

Following the gas flows from nuclear spirals to the accretion disk

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Abstract. A recent analysis of HST optical images of 34 nearby early-type active galaxies and of a matched sample of 34 inactive galaxies – both drawn from the Palomar survey – shows a clear excess of nuclear dusty structures (filaments, spirals and disks) in the active galaxies. This result supports the association of the dusty structures with the material which feeds the supermassive black hole (hereafter SMBH). Among the inactive galaxies there is instead an excess of nuclear stellar disks. As the active and inactive galaxies can be considered two phases of the “same” galaxy, the above findings and dust morphologies suggest an evolutionary scenario in which external material (gas and dust) is captured to the nuclear region where it settles and ends up feeding the active nucleus and replenishing the stellar disk – which is hidden by the dust in the active galaxies – with new stars. This evolutionary scenario is supported by recent gas kinematics of the inner few hundred parsecs of NGC 1097, which shows streaming motions (with velocities $\sim 50 \text{ km s}^{-1}$) towards the nucleus along spiral arms. The implied large scale mass accretion rate is much larger than the one derived in previous studies for the nuclear accretion disk, but is just enough to accumulate one million solar masses over a few million years in the nuclear region, thus consistent with the recent finding of a young circumnuclear starburst of one million solar masses within 9 parsecs from the nucleus in this galaxy.

Keywords. Galaxies: active – galaxies: nuclei – galaxies: kinematics and dynamics – galaxies: individual (NGC 1097) – galaxies: ISM

1. Introduction

The relation between the morphologies of host galaxies and the presence of nuclear activity has been investigated for many years. One of the first studies arguing for a difference between active and inactive galaxy hosts is the one of Simkin, Su & Schwarz (1980). These authors have claimed that Seyfert galaxies hosts are more distorted than inactive galaxies, showing an excess of bars, rings and tails. More recent studies did not confirm the excess of bars in Seyferts (e.g. Mulchaey & Regan 1997) while others have found a small excess (e.g. Knapen *et al.* 2000).

A number of studies using Hubble Space Telescope images of nearby galaxies have revealed a trend for active galaxies always showing a lot of dust structure in the nuclear region. Van Dokkum & Franx (1995) have found that radio-loud early-type galaxies have more dust than radio-quiet ones. Pogge & Martini (2002) and later Martini *et al.* (2003) found that Seyfert galaxies almost always present dusty filaments and spirals in the nuclear region, while Xilouris & Papadakis (2002) found that, among early Hubble types, active galaxies present more dust structure than inactive galaxies. Recently, Lauer *et al.* (2005) have also argued that dust in early-type galaxies is correlated with nuclear activity.

The goal of the present paper is to discuss the results of a recent study (Lopes *et al.* 2007) which provides a robust analysis of the relation between nuclear dust structures and activity in galaxies on the basis of optical HST images. The particular case of NGC 1097

is then discussed, for which we have obtained, in addition, kinematics of the gas associated with the nuclear dust structures (Fathi *et al.* 2006) which reveal streaming motions towards the nucleus. We then use results of previous studies (Storchi-Bergmann *et al.* 2003, Nemmen *et al.* 2006) to relate the mass accretion rate reaching the accretion disk to the larger scale mass flow rate derived from the observed streaming motions.

2. Correlation between circumnuclear dust and nuclear activity

We (Lopes *et al.* 2007) have recently selected a sample comprising all active galaxies from the Palomar survey (Ho *et al.* 1995) which have optical images in the HST archive, as well as a pair-matched sample of inactive galaxies, and constructed “structure maps”, a technique proposed by Martini & Pogge (1999) to enhance both absorption and emission structures in the images. The total sample comprises 34 matched pairs of early-type galaxies ($T \leq 0$) and 31 pairs of late-type galaxies ($T > 0$).

The results for the 34 early-type pairs of our sample are illustrated in Fig. 1 for a subsample of 10 pairs: while all (100%) active galaxies present some dust structure, only 26% (9 of 34) of the inactive galaxies possess some dust. Another difference is the finding that at least 13 of the 34 (38%) early-type inactive galaxies present bright *stellar disks*, while only one of the active galaxies show such disks. Most dust structures and stellar disks are seen within a few hundred parsecs from the nucleus. A different result was obtained for the late-type pairs: all galaxies show circumnuclear dust regardless the presence or absence of nuclear activity, and stellar disks were found only in a couple of galaxies.

