ADAPTIVE OPTICS OBSERVATIONS to PROBE the DUST/MOLECULAR TORUS of NGC 1068

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Abstract

We provide in this paper a summary of results obtained by our group on the dust torus in NGC 1068, from AO observations in the NIR (1 to 5 μm) at CFHT and ESO. A first result concerns the position of the NIR emission peak with respect to the emission peak in the visible and I band (HST data), and with respect to the central engine which is thought to correspond to the radio source S1 (Gallimore et al., 1996; Muxlow et al., 1996). From AO imaging simultaneously in the K and I bands, our best estimate is that the 2.2 μm emission peak is located 0.28±0.05" South and 0.08±0.05" West of the bright continuum source observed by Lynds et al. (1991) at 5470 Å with the HST. The emission peaks at 3.5 and 4.8 μm are coincident with that at 2.2 μm, within the error-bars. At this position, the emission peak in the NIR is found to coincide with S1, with the 12 μm emission peak (Braatz et al., 1993) and with the summit of the UV emission cone (Capetti et al., 1995). Therefore, we conclude that most probably the NIR core emission is related to dust emission from a thick torus in which the central engine is embedded and which prevents its direct view. A second result is related to the structure of the inner 1" region within the AGN, at 2.2, 3.5 and 4.8 μm. From our AO data obtained with a resolution down to 0.12" at 2.2 μm, we find 3 outstanding structures: (i) most of the NIR emission arises from a core with size less than 9 pc: this implies that the inner regions of the torus, where the dust temperature reaches sublimation temperature, are located at a radius less than 4.5 pc. (ii) an extended (±15 pc) structure can be recognized at PA=102°, on both K, L and M images. The orientation of this structure is quite close to that of the VLBA 84 GHz elongated (±1 pc) structure at PA=110° (thought to represent the ionized inner walls of the torus according to Gallimore et al., 1997), and to that of the disc-like structure (±70 pc) seen in the CO line at PA=98° (the outer and cooler region of the molecular torus, Tacconi et al., 1997). This structure might indeed be the trace of a molecular/dust torus seen almost edge-on and with radius up to 70 pc. (iii) another elongated structure is prominent at PA=10°, from 1 to 10 μm. It matches the so-called ionization cone feature and its NIR emission might arise from hot to warm dust located in the non-illuminated back-side of hidden BLR clouds and of NLR clouds identified in the cone. We have derived the 1996-1997 NIR flux from the central 3" diameter region, to be compared to that obtained in 1975 by Rieke & Low. We find that the flux from 2.2 up to 4.8 μm has doubled over 20 years, while the flux at 10 μm has only increased by 1.2. This is in perfect agreement with independent measurements by Glass (1997) at 3.5 μm. This tells us that the hot dust emission responding to an increase of the central engine UV flux is located at least 3 pc away, while cooler dust is still further out.

Introduction

Over the past decade, considerable efforts have been devoted to a better understanding of active galactic nuclei (AGN). In particular the use of HST (UV & visible domains), Adaptive Optics (AO) systems on 4m-class ground-based telescopes (NIR) and the use of interferometry (mm domain) have permitted large gains in spatial resolution and have brought more constraints in AGN modeling. Conversely, the unified model of AGN has played an important role in stimulating observational searches for the AGN constituents, among which the elusive parsec-scale torus which is thought to surround the central engine (black hole and accretion disc) and to funnel the ionizing radiation within a conical structure with axis perpendicular to the torus. Models of the NIR emission from the torus have explored so far torus sizes from 1 to 100 pc (Pier & Krolik, 1993; Efstathiou & Rowan-Robinson, 1995; Granato, Danese & Franceschini, 1997), while the thickness, inclination and composition of the torus are other key-parameters in the modeling. Given an input energy distribution from the central engine, models then predict emission maps at wavelengths from 2.2 up to 20 μm accross the 100 pc central region of the AGN. Models predict that the emission peaks at various wavelengths through the NIR window are offset from the location of the central engine as soon as the torus inclination is substantial. Models also enlighten the dependence of the NIR maps' aspects on the geometrical and model parameters. To test these predictions, one has to choose an AGN for which the torus is expected to be strongly inclined (Seyfert 2) and close enough so that the spatial resolution achievable today (0.1") corresponds to an intrinsic size commensurate with (or smaller than) the torus dimension: NGC 1068 is the ideal case. In NGC 1068, 0.1" corresponds to 7 pc and high resolution observations of this AGN have been quite effective since the early 90's: contributions from the HST (Capetti et al., 1997), from mm and cm interferometry (Tacconi et al., 1997; Gallimore et al., 1997) and from AO observations in the NIR (Marco et al., 1997; Rouan et al., 1998; Marco et al., 1998). We report in this contribution on the AO results.

