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Molecular Gas and Star Formation in Luminous IR Galaxies and QSO Hosts

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Abstract. Millimeter and radio-wave facilities built and operated by the NRAO have played a major role in increasing our understanding of the ISM and radio continuum properties of luminous IR galaxy (LIRGs) mergers and quasi-stellar object (QSO) hosts. This review focuses primarily on molecular gas (CO) surveys of the local ($z < 0.3$) population of both galaxy classes and the relevance of these observations to their star formation properties.

1. Introduction

While many galaxies were known prior to the 1980s to have IR excesses, it was the Infrared Astronomical Satellite (IRAS) all sky survey that enabled a large population of IR-excess galaxies to be discovered. The most luminous of these 'starburst' galaxies, the luminous and ultraluminous IR galaxies (LIRGs: $L_{\rm IR}[8-1000\mu{\rm m}] \geq 10^{11}$ L$_\odot$; ULIRGs: $L_{\rm IR} \geq 10^{12}$ L$_\odot$)[1], are optically observed to be primarily interacting or merging disk galaxies with luminous blue star clusters in the circum-nuclear region and extended tidal tails (e.g. Figure 1a). In addition, a significant fraction host optically visible Active Galactic Nuclei (AGN). The contribution of the optical emission to the bolometric luminosity of LIRGs is minimal, whereas the bulk of the energy emanates at mid- and far-IR wavelengths via dust heated by imbedded starbursts and AGN. Because dust masks much of the activity in LIRGs at optical wavelengths (e.g., Figure **??**), observations at X-ray, IR, radio, and millimeter wavelengths are necessary complements to optical studies, and enable (to the extent possible) a reconstruction of the distribution and energetics of sources within LIRGs. This line of reasoning is the basis for the ongoing **G**reat **O**bservatory **A**ll-sky **L**IRG **S**urvey (GOALS: `http://goals.ipac.caltech.edu`) which is a combination of Hubble Space Telescope, Spitzer Space Telescope, Chandra X-ray Observatory, and GALEX observing campaigns of a complete sample of LIRGs from the IRAS Revised Bright Galaxy Sample (RBGS: $f_{60\mu{\rm m}} > 5.24$ Jy; Sanders et al. 2003).

Interest in studying the local LIRG population has grown tremendously in the last 20 years. Much of the present-day research is primarily split between *(i)* studies making use of LIRGs as giant stellar nurseries to study star formation in extreme environments, and *(ii)* studies designed to test the hypothesis that QSOs are a transient phase in the evolution of ULIRGs into giant elliptical and

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[1] For simplicity, both LIRGs and ULIRGs will be referred to as LIRGs, except where the higher luminosity threshold is particularly meaningful.

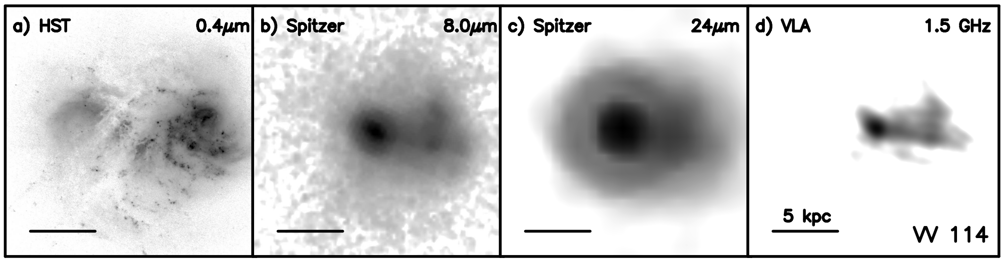

Figure 1. HST, Spitzer Space Telescope, and VLA images of the GOALS LIRG VV 114. The source of the bulk of the energy is obscured by dust at optical wavelengths, and is thus not visible in the $B-$band image.

