FUELLING STARBURSTS AND AGN

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Abstract

There is considerable evidence that the circumnuclear regions of galaxies are intimately related to their host galaxies, most directly through their bars. There is also convincing evidence for relations between the properties of supermassive black holes in the nuclei of galaxies and those of their host galaxy. It is much less clear, however, how stellar (starburst) and non-stellar (AGN) activity in the nuclear regions can be initiated and fuelled. I review gas transport from the disk to the nuclear and circumnuclear regions of galaxies, as well as the statistical relationships between the occurrence of nuclear activity and mechanisms which can cause central gas concentration, in particular bars and interactions. There are strong indications from theory and modelling for bar-induced central gas concentration, accompanied by limited observational evidence. Bars are related to activity, but this is only a weak statistical effect in the case of Seyferts, whereas the relation is limited to specific cases in starbursts. There is no observational evidence for a statistical connection between interactions and activity in Seyferts, and some evidence for this in starbursts, but probably limited to the extremes, e.g., ULIRGs. Some interesting hints at relations between rings, including nuclear rings, and the presence of nuclear activity are emerging. It is likely that the connection between the inflow of gaseous fuel from the disk of a galaxy on the one hand and the activity in its nuclear region on the other is not as straightforward as sometimes suggested, because the spatial- or time-scales concerned may be significantly different.

Keywords: galaxies: kinematics and dynamics – galaxies: spiral – galaxies: structure – galaxies: active – galaxies: starburst

1. Introduction

Black holes are ubiquitous in the nuclei of both active and non-active galaxies (e.g., Kormendy & Richstone 1995), and are thought to be at the direct origin of non-stellar nuclear activity (e.g., Lynden-Bell 1969; Begelman, Blandford & Rees 1984). The fact that the mass of the central supermassive black hole (SMBH) in a galaxy is correlated with the velocity dispersion of the bulge, and hence with its mass (Ferrarese & Merritt 2000; Gebhardt et al. 2000) provides the most tangible link between the nuclear regions and their host galaxies. But because not all galaxies with SMBHs have AGN characteristics, the presence of an SMBH in itself cannot be enough to make a galaxy "active", at least not continuously, and additional mechanisms must be considered which can ignite the nuclear activity.

In the case of starburst galaxies, defined rather loosely as galaxies which show abnormally enhanced massive star formation activity in their central regions (or in some more extreme cases throughout the galaxy), a similar question can be posed, namely what ignites the starburst. In both the AGN and the starbursts, the availability of fuel at the right place and at the right time must play a critical role. Such gaseous fuel is plentiful in the disks of galaxies, but must lose significant quantities of angular momentum in order to move radially inward. In fact, the "fuelling problem" is not the amount of fuel that is available, but how to get it to the right place, as graphically illustrated by Phinney (1994, his fig. 1). Estimates for the mass accretion rate needed to fuel AGN vary from around 10^{-4} $M_{\odot}$/year for low-luminosity AGN such as LINERs, up to around 10 $M_{\odot}$/year for high-luminosity AGN such as QSOs, or, over a putative lifetime of 10^{8} years for the AGN activity, only 10^{4} to 10^{9} $M_{\odot}$.

Large stellar bars, as well as tidal interactions and mergers, have some time ago been identified as prime candidates to drive gas efficiently from the disk into the inner kpc (see next Section). In this review we will concentrate on the observational evidence, mostly statistical in nature, for the effectiveness of these gravitational mechanisms, concentrating on the effects of bars in Section 2, and on those of interactions in Section 3. Galactic rings are considered in Sections 4 and 5, and summarising remarks are given in Section 6. Related reviews considering the fuelling of primarily AGN include those by Shlosman, Begelman & Frank (1990), Beckman (2001), Combes (2001), Shlosman (2003), Wada (2004), and Jogee (2004).

