Mem. S.A.It. Vol. 79, 1083

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Gas dust and starbursts in the central kpc of Active Galactic Nuclei

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Abstract. This review describes the properties of several components in the central kpc of active galactic nuclei (AGN) and points to old, as well as recently found relationships between dust gas and luminous starbursts in those regions. The spectroscopic properties of the broad line gas are becoming the main source for obtaining black hole mass, accretion rate and metalicity with important implications to AGN evolution. The central torus is the focus of numerous mid-infrared spectroscopic studies suggesting, in some cases, a two component origin for the spectrum: the torus itself and an additional contribution from a dusty narrow line region gas. Finally, luminous starburst regions seem to be associated with luminous AGN resulting in a significant L(starburst)-L(AGN) correlation over four orders of magnitude in luminosity. Such starbursts are not likely to be located in the central kpc. The correlation is difficult to explain and is a new important source for estimating AGN and starburst duty cycles at all redshifts.

Key words. Galaxies: active – Galaxies: QSOs – Galaxies: starburst – infrared: galaxies

1. Introduction

Among the various ways to deduce the properties of gas and dust in the central kpc of active galactic nuclei (AGN), spectroscopy is perhaps the best, especially for high redshift objects where the spatial resolution is limited. Thus, optical and ultraviolet spectroscopy is a powerful tool for deducing the physical conditions in the accretion disk, in the broad line region (BLR) in the narrow line region (NLR) of such sources. Similarly, mid-infrared (MIR) spectroscopy provides useful information about dust emission from the torus as well as from the the NLR.

This review describes, briefly, several of the important inferences obtained from spectroscopy of various emitting regions in AGN, from just outside the central accretion disk to way beyond the NLR. The physical sizes of most components scale roughly with $L^{1/2}$ thus a more proper title should perhaps be "Gas dust and starbursts in the central $L_{45}^{1/2}$ kpc of Active Galactic Nuclei", where L_{45} is the optical luminosity (λL_λ at 5100Å) in units of 10^{45} ergs s^{-1}.

2. Broad emission line clouds: optical-UV spectroscopy

Properties of the broad emission line gas are routinely extracted from their optical-UV spectrum. These include gas density and column density, gas dynamics, covering factor and even metalicity (e.g. Hamann and Ferland

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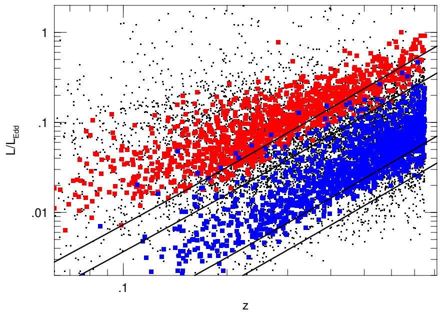

Fig. 1. Normalized accretion rate as a function of redshift for $\sim 10,000$ $z < 0.75$ SDSS AGN (From Netzer and Trakhtenbrot 2007). The group of sources above the two central diagonal lines (marking the flux limit of the sample) have mean BH mass of $10^{7.6}$ $M_{\odot}$ within a factor of 0.3 dex. The group below these lines contain BHs that are ten time more massive.

1999; Shemmer et al. 2004). Most important for this review is the ability to derive black hole mass and accretion rates. This is based on the results of reverberation mapping (RM) campaigns (e.g. Kaspi et al. 2000), more specifically on the so called "single epoch mass determination" method (e.g. Netzer and Trakhtenbrot 2007). Such methods can now be used to analyze the properties of large AGN samples, like all type-I (unobscured) AGN in the Sloan Digital Sky Survey (SDSS). The results can be used to address more fundamental issues such as BH accretion rate as a function of redshift, BH evolution trough time and the comparison with galaxy evolution.

As an example I show in Fig. 1 the application of the single epoch mass determination method to a large sample of SDSS AGN. The diagram shows the normalized accretion rate (L/L_{Edd}) for about 10,000 $z < 0.75$ AGN as a function of redshift. The original paper (Netzer and Trakhtenbrot 2007) addresses the cosmic evolution of mass and accretion rate of those sources and shows that the slope of the L/L_{Edd} vs. z correlation is similar to the slope of the cosmic star formation rate over the same redshift interval.