S0 galaxies (Sanders et al. 1988a). The QSO–ULIRG evolutionary model was strengthened in the 1990s by evidence that all nearby massive galaxies host relatively quiescent supermassive nuclear black holes (SMBHs: e.g., Magorrian et al. 1998) – i.e., a pre-existing SMBH in the massive galaxy progenitors of ULIRGs need only be fed by infalling gas during the merger to become active. In addition, LIRGs are a significant population in a cosmological context – deep submillimeter imaging studies have provided compelling evidence that the light from distant LIRGs make up a substantial fraction of the IR background (e.g., Hughes et al. 1998; Barger, Cowie, & Sanders 1999). Thus, imbedded star formation and SMBHs built in mergers during their luminous IR phase may contribute as much as half of the total energy generated in the Universe since the Big Bang.

In the local universe, ULIRGs are only rivaled in terms of their bolometric luminosities by optically-selected Palomar Green (PG: Schmidt & Green 1983) QSO hosts. Many modern day studies of QSO hosts are motivated by the proposed evolutionary QSO–ULIRG connection; however, literature exploring the possibility that mergers and interactions trigger the observed nuclear activity in QSO hosts predate the "dust-enshrouded QSO" model of ULIRGs (e.g., Stockton & MacKenty 1983). Like LIRGs, QSO hosts are known to have significant IR excesses (with $\sim 2/3$ of the PG QSO hosts detected by IRAS: Sanders et al. 1989) and optical evidence of recent or ongoing star formation (e.g., Surace, Sanders, & Evans 2001; Canalizo & Stockton 2001).

The prodigious star-formation in LIRGs and QSO hosts is fueled by abundant supplies of molecular gas (H_2), which is traced by the millimeter rotational lines of CO, HCN, etc. Further, it stands to reason that the molecular gas is also the fuel for AGN activity. It is through observations of such molecular species, and through radio continuum observations of supernovae and AGN, and neutral hydrogen (HI) observations, that NRAO facilities have played a pivotal role in the study of both phenomena. The focus of this review is on the molecular gas (primarily CO) and star formation properties of both populations of galaxies.

This discussion is restricted to the relatively local, $z \leq 0.3$ LIRGs and QSO hosts. Elsewhere in this conference proceedings, Fabian Walter provides a summary of millimeter-wave molecular gas studies of their high-z counterparts. The reader is also referred to the review article by Solomon & Vanden Bout (2005) for a summary of CO in high-z galaxies.

2. CO as a Tracer of Molecular Gas

Stars are formed in clouds comprised mostly of molecular hydrogen. However, the hydrogen molecule has no permanent dipole moment, rendering it nearly invisible in the interstellar medium. As a result, the (sub)millimeter-wave rotational transitions of the abundant CO molecule, which are collisionally excited by H_2, are used to trace the distribution, kinematics and mass of cold H_2 in galaxies. The CO line is optically thick, thus the critical density required for collisions to be a significant process can be as low as a few hundred cm^{-3}.

The molecular gas mass can be determined if the CO(1→0) luminosity, $L'_{\rm CO}$, is known (see also Scoville et al 1987). The $L'_{\rm CO}$ of a molecular cloud is

$$L'_{\rm CO} = \pi R^2 T_{\rm CO} \Delta v, \tag{1}$$

where R is the cloud radius and $T_{\rm CO}\Delta v$ is the CO emission line flux. If the cloud is in virial equilibrium, it can be shown that the mass of the cloud is

$$M_{\rm cloud} = L'_{\rm CO} \left(\frac{4\rho}{3\pi G}\right)^{1/2} \frac{1}{T_{\rm CO}}. \tag{2}$$

The quantity $\rho^{1/2}/T_{\rm CO}$ is roughly constant, i.e., warm clouds have high densities, and cool clouds have low densities. Thus,

$$M_{\rm cloud} \sim \alpha L'_{\rm CO}, \tag{3}$$

where $\alpha \sim 4\ M_\odot$ (K km s^{-1} Mpc^2)$^{-1}$ for molecular clouds in the Galaxy. We will adopt this value of α for molecular clouds in LIRGs and QSO hosts.

