Arrows denote $3\sigma$ lower limits on $L_{\text{IR}}/L_{\text{CO}}'$ of PG 1126-041, PG 1202+281, and PG 1402+261.

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The presence of host galaxies with massive cold molecular components, but the upper limits of the remaining 4 QSOs yield inconclusive results.

In order to compare the CO($1 \rightarrow 0$) and IR properties of these QSOs and IR luminous galaxies, $L_{\text{IR}}/L_{\text{CO}}'$ versus $L_{\text{IR}}$ for both a sample of cool and warm IR galaxies, as well as the IR-excess QSOs, are plotted in Figure 2. The ratio $L_{\text{IR}}/L_{\text{CO}}'$ is commonly referred to as the star formation efficiency: in starburst galaxies, it is a measure of the cumulative luminosity of massive stars responsible for heating the dust ($L_{\text{IR}}$) relative to the amount of fuel available for star formation ($L_{\text{CO}}'$). The QSOs occupy the upper portion of the $L_{\text{IR}}/L_{\text{CO}}'$ distribution of IR luminous galaxies for a given value of $L_{\text{IR}}$; this is an indication that the QSOs contribute significantly to heating the dust in their host galaxies (thus increasing $L_{\text{IR}}$) and/or that the dust is heated by massive stars formed in the host galaxy with high efficiency (per unit molecular gas mass). The latter possibility may indicate that star formation accompanies mass accretion unto supermassive nuclear black holes, and might support recent observed correlations between black hole mass and both stellar bulge mass and velocity dispersion in nearby quiescent galaxies (e.g. Magorrian et al. 1998; Ferrarese & Merritt 2000; Gebhardt et al. 2000).
Also plotted on Figure 2 are the positions the QSOs would occupy if the optical QSO nucleus was completely enshrouded in dust (i.e., if $L_{IR} = L_{bol}$, as is the case for ULIGs). If QSOs are the evolutionary products of ULIGs, and if ULIGs are powered primarily by embedded QSO nuclei, then the area of Figure 2 covered by the lines connecting $L_{bol}/L'_{CO}$ to $L_{IR}/L'_{CO}$ for the QSOs show the possible paths that dust-enshrouded QSOs may follow as they evolve towards UV-excess QSOs.

4. THE FUTURE

This CO survey is the first attempt to detect molecular gas in a complete sample of QSOs, and it builds upon previous observations of $z < 0.17$ observations of QSOs done by other groups. There are several ways in which such a survey might be improved:

- The sample size is presently very small, and it is biased towards IR-excess QSOs. A large CO survey of a volume-limited sample of QSOs would give a more accurate assessment of the diversity in the molecular gas content of QSOs.
- These observations were done in low-resolution mode (4" beam) for the simple purpose of making CO detections of these QSOs. Higher resolution (0.5") CO(2 → 1) observations of the detected QSOs are required to determine the spatial distribution and detailed kinematics of the molecular gas. Recent CO observations by Schinnerer et al. (1998) have shown the CO in I Zw 1 (PG 0050+124) to be extended.

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