MILLIMETER-WAVE SPECTROSCOPY AND MAPPING OF QUASAR HOSTS, AND THE STATUS OF ULIRGS AS QUASAR 2S

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ABSTRACT

It is becoming possible to detect high redshift quasars in various molecular lines, and to show by mapping lensed objects that the strong dust and molecular emission arises in warm dense \( \sim 100 \) pc-scale “tori.” The properties of ULIRGs, at least those with AGN-like narrow line regions, are very similar, as expected in the hidden quasar hypothesis. Several of the latter are in fact confirmed as “Quasar 2s” by spectropolarimetry.

INTRODUCTION: DETECTIONS OF MOLECULES IN QUASAR HOSTS

Millimeter-wave observatories are just now reaching the sensitivities and spatial resolutions required for studying nuclear molecular tori and host galaxies associated with quasars. In the late 1980s and early 1990s, the mm and submm dust continuum was detected in some low-redshift (\( \sim 0.1 \)) quasars (e.g. Chini et al. 1989, Barvainis et al. 1992). Subsequent spectroscopy showed strong CO emission, as expected for luminous dusty sources (e.g. Sanders et al. 1988; Barvainis et al. 1989b; Alloin et al. 1992).

In general the detections and limits similar to those for ultraluminous infrared galaxies at the same far-IR luminosity [Alloin et al. 1992, Figure 3]. This supports the notion that ultraluminous IRAS galaxies harbor hidden quasars. Spectropolarimetric observations have shown this to be true in many cases, and furthermore that the quasars are not “buried” but are visible from other directions.

DETECTIONS AT HIGH REDSHIFT

Following breakthrough detections of the ultraluminous IRAS galaxy F10214+4724 (Brown and vanden Bout 1992, Solomon et al. 1992b), our group studied the Cloverleaf quad lens BAL quasar in various lines (Barvainis et al. 1994, 1997), including deep high resolution mapping in the CO 7-6 line (Alloin et al. 1997, Kneib et al. 1998; See Yun et al. 1997 for an earlier OVRO image).

\(^1\)Kennicutt (1990) has extended the L(CO) - L (FIR) correlation for galaxies by adding points for a burning cigar, a Jeep Cherokee, the 1988 Yellowstone National Park forest fire, and Venus. I think the lesson is you get correlations in luminosity - luminosity plots (even without any sample incompleteness) just because big things have more of everything. There is probably a good correlations between the number of bookstores in a city and the number of bars, even with a complete sample, but no direct connection is necessarily implied. However, there is much other evidence that the IR continuum in quasars is dust emission (e.g. Barvainis 1992), and that it is intimately related to the molecular emission (e.g. Alloin et al. 1992.)
The last two years have brought detections of BR 1202-0725 at \( Z=4.7 \) (Ohta et al. 1996, Omont et al. 1996), 53W002 at \( Z=2.3 \) (Scoville et al. 1997), MG 0414+0534 at \( Z=2.6 \) (Barvainis et al. 1998), BRI 1335-0415 at \( Z=4.4 \) (Guilloteau et al. 1998), and APM 08279+5255 at \( Z=3.9 \) (Downes et al. 1998).

Two factors have enabled the detection and study of high-redshift dust and molecular emission, aside from rapid increases in instrumental sensitivity and resolution. The K-correction term is so favorable for this situation that the continuum and line fluxes are both flat or increasing with redshift! And in most of the detected objects the fluxes are greatly boosted by gravitational lensing. Prospective improvements in instrumental sensitivity can do the amplification job that lensing does so that soon the early universe of (relatively) ordinary objects will be revealed (e.g. Barvainis 1996); it will take a little longer to do without the lensing magnification of the angular sizes, required for resolving much of the emission.

**SUMMARY OF MILLIMETER OBSERVATIONS OF THE CLOVERLEAF QUAD LENS QUASAR**

All of the high-Z CO detections warrant follow-up observations of other millimeter lines in order to evaluate the molecular and atomic masses as well as the physical conditions. Mapping with reasonable velocity resolution also provides a wealth of information on morphology and dynamics. These follow-up observations are in advanced stages only for F10214+4724 at \( Z=2.3 \) and for the Cloverleaf quad at \( Z=2.6 \).