3. Molecular Gas in LIRGs

The NRAO 12m telescope played a significant role in molecular gas observations of LIRGs in the 1980s. One of the landmark extragalactic observations made during this period was the detection of CO(1→0) in Mrk 231 (Sanders, Scoville, & Soifer 1987), the highest z ULIRG in the GOALS sample. The early 12m telescope observations of LIRGs culminated in the Sanders, Scoville, & Soifer (1991) publication. Independent single-dish surveys of large samples of LIRGs were done with the IRAM 30m (Solomon et al. 1997) and NRO 45m (Yao et al. 2003) telescopes. These surveys, along with papers covering fewer galaxies published over the same time period, showed LIRGs to contain up to several times the molecular gas mass of the Milky Way, providing evidence for sufficient fuel for extended, high luminosity starbursts and AGN activity.

In addition to the single-dish work, there is a rich literature of interferometric observations of LIRGs. Several large surveys (i.e., containing observations of 5–10 LIRGs) have been published, most notably the Plateau de Bure survey by

Downes & Solomon (1998) and the Owens Valley Millimeter Array (OVRO) survey by Bryant & Scoville (1999). A spatial comparison of the aperture synthesis CO maps of LIRGs with data obtained at other wavelengths has led to three compelling results. First, observations of a few late stage mergers (e.g. Arp 220, NGC 2623) have shown the bulk of their molecular gas to be within the inner kpc of the nucleus. These central concentrations can contain more molecular gas than the Milky Way, which has led to speculation that the CO emission is not contained in individual molecular clouds, but is instead a continuous distribution of gas (see Solomon et al. 1997). Second, for several double-nucleus LIRGs with nuclear separations greater than the resolution of the interferometric observations, the bulk of the CO emission is observed to be between the nuclei (VV 114, NGC 6240, NGC 6090, and II Zw 096: Yun, Scoville, & Knop 1994; Bryant & Scoville 1999; Taconni et al. 1999; Gao et al. 1999) likely as the result of ram-pressure stripping of gas during close passages of the nuclei. Third, in several double-nucleus systems with warm, Seyfert-like *IRAS* colors, the CO emission is observed to be associated with the dominant AGN nucleus (PKS 1345+12, Mrk 463, IRAS F08572+3915: Evans et al. 1999, 2002). These observations support the idea that molecular gas is the fuel for AGN activity, as well as star formation. Dynamical masses, $M_{\rm dyn}$, have also been derived from the interferometric data, and have been shown in some cases to be less than the H_2 mass derived using the standard Galactic α (Downes & Solomon 1998). The $M_{\rm dyn}$ can constrain α to be as low as 0.8 $M_\odot$ (K km s^{-1} Mpc^2)$^{-1}$. Such low values may be a result of significant fractions of the molecular gas in inter-cloud regions.

4. Molecular Gas in QSO Hosts

Another landmark extragalactic observation made with the NRAO 12m telescope in the late 1980s was the first CO(1→0) detection of a UV-excess QSO host – the $z = 0.16$ PG QSO Mrk 1014 (Sanders, Scoville, & Soifer 1988b). This observation was quickly followed by IRAM 30 telescope CO detections of the PG QSO hosts IZw1 (Barvainis, Alloin, & Antonucci 1989), PG 0838+770 and PG 1613+658 (Alloin et al. 1992), and the OVRO CO detection of 3C 48 (Scoville et al. 1993). Despite the early success in detecting CO in QSO hosts in the local universe, and the obviously intriguing possibility of associating luminous UV-excess AGN with molecular gas-rich host galaxies and star formation, further progress in CO surveys of local QSO hosts would not be made until the next decade. This is undoubtedly the result of the detection of CO in the $z = 2.3$ *IRAS* galaxy F10214+4724 (Brown & Vanden Bout 1991, 1992) – after this discovery, a significant fraction of extragalactic millimeter-wave telescope time was devoted to searching for CO in galaxies at high-z (> 2). These surveys pushed the (sub)millimeter-wave instrumentation and observational techniques to the limit, which has ultimately proven to be beneficial to studies of faint CO sources like the local QSO hosts.