Data sets

Special montage of AO observations

Prior to any discussion regarding the nature and physics of the components (compact and extended) identified in UV, visible, NIR and radio wavelengths within the 1"×1" central region of NGC 1068, as well as their relationship, it is imperative to register precisely the images at different wavelengths. This is however a quite difficult task as there are no sources in the field of NGC 1068 to be used as astrometric references.

In the K band (2.2 μm) we now can achieve a high angular resolution thanks to AO systems. We used COMEON+ at ESO to observe NGC 1068 in the K band on October 1993. Thus, we decided also to setup the experiment, adding a dichroic foil along the imaging light-path (Fig.1), to observe simultaneously in the visible (I band) with a CCD camera, and in the NIR (K band) with SHARP, in order to position and scale very accurately images in the two bands (Marco et al., 1997).

Standard AO observations

Thanks to AO systems again, we now have the opportunity to probe in the NIR the inner structure of AGN at the diffraction limit of 4 meter class telescopes.

We used two different systems to observe NGC 1068 from 1 to 5 μm:

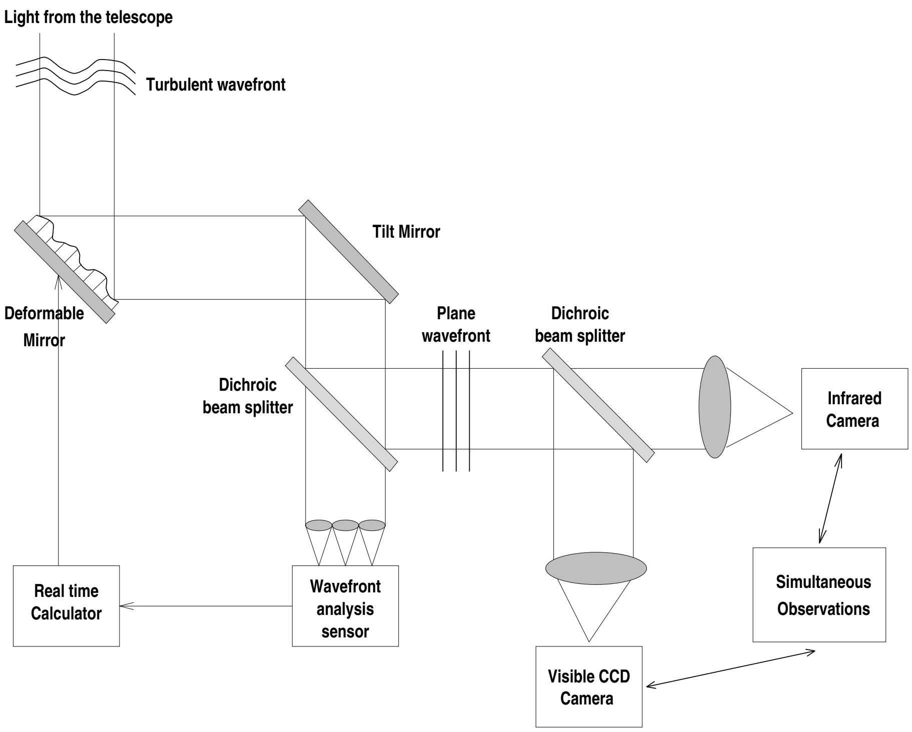

Figure 1: Experimental setup for the simultaneous observations in the NIR & the visible with COME ON+

