

Fueling and morphology of central starbursts

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Abstract.

Of the mechanisms proposed to bring gaseous fuel into the central starburst regions of a galaxy, non-axisymmetries in the gravitational potential set up by interactions or by bars are among the most promising. Nevertheless, direct observational evidence for a connection between interactions and bars on the one hand, and starburst (as well as AGN) activity on the other, remains patchy. These general issues are reviewed before proceeding to discuss, within this context, massive star formation in the circumnuclear regions of spiral galaxies, in particular star-forming nuclear rings and pseudo-rings. Such rings are common, and are closely linked to the dynamics of their host galaxy, which in almost all cases is barred. The possible existence of a population of nuclear rings on scales which are too small for detection with standard ground- or even space-based techniques will be discussed.

INTRODUCTION

Some of the most important open questions relating to starburst activity in galaxies are what combination of physical conditions leads to the triggering of the burst, and how long a starburst can be sustained. These questions are intimately related to another one, namely how a starburst is fueled. One obvious prerequisite for the occurrence of a starburst is the availability of sufficient gaseous fuel for the much enhanced star formation, of the right properties, e.g., temperature, density, and dynamics, and at the right location at the right time.

Important parallels exist between the problems of fueling starbursts and active galactic nuclei (AGN), at least low-level AGN such as Seyferts and LINERs. Both will need a well-regulated supply of gas being fed into the nuclear region of a galaxy from its disk, and both can be expected to be correlated with agents capable of driving such inflow. Of these, bars and galaxy interactions are the most important, because they lead to non-axisymmetries in the gravitational potential which in turn lead to gas shocks and subsequent loss of angular momentum, allowing the gas to move radially inward.

In this review paper, the current observational evidence for fueling starbursts by means of non-axisymmetries in the galactic potential, specifically bars and interactions, is briefly reviewed, making reference to parallel work on Seyfert host galaxies. Various aspects of nuclear rings are then considered, which can be seen as a specific morphological class of low luminosity starbursts. Relations between nuclear rings and their host galaxies are explored, as well as possible links between the occurrence of galactic rings and the presence of nuclear starburst or AGN activity. The size distribution of nuclear rings is also addressed. The main points addressed and conclusions reached in this review are outlined briefly in the final section.

FUELING OF STARBURSTS

The so-called “fueling problem” in starbursts (as well as in AGN) is not the amount of gas present, but how to transport this gas from the main body of the host galaxy to the central region where it is needed to feed the activity. Assuming typical starburst gas consumption rates and lifetimes (of, say, a couple of solar masses per year and of order $10^7 - 10^8$ years) it is easily seen that the outer regions of the host galaxies of starbursts will in general contain more than enough gas to fuel the burst. The problem, then, is how to deliver this gas to the starburst region in the center of the galaxy. To transport the gas radially inward, it must lose most of its angular momentum, for which a number of mechanisms can be invoked. The most important of these are gravitational, driven by a non-axisymmetry in the galactic potential set up by a bar or a galaxy interaction or merger, and effective on spatial scales of tens of parsecs to kiloparsecs, and possibly even smaller than that.

There is an important parallel here between the fueling of central starbursts and the fueling of AGN, both of which require similar gas delivery methodology into the nuclear regions of the host galaxy. In AGN, the problem may be more acute because the scales on which material needs to be delivered are most probably much smaller than in the case of starbursts, possibly on the scale of AUs ($\sim 10^{-6}$ parsec) for AGN. The fueling of starbursts and especially AGN has been reviewed rather extensively in the recent literature, and here only a brief summary of the work relevant to gravitational fueling of starbursts will be given. For more complete discussions, although mostly biased to the fueling of AGN rather than starbursts, the reader is referred to reviews by Shlosman, Begelman & Frank (1990), Combes (2001), Shlosman (2003), Knapen (2004a,b), and Jogee (2004).

