VISIR Observations of Local Seyfert Nuclei and the Mid-infrared — Hard X-ray Correlation

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High angular resolution mid-infrared observations with the VISIR instrument at the Very Large Telescope have allowed the distribution of dust around local active galactic nuclei (AGN) to be studied. The observational results support the unified scenario for AGN and bring constraints on the properties of its key component, a dusty torus obscuring the view onto the AGN when viewed close to the equatorial plane.

Active galactic nuclei have been a prime target of extragalactic astronomy for many years. These fascinating objects comprise a supermassive black hole, a hot accretion disc feeding the black hole and an additional supply of cold gas and dust. They have many manifestations: quasars, radio galaxies, Seyfert galaxies — all of which are governed by the same physical mechanisms.

The dusty torus in AGN

The local incarnations of AGN — also known as Seyfert (Sy) galaxies — can be separated into two classes: Sy 1 galaxies with an unobscured view onto the hot, optically bright accretion disc and the surrounding broad line region (BLR); and Sy 2 galaxies that are observed through a veil of gas and dust. This has led astronomers (see, for example, Rowan-Robinson, 1977; Antonucci, 1982) to develop the unified scenario for AGN. The cornerstone of this scenario is the existence of a torus-shaped supply of molecular gas and dust that obscures the central parts of the AGN when viewed close to the equatorial plane (see Figure 1 for an illustration). Thus, Sy 1 and Sy 2 galaxies are the same beasts, just seen from different directions.

While the unified scenario has proved to be very successful and has passed many observational tests, little is known about the physical state of the torus itself. Some possible geometries for the dust distribution are shown in Figure 2:

- Panel a displays a classical smooth distribution with a constant ratio of height/radius. Such a torus has essentially the same geometry as the accretion disc in the centre of the AGN, but with much lower temperatures and a much larger extent. The border between the torus on one side and the accretion disc and broad line region on the other side is determined by the sublimation temperature of the dust. When the gas becomes too hot, the dust particles are destroyed, the gas is ionised and a hot BLR or accretion disc is observed instead of a dusty torus.
- Panel b shows the same geometry, but with the dust and gas arranged in distinct clouds. There are theoretical arguments for such clumpiness, based on the dynamical stability of the torus (Krolik & Begelman, 1988).
- Panel c illustrates the idea of the "receding" torus, first proposed by Lawrence (1991). The consequence of this model is that AGN of high luminosity will appear as obscured less frequently than AGN of low luminosity, since, when the luminosity increases, the sublimation radius and thus the inner edge of the torus move outwards. This, in turn, means that the solid angle covered by the torus as seen from the centre of the AGN decreases. There are some observational indications for this effect, but the question of the geometry of the torus in this case is far from settled.

There are many approaches to the study of the physical state of the torus. The one that seemed most promising to us was to combine mid-infrared (MIR) and hard X-ray observations. The intrinsic X-ray luminosity is a good proxy for the total luminosity of the accretion disc. The MIR emission of an AGN, on the other hand, is dominated by thermal emission of the dust within the torus. As the torus is heated by the accretion disc, one would expect a correlation between MIR and hard X-ray luminosities. Since, in Sy 1 galaxies, we can see the hot dust in the inner part of the torus, while in Sy 2 galaxies — according to the unified scenario — we can only see the cooler dust in the outer part of the torus, one would expect to find a difference in the MIR and intrinsic hard X-ray luminosities.

Two studies on the mid-infrared–hard X-ray correlation by Krabbe et al. (2001) and Lutz et al. (2004) found the expected correlation between MIR and hard X-ray

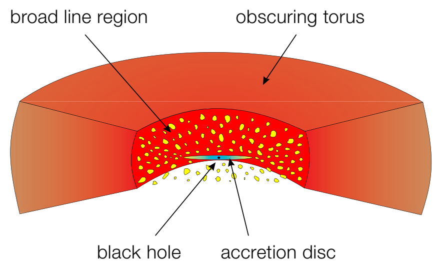


Figure 1. Sketch of the inner part of an AGN as predicted by the unified scenario. Depicted are the black hole, the accretion disc, the clumpy broad line region and the obscuring torus. The narrow line region and a possible jet are omitted for clarity.