- ADONIS at ESO La Silla Observatory (August 1996), with the COMIC camera, in the L & M bands (Marco et al., 1998), see Fig.6.
- PUEO at CHFT (February 1997), in the J, H & K bands, with the MONICA camera (Rouan et al., 1998), see Fig.6. NGC 1068 has also been observed later again in the K band with PUEO and the KIR camera (December 1997), fully confirming the results obtained previously with MONICA.

Classical observations in the 10 μm window

In the mid-IR, observations under good seeing conditions can lead to diffraction limited images even without AO systems. That was the case when NGC 1068 has been observed at 10 μm with CAMIRAS at the ESO 3.60 m telescope (Lagage et al., 1998), see Fig.5. The final angular resolution is 0.7" (diffraction-limited).

Location of the NIR emission peaks at different wavelengths

Several attempts have been made to determine the location of the NIR emission peaks, in the K, L & M bands.

Using simultaneous visible and infrared AO observations, Marco et al. (1997) found the K band emission peak to be located 0.28±0.05" South and 0.08±0.05" West of the bright continuum source observed by Lynds et al. (1991) at 5470 Å with the HST.

Later, Rouan et al. (1998) observed NGC 1068 with PUEO. In order to get the relative positioning, they rely on observations of a nearby star interlaced with the NGC 1068 measurements, which provides a positional reference both on the WFS and on the NIR camera. They derive an offset of 0.18±0.05" South and 0.15±0.05" West.

Using the same method, Marco et al. (1998) found the emission peaks at 3.5 and 4.8 μm to be coincident with that at 2.2 μm, within the error-bars.

Comparison with other results

Quirrenbach et al. (1997) observed NGC 1068 with COME ON+ in October and November 1994 to establish the offset between the visible continuum and the H & K bands. They switched between NGC 1068 and two reference stars located $\approx 2°$ from the galaxy. They published that the centroid of the 5000 to 9000 Å continuum is displaced 0.41±0.10" to the North and 0.23±0.10" to the East of the K band emission peak. They found the location of the H and K band emission peaks to be identical within the errors. Their result is roughly compatible with our measurements.

This same data is also presented and discussed in Thatte et al. (1997). From their figure 6, one derives however different offsets for the K band emission peak: 0.216±0.10" South and 0.095±0.10" West of the blue continuum peak, closer to our own measurements.

Comparison with radio, 12 μm, UV cone summit, and central engine location

In the radio range, a detailed discussion has been provided by Gallimore et al. (1996), based upon new measurements of the maser positions and kinematics.

In the mid-IR, there has been one attempt to perform astrometric measurements. The 12.4 μm peak detected by Braatz et al. (1993) has been placed by these authors with respect to the visible continuum image observed by Lynds et al. after smoothing the HST visible image to the spatial resolution of the 12.4 μm image. The 12.4 μm peak appears to be located 0.3±0.15" South of the emission peak in the visible (defined as the visible nucleus seen by Lynds et al., 1991).

In the [O III] line emission, in the visible and UV continuum emission, we rely on the HST observations (Macchetto et al., 1994; Capetti et al., 1995). From the post-COSTAR data set (Macchetto et al., 1994), the UV and visible continuum maps have been positioned very precisely one with respect to the other, as many point-like sources can be identified within the field-of-view. The UV and visible 5470 Å continuum emission peaks (which do not correspond to the true nucleus but are scattered light from the nucleus) are found to be coincident. The 5470 Å bright continuum peak observed by Lynds et al. (1991) and corresponding also to our I band continuum peak as confirmed by the HST WFPC2 data (Marco et al., 1997), is located 0.05" North of the [O III] NLR-B cloud and is not associated with an isolated particular [O III] NLR cloud. The [O III] emission peak is found within NLR-B cloud (Evans et al., 1991).

