Nuclear spirals in galaxies: gas response to asymmetric potential. II. Hydrodynamical models

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ABSTRACT
Nuclear spirals naturally form as a gas response to non-axisymmetry in the galactic potential, even if the degree of this asymmetry is very small. Linear wave theory well describes weak nuclear spirals, but spirals induced by stronger asymmetries in the potential are clearly beyond the linear regime. Hydrodynamical models indicate spiral shocks in this latter case that, depending on how the spiral intersects the $x_2$ orbits, either get damped, leading to the formation of the nuclear ring, or get strengthened, and propagate towards the galaxy centre. Central massive black hole of sufficient mass can allow the spiral shocks to extend all the way to its immediate vicinity, and to generate gas inflow up to $0.03 \, M_\odot \, \text{yr}^{-1}$, which coincides with the accretion rates needed to power luminous local Active Galactic Nuclei.

Key words: hydrodynamics — shock waves — galaxies: kinematics and dynamics — galaxies: ISM — galaxies: spiral — galaxies: structure — galaxies: nuclei — ISM: kinematics and dynamics

1 INTRODUCTION
It has been recently proposed that nuclear spirals in galaxies may be related to the fueling of Seyfert activity (Regan & Mulchaey 1999). This was a straightforward conclusion when a search for the fueling mechanism using highest-resolution optical observations of a sample of Seyfert nuclei with the Hubble Space Telescope returned nuclear spirals in 6 out of 12 galaxies. Nuclear spirals turned out to be much more frequent in Seyfert galaxies than gas inflow related to nuclear bars, the commonly proposed feeding mechanism. Observations of a larger sample that followed (Martini & Pogge 1999) found nuclear spirals in 20 out of 24 Seyfert 2 galaxies, and in a later sample of 46 Seyfert 1 and 2 galaxies (Pogge & Martini 2002) almost all were classified as having nuclear spirals. The authors of these latter surveys also showed that nuclear spirals are not self-gravitating, and that they are likely to be shocks in nuclear gas discs. The most recent study (Martini et al. 2003a,b) involves a sample of 64 Seyfert galaxies, as well as a control sample, which together are big enough so that trends can be noticed. In particular, the authors of this study point out that all grand-design nuclear spirals occur in barred galaxies, but not all barred galaxies develop nuclear spirals — some of them have nuclear rings. Tightly-wound nuclear spirals tend to avoid barred galaxies instead.

Why do some barred galaxies develop nuclear spirals, while other develop nuclear rings? Why do tightly wound nuclear spirals prefer galaxies that do not have a bar? Can any type of nuclear spirals generate inflow sufficient to feed local Seyfert nuclei? Seyfert galaxies require mass accretion rates of $\sim 0.01 \, M_\odot \, \text{yr}^{-1}$ (e.g. Peterson 1997). Here I attempt to answer these questions under an assumption that nuclear spirals are density waves generated in gas by a rotating potential, as described in the accompanying Paper I (Maciejewski 2004). Implications of the linear theory (originally proposed by Goldreich & Tremaine 1979) derived in Paper I will serve here as a guideline, but by themselves they cannot provide answers to the questions above, since the amplitude of strong bars very much exceeds the linear theory.

In the linear approximation the arm/interarm density ratio is a scalable value, as long as the perturbation is small. To estimate how big this ratio is for a given asymmetry in the potential, one can search for nonlinear solutions (e.g. Yuan & Cheng 1989, 1991) or directly involve hydrodynamical modeling. The second approach has the advantage that a whole range of non-axisymmetries, from small ones to ones of the order of the axisymmetric component, can be studied with the same tool. I take this approach, and I construct in this paper hydrodynamical models of gas flow in the nuclear regions of weakly and strongly non-axisymmetric potentials.

To study structures in gaseous nuclear discs of galaxies with the help of hydrodynamical models exceptionally high resolution is required, which has been achieved only recently. Athanassoula’s models of gas flow in barred galaxies (1992b) show curling of the inner parts of the straight principal shock, but the resolution of these models prevents us from following this feature further inwards. Nuclear spirals
generated by the bar inside the straight principal shocks, and winding by more than a π-angle, were first noticed in hydrodynamical simulations by Maciejewski (1998, 2000), and Englmaier & Shlosman (2000). The latter work interpreted these features in terms of spiral density waves, weak enough so that the linear theory is applicable. On the other hand, Maciejewski, Teuben, Sparke & Stone (2002, hereafter MTSS02) point out that nuclear spirals in their models take the form of a shock, which is beyond the scope of the linear treatment.

In this paper I construct hydrodynamical models of nuclear spirals for realistic gravitational potentials represented by rotation curves characterized in Paper I. In particular, I am interested in how the gas flow in the nucleus is modified by the presence of a central massive black hole (MBH) or a density cusp. As pointed out in Paper I, the central MBH significantly changes the nuclear gravitational potential, and therefore it should be able to regulate gas flow around itself. Here, I investigate how its presence modifies gas inflow onto the centre. In Section 2, I list the models to be analyzed in this paper, and I describe the code with which they were extracted continuously from the bulge, and its strength remains unchanged afterwards till the end of the simulation. The method to introduce the secondary bar is discussed in Section 5 devoted to models of nested bars.

Polar grid has singularity at \( r = 0 \), and models built on it cannot include the galactic centre, but they stop at a certain minimal radius: the inner grid boundary. The calculated gas flow in the innermost parts of the galaxy may depend on the boundary conditions adopted there. Usually outflow conditions are imposed with no inflow onto the grid allowed (e.g. Piner et al. 1995, Englmaier & Shlosman 2000, MTSS02). However, this boundary condition effectively means creation of a sink for gas, which may generate unphysical inflow, and unclear rules for wave reflection or absorption. Therefore in this paper I introduced also a reflection condition at the inner grid boundary. The benefit of this boundary condition is that the sink term is removed from the problem, because no gas leaves the grid. Consequently, more conservative estimates for gas inflow can be given (Section 3.4). With this

### Table 1. The list of models

| #  | model name | MBH mass in \( M_\odot \) | sound speed in gas | type of asymmetry | radial extent of the grid | inner grid boundary |
|----|------------|-----------------|-------------------|-------------------|--------------------------|-------------------|
| 1  | 0W20o      | 0               | 20 km s\(^{-1}\)  | weak oval         | 0.02 - 16 kpc           | outflow           |
| 2  | 0W05o      | 0               | 5 km s\(^{-1}\)   | weak oval         | 0.02 - 16 kpc           | outflow           |
| 3  | 8W20o      | \( 10^8 \)      | 20 km s\(^{-1}\)  | weak oval         | 0.02 - 16 kpc           | outflow           |
| 4  | 8W20r      | \( 10^8 \)      | 20 km s\(^{-1}\)  | weak oval         | 0.02 - 16 kpc           | outflow           |
| 5  | 8W20c      | \( 10^8 \)      | 20 km s\(^{-1}\)  | weak oval         | 0.02 - 16 kpc           | reflection        |
| 6  | 8W05o      | \( 10^8 \)      | 5 km s\(^{-1}\)   | weak oval         | 0.005 - 4 kpc           | reflection        |
| 7  | 0S20r      | 0               | 20 km s\(^{-1}\)  | strong bar        | 0.02 - 16 kpc           | reflection        |
| 8  | 0S05r      | 0               | 5 km s\(^{-1}\)   | strong bar        | 0.02 - 16 kpc           | reflection        |
| 9  | 8S20r      | \( 10^8 \)      | 20 km s\(^{-1}\)  | strong bar        | 0.02 - 16 kpc           | reflection        |
| 10 | 0D20o      | 0               | 20 km s\(^{-1}\)  | double bar        | 0.02 - 16 kpc           | outflow           |

