Luminous IR Galaxies : the acute view of Adaptive Optics

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Abstract:

Several problems related to the understanding of the extraordinary class of IR luminous galaxies (L > $10^{11} L_{\odot}$) clearly require to reach scales of 10 pc, i.e. angular scales in the 100 mas range, a performance that near-IR imaging, when fed by adaptive optics, can reach, even when the reference for wavefront sensing is a moderately bright nucleus. We present several results in this field, obtained with Pueo, the CFHT AO system which is briefly presented. We first show that resolving at K the central source of the ULIRG Arp299 is a strong indication that the primary source of power is a starburst and not a buried AGN as was once proposed. This is not the case of Mkn 231, another ULIRG, where the central core is unresolved and shows colors typical of an un-obscured AGN, with however a very bright star forming region detected at $\approx$ 100 pc from the nucleus. A second result deals with a number of super clusters of very young stars that AO allows us to resolve in three ULIRGs: Mkn 231, Arp 299 and NGC 7469; thanks to multi-color photometry we can derive for each cluster an approximate luminosity that appears to be between 10 and several hundred times larger than the luminosity of – already very bright – stellar clusters in classical starburst galaxies such as M82; in addition, we show that the most luminous clusters are belonging to the brightest galaxies. The mechanism of stellar formation in ULIRGs appears thus not only a huge one, but also a very special one with a peculiarly efficient star formation in regions which remain as small as a few ten pc. Finally, we present what is likely a second case – after NGC 1068 – of a direct detection of a molecular/dust torus in the environment of a Seyfert 2 nucleus. This one belongs to the IR luminous galaxy Mkn 620 and the deconvolved K image clearly reveals the trace, both in emission and absorption of the torus. The torus radius of 25 pc, a size close to the one deduced in NGC 1068, favors the kind of models predicting a more extended and diluted torus.

1. INTRODUCTION

Among the most spectacular results of IRAS, was the discovery that a number of galaxies were extremely luminous in the infrared (4. 10^9 to 4. $10^{12} L_{\odot}$), a few of them, constituting the extreme class of the so-called Ultra-Luminous InfraRed Galaxies (ULIRGs), emitting a tremendous power, over 10^{12} $L_{\odot}$. For most members of this last class, the fraction IR /total can reach 98 %, the source of energy being essentially concentrated in the nuclear region, typically in the central few 100 pc. If the vast majority of the luminous IRAS galaxies exhibit all tracers of very YSOs, clearly indicating that this luminosity is associated with a violent burst of stellar formation in the nuclear region, this is less clear for the ULIRGs where dust opacity is so large that it actually hides the phenomena associated to the most central activity. For those ULIRGs, it was proposed that a large fraction of the luminosity may originate from a recently borne Active Galactic Nucleus (AGN) (Sanders et al., 1987). The problem of the relationship between AGN and starburst activity is indeed a long standing one (e.g. Sanders, 1992) if one considers that: a) the same conditions that favor a burst of star formation (gas concentration and bar or interaction) are also generally found in the case of AGNs; b) the two types of activity are frequently associated in the same galaxy, as exemplified by NGC1068 or NGC 7469.

The extreme activity in luminous IR galaxies is an important process in extra-galactic astrophysics because it strongly affects the evolution of the galaxy and its environment and because it should have played a major role in the evolution of the early universe, the starburst phenomenon being most likely the result of interaction and/or merging between galaxies. It is thus important to understand the detailed characteristics of the phenomena, one difficulty being the large distance where most of those objects lie.

Several problems pertaining to the understanding of this extraordinary class of galaxies clearly require to reach scales of 10 – 100 pc, i.e. angular scales in the 100 mas range (e.g. Rouan, 1996):

- What is the primary source of power in ULIRGs ? is it an enshrouded AGN or a huge starburst ?
- Are the characteristics of the young stellar clusters standard, or do they relate to the overall burst intensity ?
- How is the gas driven to the center ? are there micro-spiral systems and micro-bars to produce the required braking torque as suggested by theory ?
- Are there traces of the AGN environment such as torus, disks etc. ?