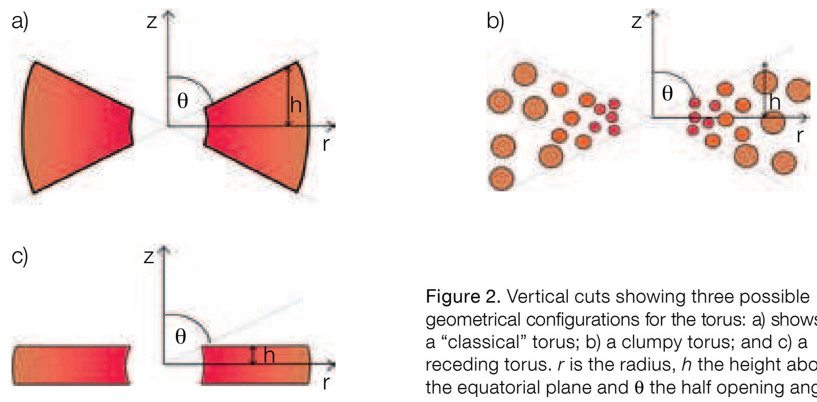


Figure 2. Vertical cuts showing three possible geometrical configurations for the torus: a) shows a "classical" torus; b) a clumpy torus; and c) a receding torus. *r* is the radius, *h* the height above the equatorial plane and θ the half opening angle.

luminosities, but not the expected difference in luminosity ratio between Sy 1 and Sy 2 galaxies.

Ramifications of assessing the MIR and X-ray properties of AGN

One limitation of earlier studies on the mid-IR–hard X-ray correlation was the low angular resolution of the MIR observations. Unfortunately, Seyfert galaxies frequently host regions of active star formation close to the AGN which also emit in the MIR regime. If it is not possible to spatially resolve these star-forming regions, a separation, e.g., by spectral decomposition methods, is very difficult. We decided to base our study on observations with the VSIR instrument (Lagage et al., 2004) at the Very Large Telescope (VLT), which offers the best combination of spatial resolution and sensitivity in the mid-infrared currently available in the world.

Besides the angular resolution of the MIR observations, another issue was the reliability of our X-ray data. As mentioned above, we need the intrinsic X-ray luminosity in order to have a proxy for the total luminosity of the accretion disc. Unfortunately, X-rays are also absorbed within the torus. However, high quality X-ray spectra allow us to correct for this effect, since absorption alters the X-ray spectral appearance of an AGN in a characteristic way. Therefore, we decided to observe a sample of Sy 1 and Sy 2 galaxies with VISIR for which high quality X-ray data were available.

In order to make the best use of VISIR's high angular resolution capabilities, we decided to only observe relatively nearby AGN. We set the limit for our sample selection at a redshift of 0.1.

VISIR observing campaigns

Between April 2005 and September 2006, we observed 29 Seyfert galaxies with VISIR and detected 25 of them. We used a standard chop/nod-procedure to remove the very bright atmospheric background in the MIR. In order to achieve the highest possible angular resolution, we chose VISIR's small field objective, which provides a pixel scale of 0.075 arcseconds and a field of view of 19 x 19 arcseconds.

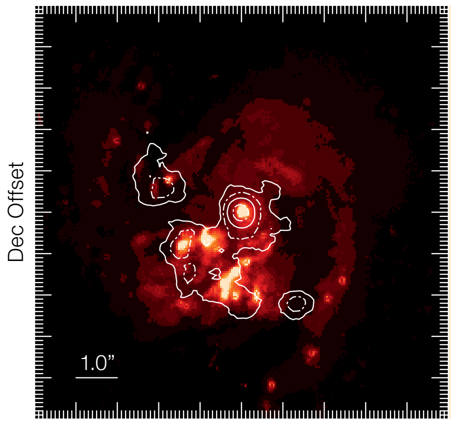
With this setup, we reached a typical resolution of 0.3 arcseconds, thereby significantly improving the resolution compared to previous studies. Most of the observed objects appear point-like — only in three cases did we detect extended emission around the AGN. One example of a target with extended emission — NGC 5135 — is displayed in Figure 3. In this overlay of VISIR and Hubble Space Telescope data, we see that some sources of optical and MIR emission coincide, while others do not. Where MIR sources do not have an optical counterpart, we probably see the early stages of star formation when young stars are heating their environment, but are not yet powerful enough to blow away the dusty veil that is hiding them.