When F10214+4724 was first discovered, because of its incredible reported luminosity and the simultaneity with a certain geopolitical event, I started thinking of it as the Mother of All IRAS Galaxies. The original reported CO J=2-1 luminosity, in Brown and vanden Bout 1991, is \( L_{\text{CO}} = 1.9 \times 10^{10} h^{-2} L_\odot \). This is stated to be 15,000 times the Milky Way value. The corresponding \( H_2 \) mass would then be \( 1.8 \times 10^{13} h^{-2} L_\odot \) for \( q_0=1/2 \), if the conversion factor is similar to that of Galactic molecular clouds. However, since then the CO flux (Radford et al. 1996), the luminosity distance (Solomon et al. 1992a), and probably the CO-to-\( H_2 \) conversion factor (see e.g. Solomon et al. 1997, Barvainis et al. 1997) have been revised downwards substantially; also the lensing amplification was recognized and corrected (e.g. Radford et al. 1995, Green and Rowan-Robinson 1996). Thus the point for F10214 or the \( L(\text{CO}) \) vs \( L(\text{FIR}) \) plot of Kennicutt 1990 has now moved to just above the point representing the Jeep Cherokee.

The bulk of the CO emission in F10214 comes from a \( \sim 1'' \) source (e.g. Downes et al. 1995, Scoville et al. 1995) and the same is true for the Cloverleaf (Yun et al. 1997, Alloin et al. 1997, Kneib et al. 1998).

The best mapping data on the Cloverleaf CO is that of Kneib et al.; it has better surface brightness sensitivity, especially to \( \sim 1'' \) extended emission, than Alloin et al., and substantially better sensitivity and resolution than Yun et al. The maps detect the four images very well, and resolve each one individually. As interpreted by Kneib et al. with a detailed and fairly well-constrained lens model, the source must be intrinsically quite small - only \( \sim 100 \text{ pc} \) in radius for \( h = 0.5, \ q_0 = 1/2 \). (This size constraint and the observed flux requires that \( T_B \gtrsim 40\text{K} \); the \( T_B \) constraint deduced from modeling below requires that the radius is at least 40pc.) It is possibly rotating, although an unrelaxed merger is also a plausible interpretation. The interior dynamical mass is of order \( 10^9 h^{-1} M_\odot \). This compares with a deduced molecular and atomic mass of a few times \( 10^{10} m^{-1} h^{-2} M_\odot \), where \( m \) is the lens amplification (Barvainis et al. 1997), and a minimum black hole mass of \( \sim 1 \times 10^9 m^{-1} h^{-2} M_\odot \) by the Eddington limit argument. New observations of another dusty lensed BAL at even higher redshift, APM 08279+5255 at \( Z=3.9 \), paint a very similar picture for that object (Downes et al. 2005).

\[ \text{This type of data is helpful for constraining macrolensing parameters. Unlike in the optical, the mm images are unaffected by variability, microlensing, and foreground extinction.} \]
With this size scale and gas mass, we are clearly talking about nuclear gas rather than the distributed gas of a protogalaxy. This gas may be analogous to that seen in nearby luminous AGN such as NGC 1068 (Planesas et al. 1991, Jackson et al. 1993, Tacconi et al. 1994). In both cases it probably plays the role of the (outer part of the) dusty torus invoked in Unified Models for AGN (Antonucci 1993). The spectral energy distributions of the Cloverleaf and F10214 are remarkably similar in the far-IR, with the differences very well explained as resulting from absorption and scattering (Barvainis et al. 1995). The scattered UV light in F10214 reveals a hidden quasar (Goodrich et al. 1996), so it seems certain that that object appears as a quasar from some other directions in space. Again this is generally consistent with a simple and far-reaching Unified Model, in which many ultraluminous IRAS galaxies are simply “Quasar 2s,” the high luminosity extension of the Seyfert 2s. The optical light from F10214 is mainly from the reflecting mirror or periscope familiar from studies of local Seyfert 2s, other luminous IRAS galaxies, and distant narrow line radio galaxies.

Our group has also made a rather detailed multi-line observational and theoretical study of the integrated emission from the Cloverleaf (Barvainis et al. 1997). Four lines from the CO ladder have been observed well: J = 3-2, 4-3, 5-4 and 7-6. The line brightness temperatures seem to rise with J and then fall off, suggesting warm dense gas of only moderate optical depth. This would imply high effective emissivity and thus a fairly low molecular mass for the observed CO luminosity. Since systematic observational errors are still possible, the relatively low optical depths shouldn’t be considered proven. (\(^{13}\)CO might be detectable and provide a more reliable molecular mass.) The strong CI line implies a large atomic mass, larger than that of \(H_2\) (assuming the moderate optical depths for CO). An HCN detection needs confirmation, but is at the level expected based on ultraluminous IRAS galaxies; of course it requires a considerable mass of gas which is quite warm and dense. The physical conditions and masses inferred from this multi-line study are in accord with the 100-pc scale nuclear “torus” suggested by the direct imaging.