2 THE CODE AND SETUP OF THE MODELS

The models were calculated using the CMHOG hydrodynamical code (Piner et al. 1995, MTSS02), which solves the single-fluid equations in their Eulerian form on a fixed polar grid. The gas is isothermal with the sound speed \( c = 20 \) km/s (hereafter termed hot gas), the value suitable for centres of galaxies (Englmaier & Gerhard 1997), but runs with \( c = 5 \) km/s (hereafter termed cold gas) have also been done for comparison. The gas is not self-gravitating. All models are built on the grid covering half of the plane, and point symmetry is assumed. The grid has 174 cells spaced logarithmically in the radial direction, and 80 cells covering a 180° angle.

In order to discuss the physical processes operating in relation to nuclear spirals, I chose 10 hydrodynamical models showing typical features for a given gravitational potential and gas characteristics. The models, with their parameters, are listed in Table 1. Models starting with ‘0’ are built for the potential characterized by rotation curve \( A \) from Paper I (linear inner rise), and models starting with ‘8’ are for the potential characterized by rotation curve \( B \) (a \( 10^8 M_\odot \) MBH added in the centre). The potential in all models includes an \( n = 2 \) Ferrers bar. The bar is either identical to the primary bar in models of MTSS02 (termed ‘strong bar’ in Table 1, model names with ‘S’), or its quadrupole moment is 10 times smaller than in MTSS02 models, and the axial ratio of the bar is decreased to 1.5 from the original 2.5 for strong bar (hereafter I call it ‘weak oval’, model names with ‘W’). The potential with a double bar is identical to that in MTSS02.

In the linear approach, the potentials of both the strong bar and the weak oval have the outer Inner Lindblad Resonance (ILR) at 2.3 kpc, and, in the absence of a central MBH (models starting with ‘0’), they also have an inner ILR (iILR) at 0.13 kpc. Models with a central MBH (models starting with ‘8’) have no iILR.

For each model, the initial gas density is constant throughout the grid (10 \( M_\odot \) pc\(^{-2}\)), and the initial kinematics is gas motion on circular orbits with rotation velocity derived from the axisymmetric potential, where the bar mass was incorporated into the bulge component. Then, through the first 0.1 Gyr of each run, the bar or oval is extracted continuously from the bulge, and its strength remains unchanged afterwards till the end of the simulation.

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condition, waves in gas are fully reflected at the inner boundary. In Section 3.3 I show that the reflected wave is unlikely to play important role in gas dynamics.

3 GAS FLOW IN A WEAK OVAL

Models 1–6 are built for the potential with a weak oval, whose departure from axisymmetry is much smaller than that for a strong bar studied by MTSS02. The $Q_T$ parameter, defined as the maximum ratio of tangential to radial force (Combes & Sanders 1981), is 0.21 for models with a strong bar, but only 0.01 for models with a weak oval. In a real galaxy, such asymmetry will most likely remain undetected, leading to unbarred classification even in the recent detailed infrared studies (e.g. Laurikainen, Salo & Buta 2004).

3.1 Global morphology and kinematics of a nuclear spiral in hot gas

A snapshot of gas density, representative for a nuclear spiral generated by a weak oval in hot gaseous disc is shown in Fig.1. It was taken from Model 8W20, 0.4 Gyr into the run, once the flow has stabilized. Model 0W20 shows the same morphology, except for its innermost parts, because gravitational potentials in these two models are almost identical at radii above a few hundred parsecs. The nuclear spiral is clearly visible in the top panel of Fig.1, although the straight principal shocks disappeared completely once the bar was replaced by a weak oval. The density contrast between the arm and the inter-arm region is about 2 (Fig.1, middle panel), therefore the spiral should be clearly visible in the color maps. On the other hand, this contrast is small enough, so that the perturbation of the velocity field is small. Therefore there are no shocks forming in the gas, and gas flow in discs with this type of the nuclear spiral is almost circular.

Unlike nuclear spirals in strong bars, which unwind outwards rapidly in order to match the principal shock in the bar, nuclear spirals in weak ovals follow the linear mode longer, and wind up to 3 times around the centre (6π angle). After the flow gets stabilized, the bisymmetric nuclear spiral seen in Fig.1 remains unchanged in the frame rotating with the bar: it does not rotate, neither it winds up or unwinds around the centre. Between the inner grid boundary, and the outer ILR (oILR) it winds around the centre by about a 5π angle.

3.2 The $m = 4$ spiral outside the oILR

In the linear approximation, the nuclear spiral should not extend outwards beyond the outer ILR (Paper I, Section 3.1). In fact, from the top panel of Fig.1 one can see that a clear double-arm spiral does not extend out beyond the oILR at 2.3 kpc (dashed circle). However, there is spiral structure detectable in gas morphology out to about 3.5 kpc. The density contrast is much weaker there, and a closer inspection indicates that a clear arm is present outside the two-arm one. Linear theory (see Paper I, Section 3) predicts that such a spiral can be generated by an $m = 4$ mode in the potential, and that it should extend from the galactic centre out to the radius where $\Omega - \kappa / 4 = \Omega_B$. This is the

Figure 1. Top: Snapshot of gas density in model 8W20r, in which a weak oval asymmetry is present in the potential characterized by rotation curve $B$ in Paper I. Gas density is shown at time 0.4 Gyr, after the morphology of the flow has stabilized. Darker color indicates larger densities. The solid ellipse outlines the oval, and the dashed circles mark the oILR at 2.3 kpc and the corotation at 5.6 kpc. The dotted circle marks the position of the 4:1 resonance at 3.9 kpc. Units on axes are in kpc. Middle: Radial density profile (dotted line), and azimuthal velocity (solid line), plotted against rotation curve $B$ from Paper I (dashed line) as a function of radius along the vertical line in the top panel, in models 8W20, at time 0.4 Gyr. To show the structure of the innermost regions, at radii smaller than 0.3 kpc data from model 8W20c are being used instead of 8W20r. The velocity units are in km s$^{-1}$, the density units are arbitrary. Bottom: Density variation in model 8W20r along two circles: at 1.5 kpc (dashed line) and at 3 kpc (solid line). Because of the assumed bisymmetry of the models, variations over only 180° are shown. The density units are arbitrary, the azimuthal angle is in degrees.
(4 : −1) resonance in notation of Paper I, hereafter called for simplicity 4:1. For our potential it is located at 3.9 kpc (dotted circle in the top panel of Fig.1), which is consistent with the observed extent of the four-arm spiral. Ferrers’ bar can be decomposed into even-\(m\) components, among them \(m = 4\), and this component is responsible for a four-arm spiral outside the proper nuclear spiral. Note that two arms of this four-arm spiral are just continuations of the two-arm nuclear spiral from smaller galactic radii, albeit with much lower density contrast. In addition, two other arms start at the oILR, at position angles \(\sim 90^\circ\) and \(\sim 270^\circ\), and extend outwards. The transition from a two-arm spiral inside the oILR to a four-arm one outside is illustrated in the bottom panel of Fig.1, which shows the density profiles as a function of angle along the rim of two circles: one of radius 1.5 kpc, which is located inside the oILR, and the other one of radius 3 kpc, placed between the oILR and the 4:1 resonance. 