2. The effects of bars

Theoretically and numerically, bars are expected to concentrate gas in the central regions of spiral galaxies because the torqued and shocked gas within the bar loses angular momentum which allows the gas to move further in (e.g., Schwarz 1984; Combes & Gerin 1985; Noguchi 1988; Shlosman, Frank & Begelman 1989; Knapen et al. 1995a). The dynamics of bars and their influence on the circumnuclear regions has most recently been reviewed by Kormendy & Kennicutt (2004), and previously by, e.g., Sellwood & Wilkinson (1993) and Shlosman (2001). The general theoretical and numerical formalism of bars is now well understood, and different aspects of it are continuously being confirmed by observations. For instance, we recently investigated the well-known numerical result that stronger bars will lead to straight dust lanes along the leading edges of the bar, whereas the dust lanes will be more curved in weak bars (Athanassoula 1992). Using a small number of barred galaxies for which we had adequate data, we could indeed confirm observationally that there is an anti-correlation between the amount of curvature of the dust lanes and the gravitational bar torque, or bar strength (Knapen, Pérez-Ramírez & Laine 2002; see Fig. 1). In another study (Zurita et al. 2004), we used Hα Fabry-Pérot data of the strongly barred galaxy NGC 1530 to show in a graphic, two-dimensional way that indeed, as predicted by theory, large velocity gradients are found at the position of the dust lanes. Within those lanes, directly tracing enhanced concentrations of dust and thus gas, but indirectly tracing the location of shocks in the gas, the large velocity gradient prohibits massive star formation, which we observe to be located just outside the regions of largest shear or velocity gradient (Zurita et al. 2004; see Regan, Vogel & Teuben 1997 for an Hα Fabry-Pérot map at lower resolution which nevertheless indicates the shocks in the velocity field).

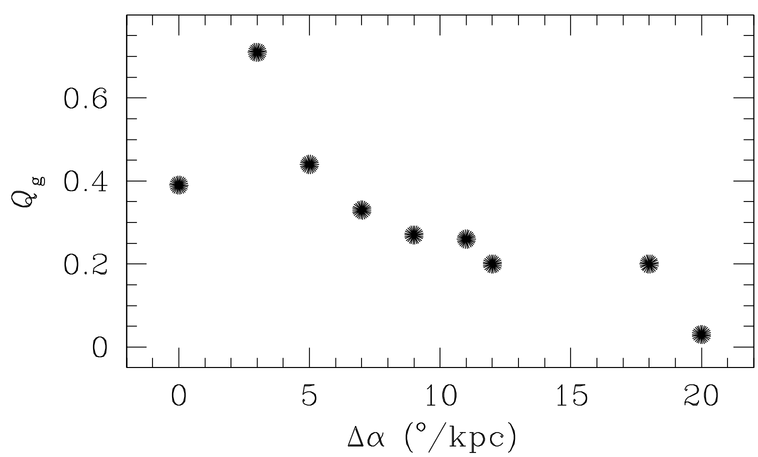

Figure 1. Gravitational bar torque $Q_{\rm g}$, an indicator of bar strength, as a function of the curvature of the dust lanes $\Delta\alpha$ in a sample of 9 barred galaxies. Small values of $\Delta\alpha$ indicate straight dust lanes, which are seen to occur in strong bars, thus confirming theoretical and numerical predictions. Data from Knapen, Pérez-Ramírez & Laine (2002).

Considering now specifically the theoretical and numerical view that bars can instigate radial inflow of gas, and thus lead to gas accumulation in the central regions of barred galaxies, several pieces of observational evidence to fit this picture have been forthcoming in recent years, both from observations of gas tracers in barred and non-barred galaxies (e.g., Sakamoto et al. 1999; Jogee, Scoville, & Kenney 2004; Sheth et al. 2004), and from other, less direct, measures of the gas concentration (e.g., Maiolino, Risaliti, & Salvati 1999; Alonso-Herrero & Knapen 2001). These results have been reviewed in somewhat more detail by Knapen (2004a), and we limit ourselves here to the conclusion that there is increasing observational support for the theoretical suggestion that bars lead to gas accumulation in the central regions of galaxies.

One must keep in mind that in all cases the observed correlation between the presence of a bar and increased central gas concentration is *statistical*, and not very strong, that there is a large overlap region in which the properties of barred and non-barred galaxies are very similar indeed (for instance, in the study by Sakamoto et al. 1999 just over half of the 19 sample galaxies are in the overlap range of gas concentration parameter $t_{\rm con}$, which is inhabited by both barred and non-barred galaxies), and that in the CO studies the X factor which gives the transformation of CO luminosity to mass is assumed to have the same value in the circumnuclear regions and in the disk. One can also question whether the statistical gas accumulation by bars is in fact related to the occurrence of nuclear activity of the non-stellar or stellar variety, and a careful consideration of both spatial- and timescales must be made to connect gravitationally driven inflow to fuelling of the starburst and/or the AGN. Finally, there is as yet no convincing direct observational evidence of inflow in a barred galaxy, mainly because the inflow rates are so low that they may be unobservable in practive (see above), and because most of the gas in bars moves around the bar, and will thus move inward during a part of its orbit, but then move outward again on a subsequent part (see discussion in Knapen 2001).