To tackle several of those questions, Adaptive Optics can bring the power of its acute view, especially in the near-infrared, where several advantages must be emphasized: (i) the scale of 100 pc represents 200 mas at 100 Mpc, a performance well within reach of AO systems; (ii) the best resolution of AO is achieved at K (0.12") ; (iii) probing through the dust, most generally very dense in ULIRGs, is much more efficient at near-IR where typically $A_K = 0.12\ A_V$; (iv) emission from dust, stars, H^+, H_2, free-free, synchrotron, all exhibit a contribution in the near-IR, generally characterized by a unique location on the [J-H]/[H-K] diagram ; (v) in several cases, the nucleus is bright enough to be used as the reference for wavefront sensing, particularly with PUEO, the CFHT AO system, which features a sensitive wavefront sensor.

2. Pueo, the CFHT AO system

The Adaptive Optics Instrument for the 3.6 m Canada-France-Hawaii Telescope (CFHT) is now in an active phase of exploitation. The instrument and performances have been described in several publications (Rigaut et al., 1995, 1998; Arsenault et al., 1994). The hearth of the system is a 19 electrodes bimorph mirror (1:6:12), used with a 19 sub-aperture curvature wavefront sensor and a separate tip-tilt re-imaging mirror. We have reported astronomical images with median Strehl ratio of 20 (@ 1.25 μ m) to 60 % (@ 2.2 μ m), with a FWHM of 0.1 arcsec and a sensitivity allowing image quality improvement with guide stars as faint as m_R=17. Such a system, with few degrees of freedom but a high bandwidth (100 Hz) , is particularly well suited to Mauna Kea seeing conditions where turbulence is weak yet fast. Modal control is an important feature of this system and allows optimal gain to be applied on the different modes, according to the state of the turbulence. The wavefront sensor, of the curvature type, uses photon counting Avalanche Photo-Diodes providing excellent performances in terms of sensitivity on the reference source : this is especially important when the source is the nucleus of a galaxy. Servoing the system on nuclei as faint as $m_V = 15$ is currently achieved.

3. What powers ULIRGs ? AGN or starburst ?

Determining if the main source of energy in ULIRGs is a hidden AGN or a compact huge starburst (typically 100 $M_\odot\ yr^{-1}$) is a major question, and still a matter of debate twelve years after the proposal by Sanders et al (1987) that those objects could harbor a dust enshrouded, recently born, quasar. High angular resolution radio interferometric measurements (Condon et al., 1991) and recent ISO spectra (Lutz et al., 1996) strongly suggest that a compact starburst powers most of those galaxies, but the question still deserves attention, since an AGN (Seyfert nucleus), often a buried one, is indeed detected at visible or radio wavelengths in few ULIRGs. The idea here, is to try to measure the actual diameter of the main central source at K and to compare it to what is expected in each case: if the source is resolved, then there is a good chance that the prime source of energy cannot be an AGN, since any radiative transfer model around a point source would produce a distribution of the emission from the hot dust which would be in practice unresolved (less than 1 mas). On the other hand, an unresolved source is not a proof of an AGN since an ultra-compact starburst can still be advocated.