Building up from these results and using our precise relative positions of the K and I band images we are led to the sketch shown on Fig.4, where our NIR isophotes have been overlaid on the [O III] HST image, and compared with other wavebands data.

Structure of the inner 1" region in the AGN of NGC 1068

What is the relevance of the NIR peak to the true nucleus, and which signatures do we expect from this nucleus ? Since the observations in polarized light of broad permitted lines from the nuclear region by Antonucci & Miller (1985), the presence of a very thick dust/molecular parsec-scale absorbing torus around the central engine, has been suspected. The location of the "true" nucleus has been argued on the basis of :

(i) its energetic radiation : the apex of the ionizing cone from the [O III] line emission distribution (Pogge, 1988, Evans et al., 1991),

(ii) its dust/molecular component : CO line emission (Tacconi et al., 1997), location of the water mega-maser (Gallimore et al., 1996),

(iii) its polarization properties : the pattern of the UV polarization vectors (Capetti et al., 1995),

(iv) the location of the unusual, flat spectrum radio source S1 (Muxlow et al., 1996)

As the emission peak in the NIR (2.2, 3.5 and 4.8 μm) is coincident with S1, with the 12 μm emission peak (Braatz et al., 1993) and with the summit of the UV cone emission (Capetti et al., 1995), we conclude that most probably the NIR core emission is related to dust emission from a thick torus in which the central engine is embedded and which prevents its direct view. The hot dust ($T_{dust} \approx 1400$ K) is heated directly by the hidden central engine.

The high angular resolution images obtained with PUEO (0.12") and ADONIS (0.3") reveal the structure of the inner 1" region within the AGN, at 2.2, 3.5 and 4.8 μm.

From these data, we find 3 outstanding structures:

(i) most of the NIR emission arises from a core with size less than 9 pc: this implies that the inner regions of the torus, where the dust temperature reaches sublimation temperature, are located at a radius less than 4.5 pc.

(ii) an extended ($\pm$15 pc) structure can be recognized at PA=102°, on both K, L and M images. The orientation of this structure is quite close to that of the VLBA 84 GHz elongated ($\pm$1 pc) structure at PA=110° (thought to represent the ionized inner walls of the torus according to Gallimore et al., 1997), and to that of the disc-like structure ($\pm$70 pc) seen in the CO line at PA=98° (the outer and cooler region of the molecular torus, Tacconi et al., 1997). This structure might indeed be the trace of a molecular/dust torus seen almost edge-on and with radius up to 70 pc.

(iii) another elongated structure is prominent at PA=10°, from 1 to 10 μm. It matches as well the so-called ionization cone feature and its NIR emission might arise from hot to warm dust located in the non-illuminated back-side of hidden BLR clouds and of NLR clouds identified in the cone.

Spectral Energy Distribution of the central 0.6" core and variability

One crucial parameter in model predictions of the NIR emission maps is the spectral energy distribution (SED) of the central engine. Getting an observational hand on the SED implies gathering measurements which have been obtained however with different spatial resolutions. On the high energy side of the SED, X to UV, we are quite confident this does not cause much trouble: firstly, the central engine is point-like, and secondly the central engine is by a large factor the dominant (if not the sole) contribution: then a change in spatial resolution will not affect the measurement so much, as long as it encloses the entire point-like source. For wavelengths between 1 and 10 μm, this favorable situation does not hold anymore and we should use, for the modeling, measurements corresponding to the smallest possible "diaphragm".

From our set of AO images, we have reconstructed the SED of the core emission through an 0.6" diameter diaphragm, as displayed on Fig.2. In this plot, the contribution from the stellar component has been removed for the J and H bands, following the spatial profile analysis performed by Rouan et al. (1998), which led to the discovery of two stellar-light exponential discs with characteristic radii 0.26 and 3.1", respectively 19 and 220 pc, also associated with bars of corresponding sizes. Then, the SED shown on Fig.2 refers only to the central engine and its immediate environment, including the inner regions of the suspected dust torus. A revision of the AGN modeling for NGC 1068 will incorporate this new SED in the 1 to 10 μm window (work in progress).