Along the first circle, there is only one clear density maximum per \(\pi\) angle, which indicates a two-arm spiral. The density ratio is about 1.8. Along the second circle, two weak but still clear density maxima are seen in a \(\pi\) angle. This is characteristic for a four-arm spiral. The density ratio between maxima and minima along this circle ranges between 1.1 and 1.2, depending on which maximum/minimum values are taken. Thus one may expect weak four-arm spiral structures outside grand-design two-arm nuclear spirals.

The smooth transition from the nuclear spiral to the four-arm spiral in the hydrodynamical models can be also seen in the radial changes of the pitch angle (Fig.2b, open circles). It closely follows the linear prediction for a two-arm spiral inside the oILR (Fig.2b, solid line), but its value remains almost unchanged also at larger radii, where the nuclear spiral should unwind and disappear. There, spiral arms of the nuclear spiral continue outwards, assuming outside the oILR pitch angle predicted by the linear theory for a four-arm spiral (dotted line in Fig.2b). Thus continuation of the nuclear spiral to larger radii may hide the presence of the oILR in the galaxy.

### 3.3 Morphology of the innermost regions

The linear theory says that if inside the oILR another ILR is present, the nuclear spiral should not propagate inwards of this ILR (the iILR). Here I follow the hydrodynamical realization of this rule, using models of gas flow in gravitational potentials with the iILR (models 0W20), and without it (models 8W20). Note that the inclusion of a \(10^8 M_\odot\) MBH, which is the sole difference between the gravitational potentials in these models, is sufficient to remove the ILR in a galaxy with a constant-density core.

In models 0W20 (rotation curve A), the nuclear spiral unwinds rapidly when it approaches the iILR from the outside, with its pitch angle well following the linear prediction (Fig.2b), and it disappears just outside the ILR. It remains strong all the way until reaching the iILR, which may be the reason why the leading spiral predicted by linear theory to form at the iILR (Paper I) is absent. On the other hand, the 8W20 models (rotation curve B) have only one ILR, and a clear nuclear spiral extends there all the way to the inner boundary (Fig.2c).

In the model 8W20r, the wave generating this nuclear spiral reflects from the inner boundary and interferes with the incoming wave, which may perturb the solution. However, the original wave moving inwards is focused towards...
the centre, while the reflected wave diverges away from the centre, and it is quickly overcome by the incoming wave. Thus the perturbation caused by reflection does not propagate beyond the innermost 10-20 cells, which on the standard grid corresponds to the range of radii 30 – 45 pc. Moreover, this boundary condition has parallels to the actual physical situation, when the wave propagating inwards encounters the accretion disc of the MBH with density likely higher, which causes reflection, and any inflow in the spiral accumulates in the accretion disc.

Nevertheless the steady-state solution for model 8W20r does not reflect the winding of the spiral in the innermost regions predicted by the linear theory (compare the central-bottom panel of Fig.2 in Paper I to Fig.2c here). This is clearly seen as a discrepancy between the value of the pitch angle predicted by the linear theory, and measured in the model (Fig.2d, open circles) at radii below 200 pc. After the flow stabilizes, the maximal pitch angle (36°) is clearly larger than the linear prediction (23°), and the maximum occurs at a smaller radius. However, when the model is examined before the flow settles down (here at 0.25 Gyr), the measured pitch angle is much closer to the linear prediction (Fig.2d, triangles).

To investigate whether this effect is numerical (vicinity of the inner grid boundary), I built two more versions of model 8W20: one with the outflow inner boundary condition (8W20a), and one still with the reflective inner boundary, but extending four times further towards the galaxy centre, down to the radius of 5 pc (8W20c). In this last version, a nuclear spiral winding up towards the centre develops during the early stages of the simulation. Its shape (Fig.2e) is similar to that in the central-bottom panel of Fig.2 in Paper I, and its pitch angle closely follows the linear theory (Fig.2f, triangles). However, when the flow stabilizes, the innermost part of the nuclear spiral unwinds, with its pitch angle growing and reaching the same values as in model 8W20r (Fig.2f, open circles). This result remains unchanged when outflow through the inner boundary is allowed (model 8W20o). In fact, once the flow stabilizes, the morphology of the nuclear spiral in all 3 versions of model 8W20 gets identical, and it remains so till the end of each run at 0.9 Gyr (Fig.3). Regardless of whether gas accumulates in the innermost cells of the grid in models with reflective inner boundary condition (8W20c, 8W20r) or whether it is removed from the grid when outflow is allowed (8W20o), the nuclear spiral reaches the same steady state. Thus I conclude that the unwinding of the innermost part of the nuclear spiral is not an effect of proximity of the inner grid boundary, but rather has hydrodynamical origin. However, it is unlikely to be an effect of wave reflection in the galaxy centre, since it also appears in the model version with the outflow boundary condition.

### 3.4 Gas inflow triggered by a nuclear spiral in a weak oval

The rate of inflow can be deduced from how the mass contained within various radii changes with time. For model 8W20r, Fig.4 shows gas mass within a number of radii as a function of time. Only mass enclosed in the innermost circle of the radius of 40 pc changes significantly. Throughout the run it increases from $0.37 \times 10^5 M_\odot$ to $2.14 \times 10^5 M_\odot$, but most of the inflow occurs between 0.25 Gyr and 0.4 Gyr, when over $1.5 \times 10^3 M_\odot$ is dumped into radii below 40 pc. Thus average inflow during this period of 150 Myr is about $10^{-3} M_\odot$ yr$^{-1}$. This inflow occurs exactly when the transition from a tightly wound spiral (Fig.2e) to the steady-state solution (Fig.2f) occurs. Thus the formation of a nuclear spiral results in a single event of gas inflow into innermost parsecs of the galaxy, which dumps there about $10^3 M_\odot$ of gas. After this single dump, the mass inflow is negligible, consistent with zero. Such a one-time dump happens only in the models with the nuclear MBH (8W20). In models without it (0W20) the mass accumulated in the innermost regions does not change significantly with time.

Nuclear spirals may be generated not only by weak ovals, but also by transient phenomena like a passing globular cluster or a giant molecular cloud. Such nuclear spirals would then also be transient and reoccurent. Model 8W20r indicates that every time the spiral reappears, it dumps some $10^3 M_\odot$ of gas onto the innermost parsecs of the galaxy, which may provide a way to sustain a weak nuclear activity. However, for such reoccurent dumping to take place, material has to be replenished into the inner 100 pc, because formation of the spiral leads to mass increase within this radius of a few percent only, while 60% of gas within 100 pc radius ends up within 40 pc radius after formation of the spiral.