Bars fueling starbursts

Bars are expected theoretically and numerically to lead to gas concentration toward the central regions of galaxies because gas in the bar can lose angular momentum due to torques and shocks (e.g., Schwarz 1984; Combes & Gerin 1985; Noguchi 1988; Shlosman, Frank & Begelman 1989; Knapen et al. 1995a,b). There is some direct observational evidence that bars indeed instigate central concentration of gas, the most comprehensive of which comes from surveys of molecular gas concentration in barred as compared to non-barred galaxies, as traced through the emission by CO molecules. Sakamoto et al. (1999) found that, statistically, the ten barred galaxies in their sample have more concentrated CO emission, and thus, presumably, molecular hydrogen, than their ten non-barred galaxies (see also Sheth et al. 2002 for a confirmation of this result with larger samples). The reader is referred to Knapen (2004a) for a more detailed discussion of the evidence for gas concentration by bars, as well as of some of the caveats which need to be taken into account.

Accepting that bars cause gas inflow, the question is then whether this also leads to AGN or central starburst activity. On the former, the bar fraction is indeed higher among Seyfert host galaxies than among non-Seyferts, but the statistical significance

of this result does not quite reach 3σ . Moreover, the bar fractions (of 80% and 60%, respectively) indicate that most galaxies are barred, irrespective of their nuclear activity, and that there are significant numbers of galaxies, even Seyfert hosts, in which no bar can be distinguished (Knapen, Shlosman & Peletier 2000; Laine et al. 2002; Laurikainen, Salo & Buta 2004; see Knapen 2004b for a more detailed review).

Nuclear starbursts clearly occur preferentially in barred hosts (e.g., Hummel 1981; Hawarden et al. 1986; Devereux 1987; Dressel 1988; Puxley, Hawarden, & Mountain 1988; Arsenault 1989; Huang et al. 1996; Martinet & Friedli 1997; Hunt & Malkan 1999; Roussel et al. 2001). Huang et al. (1996) studied IRAS data and confirmed that starburst hosts are preferentially barred, although with the proviso that the result holds for strong bars (SB in RC3 terminology) and in early-type galaxies only, as later confirmed by Roussel et al. (2001). All studies referred to above use optical images or information from catalogs such as the RC3 (de Vaucouleurs et al. 1991) to derive whether a galaxy is barred or not. Given the higher bar fractions and higher accuracy in bar determination that are achieved when using near-IR images, there is thus considerable scope for further study, by using near-IR images of well-selected samples of starburst and control galaxies.

Interactions fueling starbursts

Since interactions between galaxies can lead to angular momentum loss of inflowing material and thus to gas inflow, they can be invoked to explain the fueling of starbursts and AGN (e.g., Shlosman et al. 1989, 1990; Mihos & Hernquist 1995). For Seyfert galaxies, however, there is *no evidence at all* in the literature for statistical connections between galaxy mergers and interactions on the one hand, and the occurrence of AGN activity on the other (see Knapen 2004b for a review with relevant references to other work). And unlike the case of bars which has been discussed above, there is a marked difference here between the behavior of low luminosity AGN and starburst activity, with the latter very clearly influenced by interactions, at least in the extremes. This is most obvious in the case of the ultra-luminous infrared galaxies (ULIRGs), powered mainly by very powerful starbursts (Genzel et al. 1998) and, apparently without exception, associated with galaxies involved in mergers or other strong interaction processes (e.g., Joseph & Wright 1985; Armus, Heckman, & Miley 1987; Sanders et al. 1988; Clements et al. 1996; Murphy et al. 1996; Sanders & Mirabel 1996). It is clear that the most extreme of the starbursts need the occurrence of the destructively powerful event in the host galaxy which is a galaxy merger, but it is unlikely that all such mergers lead to the kind of starbursts exemplified by the ULIRGs (or even more normal, lower luminosity starbursts). It is not even clear whether interactions lead to enhancements of the star formation activity *in general*. Illustrating this point are the results from Bergvall, Aalto & Laurikainen (2003), who find no evidence for significantly enhanced star-forming activity among interacting/merging galaxies as compared to non-interacting galaxies, but do report a moderate increase in star formation in the very centers of their interacting sample galaxies.