Extended emission and comparison to Spitzer data

For NGC 5135 and a second object, NGC 7469, we can estimate that within the innermost 3.0 arcseconds around the AGN, at least roughly 45% of the MIR flux does not originate from the AGN. For NGC 7469, this result is in good agreement with an actual comparison of our VISIR data to archival spectra recorded with the IRS instrument aboard the Spitzer Space Telescope; the latter provides an angular resolution of ~ 3.0 arcseconds. We performed this comparison for all objects that we had observed in at least two MIR filters and for which archival IRS data were available. Interestingly, we found some cases of significant deviation of the IRS and VISIR fluxes where no extended emission was visible in the VISIR images (Horst et al., 2009). One example for this is shown in Figure 4. We interpret this discrepancy as caused by smooth, extended emission that is not observed with VISIR due to its limited sensitivity to this kind of emission. In a few cases, flux changes due to time variability between the two observing epochs, while unlikely to be the origin of this effect, cannot be completely ruled out.

The extra-nuclear emission — either directly observed with VISIR or visible through the comparison to the Spitzer data — underlines that giving priority to high angular resolution, instead of the higher sensitivity of space telescopes, was the right approach for our purpose. Of course, we cannot rule out significant

Figure 3. The central part of NGC 5135 in an overlay of optical Hubble Space Telescope data and our VISIR observations. The optical data is shown as a false colour image and the VISIR data as a contour plot. This figure is reproduced from Horst et al. (2009).



contamination in our own data, but at least it will be far less than for larger aperture observations. We discuss the important point of contamination in our data in more detail in the next section.

The mid-infrared–hard X-ray correlation

The primary goal of our observing campaigns was to study the mid-infrared–hard X-ray correlation. First of all, like our predecessors, we found a strong and significant correlation between these two quantities. The correlation is shown in Figure 5. In this figure, we plot hard X-ray *v.* MIR luminosity on a log–log scale. Blue squares represent Sy 1 nuclei, red diamonds are for Sy 2 nuclei and green triangles for low ionisation emission line regions (LINERS), a class of AGN with less pronounced nuclei and — relative to the AGN power — more star formation than Seyfert galaxies. Arrows mark either the upper limits of the MIR luminosity of non-detected sources or the lower limits of sources with equivocal X-ray spectra. The dotted line depicts the best-fit power-law to our first sample, observed in 2005 (see Horst et al., 2006); the dashed line then shows the best fit to the two samples combined.

The correlation has some important features. One of these is the slope, which is close to unity. On a log–log scale, a slope of one indicates a linear dependency between the two plotted quantities. Thus, we find that MIR and X-ray luminosities show a linear relationship. Secondly, Sy 1 and Sy 2 galaxies exhibit the same MIR/X-ray luminosity ratio. Again, this is in

Figure 4. Comparison of VISIR photometry (black circles) with IRS spectrophotometry (black line) for Mrk 590. The horizontal error bars depict the pass-band of the VISIR filters; dashed vertical lines indicate the wavelength position of emission lines common in AGN spectra.

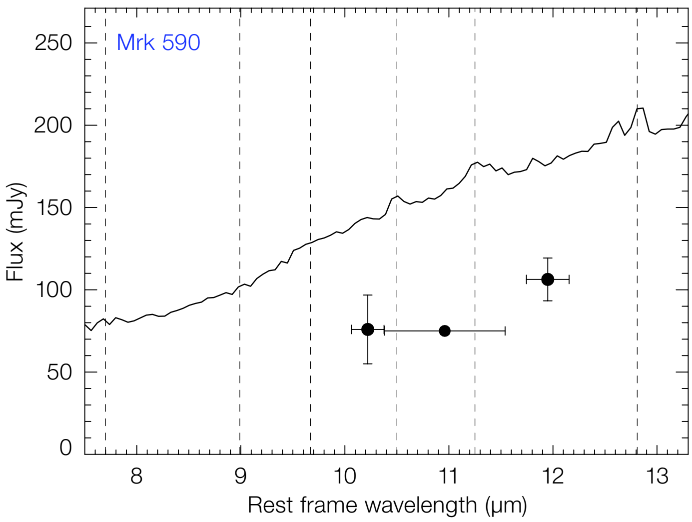
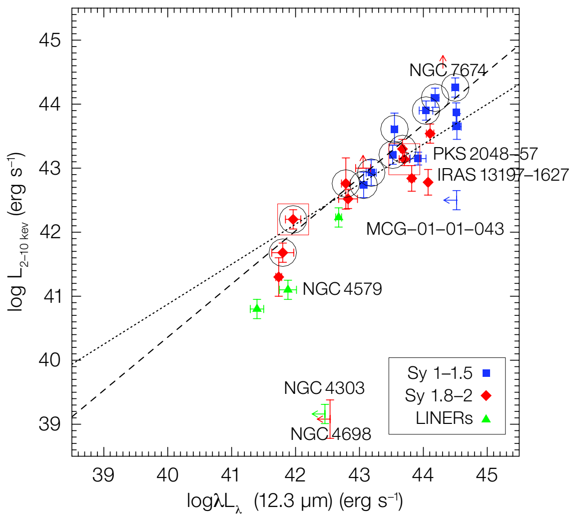