Note that by imposing the reflection condition on the inner boundary of the polar grid used in these simulations I get the lower limit for the inflow. If free outflow through the inner boundary is imposed instead, (model 8W20o, as in Piner et al. 1995), a flux of about $2 \times 10^{-3} M_\odot$ yr$^{-1}$ is
The mass accumulated there increases gradually throughout the 0.9-Gyr run by 56% and 42% of its initial value, respectively. However, this mass does not get much further inwards than 500 pc from the galaxy centre, since the mass accumulated within the radius of 250 pc actually slightly decreases throughout the run. Thus no mass transport from kpc- to pc-scale is expected by nuclear spirals of this kind.

### 3.5 Nuclear spirals in cold gas

The linear theory predicts that the pitch angle $i$ of the spiral (see eq.24 in Paper I) is proportional to the speed of sound in the isothermal gas in which the density wave propagates. Thus the spiral in models 0W05 and 8W05, that involve cold gas with sound speed of 5 km s$^{-1}$, is much more tightly wound. Only model 8W05 is shown (Fig.5), since the other one looks almost identical. From the linear theory, the pitch angle in cold-gas models is expected to be four times smaller than in the hot-gas models. For a tightly-wound spiral, at any radius $R$, the radial distance $dR$ between the adjacent density maxima is $\pi R \tan i$. In cold-gas models considered here it can be as small as 0.13$R$. This corresponds to the radial separation of only 4 cells on our grid, which is insufficient to resolve the waves and results in numerical damping. Such an effect is seen in Fig.5, where stronger spiral is only present close to the oILR at 2.3 kpc, where its pitch angle is expectedly larger. There, the arm-interarm density ratio approaches 3. This amplitude gets damped quickly inwards, although the spiral can be traced down to the radius below 1 kpc, where it winds almost by a $\pi$ angle.

As in the hot-gas case, a four-arm spiral is seen outside the oILR. According to the linear theory (Paper I), a leading nuclear spiral should develop in the vicinity of the iILR in model 0W05o. In cold gas its propagation should not be affected by the interference with the trailing spiral originating at the oILR, as it happens in hot-gas models. Interestingly, such a leading spiral does not form – I discuss reasons for it in Section 6.3. Gas inflow in cold-gas models is negligibly small: in both 0W05 and 8W05 it never exceeds $10^{-5} M_\odot$ yr$^{-1}$ even when outflow from the grid is allowed through the inner boundary.

### 4 NUCLEAR GAS FLOW GENERATED BY A STRONG BAR

The perturbation in the stellar gravitational potential coming from a typical galactic bar is too strong to be described in linear terms. Thus gas flows generated by such perturbation cannot be well described by the linear wave theory. One can get a better insight from the orbital theory of bars (Athanassoula 1992a, see also reviews by Sellwood & Wilkinson 1993 and by Maciejewski 2003). Hydrodynamical models indicate that in the main body of the bar, two symmetric shocks (the principal shocks) form on the leading sides of the bar. If the bar is strong and if it extends to its own corotation, these shocks are straight. Otherwise the shocks curl and start resembling a trailing spiral (Athanassoula 1992b). If there is an ILR in the galaxy, the principal shocks do not point at the galactic centre, but they are offset from it. Gas and dust get compressed in the principal shocks, which are seen as dust lanes in the optical images of barred galaxies (see e.g. NGC 1097, NGC 1300, NGC 4303, and NGC 6951 in the Hubble Atlas of Galaxies, Sandage 1961). Inside the inner ends of the dust lanes, there are nuclear rings (e.g. NGC 4314, Benedict et al. 2002) or nuclear spirals (e.g. NGC 1530, Regan, Vogel & Teuben 1997, Pogge & Martini 2002).

Until recently, limited computing resources prevented us from studying these nuclear structures inside the principal dust lanes, because the resolution of the models was not high enough. In the models by Athanassoula (1992b), the straight principal shocks curl inwards in their innermost parts, but they cannot be followed to much smaller radii because of the limited resolution. Piner et al. (1995) employed polar grid in their hydrodynamical code (CMHOG, used also to build models presented in this paper). Resolution of this grid increases inwards, which allowed them to clearly resolve nuclear rings. They explained formation of these rings in terms of the orbital structure in the bars. This explanation is summarized in Section 4.1 below, where I compare the mechanisms leading to the formation of nuclear rings and spirals. The CMHOG code allowed also to resolve for the first time nuclear spirals inside the straight principal shocks in the bar (Maciejewski 1998, 2000). Similar nuclear spirals were seen by Englmaier & Shlosman (2000) in their models with a different code, but also on the polar grid. In this section I analyze in detail gas flow in the central regions of a strongly barred galaxy.
4.1 How to generate nuclear ring, and how nuclear spiral

It has been commonly accepted that the nuclear ring in barred galaxies forms when the shocked gas leaves the $x_1$ orbits and settles on the lower-energy $x_2$ ones (Athanassoula 1992a,b, Piner et al. 1995). The $x_2$ orbits are almost round, and they do not intersect one another, making therefore a perfect location for gas to accumulate.

However, strong bar, like any asymmetry in the nuclear potential, should also generate nuclear spirals inside its ILR. In the orbital theory, the ILR is defined as the outer limit to which the $x_2$ orbits can extend. Thus the nuclear spiral should be cospatial with the nuclear ring. Yet some barred galaxies show clear nuclear rings, while other display nuclear spirals without rings. Still some show nuclear spirals inside nuclear rings. What is the reason for this variety?

Formation of the nuclear ring is explained by the orbital theory, and the shapes of orbits that underlie this ring solely depend on the properties of the gravitational potential. On the other hand, the nuclear spiral has a wave-like nature, and its properties are determined by the dispersion relation (eq. 16 in Paper I). This relation depends not only on the gravitational potential, but also on the gas characteristics. If gas is assumed to be isothermal, it depends on the sound speed in gas.

Thus two mechanisms: orbital and wave-like, compete in shaping the dynamics of gas flow in central parts of galaxies. Using two models of gas flow in a strongly barred galaxy, I examine the outcome of this competition when the gas is hot (model 0S20r), and when it is cold (model 0S05r). Aside for two different sound speeds in gas, all other parameters in these models are identical.

On the early stages of evolution, right after the bar has reached its full strength, the shocked gas tends to settle on the $x_2$ orbits marked in Fig.6 with dashed lines. At the same time, the inner parts of the principal shock in the bar curl inwards, and tend to follow the linear dispersion relation inside the ILR. Thus in general, the shocked gas tends to follow a path different from the direction in which the shock propagates, because the pitch angle of the shock is different from the pitch angle of the orbit at a given location (Fig.6, inserts). Moreover, the linear formula for the pitch angle of the spiral wave (eq. 24 in Paper I) indicates that this angle is larger for larger sound speeds.

In the hot gas (model 0S20r, Fig.6, left panel), the sound speed is high, thus the pitch angle of the spiral is large. As shown in the insert, this pitch angle is always larger than the pitch angle of the $x_2$ orbits which the shock crosses. The shock propagates inwards crossing each $x_2$ orbit only once, and then moving to smaller orbits. Thus the post-shock gas, which tends to settle on these orbits, always moves away from the shock front. In other words, the spiral shock propagates out of the post-shock gas condensation, into regions where the density of gas is much lower. This is clearly seen in the left panel of Fig.6, after the shock crosses the second outermost $x_2$ orbit. Propagation of shock from a high-density to low-density medium triggers a shoe-lace effect: the shock gets strengthened. In model 0S20r it gains strength high enough that it continues to propagate all the way to the galactic centre. On the other hand, the post-shock gas tends to settle on the $x_2$ orbits, as the gas condensation between the two outermost $x_2$ orbits indicates.