**RELATIONSHIP OF ULTRALUMINOUS IRAS GALAXIES TO QUASARS**

In the 1970s it was commonly held that there must be few if any “Quasars 2s,” that is, objects with just narrow emission lines, but as luminous as quasars. But the Seyfert 2 optical continua are generally dominated by the light from old stellar populations, so they wouldn’t scale up with luminosity of the central engine. It’s true that Quasar 2s would have luminous narrow lines, but the narrow line equivalent widths go down as luminosity increases in Type 1 AGN, so the NLR luminosities of the Quasar 2s might not be huge. The point is that Quasar 2’s would not be so easy to find.

In the Unified Model, claimed to be correct “to zeroth order” (Antonucci 1993), all AGN are surrounded by obscuring tori which probably have dust opacity dominating in the optical region of the spectrum. These hide the nuclear continuum and broad line region in the 2’s. The waste heat from the tori appears in the IR, and while it may not scale exactly with luminosity if the torus opening angle is changing, it should still be conspicuous in Quasar 2s. This is strongly supported by the rather well established dust emission in quasars: it accounts for \(\sim 30\%\) of the luminosity in UV-selected objects (e.g. Sanders et al. 1989). This further implies that if the tori are opaque and if they produce most of the FIR (as is very likely in the Cloverleaf, for example), then the torus covering factor is typically \(\sim 30\%\); thus there should be twice as many Quasar 1s as 2s at a given value of an isotropic parameter such as far-IR (but *not* bolometric) luminosity. A Quasar 2 should also show Seyfert-like narrow lines ratios, with strong emission from low-ionization species such as [OI] and [NII], and also from high ionization species such as [OIII].

These expectations are borne out for a large fraction of ultraluminous IRAS galaxies. At the highest luminosities at least half have Seyfert 2-like narrow line ratios (e.g. Kim et al. 1998; see also Surace
and Sanders 1998 for the finding that all twelve ULIRGs imaged at 2.1µ show strong point sources which they attribute to hidden AGN). In many cases, the polarized flux spectrum has been measured and it shows the Type 1 nucleus. The space densities of ultraluminous IRAS galaxies and quasars are approximately consistent with the above expectations (Gopal-Krishna and Biermann 1998). The same is true on the radio loud side, with a large fraction of the most luminous 3C radio galaxies already shown to be quasars in polarized flux, with polarization position angle indicative of polar scattering as in the Seyfert 2s, and consistent with the Unified Model. Again at least for the most luminous and distant objects, the space densities of Type 1 and Type 2 radio loud AGN are consistent with expectations (Barthel 1989).

What I’d like to do with the remainder of this section is to discuss some issues which have arisen in the literature recently, attempting to be as disagreeable as possible.

Let’s consider whether ISO and ASCA have anything to say whether ultraluminous infrared galaxies contain optically obscured AGN, and whether AGN or starbursts contribute more than 50% of their power. In general I think it is an unjustified assumption that you can see through to the nucleus in the mid-IR. Soon after the polarized light trick revealed hidden Type 1 nuclei in Seyfert 2s and narrow line radio galaxies (results published in 1982-1985), it was recognized that the nuclear x-rays in the Type 2s must be blocked by the tori (Antonucci 1984), and that the tori are thus Compton thick in many cases (Krolik and Begelman 1986). The lack of broad Br in total flux in NGC1068 provides a similar constraint (Aν > 10^100). Molecular mapping of NGC1068 (references given above), and for example Arp220 (Scoville, this meeting), confirm it.

More recently x-ray spectra (many papers by Awaki, Koyama and others) showed columns of 10^{23} cm^{-2} to > 10^{24} cm^{-2}, including some Compton-thick cases. Maiolino et al. (1998) argue persuasively that these earlier studies selected preferentially the lowest column densities by selecting objects with known polarized broad lines. The latter are known to have relatively highly inclined tori (warm IR colors) in the Unified Model (e.g. Heisler et al. 1997 and several important references therein). In any case the other bright Seyfert 2’s have much larger columns with many Compton thick examples found (Maiolino et al. 1998). Therefore, going to the mid-IR does not penetrate such tori in general. There may be cases in which a high sight line or a “nonstandard” dust distribution allows such penetration, but it certainly shouldn’t be generally assumed. In fact if the tori contain star forming regions, mid-IR spectra should show HII-region line ratios.

One can make quantitative (though model-dependent) arguments that the power in certain mid-IR emission lines implies a certain total starburst contribution to the luminosity. But in order to prove the starburst contributes most of the luminosity (which means > 50%) you’d need to show that the observed feature correlates with starburst bolometric luminosity with a very small dispersion. Similarly a Seyfert-like x-ray source proves that the AGN dominates the bolometric luminosity only if the two can be shown to correlate with a sufficiently small dispersion.