The BLR is probably not a distinct isolated region. It is part of a continuous distribution of gas extending all the way from just outside the inner accretion disk to hundreds of parsecs from the center. The effective boundary is probably determined by the dust sublimation radius which is estimated at

$$R_{sub} \simeq 0.7 L_{46}^{1/2} \text{ pc}, \quad (1)$$

where L_{46} is the bolometric luminosity in units of 10^{46} ergs s^{-1} and the exact scaling depends on grain size and composition. This idea, suggested by Netzer and Laor (1993), is now confirmed, observationally. First, RM-based measurements of the BLR size (the part emitting the hydrogen Balmer lines) give a radius which is roughly

$$R_{BLR} \simeq 0.45 L_{46}^{0.6\pm0.1} \text{ pc}, \quad (2)$$

very similar to R_{sub}. Moreover, there are several direct measurements of the innermost dust location, in several nearby AGN, using dust RM based on the comparison of the V and K band luminosities (Suganuma et al. 2006). These indicated sizes that are slightly larger than the size of the H_{β} emission region.

The physical explanation for the apparently BLR boundary is based on the properties of the dust. For galactic type grains, the dust competes very efficiently with highly ionized gas in absorbing the Lyman continuum photons thus reducing, significantly, the intensity of all emission lines coming from the ionized gas. The current view is of a continuous gas and dust distribution that extend out from R_{sub} all the way to the NLR. Much of the gas, especially the part which is of the highest ionization, is practically invisible since the line intensities are very low. As argued below, this dust contributes also to the observed MIR emission of AGN.

3. Torus and other dusty components: mid-infrared spectroscopy

The central structure (torus) that extends from R_{sub} to several parsecs away from the center, is described, in detail, by M. Elitzur (this proceedings). *Spitzer* spectroscopy is perhaps the best tool for understanding the properties of such structures in a large number of sources (direct imaging, which is better in many ways, is only available for a handful of nearby sources). Such spectroscopy can be used to distinguish between various AGN types (e.g. Hao et al. 2007), to search for starburst indicators (see below) and to provide a direct measure of the covering factor of the central dusty structure.

Recently, we have analyzed a sample of 28 AGN selected by their optical properties. These are all PG (blue excess) type-I AGN with intermediate to high luminosity and $z < 0.35$. The objects were observed by *Spitzer*-IRS as part of a large project aimed at the comparison of AGN and ULIRGs of similar bolometric luminosity. The spectra cover the entire IRS accessible range (about 4–40 μm). The MIR spectra (see Fig. 2) show the clear signature of PAH emission, typical of starburst regions (see §4) and strong silicate emission features at 10 and 18 μm. The observations (Schweitzer et al. 2006) and analysis (Netzer et al. 2007; Schweitzer et al. 2008) indicate that the intrinsic AGN MIR spectrum does not extend beyond about 40 μm (see §4). Moreover, the fitting of the silicate emission features required additional dust components at typical distances of $\sim 170 R_{sub}$. This dust could not possibly be associated with the inner torus and we suggested that it is located in the inner part of the NLR. A more recent study by Mor et al. (2008, in preparation), using more realistic torus models, suggest larger distances for these components, $\sim 1000 R_{sub}$. This places the emitting dusty gas well inside the NLR (see Fig. 3 for illustration of the expected properties of such gas).

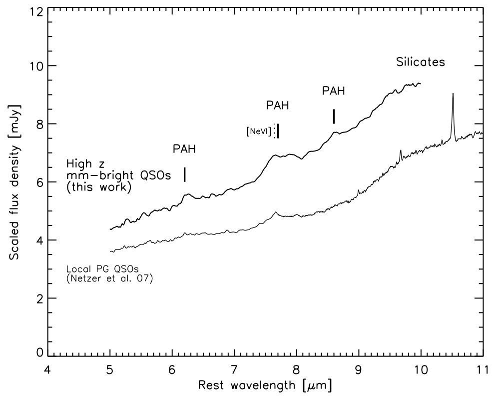

Fig. 2. Composite MIR spectra of low-z "QUEST" QSOs (lower curve, based on Schweitzer et al. 2006) and high-z QSOs (upper curve, from Lutz et al. 2008). Note the strong PAH features at various wavelength in both spectra, in particular the feature around rest wavelength 7.7 μm.