In the cold gas (model 0S05r, Fig.6, right panel), the sound speed is low, thus the pitch angle of the spiral is small. It can become smaller than the pitch angle of the $x_2$ or-
bits at their intersection with the shock (Fig.6, insert of the right panel). When it happens, the shock, still propagating inwards, crosses the $x_2$ orbits from inside out. This means that the dispersion relation forces the shock to propagate back into the post-shock gas, which tends to settle on these $x_2$ orbits. In this gas condensation the shock gets damped. This happens before the shock reaches the major axis of the bar in the right panel of Fig.6. Once the spiral shock weakens and disappears inwards, the gas settles on closed trajectories originating from the $x_2$ orbits. However, they are not exactly the $x_2$ orbits, since the shock constantly penetrates the gas lane from inside, forcing the steady-state solution to be rounder than the $x_2$ orbits in the same area. This mechanism is confirmed by detailed hydrodynamical simulations of nuclear rings, where they appear almost circular, while the underlying $x_2$ orbits are significantly flattened (Piner et al. 1995, MTSS02).

In short, the nuclear spiral shock, being a continuation of the principal shock in the bar, can propagate towards the galactic centre when it is able to escape the gas condensation emerging from this principal shock. It can do it when the pitch angle of the spiral is large enough. If this pitch angle is too small, the spiral shock gets damped in this gas condensation, and a nuclear ring forms.

4.2 Properties of the nuclear spiral

I analyze properties of nuclear spirals in the central regions of a strongly barred galaxy using 2 hot-gas models: 0S20r and 8S20r. The early evolution of both models shows that as the time passes, the nuclear spiral starts at the inner ends of the principal shocks and propagates inwards (Fig.7, top panel). However, the density enhancement related to it is very small (below 40%), and the spiral is only seen as large $div^2 \mathbf{v}$, for negative $div \mathbf{v}$, which indicates the shock. Thus on the early stages of evolution, the principal shock in the bar gets extended inwards as a nuclear spiral shock. It has a number of properties that make it different from the density wave predicted by the linear theory:

- the strength of the shock does not drop significantly when its shape converts from straight to spiral; to the contrary, as can be seen in the middle panel of Fig.7, the strength of the spiral shock (measured by $div^2 \mathbf{v}$) at the radius of 400 pc, where it winds by $5\pi/4$ angle, is larger than that of the principal straight shock (at 1.5 kpc at this position angle);
- the nuclear spiral in model 0S20r, having the iILR, does not stop at this resonance, but crosses it, and is propagating inwards, while in the linear theory the wave does not extend beyond the resonance;
- throughout the extent of the spiral shock, its pitch angle differs significantly from the linear prediction for both models 0S20r and 8S20r (bottom panel of Fig.7), although model 0S05r indicates that it still increases with the sound speed in gas, as in the linear theory.

In both models 0S20r and 8S20r, at the simulation time about 130 Myr, the spiral shock reaches the inner boundary of the polar grid located at the radius of 20 pc. All plots in Fig.7 show characteristics of the models at this moment. Due to the imposed reflective inner boundary condition, the wave making the nuclear spiral reflects at this boundary.

\begin{figure}
\centering
\includegraphics[width=0.8\textwidth]{figure7}
\caption{Top: Snapshot of gas density (greyscale), and of $div^2 \mathbf{v}$ (for $div \mathbf{v} < 0$, contours, shock indicator) in model 0S20r, at the time of 130 Myr, when the spiral shock reaches the inner grid boundary. The dashed circles mark the iILR at 0.13 kpc and the oILR at 2.3 kpc. Overplotted are dotted circles of radii 40 pc, 100 pc, 250 pc, 500 pc, 1 kpc and 2 kpc, in order to help in relating the amount of inflow in Fig.9 to the observed morphology. Units on axes are in kpc. Middle: Radial density profile (dotted line), $div^2 \mathbf{v}$ for $div \mathbf{v} < 0$ (short-dashed line), and azimuthal velocity (solid line) with the rotation curve (long-dashed line) as a reference are plotted for the snapshot from the top panel as a function of radius along the line connecting the centre with the bottom-right corner of that panel. The velocity units are in km s$^{-1}$, the density and $div^2 \mathbf{v}$ units are arbitrary, but the same as in Fig.8. Bottom: Tangents of the pitch angle $t$ of the shock, as indicated by maxima of $div^2 \mathbf{v}$ in models 0S20r (open circles) and 8S20r (filled triangles) plotted for the same time as the snapshot from the top panel. The lines mark the linear prediction for an $m = 2$ spiral in the potential of model 8S20r (solid), and 0S20r (dashed).}
\end{figure}
and interferes with the incoming spiral wave. However the reflected wave geometrically diverges, and it perturbs the incoming wave, which converges on the centre, only at the innermost radii (see also Section 3.3). Note that the wave reflecting at the inner boundary may initially be weak, and not a shock, since \(div \mathbf{v} \) along the spiral decreases in the innermost parts of the galaxy at these early stages of evolution (Fig.7, top panel). This is consistent with the nuclear spiral in model 8S20r following the linear prediction for the pitch angle at the innermost radii below \( \sim 50 \) pc (Fig.7, bottom panel).

After the reflection of the spiral wave from the inner boundary, its morphology quickly reaches a steady state, and it remains unchanged till the end of the runs at 0.5 Gyr. In model 0S20r, the spiral shock recedes from the centre after the reflection, and in the steady state it is confined to the outside of the iILR. Characteristics of the flow in model 8S20r at the time when its appearance has stabilized are presented in Fig.8. Several interesting features of the flow can be observed:

- as can be seen in the middle panel of Fig.8, the strength of the shock is roughly the same at 1.1 kpc, 0.3 kpc, and 0.05 kpc — the first location is at the principal straight shock, while the two last locations are at the nuclear spiral shock; comparing middle panels of Fig.8 and Fig.7 one can see that the strength of the spiral shock at 0.3 – 0.4 kpc has not changed throughout the run (models 0S20r and 8S20r do not differ much at radii that large);
- variations in the profile of the tangential velocity (Fig.8, middle panel), which are much larger than in the model 8W20r with a weak oval (Fig.1, middle panel), also indicate that the departures from the circular rotation are nonlinear here, and indicative of a shock;
- the structure of the shock is best resolved in the cut through the spiral at 0.3 kpc (Fig.8, middle panel): regions of enhanced density (dotted line) occur directly outside of the regions of large velocity convergence, which indicates the shock (dashed line), with the contact between the two zones at 0.33 kpc; for the trailing spiral it means that the density enhancement occurs downstream from the shock;
- contrary to the early stages of evolution (Fig.7, top panel), when largest density concentration occurs around the principal shock, at later stages (Fig.8, top panel) it is located in the nuclear spiral; middle panels of Figs. 7 and 8 (drawn to scale) show that the peak density increased between the early and late stage by a factor of about 2 in the principal shock at 1.1 – 1.9 kpc, but in the nuclear spiral at 0.3 – 0.4 kpc the rise is by a factor of more than 20;
- the pitch angle of the nuclear spiral (Fig.8, bottom panel) still differs from the linear prediction (it is persistently larger), although it shows similar trends: the linear wave theory proposed by Englmaier & Shlosman (2000) to explain the nuclear spirals in bars points out these trends, but the flow is nonlinear and literal application of the linear theory is not adequate here.