In the remainder of this Section, we will review the question of whether there is observational evidence that bars are related to the occurrence of nuclear activity.

2.1 Bars and starburst activity

There is a clearly observed trend for nuclear starbursts to 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). For example, Hummel (1981) reported that the central radio continuum component is typically twice as strong in barred as in non-barred galaxies; Hawarden et al. (1986) found that barred galaxies dominate the group of galaxies with a high 25μm/12μm flux ratio; and Arsenault (1989) found an enhanced bar+ring fraction among starburst hosts. Huang et al. (1996) revisited IRAS data to confirm that starburst hosts are preferentially barred, but did point out that this result only holds for strong bars (SB class in the RC3 catalogue, de Vaucouleurs et al. 1991) and in early-type galaxies, results confirmed more recently by Roussel et al. (2001). In contrast, Isobe & Feigelson (1992) did not find an enhanced far-IR to blue flux ratio among barred galaxies, and Ho, Filippenko & Sargent (1997) found only a very marginal increase in the detection rate of H II nuclei (indicative of starburst activity) among the barred as compared to non-barred galaxies in their sample, only among the late-type spirals (Sc-Sm), and most likely resulting from selection effects rather than bar-induced inflow (Ho et al. 1997). All results mentioned above rely on optical catalogues such as the RC3 to derive the morphological classifications, whereas it is now well-known that the presence of a bar can be deduced more reliably from near-IR imaging (e.g., Scoville et al. 1988; Knapen et al. 1995b). Although near-IR imaging leads to enhanced bar fractions as compared to optical imaging (e.g., Knapen, Shlosman & Peletier 2000; Eskridge et al. 2000), it is not clear how it would affect the results on bars and starbursts.

The statistical studies referred to above thus seem to show that bars and starbursts are connected, but that the results are subject to important caveats and exclusions. Further study is needed, determining bar parameters from near-IR imaging, using carefully defined samples, and exploring more direct starburst indicators than the IRAS fluxes which have often been used. Higher-resolution imaging of the starburst galaxies is also needed, to confirm the possible *circum*nuclear nature of the starburst, already suggested back in 1986 by Hawarden et al.

2.2 Bars and Seyfert activity

Seyferts are almost ideal for a study of AGN host galaxies: they are relatively local and occur predominantly in disk galaxies (see Fig. 2 for a nice example). One of the aspects of the host galaxy – Seyfert activity connection that has received a good deal of attention over the years is the question of whether Seyfert hosts are more often barred than non-Seyferts. Starting with the work of Adams (1977), many authors have dedicated efforts to resolve this question, without finding conclusive evidence (e.g., Adams 1977; Simkin, Su, & Schwarz 1980; Balick & Heckman 1982; MacKenty 1990; Moles, Márquez, & Pérez 1995; Ho et al. 1997; Crenshaw, Kraemer, & Gabel 2003). Unfortunately, many of these investigations are plagued by the absence of a properly matched control sample, by the use of the RC3 classification or, worse perhaps, ad-hoc and non-reproducible classification criteria to determine whether a galaxy is barred; and all of them are based on optical imaging.

Near-IR imaging is much better suited for finding bars (see Section 2.1), and a small number of studies have combined the use of high-quality, near-IR imaging with careful selection and matching of samples of Seyfert and quiescent galaxies. One such study, by Mulchaey & Regan (1997), reports identical bar fractions, but Knapen, Shlosman, & Peletier (2000), using imaging at higher spatial resolution and a rigorously applied set of bar criteria, find

