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A STELLAR CUSP AT THE HEART OF NGC1068

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Abstract. Polaro-imaging observations with SPHERE in the near infrared + adaptive optics of the heart (500 pc) of the type-2 AGN NGC1068 allow to reach a resolution of the order of 2 pc. In addition to an elongated structure on 60 pc, exactly aligned with the molecular torus seen by ALMA, the radial distribution of brightness in H and K corresponds to two power-laws with a high value of the exponent, indicative of a cuspy distribution. Different models are tested to explain both the high value of the exponent and why they are different between H and Ks bands. The most satisfactory is the one combining a stellar cusp with radius 100 pc, together with emission of hot dust directly illuminated by the accretion disk and an unresolved point like central source (1pc) of very hot dust, close to the sublimation temperature. An empirical relationship between brightness and radius of the cusp in the hearts of bright or ultra-bright IR galaxies is also established, from a rather large sample. Cuspy stellar distribution, sculpted or not by dark matter, appear to be an important component of AGN where recent star formation occurred.

Keywords: Galaxies: Seyfert, high angular resolution, near-infrared, cusp

1 Introduction

The cusp/core problem, identified twenty years ago, is the apparent inconsistency between the predicted and observed dark matter density profile at centre of galaxies: cosmological simulations predict a steep power-law (cusp), while observations of low surface brightness disk and gas-rich dwarves rather show a constant density (core). The controversy is still alive with on one hand discussions on mechanisms that could transform cusps into cores such as supernova feedback (Pontzen & Governato 2012 , J. Freundlich in this proceedings), self-interaction and on the other hand identification of bias in data analysis (triaxiality, . . .).

In an active galactic nucleus (AGN), the feeding of the central engine (hereafter CE), i.e. the accretion disc, requires a high accretion rate of matter (0.3 in Seyfert galaxies to 10 $M_{M_\odot}\ yr^{-1}$) through a still unclear mechanism for the needed loss of angular momentum at short scale. Hopkins & Quataert (2011)), using the results of their multi-scale hydrodynamical model proposed that lopsided cuspy stellar discs at a scale of ≈ 10 pc would be the dominant cause for this angular momentum transport below this scale.

Is there a direct relationship between dark matter and the formation of such a stellar cusp may be a matter of debate, but in any case trying to identify if a cusp is indeed present is important.

The combination of adaptive optics (AO) on large telescopes and imaging in the near-IR (NIR) gives the opportunity to search for such stellar cusp at least on nearby AGNs.

NGC 1068 is one of the closest AGN (14.4 Mac). One consequence is that the nucleus is bright enough to be used as the guide source for the AO system, allowing to obtain images in the NIR at angular resolution of ≈ 40 mas, i.e. ≈ 3 pc.

A cusp being characterised by a power-law profile, we present here an analysis in terms of radial profile of AO images of NGC 1068 in K_s and H bands obtained with SPHERE on the VLT. The images already showed a polarisation angle map with a clear centro-symmetric pattern, tracing both parts of the ionisation bicone and featured a central non-centro-symmetric pattern approximately 60 pc $\times$ 20 pc wide, with aligned polarisation, that is interpreted as the trace of the outer envelope of the torus, revealed through a double scattering process (Gratadour et al. 2015; Grosset et al. 2018): see Fig.1. Note that there is a fairly good alignment of the elongated pattern with the molecular torus seen by ALMA García-Burillo et al. (in prep.).