### 4.3 Inflow in the spiral shock

The inflow in the spiral shock has been determined analogously to that in the weak nuclear spiral presented in section 3.4 (Fig.4). The evolution with time of mass accumulated within a number of radii for models 0S20r and 8S20r is shown in the top panel of Fig.9. The difference between Figures 4 and 9 is clear: there is strong inflow at virtually all radii in models with a bar, and especially in model 8S20r which includes a \(10^8 M_\odot\) MBH in the centre.

The circle of radius 4 kpc occurs slightly outside the 4:1 resonance in the assumed potential, which is the outer limit of the straight principal shock (see MTSS02), there-
10.67 M\(_\odot\) corresponds to the average inflow of 0.7 M\(_\odot\) per year away angular momentum from gas. However, the velocity of this spiral shock, like the principal shock in the bar, takes time to reach this radius. Nevertheless, this inflow is considerable. It is so because the mass included in each of these circles increases several times compared to its initial value.

The principal shock in the bar cuts through the circles of radii 2 kpc and 1 kpc (see Fig.8, top panel), and largest inflow is expected here. In fact, in the period between the stabilizing of the the morphology of the large-scale flow at 200 Myr, and at the end of the run at 500 Myr, the mass within the radius of 250 pc is expected here. In fact, in the period between the stabilizing of the the morphology of the large-scale flow at 200 Myr, and at the end of the run at 500 Myr, the mass within the radius of 250 pc is expected here. In fact, in the period between the stabilizing of the the morphology of the large-scale flow at 200 Myr, and at the end of the run at 500 Myr, the mass within the radius of 250 pc is expected here. In fact, in the period between the stabilizing of the the morphology of the large-scale flow at 200 Myr, and at the end of the run at 500 Myr, the mass within the radius of 250 pc is expected here. In fact, in the period between the stabilizing of the the morphology of the large-scale flow at 200 Myr, and at the end of the run at 500 Myr, the mass within the radius of 250 pc is expected here. In fact, in the period between the stabilizing of the the morphology of the large-scale flow at 200 Myr, and at the end of the run at 500 Myr, the mass within the radius of 250 pc is expected here.

However, another mechanism of inflow in nuclear spirals generated by a strong bar takes place at the innermost radii. In Section 3.4, I noticed a period of inflow in the weak spiral related to the change in its innermost morphology. It is best seen in Fig.4 as a change of mass accumulated within the radius of 40 pc. Similar increase within this radius is seen in model 8S20r after the spiral shock reaches the inner grid boundary at about 130 Myr (Fig.9, top panel). Between that time and 200 Myr, the mass within the radius of 40 pc increases from 0.37 \times 10^{5} M_{\odot} to about 6 \times 10^{5}. However, contrary to the weak spiral in model 8W20r, inflow in the spiral shock never ceases (Fig.9, bottom panel), but it rather increases with time, reaching the value of about 0.03 M_{\odot}/yr at the end of the run. Similar rate of inflow is present at the radius of 100 pc, and both rates similarly evolve in time.

Note that the mechanism extracting angular momentum from gas in the the nuclear spiral continues to work at the same efficiency per density unit. The increasing density means increasing inflow. Thus gas from the inflow in the principal shock gets collected on the nuclear spiral, and when its highest condensation moves inwards along this spiral towards a certain radius, the inflow at this radius increases. In the models it can be seen on the example of the 500 and 250 pc radii. Top panel of Fig.8 indicates that the maximum density in the spiral has already passed the radius of 500 pc, and keeps propagating inwards along the spiral. This is consistent with the inflow through this radius plotted in the bottom panels of Fig.9: it was constantly increasing between 100 and 400 Myr, when the density peak in the spiral was propagating inwards to reach the radius of 500 pc. When it reached this radius, the amplitude of inflow stabilized. However, the inflow does not decay after that time, because the principal shock keeps the gas supply open. Note that at the end of the run, the inflow in the nuclear spiral at 500 pc is the same as that in the principal shock at 1 kpc, which indicates that some kind of equilibrium has been established.

On the other hand, the density peak in the spiral does not reach the radius of 250 pc within the simulation time (Fig.8, top panel), and inflow through this circle keeps increasing (Fig.9, middle panel). At the end of the run it reaches the value of 0.2 M_{\odot}/yr\(^{-1}\), 3.5 times smaller than that in the principal shock, and in the nuclear spiral at 500 pc. However, the evolution of the models suggests that when the density peak reaches also this radius, the inflow will stabilize at the value equal to that at the larger radii, and it will be the same for each smaller radius, so that eventually a steady-state develops throughout the spiral, with the inflow in the spiral equal to that in the principal shock. However, it takes some 0.5 Gyr to establish such inflow at 500 pc, and likely over 2 Gyr to establish it at 250 pc. Thus although in principle nuclear spirals can cause strong inflow of about 1 M_{\odot}/yr\(^{-1}\)at arbitrarily small radii, it is uncertain whether such spirals exist for periods long enough, so that the inflow has time to reach these small radii.

![Figure 9. Top: Mass accumulated within various radii (indicated in the plot) as a function of time for model 8S20r (solid line) and 8W20r (dotted line). Bottom: Mass inflow averaged over 20-
Myr intervals as a function of time in model 8S20r. The inflow is followed through circles of various radii indicated in the plot. Note the small, but not negligible inflow triggered at the innermost radii in model 8S20r after the arrival of the spiral shock there (at about 130 Myr).](https://example.com/figure9.png)
The inflow of $\sim 0.03 M_\odot \text{yr}^{-1}$ takes place only in the model with the MBH in the centre (8S20r). The top panel of Fig.9 indicates that the evolution of mass accumulated in the inner 40 and 100 pc is significantly different in model 0S20r without the MBH. In this model, after the spiral shock reaches the inner grid boundary, the mass enclosed within 40 pc increases initially by some 70%, but later it decreases, and oscillates around lower values. A quasi-monotonical mass increase occurs after 300 Myr, but it is likely related to the first mechanism of inflow described above, which propagates inwards from larger radii. In any case, the mass enclosed within radius of 40 pc at the end of the run in model 0S20r is $3.2 \times 10^5 M_\odot$, which corresponds to the average inflow of $0.0015 M_\odot \text{yr}^{-1}$ in the period between 300 and 500 Myr. This inflow is 20 times smaller than in model 8S20r with a MBH.

5 NUCLEAR SPIRALS IN DOUBLE BARS

Hydrodynamical models of gas flow in dynamically possible double bars (each bar supported by orbits calculated in this potential) were built by MTSS02. Already the orbital analysis (Maciejewski & Sparke 2000) indicated that straight principal shocks cannot form in the inner bar in such systems, but gas should rather settle in rings elongated with the inner bar. Hydrodynamical models of MTSS02 confirmed these predictions, and evolutionary stars+gas models of Rautiainen et al. (2002) showed that gas settles on orbits calculated by Maciejewski & Sparke (2000). However, these models have been constructed for cold gas only.