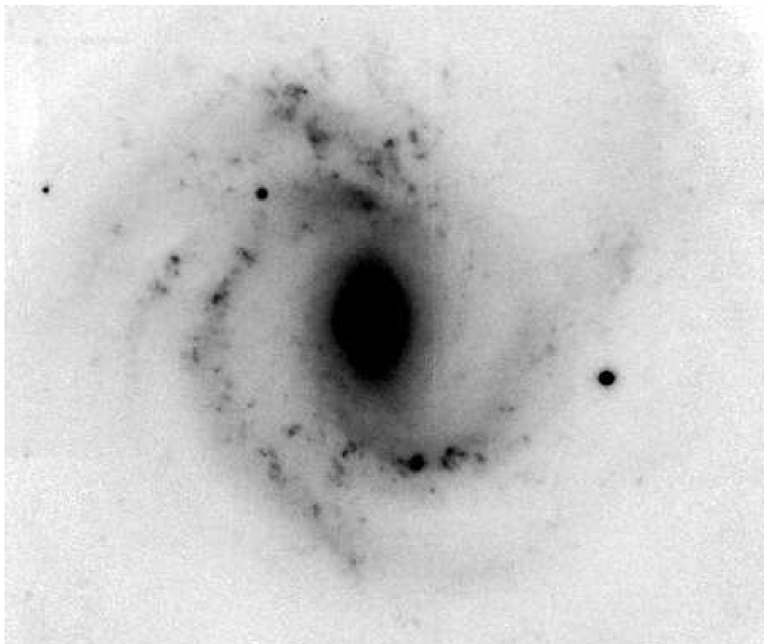

Figure 2. Near-IR K_s image of the Seyfert host galaxy NGC 4303, showing a prominent bar and a well-structured set of spiral arms. North is up, East to the left, and the size of the image shown is approximately four minutes of arc. The image was taken with the INGRID camera on the William Herschel Telescope, see Knapen et al. (2003) for more details.

a marginally significant difference, with a higher bar fraction in a sample of CfA Seyferts than in a control sample of non-Seyferts (approximately 80% vs. 60%). The results found by Mulchaey & Regan (1997) can be reconciled with those reported by Knapen et al. (2000) by considering the lower spatial resolution employed by the former authors.

Laine et al. (2002) later confirmed this difference at a 2.5 σ level by increasing the sample size and using high-resolution *HST* NICMOS near-IR images of the central regions of all their active and non-active sample galaxies. Laine et al. (2002) also found that almost one of every five sample galaxies, and almost one of every three barred galaxies, has more than one bar. The nuclear bar fraction, however, is not enhanced in Seyfert galaxies as compared to non-Seyferts (see also Erwin & Sparke 2002).

In a recent paper, Laurikainen, Salo & Buta (2004) study the bar properties of some 150 galaxies from the Ohio State University Bright Galaxy Survey (Eskridge et al. 2002) in terms of their nuclear properties, among other factors. Using several bar classification methods on optical and near-IR images, they find that only a Fourier method applied to near-IR images leads to a significant excess of bars among Seyferts/LINERs as compared to non-active galaxies: a bar fraction of 71%±4% for the active/starburst galaxies, versus 55%±5% for the non-active galaxies (at a significance level of 2.5σ)[1].

The Fourier method employed by Laurikainen et al. (2004) is objective but sensitive largely to classical bars with high surface brightnesses, and in this respect similar to the strict criteria applied by Knapen et al. (2000) and Laine et al. (2002), who basically rely upon significant a rise and fall in a radial ellipticity profile for bar identification. The results of the Fourier analysis by Laurikainen et al. (2004) are remarkably similar to those from Knapen et al. and Laine et al., apparently because all trace prominent bars in near-IR images. Laurikainen et al. find that the excess of bars among Seyferts/LINERs does not manifest itself in an analysis of optical images, which agrees with the general lack of excess found by the many authors who relied upon optical imaging for their bar classification (see references above). Laurikainen et al. (2004) also find that the bars in active galaxies are weaker than those in non-active galaxies, a result which confirms earlier indications to this effect by Shlosman, Peletier & Knapen (2000) and by Laurikainen, Salo, & Rautiainen (2002).

We can thus conclude that there is a slight, though significant, excess of bars among Seyfert galaxies as compared to non-active galaxies. This result is found only when using near-IR images, and only when applying rigorous and objective bar classification methods. Even so, there remain important numbers of active galaxies without any evidence for a bar, and, on the other hand, many non-active galaxies which do have apparently suitable bars. Given that any fuelling process must be accompanied by angular momentum loss, most easily achieved by gravitational non-axisymmetries, either the timescales of bars (or interactions, see below) are different from those of the activity, or the non-axisymmetries are not as easy to measure as we think, for instance because they occur at spatially unresolvable scales, and could be masqueraded to a significant extent by, e.g., dust or star formation (Laine et al. 2002), or because they occur in the form of weak ovals (e.g., Kormendy 1979) which will not necessarily be picked up by ellipse fitting or Fourier techniques. Additional work is clearly needed, but it is not clear whether this should be aimed primarily at the large-scale bars described in this Section, or perhaps better at the kinematics and dynamics of the very central regions of active and non-active galaxies. In any case, the use of carefully matched samples and control samples is of paramount importance.

[1] It is an interesting exercise to add the numbers found by Laurikainen et al. (2004) to those found by Laine et al. (2002), which would give largely the same overall result in terms of bar fractions, but with smaller error bars thanks to the increased sample sizes, and an overall significance level of more than 3σ. Formally this is not allowed though because the original samples have been selected using different methods, and should not simply be added.