The first "large" CO(1→0) survey of local PG QSO hosts made use of the collecting area of OVRO to observe ~ 10 hosts with known, *IRAS*-measured IR excesses (Evans et al. 2001). This survey was followed by a CO survey with OVRO of a volume-limited ($z < 0.1$) sample of PG QSO hosts (Scoville et al.

2003). Both OVRO surveys were detection experiments done in low-resolution mode, thus no information on the extent or detailed kinematics of the gas was derived (e.g., see Figure 2). A much larger volume-limited ($z \leq 0.3$) survey with the IRAM 30m telescope is currently underway (Evans et al., in preparation). To date, $\sim 1/3$ of the PG QSO hosts at $z \leq 0.3$ have been detected in CO. *Thus, a significant fraction of UV-excess QSOs reside in molecular gas-rich host galaxies.* This result is in line with the high success rate of detecting strong IR thermal dust emission in PG QSO hosts (Sanders et al. 1989; Haas et al. 2003).

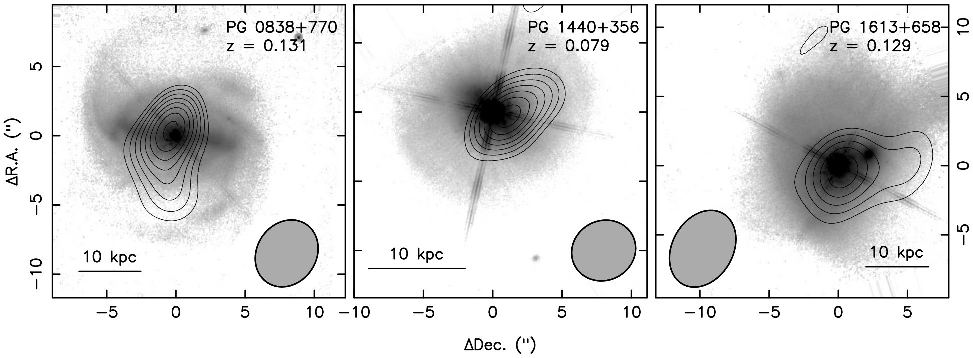

Figure 2. Grey scale HST NICMOS images of three PG QSO hosts. Aperture synthesis CO($1 \rightarrow 0$) contours, obtained with OVRO, are superimposed. The resolution of the OVRO data is $\sim 4-6''$, whereas the HST data is $\sim 0.2''$. The HST NICMOS data are from Veilleux et al. (in preparation).

Approximately 1/3 of the PG QSO hosts searched for CO(1→0) emission to date have not been successfully detected. Such non-detections do not necessarily indicate that the QSO host is molecular gas-poor. First, the local space density of QSOs is low, thus even the nearest QSO hosts are relatively distant (i.e., $z \geq 0.05$). As a result, their measured $L'_{\rm CO}$ 3σ upper limits can be as high as the $L'_{\rm CO}$ of the Milky Way Galaxy. Second, the available bandwidth for most 3mm CO observations to date is 512 MHz (~ 1400 km s^{-1} at 3mm). Thus, if the optical z of the QSO has been measured from emission lines that are produced in high-velocity outflows, the systemic z, and thus the z of CO, may lie outside the observed frequency range of the observations.