The above findings imply a strong correlation between circumnuclear dust and nuclear activity, indicating that the dust is connected to the material which is currently feeding the active nucleus, and is probably tracing this material on its way to the nucleus. The morphologies of the dust structures range from chaotic filaments to regular dusty spirals and disks, suggestive of a “settling scenario” for the dust, as proposed by Lauer *et al.* (2005). Our finding of nuclear stellar disks in inactive galaxies suggests that there is one further step in this evolutionary scenario: the stellar disk, which shows up in the inactive phase of the galaxy. The evolutionary scenario can be described as follows: externally acquired matter is traced by the chaotic filamentary structure which gradually settles into more regular nuclear spirals and disks. Stars then form in the dusty disks, and when the gas and dust are fed to the black hole, nuclear activity ceases and the stellar disks are unveiled (Ferrarese *et al.* 2006). As stellar disks should be longer lived than the gaseous dusty disks, the stellar disks are probably present also in the active phase, but are obscured by dust. In the evolutionary scenario proposed above, the episodic accretion of matter then replenishes the disk, which grows together with the mass of the nuclear black hole.

On the theoretical side, support for the evolutionary scenario includes the work of Maciejewski (2004) who demonstrated that, if a central SMBH is present, nuclear disks of gas and dust can develop spiral shocks and generate gas inflow compatible to the accretion rates observed in local active galaxies. On the observational side, kinematic evidence for inflow along nuclear dusty spiral arms has been found so far in one case: NGC 1097 (Fathi *et al.* 2006).

3. Streaming motions along nuclear spirals in NGC 1097

The observations of NGC 1097 were obtained with the Integral-Field Unit of the Gemini Multi-Object Spectrograph and allowed the mapping of the gas kinematics in the inner few hundred parsecs (Fathi *et al.* 2006). After subtracting a circular velocity model, streaming motions along spiral arms with inward velocities of up to 50 km s^{-1} were