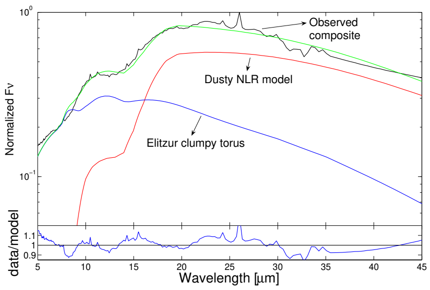

Fig. 3. An example of a two component fit to the mean MIR spectrum of the QUEST AGN (the composite shown in Netzer et al. 2007). The model includes two parts; a clumpy torus from Elitzur's tables and a dusty NLR cloud (Mor and Netzer 2008).

4. Dusty NLRs: optical-infrared spectroscopy

The narrow line region (NLR) is arguably the best studied zone in AGN. Its spectroscopic properties are known from numerous studies of low and high-z sources and the spatially resolved distribution was mapped in dozens of nearby AGN, mostly using HST imaging. Here I shall focus on the dust-related properties of NLR clouds.

The NLR is probably composed of numerous large (compared with the BLR) size clouds with a range of density and distances from the central source. The size of the NLR has been the subject of much discussion, especially in type-I sources (e.g. Bennert et al. 2002; Baskin and Laor, 2005). Since the observed ionization range is large, and the radial distribution significant, it is not very meaningful to assign a number to a "typical" NLR size. Imaging of the strong [O III] λ5007 line in $z < 0.3$ sources suggest outer sizes of about 1000–3000 R_{sub}. Obviously some [O III] λ5007 emission is seen to much larger distances and the above estimate refers to the region producing ~90% of the line emission. This approximation cannot extends to the highest luminosity AGN since, for such sources, the derived NLR size exceeds the galaxy size, even for the largest known galaxies (see a detailed discussion in Netzer et al. 2004).

Most NLR clouds are dusty except, perhaps, the part of the NLR with the highest level of ionization (the so-called "coronal line region"). This is deduced from various observations (narrow Blamer line ratios, etc.) as well as from theoretical arguments (Netzer & Laor1993; Dopita et al. 2002). The spectral properties and the overall luminosity of such dust depend on the distance from the center, the dust covering factor and the dust column density. The exact grain composition is less important although it can result in noticeable spectral differences from one source to the next and for dust in a hot torus compared with dust in Galactic HII regions. The line luminosity of the same dusty gas is determined by the ionization parameter (the combination of gas density and distance), the gas column density (if optically thin) and the gas covering factor. Thus, it is not straight forward to compare properties deduced from emission lines and from IR-continuum observations. For example, dusty clouds very close to the ionizing source can contain very hot dust and, at the same time, produce very weak emission lines from highly ionized species if the gas density is high (low ionization parameter).

The realization that some of the silicate emission is due to dusty NLR clouds could, in principle, help to solve for all unknown properties since it gives a direct handle on the distance of the emitting dust. This can be achieved by calculating the continuous (dust produced) spectrum and the emission line spectrum of dusty NLR clouds over a range of density, column density and distance. Such models can then be compared to the optical-infrared spectrum of AGN with various luminosities and spectral properties.

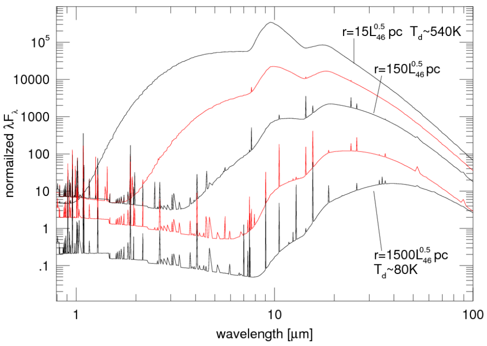

Fig. 4. Predicted spectra of dusty NLR clouds located at various distances, as marked, from a central AGN with $L = 10^{46}$ erg/sec.500 The gas density in these models is 10^4 cm^{-3} (adopted from calculations by B. Groves presented in Schweitzer et al. 2008).