NUCLEAR RINGS

Nuclear rings are common, occurring in around one fifth of all disk galaxies (Knapen 2005). Their properties have been reviewed in detail by Buta & Combes (1996), with more recent aspects described by Kormendy & Kennicutt (2004) and Knapen (2004a, b). Galactic rings, including nuclear ones, can form in the vicinity of resonances in a gaseous disk, usually set up by a bar or other form of non-axisymmetry in the gravitational potential. Gas concentrates near such resonances, can become unstable, and collapse to lead to the massive star formation associated with rings. Nuclear rings are associated with Inner Lindblad Resonances (ILRs), usually occur in barred galaxies, and have typical radii of 0.5 – 1 kpc, issues which are discussed in more detail, below. Nuclear rings form significant numbers of stars which can help shape a pseudo-bulge, and so drive secular evolution (Kormendy & Kennicutt 2004), but which also contribute a couple of percent to the overall star formation rate of the local universe (R. C. Kennicutt, these proceedings, p. 000).

Nuclear rings and their host galaxies

Nuclear rings have long been known to occur preferentially in barred galaxies, and in early-type disk galaxies (see review by Buta & Combes 1996). Knapen (2005) quantified this using $H\alpha$ imaging of a statistically representative sample of 57 spiral galaxies¹. The distribution of the morphological types of the nuclear ring host galaxies peaks at type Sbc, while no rings were found in types later than Scd, and very few in earlier types. In later types, the bulge may not be massive enough to ensure the presence of ILRs, whereas in earlier types, there may not be enough gas present.

Of the 12 nuclear rings in Knapen's (2005) survey, 10 occur in galaxies classified as either SAB or SB in the RC3, but two are classified as non-barred. Upon closer inspection, though, it turns out that both these galaxies, NGC 1068 and NGC 4736, do have bars, albeit rather small, and only visible in near-IR imaging (Scoville et al. 1988; Thronson et al. 1989; Shaw et al. 1993; Möllenhoff et al. 1995; Wong & Blitz 2000; Laine et al. 2002; Knapen 2005). This is a general picture in the literature, where by far most nuclear rings are associated with bars in their host galaxies. There are, however, a number of cases where galaxies without any trace of a bar, even in the near-IR, do show prominent nuclear rings. As an example, careful imaging in optical and near-IR bands, from both the ground and from the *Hubble Space Telescope (HST)*, confirms the absence of a bar in the disk of the small nuclear ring host galaxy NGC 278 (even though it has been classified as SAB in the RC3). However, 21 cm HI imaging reveals that in the

¹ These data are part of a larger data set, consisting of images in the B, R, I, K_s broad bands, as well as in $H\alpha$, of the 57 sample spirals. The description of these data has been published by Knapen et al. (2003, 2004a), and the images themselves are freely available to interested researchers through the Centre de Données Stellaires via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via <http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/426/1135>, or through the NASA/IPAC Extragalactic Database (NED).

outer regions of this small galaxy both the gas morphology and kinematics are severely distorted, which indicates that NGC 278 has recently undergone a minor merger event with an even smaller galaxy, possibly similar to a Magellanic Cloud, which would have led to a destabilization and non-axisymmetry of the gravitational potential, and hence to gas inflow, the formation of resonances, and ultimately the formation of the star-forming nuclear ring (Knapen et al. 2004b). It is not known at present whether other unbarred nuclear ring host galaxies, such as NGC 7742, may exhibit the same clues to an interactive past from HI data, but this would be well worth checking.