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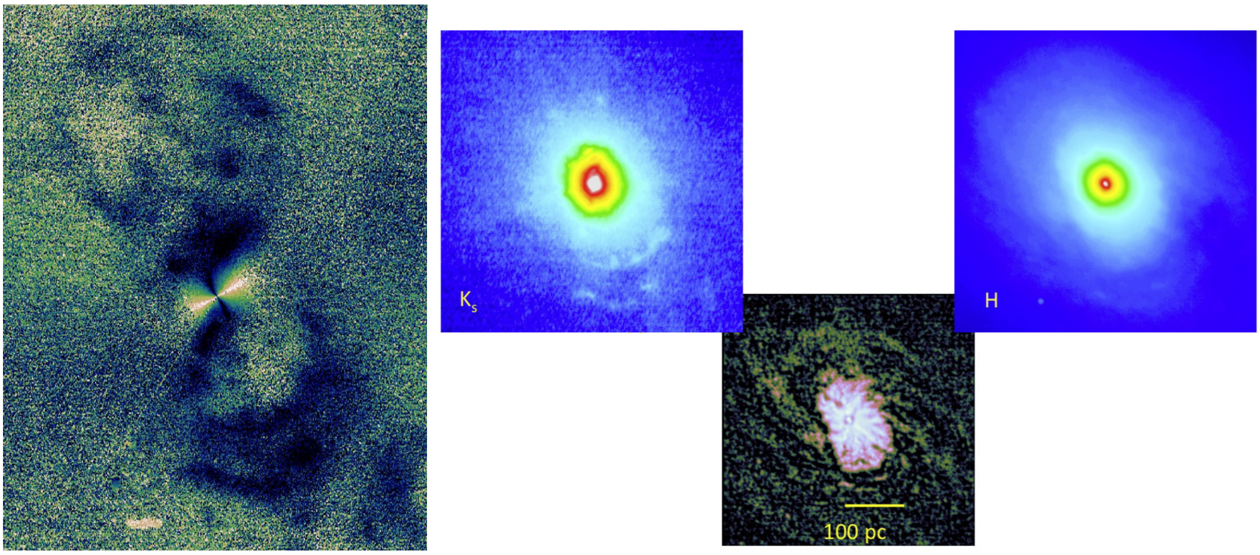

Fig. 1. Left: map of the polarisation angle at 1.65 μm of the central region in NGC1068, revealing both the lobes of the biconical Narrow-Line Region and the central elongated structure tracing the torus (Gratadour et al. 2015). Right top: Ks and H SPHERE images. Right bottom: H images processed to enhance the local contrast and revealing hints of a spiral structure.

2 The median radial brightness profile

We show on Fig.2-left the median radial profiles around the central core deduced from the H and Ks images, together with the PSF profile at K_s measured on a nearby reference star. The H-band profile is almost perfectly fitted by a power law of exponent -1.2, while the K_s-band profile id fitted by a combination of a power-law profile of exponent -2.0 plus the PSF profile properly weighted. In particular, we note that the small bumps on the K_s-band profile, close to the peak, are well fitted by the first and even the second Airy rings of the PSF. The straightforward interpretation is that the K_s-band profile results from the contribution of a central point source and of a smoother distribution that is directly related to the H-band emission. We can safely interpret the point source component as the internal wall of torus heated to dust sublimation temperature around 1400K, as generally admitted.

The two main questions raised by the fit are: a) are we indeed viewing an actual stellar cusp or is it some other source of radiation that mimics a cusp ? b) if yes, why are the exponents of the power-law so different if they trace the same stellar population ?

2.1 Possible nature of the cusp

In the literature, there are at least 3 families of cusp which are identified: *i)* around a massive black hole a cusp forms as the result of 2-bodies interactions that create some segregation between stars and a cusp with exponent between -1.3 and -1.8. However in the case of NGC1068, the relaxation time to reach this state would be too long; *ii)* a compact nuclear cluster, a rather current situation that would be found in 75% of Scd and 70% of E - S0; typical radius and exponent would be R $\approx$ 7pc and -0.6. *iii)* a central starburst cusp, a case found in galaxies forming stars at a high rate; typical radius and exponent would be R $\approx 45 - 2400$ pc and -0.8.

We have examined the catalog of central starburst cusp established by Haan et al. (2013) and found an interesting relation between exponent, radius and luminosity of the cusp: $\gamma = 1.133 \times [log10(L_{cusp}/R_{cusp}) - 6.63]$, as illustrated on Fig. 2-right where the location of NGC1068 is indicated by a star symbol. We conclude that the central cusp in NGC 1068 belongs likely to this class of central starburst cusp.