Fig. 4 shows the predicted spectrum of NLR clouds with a characteristic density of 10^4 cm^{-3} located at various distances from a "typical" high luminosity AGN (the assumed SED is deduced from observations of such objects). The diagram shows the distinct hot dust features including the high temperature peak and the two silicate emission features at $\sim$ 10 and $\sim$ 18 μm. It is easy to imagine how such features can contribute to the observed MIR spectrum in a case where the emissivity of the NLR component is large enough, i.e. it covering fraction is significant.

5. Powerful starburst regions: far-infrared observations

According to various evolutionary scenarios (e.g. Sanders et al. 1988; Norman & Scoville 1988), luminous AGN phases coincide with or follow periods of intense star formation. The observations are still limited in spatial resolution and cannot be used to test the more advanced models, those that combine galaxy merging, gas transport, star formation, accretion and feedback processes. However, there are indications for intense star formation events in the host of high redshift QSOs. Perhaps the most important indication is the detection of sub-mm or mm continuum (rest frame far-infrared) from dust in several high-z, high luminosity AGN. This emission indicates high star formation rates, above 300–500 $M_\odot$/yr.

We have recently obtained independent support for this500 suggestion by looking at two AGN samples. The QUEST sample described in the previous section (Schweitzer et al. 2006) and a new sample of 12 high z high luminosity QSOs (Lutz et al. 2008). The high-z sources are mostly mm-bright AGN with bolometric luminosities of 10^{46}–10^{48} ergs s^{-1}.

We have used several PAH features, well known star forming region indicators, in order to separate the AGN emission from the starburst emission. PAH features are know to be present in star forming environments with a wide range of physical conditions but are absent in the vicinity of powerful AGN. The main mid-infrared PAH emission features are at 6.2, 7.7, 8.6, and 11.3μm. The calibration factor between PAH luminosity and star formation rate depends somewhat on the average physical conditions in the interstellar medium of the host galaxies. For the specific case of star formation in QSO hosts, the calibration uncertainty is outweighed by several advantages. PAH emission from starbursts is very luminous and thus less easily outshone by the powerful AGN source. Unlike other star formation indicators (e.g. Hα), the PAHs are not overwhelmed by strong AGN emission in the very same tracers. It is also more reliable than the optical [O II] λ3727 line which is sensitive to dust obscuration typical of starburst regions.

In Schweitzer et al. (2006) and in Netzer et al. (2007) we applied the technique of comparing PAH and FIR luminosities to the local QUEST PG QSOs. We detected PAH emission in many of these objects and concluded, based on the strong correlation between L(PAH) and L(FIR), that most of their 10^{10}–$10^{12}L_\odot$ far-infrared luminosity is due to star formation. Comparing average spectra and SEDs of groups of QSOs that are differing in their level of far-infrared emission, we were able to subtract the starburst contribution and derive an infrared SED for the pure AGN. In Lutz et al (2008) we show similar results for the more luminous, high-z QSOs. Fig. 5 shows the PAH vs. FIR (60 μm) luminosities for the two samples, at low and high redshifts. The correlation is highly significant confirming the suggestion that most, or perhaps all of the FIR emission is due to star forming regions.

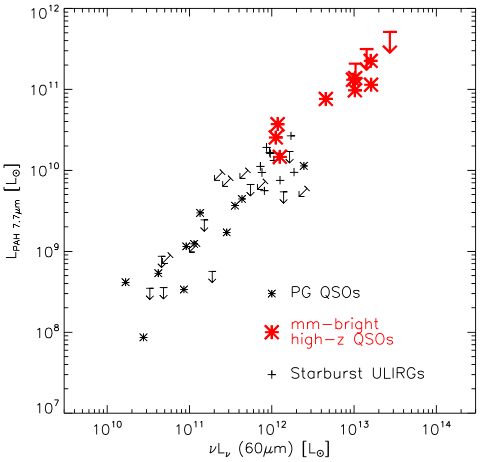

Fig. 5. The correlation of the luminosity of the PAH feature at 7.7 μm with FIR luminosity for the samples shown in Fig. 2. The strong correlation, combined with the assumption that the PAH emission is due to star forming regions, is an indication that most of the observed FIR flux is due to starburst emission.