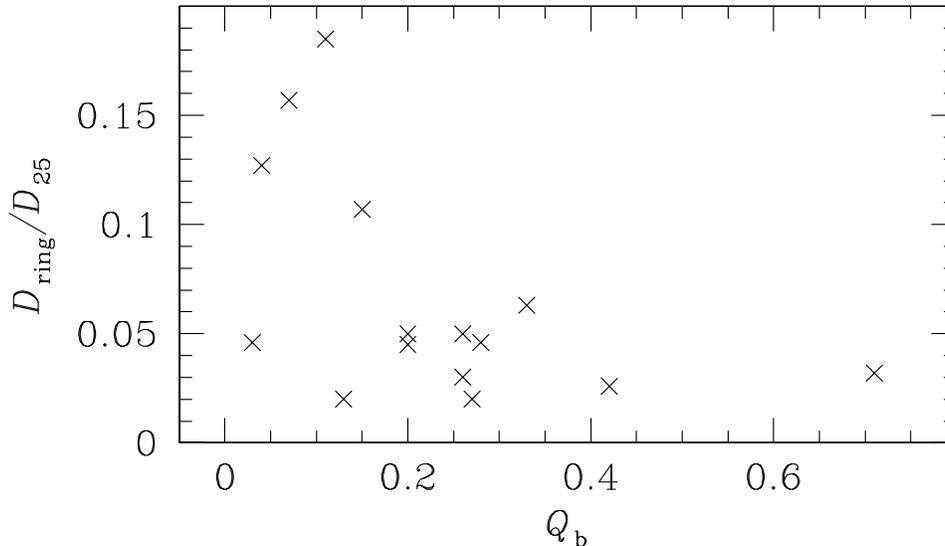


FIGURE 1. Relative size, or ring diameter divided by galaxy diameter, of 15 nuclear rings as a function of the gravitational torque (Q_b) of the bar of its host galaxy. Data from Knapen (2005).

In general, though, we can say that observed ring statistics (reviewed by Buta & Combes 1996) firmly support a picture in which resonances set up by a galactic bar induce the formation of rings. Moreover, we can also confirm that, as expected by numerical modeling and theory, the properties of the bars shape the properties of the nuclear ring. As an example, we mention the relation between bar strength and nuclear ring size, as reported by Knapen, Pérez-Ramírez & Laine in 2002, and recently confirmed with a larger number of rings by Knapen (2005). We found that whereas nuclear rings of all sizes can and do occur in weak bars, there is a complete absence of *large* nuclear rings from galaxies with *strong* bars² (Fig. 1). This result nicely agrees with theoretical expectations, in which the ILRs, and thus the nuclear rings, occur near the interface between the parallel (to the bar) x_1 and perpendicular x_2 orbit families. Since rings depend on gas concentration, they can only occur where the spatial extent of these two orbit families does not overlap. In strong bars, which have larger ellipticity (are “thinner”) than weak bars, the physical space around the galaxy nucleus where non-overlapping x_2 orbits can

² Here, we use the ratio of ring and host galaxy radius as a measure of nuclear ring size, and the gravitational torque parameter, Q_b , as a measure of the bar strength (for the latter see the work by Buta, Block & Knapen 2003 and Block et al. 2004, and references therein to earlier work).

occur is smaller, and as a result only smaller rings can form in such bars (see Heller & Shlosman 1996). The absence of large rings in strong bars is thus strong support for the picture where nuclear rings are formed as a result of resonances set up by a galactic bar.

Galactic rings and nuclear activity

The possible causal connections between galactic rings and nuclear activity have received relatively little attention in the literature, as compared to the amount of attention received as separate topics, or even in comparison to topics like the connection between nuclear activity and other host galaxy properties such as the presence of bars or interactions. Anecdotally, a number of famous galaxies host both an AGN and a nuclear ring or pseudo-ring, for example, NGC 1068 or NGC 4303. The relative lack of attention may be at least partly due to the fact that one might not *a priori* expect relationships between rings and nuclear activity. The spatial scales of even the smallest nuclear rings are much larger than those of AGN activity, and the timescales of the two phenomena are essentially unknown but not necessarily related. In addition, rings are a known consequence of the presence of bars in disks, and logically bars have received more attention as possible primary instigators of nuclear activity. For starburst activity such a link has indeed reliably been found, but for AGN activity the link is not nearly as direct (see the discussion earlier in this paper and in the references listed there).