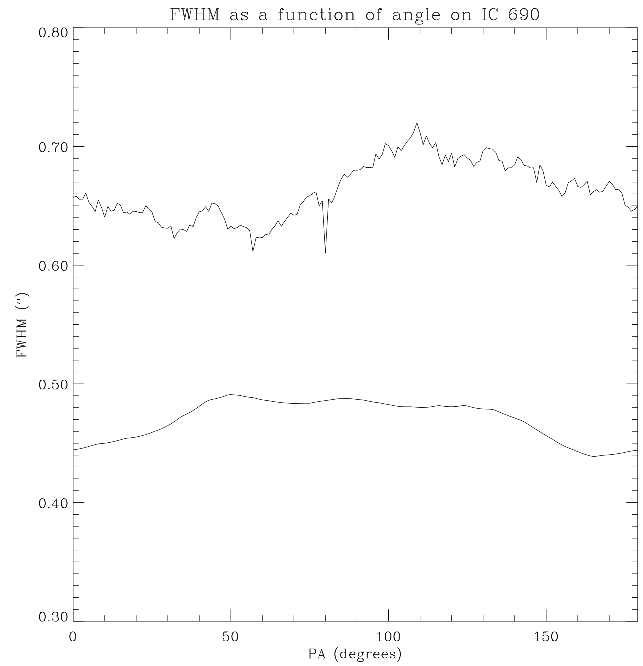

Figure 1. Radial FWHM of source A (IC 694) as a function of P.A. (upper curve), compared to the FWHM of a simulated PSF (lower curve), where the partial correction of the adaptive optics system is taken into account (faint magnitude of the reference and anisoplanatic effects). Source A appears clearly resolved and slightly elongated, with respect to the PSF.

One of the distinctive characteristic of ULIRGs being to be faint in the visible, it is somewhat a challenge to find a reference bright enough for the AO wavefront sensing in those galaxies. We have been however able to servo Pueo on the nucleus of two ULIRGs: Arp 299 and Mkn 231. The former is a merger (NGC 3690 and IC 694) with a rather complex structure (see Lai et al, 1998 b–c) and the latter is the most luminous object in the local universe (Lai et al, 1998 a).

In the case of Arp 299, Source A (=IC694), the most active region in the merger, appears clearly resolved on our image and elongated with a diameter of $\approx$ 130 pc. In Fig. 1, we show the FWHM as a function of the polar angle, compared to the FWHM of a simulated PSF, taking the partial correction of the adaptive optics system into account (faint magnitude of the reference and anisoplanatic effects). Using the derived [V-K] = 6, we can grossly evaluate a luminosity of L= 2.5 10^{10} $L_\odot$ for source A and a surface luminosity of 3. 10^4 $L_\odot pc^{-3}$: both numbers can reasonably be associated to a huge starburst. Here, the hypothesis of an AGN as the main source of power is thus very unlikely.