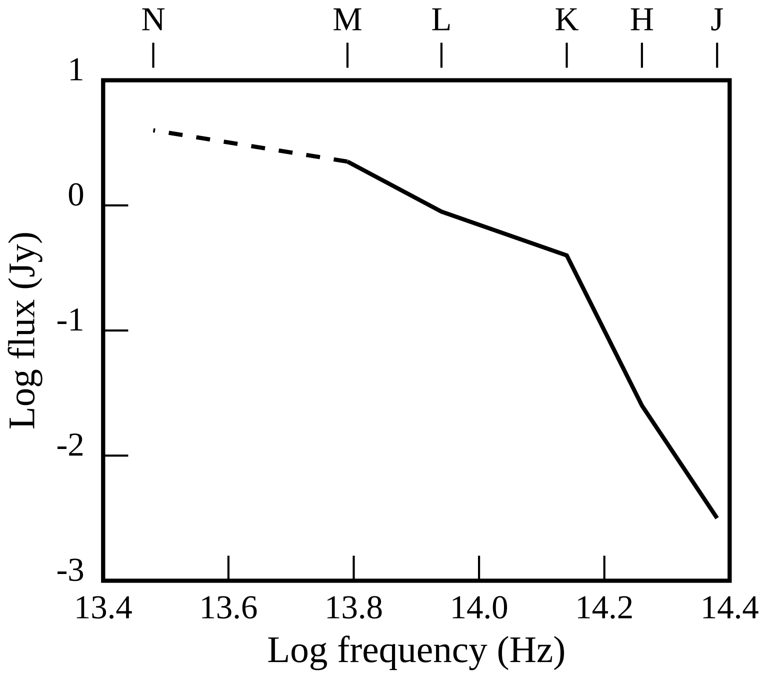

Figure 2: SED of the central 0.6" core (the value for the N band is given for 0.8")

We were interested as well in comparing our 1996/1997 measurements to those performed by Rieke & Low as early as 1975. Therefore, we have derived, for a 3" diameter diaphragm the observed fluxes at 1.25, 1.65 (both uncorrected for the stellar contribution), 2.2, 3.4, 4.8 and 10 μm, from our data set. A comparison of the fluxes at both epochs is provided in Table 1. One notices immediately that a flux increase has occurred over this time interval: by a factor 2 between 2.2 to 4.8 μm, while slightly less, by a factor 1.2, at 10 μm. According to Glass (1995), the L band (3.4 μm) flux has doubled in 18 years, from 1974 to 1992: our result is in perfect agreement with this statement.

Assuming that the hot dust is responding to a flared-increase in the central engine UV emission and in the framework of simple light-echo effects, this tells us in addition that the location of the bulk of hot dust emitting predominantly in the K, L and M bands is at least 3 pc away from the central engine (assuming an almost edge-on configuration). The warmer dust, which emits predominantly at 10 μm, is located further out and seems to be just starting its response to the UV flux increase (Fig. 3). Again, a more detailed model is currently being worked out, which will consider as well the dust temperature

	J	H	K	L	M	N
1997	0.13	0.3	0.8	3.4	9.7	21.5
1975			0.3	1.7	5.3	17.9

Table 1: Comparison of the infrared fluxes (given in Jy) at two epochs in a 3" diaphragm

distribution and the geometrical parameters of the system (in particular its inclination).