There is some statistical evidence from the literature which indicate the potential of rings as tracers of the fueling of nuclear activity. For instance, Arsenault (1989) reported a higher incidence of the combination of bar and ring among starburst and AGN hosts than among “normal” galaxies, while Hunt & Malkan (1999) found that LINERs and Seyfert galaxies have significantly more rings (inner and outer) than normal galaxies or starbursts. In both these studies, the RC3 morphological classification was used to derive bar and ring frequencies. More recently, Knapen (2005) correlated the presence of a nuclear ring as identified from H α imaging with the presence of nuclear activity (both starburst and AGN). The latter was obtained from the NED, but the use of more robustly defined activity indicators (e.g., from Ho, Filippenko & Sargent 1997), not available for all sample galaxies, would not change the results significantly. The results are surprising: not only is the circumnuclear H α emission morphology of the AGN and starbursts in the sample of 57 galaxies significantly more often in the form of a nuclear ring than in non-AGN (only 7% of non-starburst, non-AGN and 11% of non-AGN galaxies have circumnuclear rings, versus 33% of starbursts and 38% of AGN), but also nuclear rings occur significantly more often than not in galaxies which also host nuclear activity (while 27 of the 57 sample galaxies are starburst or AGN hosts, 10 of the 12 nuclear rings occur in this class of galaxy; see Fig. 2).

There are, thus, some indications for a statistical connection between galactic rings and the occurrence of nuclear activity. For starburst activity this would not be surprising, since galaxies with relatively compact nuclear rings with a high star formation rate might well be classified as starburst, whereas on the other hand a starburst classified as nuclear may in fact be circumnuclear, but not resolved with imaging. For Seyfert and LINER activity, such a link is more puzzling, even though the connection between that type of

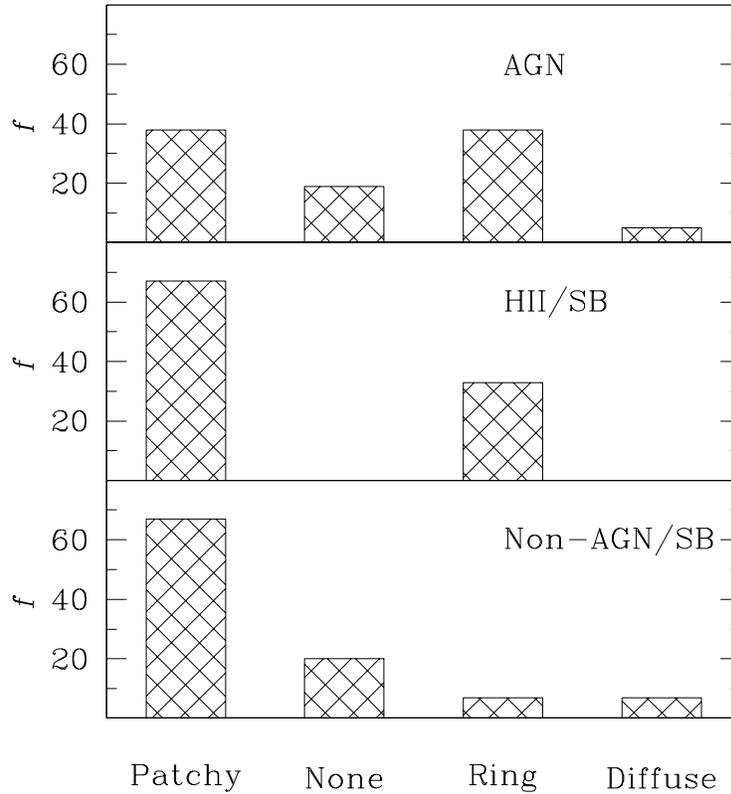


FIGURE 2. Distribution of nuclear $H\alpha$ emission morphology in those galaxies classified as AGN (including both Seyfert and LINER) in the NED (*top panel*), those classified as starburst or HII (*middle panel*), and those galaxies classified as neither (*lower panel*). Fractions are given as percentages of the total numbers of galaxies in each category (AGN, etc). Adapted from Knapen (2005).

activity and starbursts is now well known (e.g., Cid Fernandes et al. 2004 and references therein). Especially for the outer and inner rings, but also for nuclear rings which have typical radii of a kiloparsec, the spatial scales are very different from those of the AGN (thought to be as small as AU-scale), whereas the timescales of both the AGN activity and the star-forming phase in the rings may well be shorter than the dynamical time needed to bridge the range in spatial scales. For bars, especially when invoking bars within bars, all these problems seem less prominent than for rings, so it is puzzling that the statistical connections between rings and AGN, if confirmed, are more significant. All these aspects of rings and nuclear activity are in urgent need of further scrutiny.