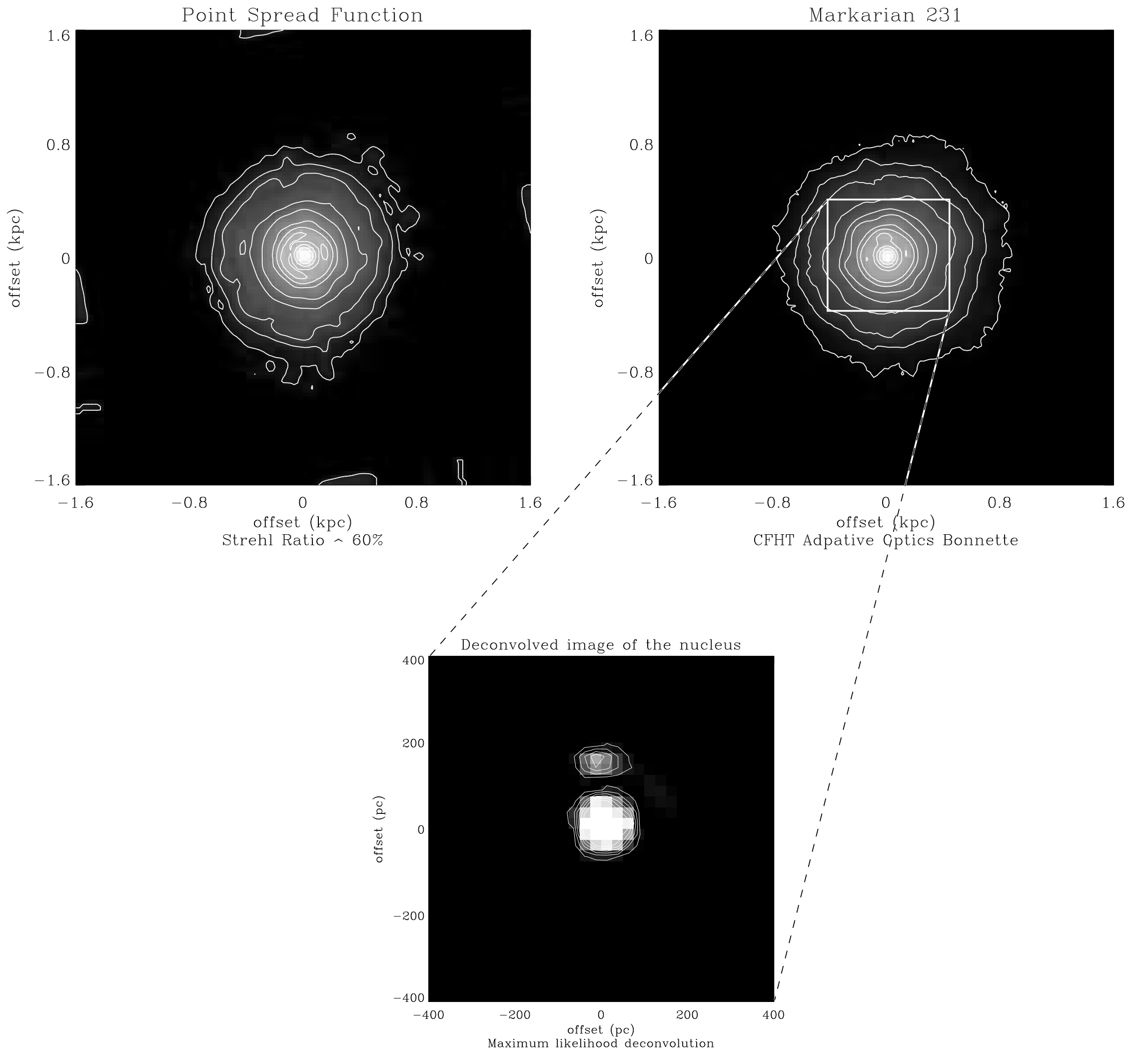

Figure 2. Upper–left : image superimposed on contours of the PSF obtained from the WFS data, in square–root scale. Field is 4.3"×4.3". Upper–right : Markarian 231, K band, same scale. Lower : an enlargement of a one arc-second square of the deconvolved image using the maximum likelihood method (linear scale).

In the case of Mkn 231, the situation is different and the central core is totally unresolved on our image (see Fig. 2 – upper), implying a diameter < 50 pc. In addition, the near-IR colors of the isolated point source, when plotted on a [J-H]/[H-K] diagram, are clearly those of a true AGN. Since the reddening is likely not very important, as inferred from IR lines ratio by Krabbe et al. (1997), our measurements give a clear indication that this source could indeed be an un-obscured AGN at the very center of Mkn231. This AGN is then likely the genuine engine at the origin of the tremendous power radiated in the infrared. However starburst activity is not lacking in Mkn 231 as shown by the deconvolved image of the nucleus (Fig. 2 – bottom) which reveals that a fainter source is detected at 100 pc from the very nucleus: this source is most likely a region of extremely active star formation whose luminosity – as derived in a rough fashion from the K luminosity and the H-K color – should be of the order of 10^{11} $L_{\odot}$, i.e. much larger than any star forming region in the local universe (see discussion below).

If we base ourselves on at least those two case, there is apparently no universal answer to the question of the primary source of energy in ULIRgs, but that the case for huge ultra-compact starbursts remains extremely strong as exemplified by Arp 299.

4. Super(mega)-clusters of young stars in ULIRGs

Do the complexes of star formation in Very luminous IR galaxies look like ordinary ones ? the huge total radiated power should then result from the addition of a large number of such clusters; or do their characteristics differ drastically from what is observed in the local universe, reflecting some unusual mechanism of stellar formation typical of those unique objects ?

Thanks to the excellent resolving power of AO imaging, it is possible to separate a number of complexes in the nuclear region of IR luminous galaxies and to study there individual properties. With this goal in mind, we have examined three IR luminous galaxies: Arp 299, Mkn 231 and NGC 7469.