3. The effects of interactions

Galaxy interactions can easily lead to non-axisymmetries in the gravitational potential of one or more of the galaxies involved, and as such can be implicated in angular momentum loss of inflowing material, and thus conceivably in starburst and AGN fuelling (e.g., Shlosman et al. 1989, 1990; Mihos & Hernquist 1995).

3.1 Interactions and starburst activity

It is well known that there is ample anecdotal evidence for the connection between galaxy interactions and starburst activity. This is perhaps clearest for the most extreme infrared sources, specifically the Ultra-Luminous InfraRed Galaxies (ULIRGs). They are powered mainly by starbursts (Genzel et al. 1998), and it has been known since briefly after their discovery that they occur in galaxies with disturbed morphologies, presumably as a result of recent interactions (e.g., Joseph & Wright 1985; Armus, Heckman, & Miley 1987; Sanders et al. 1988; Clements et al. 1996; Murphy et al. 1996; Sanders & Mirabel 1996). Given that the ULIRGs are both among the most extreme starbursts known, and are occurring in interacting galaxies, one can infer that such massive starbursts are in fact powered by gas which has lost angular momentum in galaxies which are undergoing a major upheaval, i.e., are merging or interacting.

More in general, and considering galaxies less extreme than those in the ULIRG class, there is considerable evidence for a connection between interactions and enhanced star formation in galaxies, often measured using galaxy colours which are bluer in the case of current star formation (see, e.g., the seminal paper by Larson & Tinsley 1978). But even so, a more detailed consideration can expose possible caveats. We mention the recent paper by Bergvall, Laurikainen, & Aalto (2003), who considered two matched samples of nearby interacting (pairs and clear cases of mergers) and non-interacting galaxies, and measured star formation indices based on UBV colours. From this analysis, Bergvall et al. do *not* find evidence for significantly enhanced star-forming activity among the interacting/merging galaxies, although they do report a moderate increase in star formation in the very centres of their interacting galaxies. Interesting in this respect are also recent results from a combination of Sloan Digital Sky Survey and 2dF Galaxy Redshift Survey data, presented by Balogh et al. (2004). These authors study the equivalent width of Hα emission, a measure of starburst activity, and find no correlation between its distribution among the star-forming population of galaxies and the environment.

So although mergers can undoubtedly lead to massive starbursts, they appear to do so only in exceptionally rare cases. Bergvall et al. (2003) estimate that only about 0.1% of a magnitude limited sample of galaxies will host massive starbursts generated by interactions and mergers. Most interactions between galaxies may not lead to any increase in the starburst activity. Those that do may be selected cases where a set of parameters, both internal to the galaxies and regarding the orbital geometry of the merger, is conducive to the occurrence of starburst activity (e.g., Mihos & Hernquist 1996). To further illustrate this point, we quote the results published by Laine et al. (2003), who find very little evidence for trends in starburst activity from detailed *HST* imaging of the Toomre sequence of merging galaxies.

3.2 Interactions and Seyfert activity

Interactions and mergers have long been suspected of triggering high-luminosity AGN such as QSOs (e.g., Disney et al. 1995; Bahcall et al. 1997), although many of such AGN seem to lie in entirely undisturbed elliptical systems. In fact, Dunlop et al. (2003) show that the host galaxy properties of radio-loud and radio-quiet AGN are indistinguishable from those of quiescent but otherwise comparable galaxies, and Floyd et al. (2004) find no correlation between the luminosity of a quasar and the presence of any morphological disturbance in the host.

Seyfert activity is known to occur in interacting and merging galaxies, and several rather spectacular examples are well known (for instance NGC 2992, or a number of the closest ULIRGs such as Mrk 273). To check statistically whether there is a connection between interactions and the occurrence of this type of nuclear activity, authors have considered the numbers of companions to Seyfert galaxies as compared to non-active control galaxies (e.g., Fuentes-Williams & Stocke 1988; de Robertis, Yee, & Hayhoe 1998; Schmitt 2001), or, alternatively, have searched for different fractions of Seyfert or AGN activity among more or less crowded environments (e.g., Kelm, Focardi, & Palumbo 1998; Miller et al. 2003). The conclusion from this substantial body of work must be that no unambiguous evidence exists for a direct connection between the occurrence of Seyfert activity and interactions. Some earlier work did report claims of a statistical connection, but this work was unfortunately plagued by poor control sample selection (see Laurikainen & Salo 1995 for a detailed review), and most early studies, but also some of the recent ones, are not based on complete sets of redshift information for the possible companion galaxies. In addition, Laine et al. (2002) have shown that the bar fraction among both the Seyfert and non-Seyfert galaxies in their sample is completely independent of the presence of companions (interacting galaxies were not considered by Laine et al.). We thus conclude that interactions and Seyfert activity may well be linked in individual cases, but that as yet the case that they are statistically connected has not been made convincingly.