When the outer bar is identical to that in the models analyzed in the previous section, it should by itself generate a nuclear spiral in the hot gas (see model 8S20r, Fig.8, top panel). On the other hand, the orbital structure of the inner bar supports formation of gaseous rings, like the ring in model D05 in MTSS02, which is elongated with that bar. Again, the ring and the spiral should occur at the same location since the inner bar is confined within the ILR of the outer one. Thus also in the case of double bar, there is a competition between the orbital structure and the propagating wave.

In order to see what comes out of this competition, I built a model of gas flow in the potential of a doubly barred galaxy identical to that in the models of MTSS02, but this time for the hot gas. In this model, labeled 0D20o, the sound speed in gas is $20 \text{ km s}^{-1}$, and both bars are being introduced simultaneously in the first $100 \text{ Myr}$ of the run.

In the linear approximation outlined in Paper I, the solution is additive, and each independently rotating perturbation in the potential generates its own spiral mode in gas, which propagates with a specific dispersion relation. Note however that in the model considered here, the inner bar rotates with pattern speed $110 \text{ km s}^{-1} \text{kpc}^{-1}$, therefore it has no ILR (see the top-left panel of Fig.2 in Paper I). Thus this inner bar does not generate a nuclear spiral on its own. Only the outer bar, which has a wide ILR, generates a nuclear spiral in the inner kiloparsec, as model 0S20r indicates.

Fig.10 shows two snapshots of gas density in model 0D20o for hot gas in a doubly barred galaxy. Since the pitch angle of the spiral shock in such gas is high, the spiral shock usually propagates out of the density enhancement emerging from the straight principal shock. Therefore the nuclear spiral propagates inwards in this doubly barred galaxy despite the action of the inner bar. It reaches the inner grid boundary at about 145 Myr (Fig.10, left panel). Although according to the linear theory the curvature of the spiral does not change with time at any point in the frame rotating with the outer bar, the curvature of the trajectories on which gas parcels move changes at a given point in this frame with the rotation of the inner bar. The pitch angle of these trajectories may become larger than the pitch angle of the spiral, causing discontinuities in the spiral shock propagating inwards. On later evolutionary stages, when the spiral shock traps considerable amounts of gas around itself, its shape is more influenced by the motion of the inner bar. At times, it may resemble straight principal shocks in the inner bar (Fig.10, right panel) although such shapes are transient. Note that this structure is still caused by the outer bar, even if it resembles the principal shock in the inner bar, to which it may be wrongly ascribed. Also with time a broad ring forms around the inner bar, but with moderate over-density.

Because of the complexity of this problem, detailed investigation of gas dynamics in nested bars requires further work, but this brief analysis already returned some important information: nuclear spirals generated by the outer bar in doubly barred systems can propagate inside the inner bar. Thus the presence of nuclear spirals in galaxies does not exclude a cospatial coexistence of inner bars in the same galaxies. Moreover, nuclear spirals can hide the presence of inner bars, as there is not much difference in the gas kinematics between the systems displayed in the left panel of Fig.10 and in the top panel of Fig.7.

6 DISCUSSION

6.1 Morphology of nuclear spirals

The number of galaxies with color- or structure maps of their central regions has recently become large enough, so that first attempts of morphological classification have been made (Malkan et al. 1998, Martini et al. 2003a,b). This second attempt seems to better reflect the characteristic structures observed in galactic nuclei. There nuclear spirals are segregated into one of four classes: grand design, tightly wound,
loosely wound and chaotic. Here I attempt to link this classification to the morphology observed in the models built in this paper.

Hydrodynamical models of gas flow in rotating potentials presented here show that nuclear spirals are triggered even by small asymmetries in the potential. There they propagate as weak density waves, and they are not bracketed by straight principal shocks, as it is the case in strong asymmetries induced by galactic bars. This should be expected, because the $z_1$ orbits supporting a weak oval asymmetry are round, with no cusps, and thus do not induce shocks in gas. Since there are no straight shocks to join, the spirals can continue winding around the centre, closely following predictions of the linear theory. Thus tightly-wound nuclear spirals, which can propagate freely in weak asymmetries of the potentials, may be observationally associated with galaxies where the bar is too weak to be detected. However, if the potential or conditions in gas imply large pitch angle of the spiral wave in a given galaxy, then a loosely wound spiral will appear in a galaxy classified as unbarred.

On the other hand, in strong bars nuclear spirals rapidly unwind outwards to match the shape of the straight principal shock in the bar. Thus regardless of the underlying potential or velocity dispersion in gas, nuclear spirals in strong bars are not likely to appear observationally as tightly-wound spirals. This is consistent with the statistics of Martini et al. (2003 a,b): tightly wound spirals avoid barred galaxies.

Grand-design nuclear spirals require a strong driver which acts continuously over long time periods. In the statistics of Martini et al., they appear only in galaxies classified as barred. This implies that the galactic bar can serve as such a driver, and that there may be no other driver that fulfills the criterion above. Tightly or loosely wound spirals in the classification of Martini et al. can be generated by a weak oval, or when they show clear discontinuities, by a passing perturbation in the potential (globular cluster or giant molecular cloud). With growing discontinuities, one moves to the class of chaotic spirals, whose generation mechanism is likely different (acoustic noise, see Elmegreen et al. 1998).

6.2 Gas kinematics. Feeding of the AGN.

Recent observational statistics of the central morphology in a sample of active galaxies accompanied by a control sample (Martini et al. 2003 a,b) indicates that nuclear spirals occur with comparable frequency in active and non-active galaxies. On the other hand, models presented in this paper show that nuclear spirals generated by a strong bar take the form of shocks in gas and trigger moderate gas inflow onto the central MBH, while nuclear spirals generated by a weak oval do not cause the inflow. I propose that what determines the inflow is not the driver, but the nature of the spiral. If it is a shock, then it is likely to trigger inflow. If it is not, inflow will not occur. Note that the morphology of the spiral shock departs from the linear prediction (Fig.8, bottom panel) in the sense that the pitch angle of the spiral is larger than in the linear theory. Thus spiral shocks that do not appear as grand-design spirals, are likely to be observationally classified as loosely wound spirals.

In the full sample of Martini et al. (2003a), grand-design and loosely wound spirals occur in 60% of active galaxies, and only in 23% of inactive ones. This difference is statistically significant, and it may indicate that although not all nuclear spirals are fueling the AGN, some spirals most likely do it. However, morphological considerations are not sufficient to verify this hypothesis, and observations of gas kinematics in the spirals is needed. Clear departures from circular motion are expected in spiral shocks (Fig.8), but not in weak density waves that do not trigger inflow (Fig.1).

It became recently generally accepted that all galaxies may host a MBH at their centres (see e.g. Kormendy & Gebhardt 2001 for a recent review), and there are attempts to measure the mass of this MBH from the gas kinematics around it (e.g. Macchetto et al. 1997, Bower et al. 1998, Maciejewski & Binney 2001). This method can be derailed by non-circular gas motions in the nuclear discs, especially when they exhibit spiral structure. Spiral shocks can strongly perturb the velocity field (Fig.8). However, if tightly wound nuclear spirals in fact correspond to models where the spiral is a weak density wave, then gas flow in such a spiral is almost circular (Fig.1), and methods based on gas kinematics should yield a reliable MBH mass here.