Examples of CO(1→0) spectra of QSO hosts are shown in Figure 3. Several conclusions can be drawn from the CO observations of QSO hosts obtained to date. First, the average CO emission line width ($\Delta v_{\rm FWHM} \sim 280$ km s^{-1}: Evans et al. 2006) of QSO hosts is comparable to that of ULIRGs (~ 300 km s^{-1}). If the extent of the CO emission and the distribution in disk orientations in QSO hosts are, on average, comparable to that of ULIRGs, then these gas-rich QSO hosts, as a class, reside in galaxies with masses similar to those of ULIRGs. Second, a few QSO hosts have extremely narrow ($\Delta v_{\rm FWHM} \sim 50-80$ km s^{-1}) line widths, consistent with the CO disk being observed nearly face-on. No such narrow CO emission lines have been observed for local radio galaxies, which are observed to have an average CO line width $\Delta v_{\rm FWHM} \sim 500$ km s^{-1} (Evans et al. 2005). Third, a few of the CO detections are of QSO hosts with smooth, featureless profiles, and thus the hosts are likely gas-rich, advanced merger hosts. Thus, CO

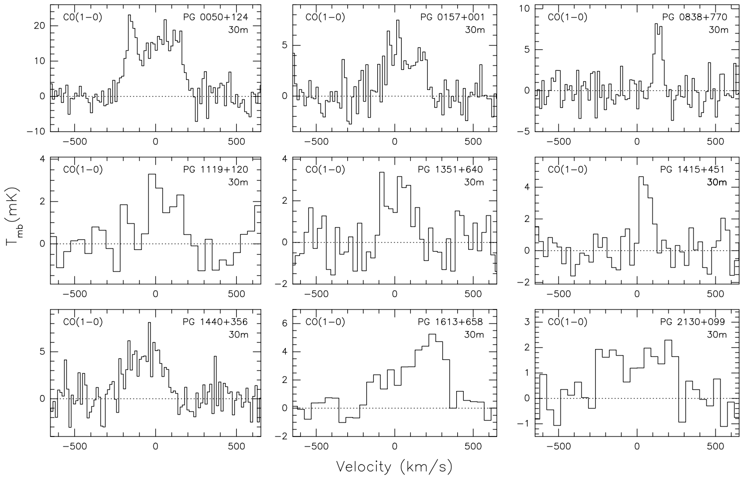

Figure 3. IRAM 30 Telescope spectra of 9 of the PG QSO hosts detected in CO to date. From Evans et al. (2006).

observations of QSO hosts may prove to be an essential complement to optical and near-IR imaging studies of the host galaxies of QSOs where the nuclear light obfuscates the ability to differentiate between an old, gas-poor elliptical host and advanced merger host.

5. The Importance of IR and Radio to Tracing Star Formation

The CO(1→0) surveys described above have thus provided evidence that LIRGs and many PG QSO hosts are molecular gas-rich. This immediately raises the question of whether the gas is fueling vigorous star formation. Addressing this issue requires a measure of the energy output from young, massive stars.

Standard diagnostics exist for estimating star formation rates (SFRs) via the X-ray, UV, optical, Hα, IR, and radio luminosities of galaxies (e.g., Kennicutt 1998). The usefulness of any individual diagnostic is dependent on the dust covering factor of the star-forming regions within the galaxy. E.g., although LIRGs are observed to contain numerous luminous blue star clusters (e.g., Figure 1a), the bulk of the star formation present is masked at optical wavelengths by dust obscuration. In addition, the optically visible star formation is often observed to be physically offset from the region where the bulk of the energy is generated; VV 114 is a prime example of this (Figure 1). As a result, the use of UV and optical diagnostics for estimating the total SFRs of LIRGs yields values that can easily be an order of magnitude or more too low. Rates calculated using IR luminosities, which trace the luminosity of imbedded sources, or radio luminosities, which (in part) trace synchrotron emission from supernovae, provide much more realistic estimates. The SFRs estimated for LIRGs from IR and radio luminosities are in the range of tens to hundreds of $M_\odot$ yr^{-1}. The IR or radio luminosity-derived SFRs are, however, likely overestimates due to the contribution of the AGN to dust heating and radio emission. The significance of the AGN contribution is the subject of great debate, and much extragalactic research spanning the observable electromagnetic spectrum has been (and continues to be) done to address this problem (e.g., the GOALS campaign).