4. Bars and nuclear rings

Apart from concentrating gas in the central regions of galaxies, as discussed in Section 2, bars also set up resonances which can act as focal points for the gas flow. As reviewed by, e.g., Shlosman (1999), gas concentrates there in limited radial ranges, where it can become gravitationally unstable and form stars. Rings in disk galaxies are mostly identified by their star formation, either by their blue colours or by Hα emission, and are intimately linked to the internal dynamics and the evolution of their hosts (see Buta & Combes 1996 for a comprehensive review on galactic rings).

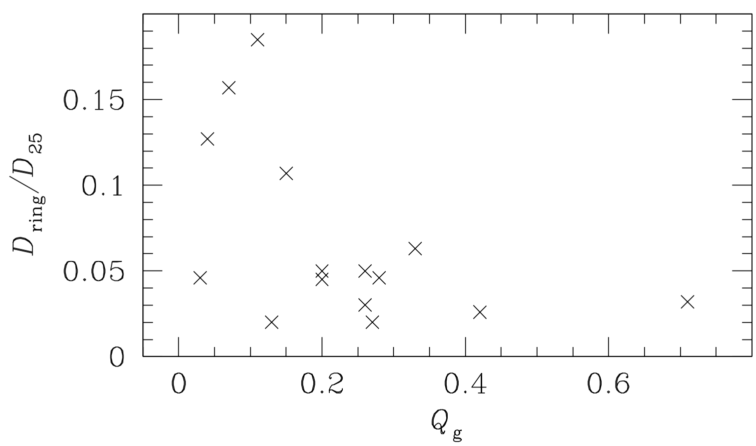

Figure 3. Relative size (ring diameter divided by host galaxy diameter) for a sample of 15 nuclear rings as a function of the gravitational torque $Q_{\rm g}$, or strength, of the bar of its host galaxy. Data from Knapen, Pérez-Ramírez, & Laine (2002) and Knapen (2004b).

Nuclear rings are those on scales of less than one to roughly two kiloparsec in radius. They are rather common, and occur in about 20% of nearby spiral galaxies (Knapen 2004b). They can be directly linked to inner Lindblad resonances (Knapen et al. 1995a; Heller & Shlosman 1996; Shlosman 1999), and are in fact found almost exclusively in barred galaxies (e.g., Buta & Combes 1996; Knapen 2004b; but see below for a counterexample). Individual gas clouds in a nuclear ring can undergo a Jeans-type collapse either spontaneously (Elmegreen 1994), or after compression by density waves set up by the bar (Knapen et al. 1995a; Ryder, Knapen, & Takamiya 2001). Nuclear rings are thus not only excellent tracers of massive star formation in starburst regions, but also of the dynamics of their host galaxies. The latter point is illustrated by Fig. 3, which shows that nuclear rings with a large size relative to their host galaxy can only occur in bars with a low gravitational torque, or:

large rings cannot occur in strong bars. This confirms the results from earlier theory and modelling that the extent of the perpendicular $x2$ orbits needed to sustain the nuclear ring is limited as the bar gets stronger, i.e., as the $x1$ orbits become more elongated (see Knapen et al. 1995a; Heller & Shlosman 1996; Knapen, Pérez-Ramírez, & Laine 2002; Knapen 2004b), and graphically shows how intricately bars and nuclear rings are related.

A small number of rings, or pseudo-rings, apparently occur in non-barred galaxies. Some of these hosts, although classified as non-barred from optical imaging in the major catalogues, are obviously barred when imaged in the near-IR (e.g., NGC 1068, Scoville et al. 1988, and NGC 4725, Shaw et al. 1993; Möllenhoff, Matthias, & Gerhard 1995). In other cases, a non-barred host galaxy may either have an oval distortion, or be undergoing the effects of an interaction with a companion galaxy. In either of these cases, the gravitational potential of the galaxy could be disturbed, and the non-axisymmetric potential could lead to ring formation, in much the same way as in the presence of a bar potential (Shlosman et al. 1989).

Figure 4. Real-colour image of the galaxy NGC 278 produced from archival $F450W$, $F606W$, and $F814W$ HST images. Area shown is about 100 arcsec on a side, or about 5.7 kpc. The blue region, apparently made up of spiral arm fragments, indicates the nuclear ring, with a radius of 1.1 kpc. Image data from Knapen et al. (2004a).