Are small nuclear rings common?

A fair number of nuclear rings are now known in the literature. Laine et al. (2002) compiled sizes for 62 of them, mostly from Buta & Crocker (1993). Laine et al. plotted the size distribution of these rings, and found a marked peak in ring size with a maximum

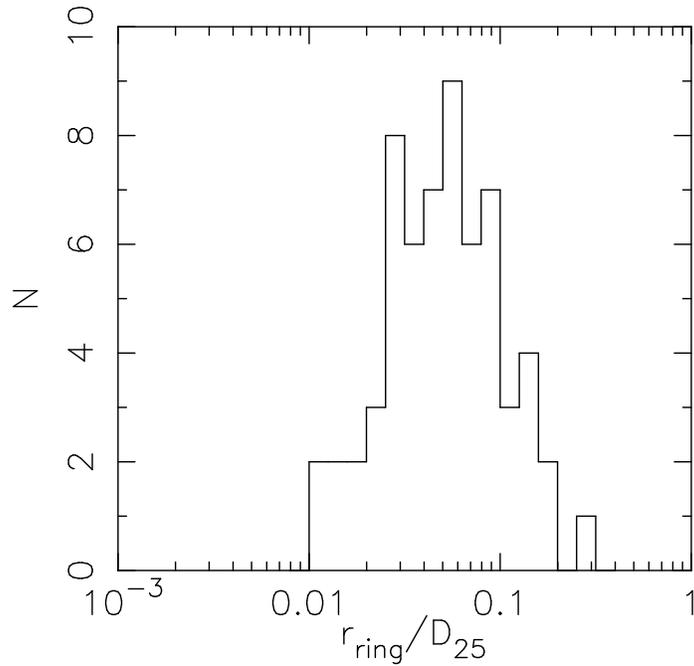


FIGURE 3. Distribution of the relative sizes of 62 nuclear rings (ring size divided by galaxy size). Reproduced with permission from Laine et al. (2002).

near $r_{\text{ring}}/D_{25} = 0.06$ (Fig. 3). The size distribution is rather narrowly peaked, coinciding with the typical radius of ILRs in the galaxies under consideration. It is possible, though, that the cutoff in the distribution on the low end is due to observational bias, where the smaller rings have simply not been resolved. Knapen (2005) points out that the median distance to galaxies hosting a nuclear ring in his sample of 57 (12.1 Mpc) is significantly smaller than the median distance to other groups of galaxies in his sample, or in fact the whole sample of 57 (16.9 Mpc), but even so, rings with sizes significantly below the peak value in Fig. 3 should be rather easily observable. It thus seems that there is a true absence of small nuclear rings.

There is anecdotal evidence in the literature, however, for nuclear rings which are significantly smaller than the typical 1 kpc for nuclear rings. For instance, in NGC 5248, Laine et al. (2001) and Maoz et al. (2001) found a ring of some 0.1 kpc (two arcsec) in radius (Jogee et al. 2002), NGC 278 contains a small ring of 0.2 kpc radius (about four arcsec; Knapen et al. 2004b), and IC 342 hosts a nuclear ring of less than 100 pc in diameter (Böker, Förster-Schreiber, & Genzel 1997). So can there be a significant population of nuclear rings on spatial scales small enough to have escaped detection in nuclear ring survey such as those by, e.g., Buta & Crocker (1993) or Knapen (2005)?