Figure 5. The mid-infrared–hard X-ray correlation as determined in this study. Blue squares are Sy 1 nuclei, red diamonds are Sy 2 nuclei and green triangles are LINERS. Arrows either depict upper limits to the MIR luminosity, in the case of MIR non-detection, or lower limits to the X-ray luminosity, in case of equivocal X-ray data. The dotted line is the best-fit power-law to our first sample, the dashed line the best-fit power-law to the combined sample. This figure is reproduced from Horst et al. (2008).



good agreement with the results of previous studies. At our high angular resolution, it is unlikely that the similarity is caused by contamination of the observed MIR luminosity with non-AGN emission. Therefore, we assume that it is intrinsic to AGN.

On account of the emphasis that we placed on the issue of angular resolution, we have to discuss the influence of contamination in our own data. In order to obtain robust results, we split our sample into two sub samples: especially well-resolved objects and less well-resolved objects. The term "well-resolved" has to be understood in terms of the dust sublimation radius that defines the inner edge of the torus. This radius can be estimated from the X-ray luminosity and is a natural scale for the dusty torus. Interestingly, we find a significant change in the MIR/X-ray luminosity ratio at an angular resolution of 560 times the dust sublimation radius (see Gandhi et al., 2009 for details). Therefore, we used this resolution as the separator for our two sub samples. The well resolved AGN are marked by black circles in Figure 5. We then checked whether the correlation would change if we used only the well-resolved objects; reassuringly, the result of this exercise showed that this is not the case. Within errors, the slopes of the two correlations are identical (the details of the statistical analysis are presented in Horst et al., 2008). Thus, we can be confident that the correlation we have determined is physically meaningful and can now discuss its implications.

Implications for the dusty torus

Our results allow us to constrain the properties of the dusty torus — at least for the AGN within the luminosity range we probed. Since we aimed for high angular resolution, we restricted ourselves to observing local AGN that are less luminous than more distant objects, e.g., quasars. Thus, it has to be kept in mind that the properties of the torus in AGN may change toward higher luminosities (and in fact there is some evidence that this is so).

Interestingly, however, we find no indication for a luminosity dependence of the appearance of the torus within our sample. Since the slope of the correlation is unity within the errors, the X-ray/MIR luminosity ratio does not change at all. Since the MIR luminosity is determined by the amount of accretion disc emission that is absorbed by the torus, it is directly proportional to the hard X-ray luminosity and the solid angle it covers when seen from the accretion disc. Thus, a constant luminosity ratio implies that the opening angle θ of the torus is constant as well. This rules out the receding torus model (panel c) in Figure 2 in its purest form. If the torus shows receding behaviour, it only does so beyond X-ray luminosities of 10^{38} W.

The fact that Sy 1 and Sy 2 nuclei follow the same correlation also has an important implication: it implies that the assumption that in Sy 1 nuclei we see hot dust, while in Sy 2 galaxies we do not, is probably incorrect. This result can only be reconciled with the existence of a torus-shaped distribution of molecular gas and dust, if the dust is arranged in distinct clouds (panel b in Figure 2). In addition, these clouds need to have a low volume filling factor within the torus. In such a configuration, we have a relatively unobstructed view through the torus onto the hot dust in its inner region.

These interesting results have motivated us to continue research along these lines. One important study was carried out by Gandhi et al. (2009) who — thanks to the arrival of the Suzaku, INTEGRAL and Swift spacecraft — managed to obtain reliable X-ray data for especially heavily obscured Sy 2 galaxies. VISIR observations of these targets showed that also they follow the correlation found in our earlier studies. The implication is that our approach has indeed allowed us to constrain the geometry and physics of the dusty torus in AGN. An interesting next step would be to widen the luminosity range covered by this study and try to assess the properties of the tori in the least, as well as the most powerful, AGN.

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