As regards Mkn 231, we already gave some results on the very bright complex found in the vicinity (100 pc to the North) of the AGN. We present in Fig. 3 and 4, the Pueo K-band images of Arp 299 and of NGC 7469 (see also Lai et al, 1998 c): they both reveal many clumps, practically unresolved, that clearly are super-clusters of newly formed stars. The clumps are distributed along superstructures such as mini-spiral arms in NGC 7469. Comparison with HST images in V band allows us to extract a [V-K] map, so that it is possible to evaluate the luminosity of those clusters, assuming that the K emission is a mixture of nebular (HII regions) and photospheric radiation.

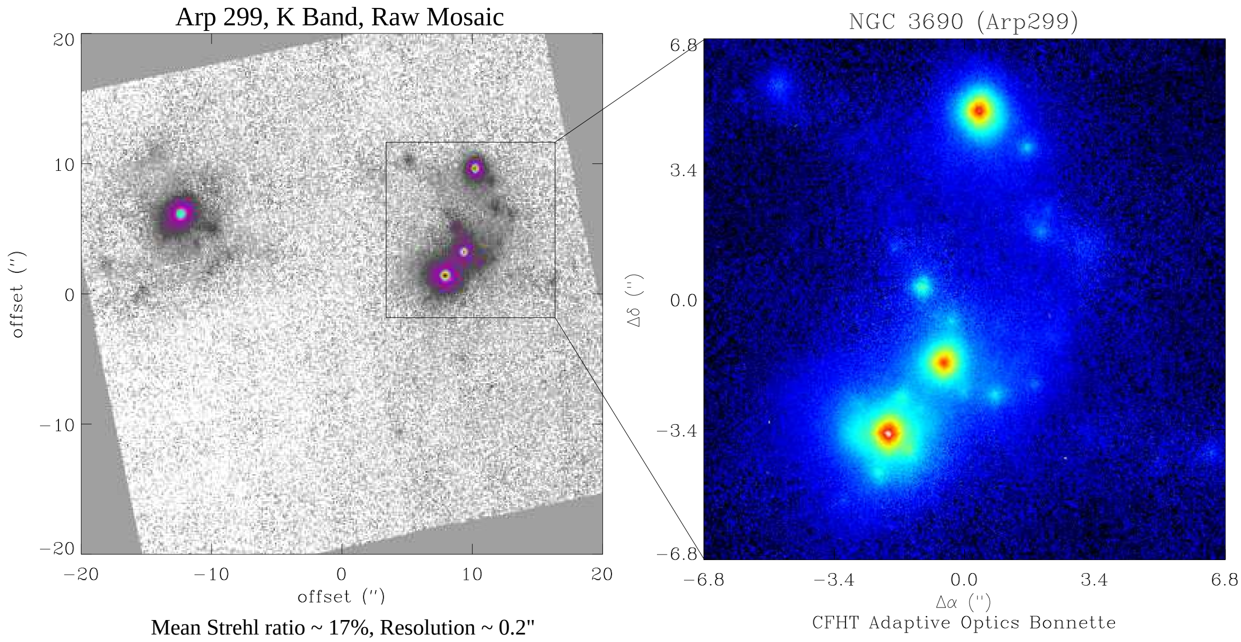

Figure 3. Left: K images of Arp 299 (IC 694 at East and NGC 3690 at West). Right: a closer view of NGC 3690 revealing many nearly resolved clumps that can be identified as very young stellar clusters. The typical resolution of the image is 0.2” .