A nice example is that of NGC 278, a small, nearby and isolated spiral galaxy ($v_{\rm sys} = 640\,{\rm km\,s^{-1}}$; $D = 11.8$ Mpc; $D_{25} = 7.2$ kpc; $M_B = -18.8$). Although classified as SAB(rs)b in the RC3, there is no evidence for the presence of a bar in this galaxy from either *HST* WFPC2 or ground-based NIR imaging (Knapen et al. 2004a). The optical disk of NGC 278 shows two distinct regions, an inner one with copious star formation and clear spiral arm structure, shown in Fig. 4, and an outer one ($r > 27$ arcsec or $r > 1.5$ kpc) which is almost completely featureless, of low surface brightness, and rather red. NGC 278 has a large H I disk, which is morphologically and kinematically disturbed, as seen from H I data (Knapen et al. 2004a). These disturbances suggest a recent minor merger with a small gas-rich galaxy, perhaps similar to a Magellanic cloud.

The scale and morphology of the region of star formation in NGC 278 indicate that this is in fact a nuclear ring, albeit one with a much larger *relative* size with respect to its host galaxy than practically all other known nuclear rings (the absolute radius of the nuclear ring is about a kiloparsec, normal for nuclear rings). Knapen et al. (2004a) postulate that it is in fact the past interaction which has set up a non-axisymmetry in the gravitational potential, which in turn, in a way very similar to the action of a classic bar, leads to the formation of the nuclear ring. The case of NGC 278 illustrates how in apparently non-barred galaxies rings can be caused by departures from axisymmetry induced by interactions, but also shows how difficult it can be to uncover this: in the case of NGC 278 only through detailed H I observations.

5. Rings and nuclear activity

Although nuclear rings and especially nuclear activity have as separate topics received considerable attention in the literature, their possible interrelation has not been much studied. Many nuclear rings, of course, are anecdotally known to occur in galaxies which also host a nuclear starburst or a prominent AGN (often of Seyfert or LINER type, given the typical parameters of the host galaxies involved), and some famous examples include NGC 1068 and NGC 4303.

In a recent paper, we explored the correlations between nuclear activity (both of the non-stellar and starburst variety) and the occurrence of nuclear rings in a sample of 57 nearby spiral galaxies (Knapen 2004b). Using information on the activity from the NASA/IPAC Extragalactic Database (NED) and ring parameters as derived from new Hα imaging (Knapen et al. 2004b), we found not only that nuclear rings significantly more often than not occur in galaxies which also host nuclear activity (only two of the 12 nuclear rings occur in a galaxy which is neither a starburst nor an AGN host; 30 of the 57 sample galaxies overall would fall into this category), but also that the circumnuclear Hα emission morphology of the AGN and starbursts is significantly more often in the form of a ring than in non-AGN, non-starburst galaxies (38% of AGN, 33% of starbursts, 11% of non-AGN, and 7% of non-AGN non-starburst galaxies have circumnuclear rings in our sample of galaxies).

Although the number of galaxies in this initial study is rather small for detailed statistical analyses, we did find this most interesting correlation between the occurrence of nuclear rings and that of nuclear activity. Our initial interpretation of this effect is that both nuclear rings, as traced by the massive star formation within them, and starbursts and AGN (of the Seyfert or LINER variety) trace very recent gas inflow. Although it is not clear *a priori* why the kpc-scale fuelling of nuclear rings and the pc-scale fuelling of activity might be so closely related, nuclear rings do seem to show a potential as tracers of AGN fuelling. These findings may also be related to the reported higher incidence of rings among Seyfert and LINER hosts than among non-AGN galaxies (Arsenault 1989 for nuclear rings; Hunt & Malkan 1999 for inner and outer rings). All these aspects of rings and nuclear activity need further scrutiny.