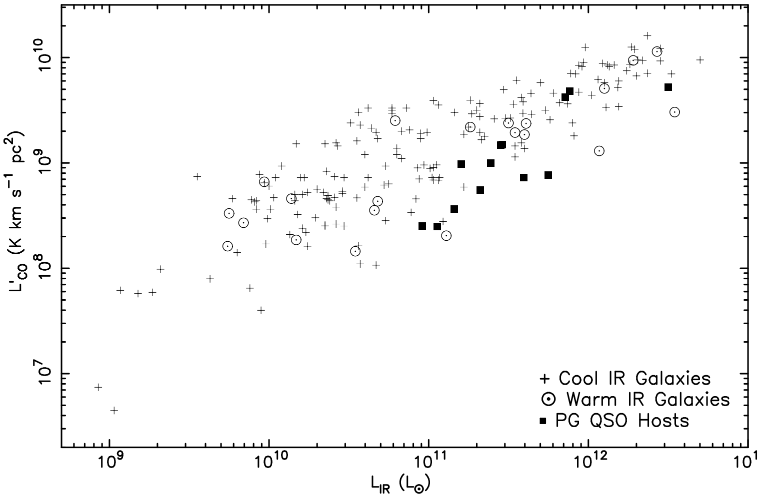

Figure 4. $L'_{\rm CO}$ vs. $L_{\rm IR}$ for CO-luminous QSO hosts and IRAS-detected galaxies. From Evans et al. (2006).

6. Star Formation Efficiencies

Given the usefulness of the IR or radio luminosities, relative to other diagnostics, to tracing star formation in luminous galaxies, it is instructive to compare one or both of these quantities to the $L'_{\rm CO}$ of galaxy samples spanning a large range in $L_{\rm IR}$. Figure 4 is a plot of the $L'_{\rm CO}$ vs. $L_{\rm IR}$ of CO-detected QSO hosts and a sample of "IR" galaxies (i.e., spiral galaxies and LIRGs). The IR galaxies have been divided into those with warm, Seyfert-like IR colors (i.e., $f_{25\mu{\rm m}}/f_{60\mu{\rm m}} \geq 0.2$) and cool, starburst-like IR colors. One feature that is immediately obvious from this plot is the low values of $L'_{\rm CO}$ in QSO hosts for their given $L_{\rm IR}$ relative to LIRGs with comparable $L_{\rm IR}$. Put another way, the QSO hosts have relatively high $L_{\rm IR}/L'_{\rm CO}$ ratios. For starburst galaxies forming stars in steady state, the quantity $L_{\rm IR}/L'_{\rm CO}$ is commonly referred to as the star formation efficiency – it is a measure of the luminosity from the embedded young stellar population (i.e., $L_{\rm starburst}$) normalized by the amount of molecular gas, $M_{\rm H_2}$, available for generating new stars. I.e.,

$$\frac{L_{\rm IR}}{L'_{\rm CO}} = \frac{L_{\rm starburst}}{(M_{\rm H_2}/\alpha)}. \tag{4}$$

This expression is almost certainly too simplistic for both QSO hosts and LIRGs, especially given the compelling evidence that all nearby, massive galaxies host SMBHs. A certain percentage of the $L_{\rm IR}$ from QSO hosts and LIRGs is due to dust-heating by an AGN, i.e.,

$$\frac{L_{\rm IR}}{L'_{\rm CO}} = \frac{(L_{\rm starburst} + \epsilon L_{\rm AGN})}{(M_{\rm H_2}/\alpha)}, \tag{5}$$

where $L_{\rm AGN}$ is the AGN luminosity and ϵ is the fraction of the AGN light that is absorbed by dust and reradiated in the IR. The high $L_{\rm IR}/L'_{\rm CO}$ of the QSO hosts is thus indicative of either *(a)* an extremely high star formation efficiency (i.e., $\epsilon \sim 0$) or *(b)* a significant contribution of dust-heating by the AGN ($\epsilon \gg 0$).