2.2 A simple radiative transfer model

To tackle the question why are the exponents so different in H and Ks if indeed we are facing a stellar cusp, we have explored different possibilities by developing a simple radiative transfer toy model that can take into

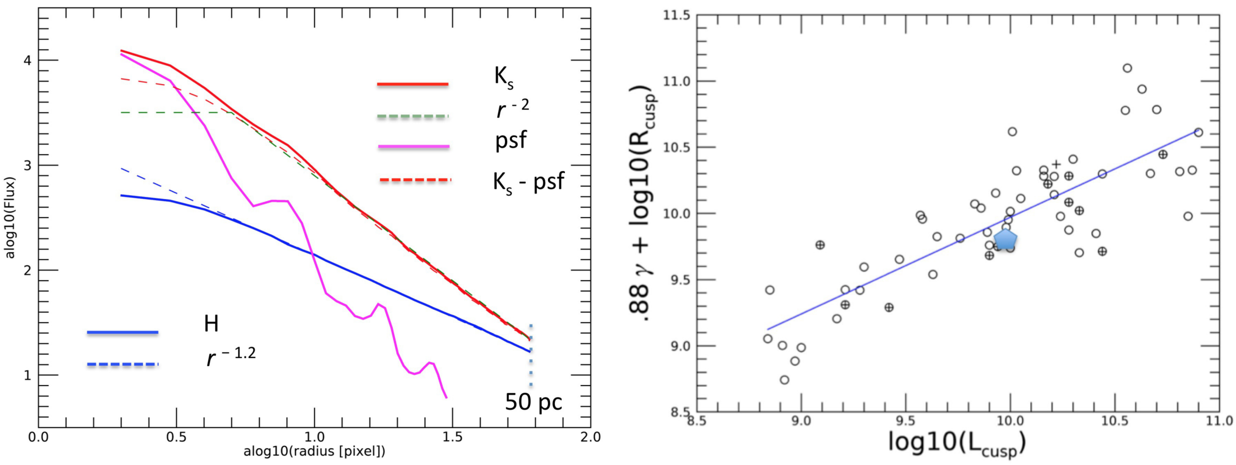

Fig. 2. Left: observed radial profiles in Ks and H (solid red and blue lines) and their fit by a pure power-law in H or by a combination of power-law and point source (magenta) in Ks. Right: cusp luminosity as predicted by the law we found (see text) vs the actual cusp luminosity for the starburst galaxies studied by Haan et al. (2013). The blue line is the linear regression. The star symbol is for NGC 1068.

account different sources of radiation: stellar cusp of profile $r^{-\alpha}$, a point like central engine and hot to warm dust mixed within the stellar cusp. The considered absorber is the same dust, distributed according to some power-law $r^{-\gamma}$. Fig. 3 gives a sketch of the geometry of the model.

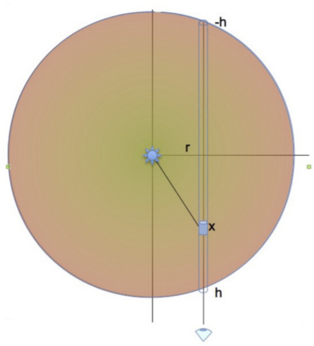

Fig. 3. Sketch of the adopted geometry for the radiative transfer model

We first tested if differential extinction between the H and Ks bands could explain the difference of exponent, if denser dust towards the central region was absorbing more efficiently the shortest wavelength, thus reducing the slope of the brightness with respect to the intrinsic stellar distribution. We could reach an almost satisfying solution, as illustrated on Fig. 4-a, but at the price of an unrealistic exponent of the stellar cusp (r^{-4}) and too large a mass of dust.

An alternative and much more acceptable solution is to consider a mix of stellar cusp and warm dust heated by the central engine. The temperatures reached by the dust mixed with the cusp is high enough to contribute significantly to the emission in the Ks band in the central 15 pc, while the most external region up to 50 pc becomes more and more dominated by the stellar cusp radiation, the combined effect of the two sources mimicking rather precisely a continuous power-law of exponent -2. Of course the same exponent of -1.2 was used for the stellar cusp in both infrared bands. The result of the modelling is illustrated in Fig. 4-b where the green solid line is the result of the observed radial distribution of brightness minus the contribution of the stellar cusp, the later being proportional to the H band profile (solid blue line): we can check that the thermal radiation from warm dust predicted by the model (dotted green line) fit quite well this difference.