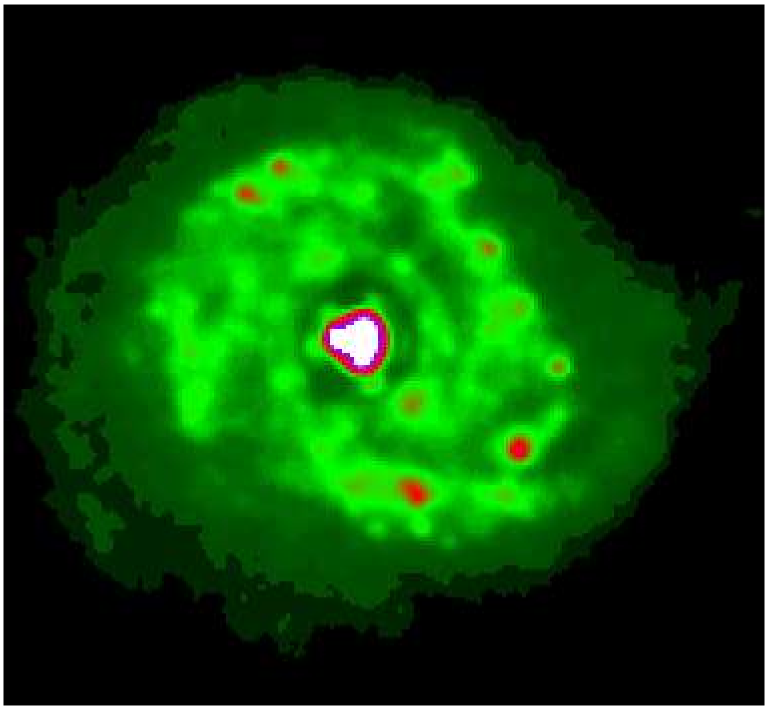

Figure 4. K images of NGC 7469, revealing a number of resolved clumps clearly arranged along the arms of a central micro-spiral structure and possibly at the ends of a micro-bar; the clumps are identified as very young stellar clusters. The field is 5.4" $\times$ 5.4" and the typical resolution of the image is 0.15".

Object	$L_{cluster}(L_\odot)$	$L_{galaxy}(L_\odot)$
NGC 7469	3.10^9	3.610^{11}
Arp 299	$0.1 - 3.\ 10^{10}$	5.10^{11}
Mkn 231	1.010^{11}	3.10^{12}
M82, NGC1569	$1. - 15.10^7$	3.10^{10}

Table 1. Typical luminosity of the young stellar super-clusters identified in three IR luminous galaxies, compared to the luminosity of clusters found in two typical starburst galaxies, M82 and NGC 1569 (last line). The last column gives the total luminosity of each galaxy.

The surprising result, as can be seen on table 1 which gives the estimated luminosities, is that those clusters feature intrinsic luminosity and surface density well above the figures generally found in the Local Cluster of galaxies: indeed, when compared to M82 or NGC1569 which feature $L_{cluster} \approx 1. - 15.10^7 L_\odot$, the luminosity we find in ULIRGs are 6 to 600 times larger ! Moreover, the trend is clearly to find the most luminous clusters in the most luminous galaxies, the top powerful of those mega-clusters being likely found in Mkn 231, with a luminosity of $10^{11} L_\odot$.

This result clearly points to a peculiarity of the star formation in IR luminous galaxies, not only regarding the global properties, but obviously also at the scale of the individual star forming regions, with an especially efficient stellar formation and possibly very high mass stars.

5. Relationship with an AGN

We have already mentioned that an AGN could be associated to IR luminous galaxies, as illustrated above by the cases of Mkn 231 or NGC 7469. The central accumulation of matter due to matter flowing from the arms under the effect of some non-axisymmetric torque will give rise on one hand to the huge starburst, but on the other hand will ultimately feed the central monster. Does the environment of the AGN keeps a trace of this relationship ? More especially can the dust/molecular torus which is predicted to encircle the proper AGN, hiding it from direct view in some cases, be detected ? and if yes, can it be related to some more larger scale structures ? In Alloin et al. (1998), it is indicated that such a direct detection of the torus was likely done in the case of NGC 1068 thanks to adaptive optics technique (Rouan et al., 1998). The alignment with the molecular disk seen at a larger scale (Tacconi et al., 1996) is also clear.