7. Star Formation Rates of PG QSO Hosts

As is clear from §6, estimating SFRs of QSO hosts (as for LIRGs) requires the non-trivial task of disentangling AGN and starburst contributions to the IR or radio emission. Attempts to assess their global SFR include the following:

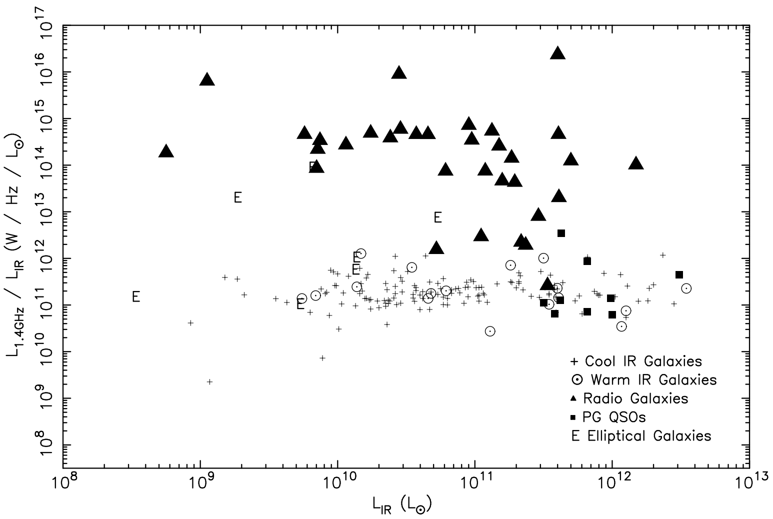

Figure 5. $L_{1.4\rm GHz}/L_{\rm IR}$ vs. $L_{\rm IR}$ for the sample of PG QSO hosts, IRAS galaxies, radio galaxies, and elliptical galaxies. The host with the highest $L_{1.4\rm GHz}/L_{\rm IR}$ actually contains a radio-loud quasar. From Evans et al. (2005).

The IR – Radio correlation: Figure 5 is a plot of the 1.4 GHz radio-to-IR luminosity ratio, $L_{1.4\rm GHz}/L_{\rm IR}$, versus $L_{\rm IR}$ of a sample of PG QSO hosts (Evans et al. 2005). For comparison, a sample of radio galaxies, CO-detected elliptical galaxies, and IR galaxies are also plotted. The IR galaxies occupy a narrow strip in $L_{1.4\rm GHz}/L_{\rm IR}$ – this "IR–radio correlation" is considered to be evidence that the starburst responsible for heating the dust (and thus producing $L_{\rm IR}$) also produces the supernovae that generate the observed radio emission. The 1.4 GHz contribution from AGN radio jets in the radio galaxy population causes an increase in their $L_{1.4\rm GHz}/L_{\rm IR}$ relative to that measured for IR galaxies. As is clear in the plot, the PG QSO hosts obey the IR–radio correlation of IR galaxies. Thus, either star formation contributes significantly to the IR and radio emission in PG QSO hosts, or the IR and radio emission from the AGN "conspire" in such a way as to produce starburst-like ratios.

The IR – HCN Luminosity Ratio: Another possible way to estimate the contribution of stars to $L_{\rm IR}$, and thus to calculate the star formation rate, is to compare the IR-to-HCN luminosity, $L_{\rm IR}/L'_{\rm HCN}$, ratio of QSO hosts with that of LIRGs with cool IR colors (Evans et al. 2006). Unlike the $L_{\rm IR}/L'_{\rm CO}$ ratio, the $L_{\rm IR}/L'_{\rm HCN}$ is observed to be relatively constant as a function of $L_{\rm IR}$ (Gao & Solomon 2004) – a median value of $L_{\rm IR}/L'_{\rm HCN} \sim 890^{+440}_{-470}$ $L_\odot$ (K km s^{-1} pc^2)$^{-1}$ is observed for $L_{\rm IR} \sim 10^{10.0-12.3}$ $L_\odot$ galaxies with cool, starburst-like IR colors. The likely reason for this is that HCN, which traces much denser ($n_{\rm H_2} \geq 10^4$ cm^{-3}) H$_2$ than CO ($\sim 10^2$ cm^{-3}), is a better probe of the gas which fuels starbursts, and is thus more tightly correlated with $L_{\rm IR}$. Given this, an increase in the $L_{\rm IR}/L'_{\rm HCN}$ in QSO hosts over what is observed for cool *IRAS* galaxies would indicate the amount of the $L_{\rm IR}$ produced by AGN dust heating. I.e.,