6. Concluding remarks

From theory and modelling, and increasingly also from observations, it is clear that bars can remove angular momentum from gaseous material, and thus drive it from the disk into the central kpc-scale regions of a galaxy (Section 2). In contrast, the evidence that this centrally condensed gas directly and immediately leads to AGN or starburst activity remains rather elusive. The relevant results, reviewed more in depth elsewhere in this paper as indicated below, have been summarised in Table 1, where bars and interactions have been labelled as primary indicators for links between the inflow-provoking mechanisms and the possibly resulting AGN or starburst activity. Also listed in Table 1 is a small number of so-called secondary indicators, which have received attention as outlining possible links between inflow and activity, but which may well be a result of one of the primary indicators. The information summarised in Table 1 can be related to the content of this paper as follows:

Table 1. Summary of observational evidence for relations between various host galaxy features and Seyfert/LINER and starburst activity

Feature	*Seyferts/LINERs*	*Starbursts*
	Primary indicators	
Bars	yes (but 2.5σ)	yes (but not in general?)
Interactions	no	yes (but extremes only?)
	Secondary indicators	
Nuclear bars	no	N/A
Rings	yes, some	yes (nuclear rings at least)

- Starbursts can be provoked by bars or interactions, at least in some cases (Section 2,1, 3.1).
- There is an increasing body of evidence that Seyfert activity preferentially occurs in barred host galaxies, but the effect is a statistical one, and not very pronounced (Section 2.2).
- There is no convincing evidence that AGN hosts are interacting more often than non-AGN (Section 3.2).
- Nuclear bars (Section 2.2) have great theoretical potential for bringing fuel very close to the centre of a galaxy (the “bars within bars” scenario, Shlosman et al. 1989) but have so far not lived up to that potential in

terms of their detections in imaging surveys, where no higher nuclear bar fractions have been found in Seyferts as compared to non-Seyferts. As far as we aware, the possible statistical connections between nuclear bars and starbursts have not yet been studied.

- There is some interesting evidence that rings, both nuclear and non-nuclear, may be related to the presence of low-luminosity AGN activity (Section 5). This issue needs further exploration, but in any case the rings will most likely have formed under the influence of either a bar or another form of non-axisymmetry in the gravitational potential of the host, hence the inclusion of rings as secondary indicators in Table 1.
- Finally, there is a direct link between starburst activity and the presence of nuclear rings, since small nuclear rings with significant massive star formation can be classified as starburst, and since many starbursts might in fact be circumnuclear rather than nuclear, albeit with small ring radii of tens to hundreds of parsec (e.g., González-Delgado et al. 1998), or possibly even smaller. Statistical links between inner/outer rings and starburst activity have not yet been explored.

Since we have known for quite some time that net radial gas inflow must be accompanied by the loss of significant quantities of angular momentum, and that the kind of deviations from axisymmetry in the gravitational potential of the host galaxy set up by bars and interactions is well suited to lead to such angular momentum loss (see reviews by Shlosman et al. 1989, 1990; Shlosman 2003), we must be missing some part of the puzzle. One possibility is that we are not looking at the right things at the right time: the spatial- as well as the time-scales under consideration may not be correct. So far, the spatial scale considered observationally has been from tens of kpc down to, roughly, a few hundred parsec. Whereas this range may be wholly adequate for the study of a major starburst, which can span up to a kpc, it may well be wholly *in*adequate for AGN fuelling, which is expected to be related to accretion to a SMBH, on scales of AUs. As far as timescales are concerned, what has been considered in the studies reviewed here is generally a rather long-lived phenomenon influencing kpc-scale regions (bar or galaxy-galaxy interaction). Starburst or AGN activity, on the other hand, occurs on essentially unknown timescales (somewhere around $10^6 - 10^8$ years could be expected for most AGN or starbursts). If the starburst or AGN activity is indeed short-lived, and possibly also periodic, the connection between the presence of activity at the currently observed epoch and any parameter of the host galaxy is not necessarily straightforward (as pointed out, e.g., by Beckman 2001).

The fact that we see any correlations at all, such as those of bar fractions with the presence of starburst or Seyfert activity, indicates that bars and interactions do have a role, presumably by establishing a gas reservoir in the central kpc region. In the coming years, we must start to disentangle the effects of gravitationally induced gas inflow, which brings gas to the inner kpc region at least, from those of possible other mechanisms which can transport the gas further in, and from the time scales and duty cycles of the activity. We seem to have reached the limits of purely morphological studies of the central regions of active and non-active galaxies (e.g., Laine et al. 2002), and must start to worry about the effects of the AGN or starburst on their immediate surroundings as we push the observations to smaller spatial scales, of tens of parsecs. One must, hence, move on to careful studies of the gas and stellar kinematics and dynamics. Integral field spectroscopy (e.g., Bacon et al. 2001), especially when used in conjunction with adaptive optics techniques, should allow a good deal of progress here, giving simultaneous high-resolution mapping of the distributions of stellar populations and dust, as well as of the gas and stellar kinematics. In combination with detailed numerical modelling, this could lead to the detection of the dynamical effects of, e.g, nuclear bars on gas flows which may be more directly related to the fuelling process of starbursts and/or AGN.

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