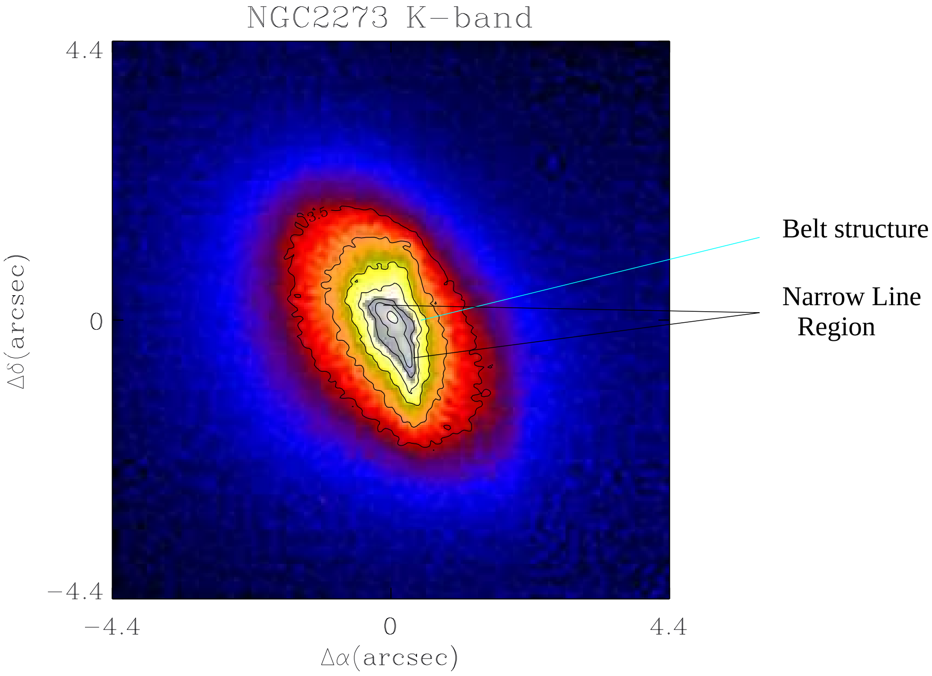

Figure 5. Deconvolved K image of the central 4.4" × 4.4" of Mkn 620 (= NGC 2273). The PSF is reconstructed from the wavefront sensor data. We propose that the central ENE–WSW belt-like structure seen both in emission on the outside and in absorption against the bright central jet-like rim (likely the NLR) is indeed the elusive torus predicted by the "unified model".

We present here new preliminary results on another Seyfert 2 nucleus, Mkn 620 (= NGC 2273), in which we think we put in evidence a similar torus structure. The K image, obtained in Dec 97 with Pueo, was deconvolved using a PSF reconstructed according to the scheme proposed by Veran et al. (1997) and the result is shown on Fig. 5. From a qualitative point of view, at least, the appearance of the central 100 pc is well in agreement with what can be expected if a thick torus intersects the bright emission of the collimated narrow line region: a dip in the bright central jet-like rim, due to the extinction by the dust of the torus, and on the external part of this putative torus, an extended ENE–WSW belt that would correspond to the warm dust seen in emission. The scale of the belt is typically 25 pc, i.e. of the same order of magnitude than the size of the torus which was likely found in NGC 1068. Those two results are clearly in the line of the so-called "unified model" of AGNs (Antonucci, 1993) and tend to favor the model of Granato et al. (1997) which assume a big, moderately thick, torus, as opposed to the compact thick one promoted by by Pier & Krolik (1994). If this result is confirmed, obviously the search for such big torus in Seyfert 2 nuclei, using adaptive optics techniques, will have to be more active, the ultimate tool for this type of study being a cooled integral field spectrograph fed by adaptive optics and able to benefit from the full angular resolution. Such a project – nicknamed *Grif* because it is in the line of the *Graf* instrument at the ESO 3.6 m telescope (Chalabaev et al., 1998) – was recently approved in the frame of the CFHT instrumentation plan, and is currently in the design phase.

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