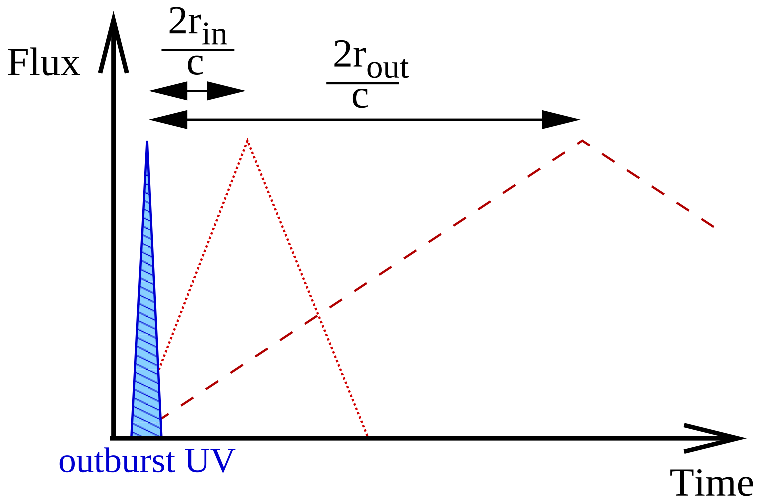

Figure 3: Sketch of the IR response to a UV outburst in the case of an almost edge-on view (dotted line for hot dust emission at r_{in}; dashed line for warm dust emission at r_{out}).

Final remarks

The above results clearly show that testing AGN models does require high spatial resolution data sets, because of the object's complexity. In addition, a similar spatial resolution has to be reached over different wavebands: with HST, NIR AO and mm interferometry this is possible, as we do access a similar 0.1" resolution. Therefore such data sets can be used in conjunction and are quite complementary.

There is still an area in which one has to be careful: the relative positioning of maps at different wavelengths poses a problem when the size of the field of view is too small for using background objects. In such a case, one should retain the possibility of obtaining simultaneously images in two different wavebands. Future AO system designs should offer the possibility of a dual output after the AO correction.

Finally, the next step to constraint AGN modeling is to obtain kinematical information, that is spectrophotometric information on a similar 0.1" scale.

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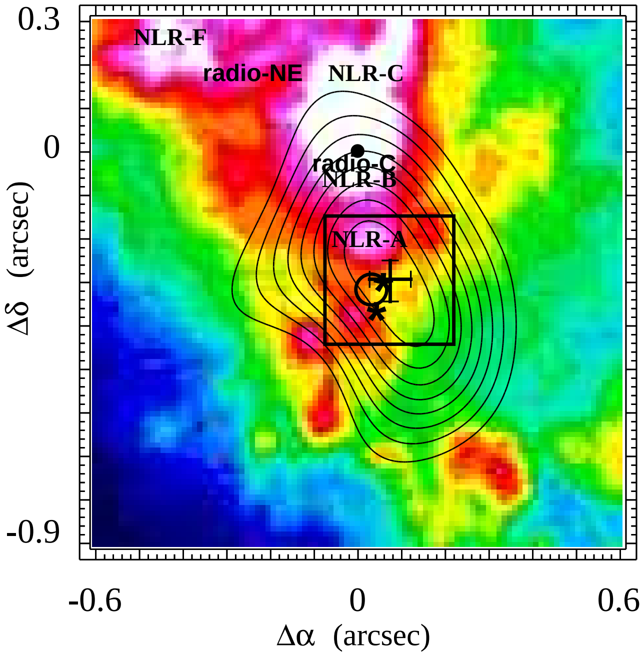


Figure 4: Contour map from old COME ON+ data (low resolution) overlaid on an image from the HST in the [O III] line (Macchetto et al., 1994). We show the [O III] line NLR-clouds as identified by Evans et al. (1991), the radio sources NE & C as positioned by Gallimore et al. (1996). North is up, east to the left. Symbols are: **dot** : the continuum peak at 5470 Å (Lynds et al., 1991), also our I peak (V and I being located at the same position, according to Z. Tsvetanov, 1996); **stars** : the radio components S1 and S2 as located by Gallimore et al. (1996) ; **box** (size indicates errorbar) : the 12.4 μm peak positioned by Braatz et al. (1993); **cross** (size indicates errorbar) : the K near-infrared peak as positioned in Marco et al. (1997); **circle** (size indicates errorbar) : the symmetry center of the UV/optical polarization (Capetti et al., 1995).