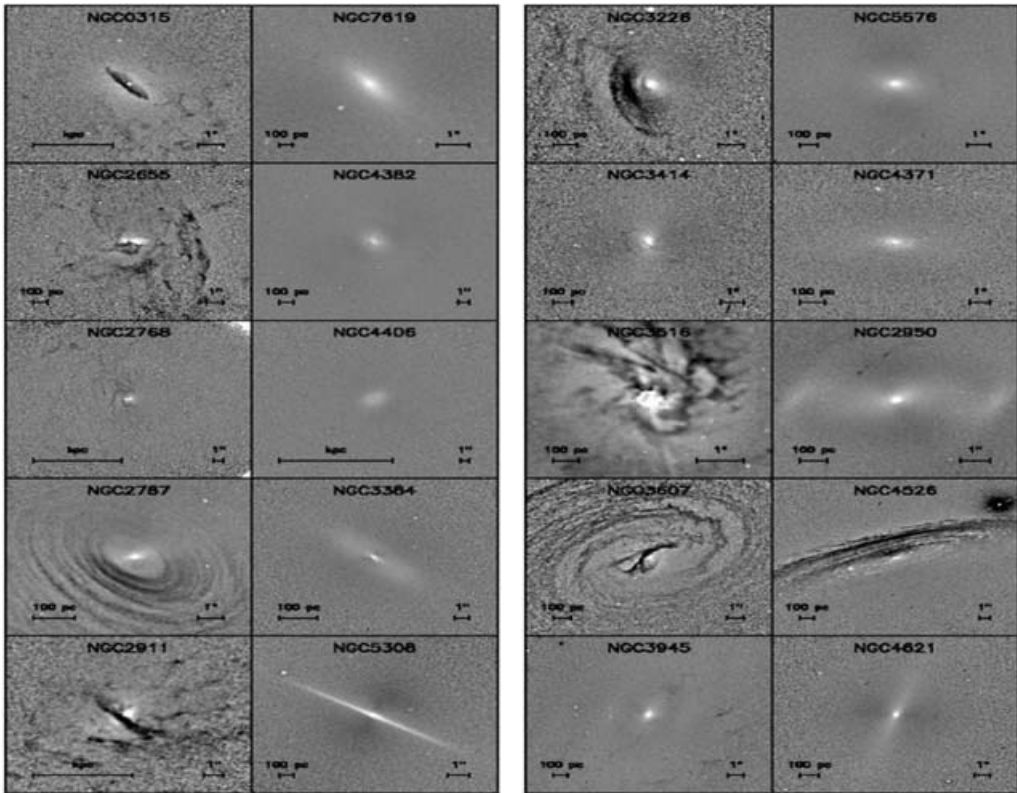


Figure 1. Structure maps for 10 matched pairs of early-type galaxies. Each image covers 5% of the galaxy diameter D_{25} . North is up and East to the left. In each pair the active galaxy is shown to the left and the inactive matched pair to the right. From Lopes *et al.* 2007.

found. Another relevant finding on this galaxy is the young obscured starburst recently discovered (Storchi-Bergmann *et al.* 2005) very close to the nucleus (within ~ 9 pc), in agreement with the suggestion that inflowing gas and dust gives birth to stars in the nuclear dusty spiral or disk (Ferrarese *et al.* 2006).

The velocity observed for the streaming motions along the nuclear spiral allows an estimate of a few Myr for the gas to flow from a few hundred parsecs to the nucleus. For an estimated gas density of ~ 500 protons cm^{-3} , and estimated circular cross-section of 3 spiral arms at 100 pc from the nucleus (opening angle 20°), we conclude that the mass flow rate along the nuclear spiral arms in NGC 1097 is ~ 35 times the one at the accretion disk of $dM/dt = 1.1 \times 10^{24}$ g s^{-1} (Nemmen *et al.* 2006), and allows the accumulation in the nuclear region of $\sim 10^6 M_\odot$ in a few Myr, which can provide the necessary matter to give birth to the nuclear starburst (Storchi-Bergmann *et al.* 2005).

4. Concluding remarks

We have found a strong correlation between circumnuclear dust and nuclear activity, and between nuclear stellar disks and absence of nuclear activity in early-type galaxies. As both the active and inactive galaxies can be thought of as the “same galaxy” observed in different phases, our findings suggest an evolutionary scenario in which the nuclear activity is triggered by capture of dusty gas to the nuclear region. The origin of the gas and dust is still not clear, but the absence of dust in the inactive phase suggests that it cannot originate from continuous mass loss from stars and is most probably external. In

our proposed evolutionary scenario, once the gas and dust are captured to the nuclear region they gradually settle into a nuclear spiral or disk, where new stars are born while the excess gas and dust is accreted by the nuclear SMBH. Replenishment of a nuclear stellar disk (observed in the inactive galaxies) is the final product after activity ceases. As a result, both the stellar component of the galaxy and its SMBH at the nucleus grow after each activity cycle, as implied by the M - σ relation (e.g. Tremaine *et al.* 2002).

The evolutionary scenario is supported by recent kinematic observations of the nuclear spiral in NGC 1097, which reveal streaming motions along the spiral arms, providing an accretion flow rate which is enough to both form the starburst recent observed surrounding the nucleus (Storchi-Bergmann *et al.* 2005) in a few Myr and feed the nuclear SMBH. As similar dusty structures are observed in most active galaxies (Lopes *et al.* 2007), streaming motions along nuclear spirals may be the main mechanism for black hole feeding in active galaxies.

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MITCHELL BEGELMAN: Are you able to distinguish flow along a bar from flow along a spiral? If so, do you see evidence of bars?

THAISA STORCHI-BERGMANN: We would be able to distinguish a bar from a spiral if there was a bar. We do not see gaseous/dusty bars. Bars have been seen in continuum images, but we do not see them in our structure maps.

YIPING WANG: Have you done any statistics of your sample to see a relationship between the star-formation rate and the accretion rate for the inflow? It seems that star-formation in the nuclear region and the accretion are linked. We propose a model aimed to explain the black hole–bulge mass relation in which this relation is important.

THAISA STORCHI-BERGMANN: The accretion rate is $\sim 0.6M_{\odot}$ per year in NGC 1097 (the only case so far in which we were able to calculate the large scale inflow rate), so we can accumulate enough mass in one million years to form the young star cluster observed at the nucleus and produce necessary star-formation and feeding. We plan more work on our sample – this is very important, but we do not have enough data right now to perform such analysis.