There are two systematic studies which can shine light on this issue. In the first of these, Maoz et al. (1996a) only found one hitherto undetected nuclear ring, which at 4 arcsec diameter should be observable from the ground. Maoz et al. used UV imaging from the *HST* with a spatial resolution of ~ 0.05 arcsec. The overall fraction of nuclear rings reported by Maoz et al. is low ($\sim 5\%$), primarily because the field of view of their images is only 22 arcsec (as recognized by Maoz et al. 1996b), implying that six or seven

of the 12 nuclear rings of Knapen (2005) would have fallen outside their imaged areas, but also because the effects of dust extinction are pronounced at the UV wavelengths used by Maoz et al., even though the effects of the latter on nuclear ring detection are not clear. The latter issue also precludes one from concluding that small nuclear rings do not exist. The smaller the radius of the nuclear ring, the more pronounced the effects of dust extinction will be, hence the more difficult to recognize nuclear rings from UV imaging.

The second study, by Böker et al. (1999) is based upon a series of *HST* NICMOS Pa α images of the central (51 arcsec across) regions of 94 spirals, at a spatial resolution of 0.2 arcsec. In their study, five galaxies only have been indicated to host, or possibly host, a nuclear ring. Inspection of the published images reveals that only four are *bona fide* rings, of which two are inner rings, and only those in NGC 2903 and NGC 1241 can be considered nuclear rings. The one in NGC 2903 is well-known from ground-based images (e.g., Wynn-Williams & Becklin 1985; see also Alonso-Herrero & Knapen 2001), the one in NGC 1241 has a diameter of four arcsec and is thus also large enough to be observed from the ground, as has in fact been done by, e.g., Mazzuca et al. (these proceedings, p. 000). Interestingly, with respect to the discussion on possible relationships between nuclear activity and rings, all four ring hosts from the survey of Böker et al. are AGN or starburst hosts!

Although it thus seems unlikely that there is a significant population of small nuclear rings (with radii of around tens of parsecs or smaller), further imaging data of well-selected samples of galaxies, and at high resolution (ideally higher than the 0.2 arcsec of Böker et al. (1999), must be analysed in detail to definitely settle this issue.

CONCLUDING REMARKS

The main points discussed in this short review are the following:

- Bars and interactions, because of the deviations from symmetry they cause in the gravitational potential of the host galaxy, are the most appropriate mechanisms to consider as fueling agents, which serve to remove angular momentum from gas and thus allow it to move radially inward in galaxies. Both starbursts and AGN will depend on the continued supply of such gaseous material to sustain their activity.
- It is clear that the most extreme starbursts, exemplified by the ULIRGs, almost exclusively occur in strongly interacting galaxies. Whether in general interactions lead to starbursts, or whether starbursts need an interaction to be triggered, are issues which are less clear. There are no indications that interactions are related to the occurrence of Seyfert- or LINER-type non-stellar activity in galaxies.
- Bars are statistically linked to starbursts, possibly with stronger connections in certain subclasses such as strong bars and early-type hosts. Seyfert hosts are also more often barred than non-Seyferts, but at a lower significance level.
- Nuclear rings are common, occurring in at least one in every five disk galaxies. Their host galaxies are generally of morphological type around Sbc, and are almost without exception barred. Nuclear rings are low-luminosity starbursts, and are com-

monly believed to occur as a result of massive star formation in gas accumulated near ILRs, and are thus resonance phenomena whose properties can be used to chart the dynamics of the host galaxy.

- Several studies report a possible statistical connection between the presence of rings in a galaxy and the presence of nuclear activity. Although the statistics and/or the data quality of these works should be improved, it is noteworthy that the ring-AGN relation may well turn out to be more prominent than the bar-AGN relation. Although the simultaneous presence of starburst and AGN activity in a galaxy has now been firmly established as a rather common occurrence, any link between rings, even nuclear ones, and non-stellar activity is puzzling because the spatial scales involved are different by many orders of magnitude. Further scrutiny, first observationally and subsequently phenomenologically, is needed.
- Small nuclear rings, on scales of tens or hundreds of parsecs, are known in a handful of well-studied nearby galaxies, but evidence for the presence of a significant population of such rings is so far lacking.

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