Having separated in this way the starburst and the AGN emission, we can now check for the correlation of the two. This is shown in Fig. 6 where we compare FIR, 60μm luminosity and optical luminosity (λL_λ at 5100Å) for our two samples and several other sources collected from the literature. The resulting very strong correlation, with a slope which is somewhat shallower than 1, is very surprising. Not only that the two energetic events co-exist in the same host, they seem to "know" about each other in a way that more luminous AGN are associated with more star formation. Apparently, there is a direct link that must be explained by the models. Note, however, that the sample does not necessarily represent the entire AGN population since its selection is biased toward high SF rate sources.

The powerful starbursts found in many of the sources studied by us cannot be located in

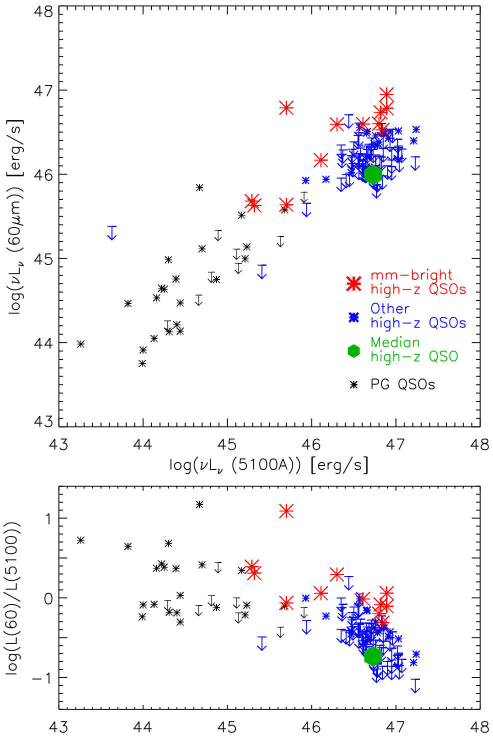

Fig. 6. The correlation of the AGN luminosity (measured at 5100Å) with the FIR luminosity (measured at 60 μm) for several AGN samples showing clear starburst signatures in their spectra (from Lutz et al. 2008). Note the strong linear correlation suggesting that starburst and AGN luminosities go hand in hand.

the central kpc. This can be shown by simple temperature-size relationships. Thus, the link between the two phenomena is found over a large scale of distances, especially in the more luminous sources. The direct measure of star formation and black hole growth available from these results provide a new way to estimate the duty cycles associated with the two phenomena. We predict this to become a very important tool in the study of the parallel evolution of massive black holes and their hosts.

The samples shown here do not represent the entire AGN population. There are sources that do not show such a clear correlation and the *Spitzer* based statistics can only be applied to small number of sources that are not necessarily drawn from complete samples. The difficulties associated with obtaining more high quality MIR and FIR observations of AGN, especially high redshift ones, will prevent us from obtaining large new samples and better statistics in the near future. However, the phenomenon is common and deserves better explanation.

6. Conclusions

Ultraviolet, optical and infrared spectroscopy are important probes of the various gas and dust components in AGN. Broad emission lines are used for estimating black hole mass and accretion rates for thousands of type-I sources and MIR spectroscopy is a powerful tool for understanding the structure and dimensions of the torus and other dusty components. A combination of all those indicators shows that, in many sources, starburst and black hole accretion go hand in hand thus changing our view of the main stages of black hole and galaxy evolution, especially those stages involving large amounts of gas accretion onto the central black hole.

Acknowledgements. It is a pleasure to acknowledge help from my collaborators in the SDSS and the high-z BH mass projects: Benny Trakhtenbrot, Ohad Shemmer and Paulina Lira. I also thank D. Lutz, E. Sturm, M. Schweitzer, B. Groves, R. Mor and the entire QUEST team, my long term collaborators in the various *Spitzer*-IRS spectroscopy projects.

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