Of course ISO spectra can and do sometimes reveal Seyfert-like narrow line regions in some Compton thick AGN for the same reason optical spectra do: the NLR extends above the torus. In fact they seem to be the same objects - so it’s not clear what ISO has added to this particular question.

It is sometimes said that the mid-IR colors of many ULIRGs are too cool for hidden AGN, but this assumes a small outer radius for the tori. It is argued by Genzel et al. (1998) that larger tori are implausible, or tightly constrained by molecular line observations in some cases. For Seyfert 2s, Maiolino et al. (1995), Section 4.3, similarly find that the Type 2s are cooler than expected, though in that case they have first removed the warm ones preferentially by excluding those with easily

3It follows that the 12µ-selected sample studied by Malkan and collaborators, designed to be isotropic and still seemingly claimed to be so, is in fact highly anisotropic. See e.g. Rush et al. (1996).
detected Type 1s in polarized flux.

G. Rieke stated at the Tucson meeting on the Galactic Center (Sept. 1998; proceedings will emerge eventually) that ULIRGs have $L_{BOL}/L_{Eddington}$ up to $\sim 0.1$ (assuming black holes with 0.5% of the bulge mass), versus up to $\sim 1.0$ for quasars. This was interpreted as showing that ULIRGs are not hidden quasars. It does rule out ULIRGs as buried quasars, where by that I mean quasars with unity dust covering factor. But I believe it is just what we would expect for Quasar 2s. First in that case $L_{BOL}$ is anisotropic by a factor of 3 or so just because the big blue bump is obscured in the 2s (based on the PG-quasar SEDs and the relative space densities, both cited above). And second, $L_{BOL}$ is anisotropic because the IR itself is also anisotropic by a factor of $\sim 3$ according to the models cited earlier for these extremely opaque tori. (I think the mere fact that Seyfert 2’s and ULIRGs which would be seen as type 1s from other directions (the spectropolarimetry argument) have steeper IR spectra than other type 1’s proves the IR is highly anisotropic.)

On another topic, I wonder if there is any evidence for an evolutionary merger sequence between quasars and ULIRGs, as proposed, for example, by Sanders et al. 1989. In one variant of the idea, using data on ULIRGs only, those dominated by starbursts would correspond to earlier merger stages than those dominated by AGN. Suppose, optimistically, that the few-keV ASCA spectra and the ISO mid-IR spectra do diagnose correctly by the line emission which is the primary energy source. (This is fairly similar to classifying by the optical spectra in any case, as explained above.) The predicted effect is not seen so far, using ASCA (T. Nakagawa, this meeting), or ISO (Genzel et al. 1998) classifications.

A related hypothesis can accommodate the possibility that all ULIRGs (with Seyfert-like narrow line spectra) would look like quasars if oriented differently. It certainly seems reasonable that the ULIRGs or Seyfert 2s would tend to have larger covering factors (smaller torus opening angles) than quasars. And the dust configurations, with their large scale heights, may be very much nonequilibrium configurations, and in fact they are only thought to be geometrical tori “to zeroth order”. Has anyone tried to evaluate statistically the relative merger stage of ULIRGs and quasars?

As a final comment, it is often stated that the light from the nuclei in Seyfert 2s and ULIRGs may be hidden by a warped thin disk or some other configuration rather than a thick disk. We do know that in some cases the nucleus is hidden by dust in the host plane, and not by a nuclear torus. This crucial point was made by Keel 1980, Lawrence and Elvis 1982, de Zotti and Gaskell 1985 and many others. Implications for tests of Unified Models are discussed in Antonucci 1993, See 2.2, and Antonucci 1998.

But in most cases a thick torus, tipped with respect to the host, is indicated by a high optical polarization oriented perpendicular to a tipped radio jet. It is a mistake to assume that the low reported broadband polarizations for some 2s are indicative of the polarization of the scattered photons. Even after removal of the light from the old stellar populations, we know that there is a diluting continuum source, called FC2 by J. Miller and collaborators (e.g. Tran 1995). It was made clear in all the polarization papers that 1) the broad line polarizations are very high - usually just a lower limit is available because the broad line can’t be seen clearly in total flux; and 2) the broad line equivalent widths in the polarized flux spectra are normal. Thus in every case a normal Type 1 nucleus is revealed in polarized flux, and the scattering polarization is very high. One misapplication of the data, claimed to argue against the thick disk for optical obscuration, is in Malkan et al. 1998; see Antonucci 1998 for other demurs regarding that paper.

Of course the only sense in which the obscurers are claimed to be geometrically thick toris is that the optical photons can only escape in the polar directions.
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