$$\frac{L_{\rm IR}}{L'_{\rm HCN}} = \frac{L_{\rm starburst} + \epsilon L_{\rm AGN}}{(M_{\rm H_2}/\alpha)} \sim {\rm constant} + \frac{\epsilon L_{\rm AGN}}{(M_{\rm H_2}/\alpha)}. \tag{6}$$

where the “constant” is 890^{+440}_{-470}. The practical difficulty of making use of $L_{\rm IR}/L'_{\rm HCN}$ is that HCN lines faint relative to CO – only one of the PG QSO hosts (IZw1) was detected in our recent HCN survey with the IRAM 30m Telescope. For IZw1, the $L_{\rm IR}/L'_{\rm HCN}$ ($= 2300$) is enhanced over what is observed for the cool *IRAS* galaxies, however, if the far-IR luminosity, $L_{\rm FIR}(40-500\mu{\rm m})$, is used instead, the $L_{\rm FIR}/L'_{\rm HCN}$ of IZw1 is close to the median $L_{\rm FIR}/L'_{\rm HCN}$ of the cool *IRAS* galaxies. A similar result is obtained for most of the warm LIRGs with HCN measurements. This is a tentative indication that, in *some* luminous AGN hosts, star formation is responsible for a moderate amount of the total mid-IR emission, but practically all of the far-IR. This result agrees with the Spitzer IRS analysis of PG QSO hosts (Schweitzer et al. 2006), and translates into SFRs of a few to tens of $M_\odot$ yr^{-1} for the QSOs detected in CO to date. Again, these results are tentative, and it is worth stressing that there are models that can account for the $L_{\rm IR}$ solely via dust-heating by a QSO embedded in a warped or clumpy torus (e.g., Sanders et al. 1989; Haas et al. 2003, and references therein).

8. The ALMA Age

Millimeter-wave observations of LIRGs and QSO hosts to date have laid the foundation for more extensive studies to be done with ALMA. The Array will have the sensitivity, resolution and speed to enable transformational science in almost all fields of astronomy, and will provide an essential bridge with wavelengths for which high-resolution observations have long been the standard. In terms of LIRGs and QSO hosts, the key science from ALMA observations is hard to presently predict, however, two obvious observational programs are:
i) High resolution CO and dust continuum observations of PG QSO hosts and LIRGs: ALMA will make it possible to obtain CO and dust continuum observations with HST-like resolution, allowing for a direct comparison with features observed in both HST and JWST data. The continuum observations are clearly important for helping to pin down the distribution of sources which may be producing the bulk of the far-IR emission. In addition, high resolution observations of fainter lines (e.g. HCN and HCO$^+$) will be possible even in faint

sources like the PG QSO hosts. Fundamental issues such as the importance of nuclear molecular gas to fueling AGN activity in both QSO hosts and LIRGs will finally be within reach. Such ALMA observations are an essential missing piece to surveys such as GOALS.
ii) Multiple Transition Observations of Molecular Species: Detailed molecular chemistry studies will be possible with ALMA. This will enable more accurate determinations of the temperature, density and kinematics of molecular gas associated with optical and IR-visible star-forming regions, AGN, and extended features such as bars, bridges and tidal tails. Such studies will make it possible to tighten the connection between molecular gas chemistry and the properties of star formation and AGN activity derived at other wavelengths.

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