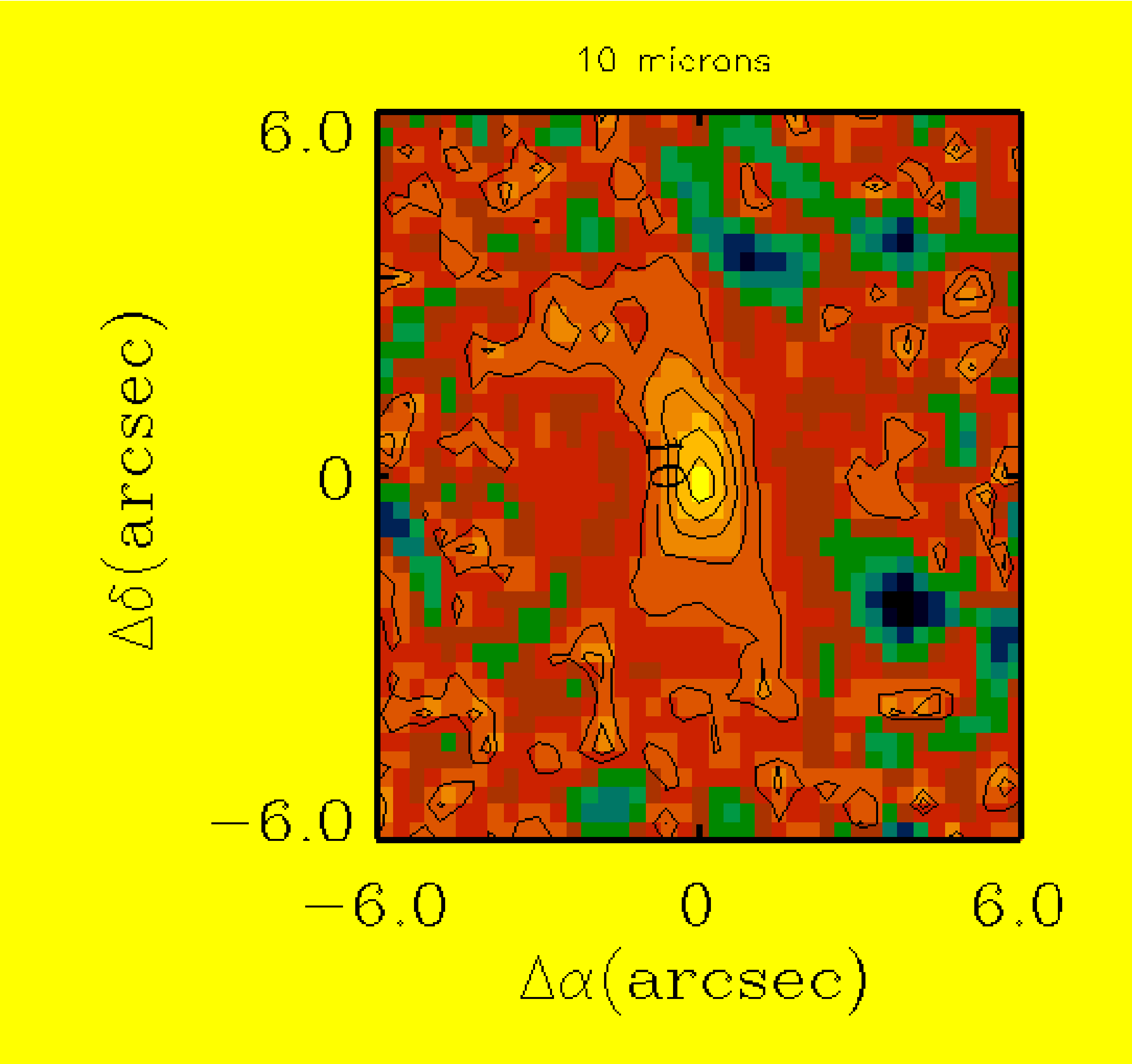
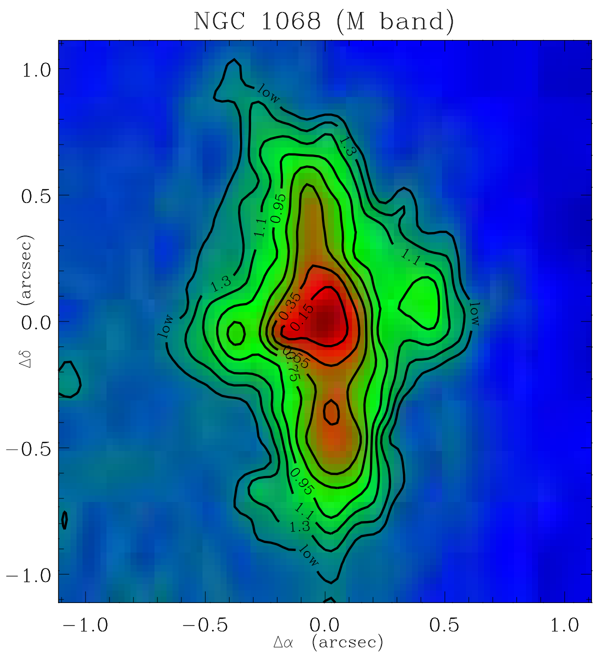
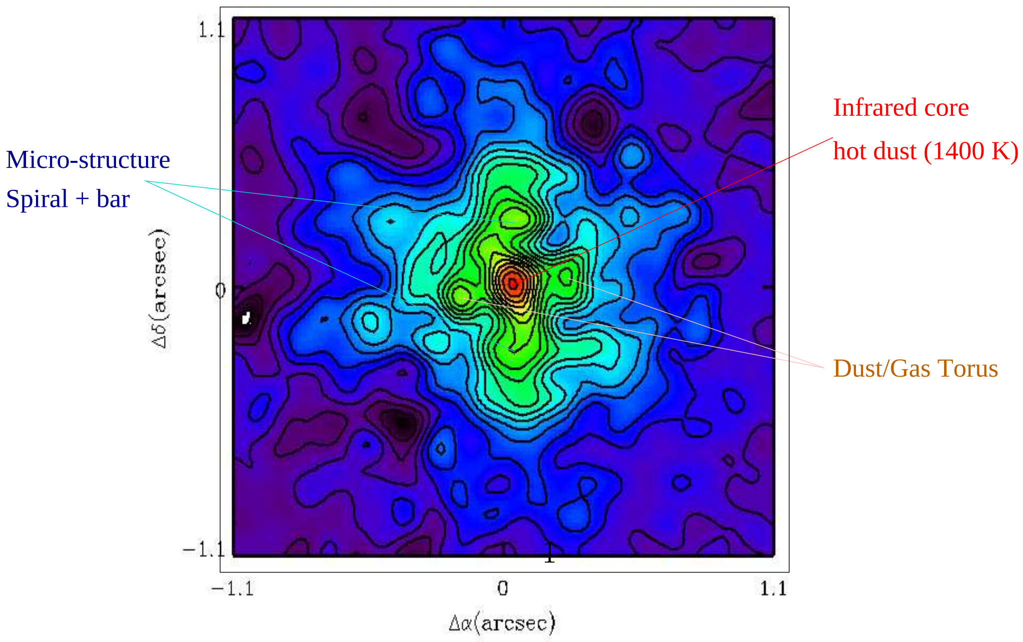


Figure 5: NGC 1068 in the N band at a resolution of 0.7”



NGC 1068 @ 4.8 μ m
2.2"x2.2" - resolution = 0.33"
(ADONIS @ ESO)



NGC1068 @ 2.2 μ m
2.2" x 2.2" - resolution = 0.11"
Deconvolution with Max Likelihood
(PUEO @ CFHT)

Figure 6: Deconvolved images at 4.8 & 2.2 μm