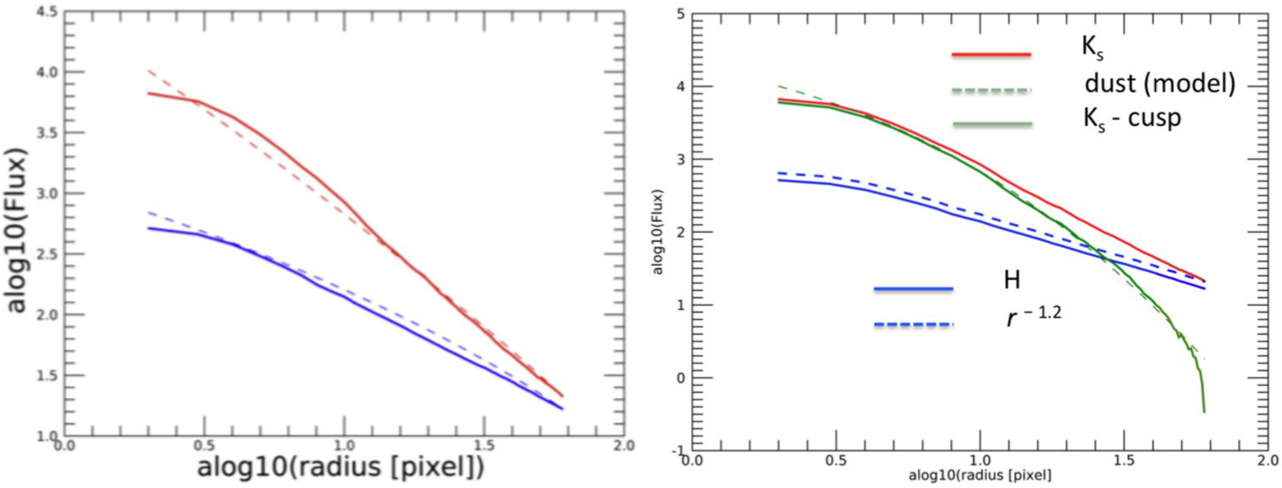

Fig. 4. Left: Effect of differential extinction solely. Red and blue solid lines: observed 2 to 50 pc radial fluxes in K_s and H band; red and blue dashed lines: K_s-band and H-band profiles resulting from the radiative transfer model, when the power law for the stellar and dust radial density have exponents of -4.20 and -1.05, respectively. Right: Preferred solution with warm dust emission. K_s-band (red solid) and H-band (blue solid) radial profiles; green solid line: K_s-band radial profile subtracted with a stellar cusp contribution proportional to the H-band profile; blue dashed line: estimated stellar cusp at K_s; green dashed line: best fit by the model of thermal dust emission (see text).

3 Conclusions

The question of wether a cuspy distribution of stars is actually observed in central region of galaxies, as predicted by dark matter halo simulation, is still a matter of debate.

At least in the case of the Seyfert galaxy NGC1068, the archetype of type 2 AGN, where near-IR images were obtained thanks to high angular resolution observations with VLT-SPHERE, we have shown that indeed a true cusp is observed. There is however the serious problem that the exponents of the power-law fitting the brightness radial profiles, differ notably between the two wavelengths (1.65 μm at H and 2.16 μm at Ks) where observation was done.

We have built a simple model of radiative transfer to try to explain this difference by considering various possibilities mixing stellar emission, dust absorption and dust thermal emission.

We reach the conclusion that at the heart of NGC1068 there are 3 components that explain the profile of the brightness : *i)* a stellar cusp of profile $r^{-1.2}$, with radius $\approx$ 100 pc, and Luminosity = 3.2 10^{10} $L_\odot$, which is a probable remnant of a recent starburst episode; *ii)* warm to hot dust heated by the central engine on $\approx$ 15 pc; *iii)* an unresolved source at $\approx$ 1400 K, likely the internal wall of a thick torus at dust sublimation temperature. Those results are presented in a more detailed way in Rouan et al. (2019).

A question remains: is the pronounced cusp a tracer of a dark matter halo ? This study just brings some elements characterising the cusp that may constrain the problem, but obviously cannot answer the question.

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