6.3 Leading spirals, nuclear rings

According to the linear theory outlined in Paper I, nuclear spirals generated at the OLR and at the oILR are trailing, and hydrodynamical models built in this paper well reproduce the trailing spirals related to the oILR. These spirals propagate inwards, as expected. However, the linear theory also predicts formation of a leading spiral at the iILR that propagates outwards. Such combinations of a leading spiral inside a trailing one are very unusual in galaxies, with the only familiar example being NGC 6902 (Grosbøl 2003). In the models presented here leading spirals do not form, even when the iILR is present. One reason for it may be the extent of the trailing spiral generated at the oILR, which propagates inwards to the vicinity of the iILR in model 0W20, and even past it in model 0S20 of a spiral shock. This may suppress formation of the leading spiral. However, in model 0W05, where the trailing spiral gets damped not far inwards from the oILR, leading spiral does not form either. Some explanation here may come from the applications of the nonlinear theory of density waves developed by Yuan & Kuo (1997). It allows to investigate the effect of viscosity on the nuclear spirals. In the results presented by Yuan, Lin & Chen (2003) it can be seen that the leading spiral forms only for high viscosity. Viscosity in the hydrodynamical code used to build models in this paper is very low, and this may be the reason for the absence of the leading spiral. On the other hand, its absence in the observed nuclei of galaxies may indicate low effective viscosity in the ISM, much lower than what the quality of the code often imposes on the available hydrodynamical models.

Another feature promoted by numerical models and definitely under-abundant in the observed galaxies are nuclear rings. Only 2 nuclear rings are found in the sample of 43 Seyfert galaxies observed by Pogge & Martini (2002), and an eye-examination of the larger sample of 123 galaxies (Martini 2003a) picks up a dozen of nuclear rings. In Section 4.1 I showed that nuclear rings form as an effect of interaction between the wave-nature of the principal shock in bar, and the orbital structure there. This interaction creates con-
tions favourable to the formation of nuclear rings when the velocity dispersion in gas is low. In fact, low velocity dispersion in gas is assumed in models that form nuclear rings (e.g. Piner et al. 1995, Regan & Teuben 2003). However, velocity dispersion in the inner discs of spiral galaxies is likely to be higher (Englmaier & Gerhard 1997, Elmegreen et al. 1998), which is consistent with the observed frequency of nuclear spirals that is higher than that of nuclear rings. Thus studies of nuclear rings may only partially reflect gas dynamics in centres of galaxies. In particular, stagnation of gas inflow in the bar caused by these rings is not a general evidence against the possibility that bar-related inflow can occur at radii typical for rings. Nuclear rings make only one type of nuclear gas flow, and another type, nuclear spirals, may extend bar-related inflow to the innermost regions of galaxies.

7 CONCLUSIONS

In this paper I analyzed high-resolution hydrodynamical models of gas flow in nuclear spirals generated in the gaseous disc by a rotating potential. Nuclear spirals form naturally even if the asymmetry in the potential is very small, with the maximal ratio of radial to tangential force (the QT parameter, Combes & Sanders 1981) about 0.01. Thus asymmetries in galaxies often to weak to be detected observationally, like a weak triaxiality of the bulge, may be sufficient to generate nuclear spirals. Models with weak asymmetry in the potential well conform to the linear prediction, while the nature of nuclear spirals in strong bars considerably differs from what is predicted by the linear density-wave theory.

Models of galaxies with weak ovals indicate that nuclear spirals form even if the asymmetry in the potential is too weak to generate straight shocks along its major axis. In such potentials, nuclear spirals are not forced to unwind rapidly outwards to match the straight shocks; they can follow predictions of the linear density-wave theory for longer, and wind more tightly than in the presence of a strong bar. This is consistent with the recent statistical analysis by Martini et al. (2003a,b) which finds that tightly wound nuclear spirals rather avoid galaxies that are barred. The smooth continuation of the nuclear spiral into a four-arm spiral seen in the models with weak ovals indicates that the extent of such tightly-wound spirals may not be a good indicator of the location of the ILR in galaxies without a clear bar. Nuclear spirals in weak ovals are not efficient in transporting gas from kiloparsec- to parsec- scale, but some inflow in the innermost parsecs of the galaxy occurs during formation of such a spiral in models without an ILR (with a central MBH). Since these nuclear spirals not only re-appear as a response to the driver, gas dumped each time onto the MBH can maintain a weak nuclear activity.

In strong bar the nuclear spiral has the nature of a shock in gas. The spiral shock is less tightly wound than what the linear theory predicts (compare Fig.1 to Fig.8). This may suggest correspondence between spiral shocks and loosely wound spirals in the classification of Martini et al. (2003a). Hydrodynamical models built in this paper show that such spiral shocks trigger gas inflow, although of different nature than that in the straight principal shock in the bar. In the outer regions of the nuclear spiral, the inflow timescale is longer than in the principal shock bracketing it from outside. Therefore gas initially accumulates there, but with time it is transported inwards along the spiral. The inflow rate at density peaks along the spiral equals that in the principal shock. Another inflow mechanism is present in the innermost tens of parsecs of the nuclear spiral in the presence of a central MBH: after the initial dumping of matter onto the centre, common with the models for weak ovals, the mass inflow does not stop, but continues at a steady rate of up to 0.03 M⊙yr⁻¹. Local Seyfert galaxies require mass accretion rates of ~ 0.01 M⊙yr⁻¹ (e.g. Peterson 1997), therefore the inflow rate in the models presented here is sufficient to feed luminous local Active Galactic Nuclei, and the feeding can continue over long timescales. An observational support for this mechanism comes from the fact that when the groups of nuclear spirals re-appear together, feeding can occur for an extended time.

Nuclear spirals are more common in galaxies than nuclear rings. Which of these two will be triggered by a barred potential depends on the interplay between the post-shock gas condensations, which tend to follow the lowest-energy orbits, and the shock, whose inner shape adheres to the rules for wave-propagation. In the ISM with low velocity dispersion, the shock is damped in gas condensation, and a nuclear ring forms. When velocity dispersion in the ISM is high, the shock propagates away from gas condensation, gets strengthened, and continues inwards as a nuclear spiral. Higher frequency of nuclear spirals than of nuclear rings in galaxies favours ISM with high velocity dispersion in centres of disc galaxies.

Secondary inner bars in barred galaxies do not halt the propagation of nuclear spirals inwards. Thus nuclear spirals can co-exist with inner bars in galaxies. Moreover, they can mask the presence of inner bars in galactic nuclei.

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REFERENCES

Athanassoula E., 1992a, MNRAS, 259, 328
Athanassoula E., 1992b, MNRAS, 259, 345
Benedict G. F., Howell D. A., Jørgensen I., Kenney J. D. P., Smith B. J., 2002, AJ, 123, 1411
Bower G.A. et al., 1998, ApJ, 492, L111
Combes F., Sanders, R. H., 1981, A&A, 96, 164
Elmegreen B. G. et al., 1998, ApJ, 503, L119
Englmaier P., Gerhard O., 1997, MNRAS, 287, 57
Englmaier P., Shlosman I., 2000, ApJ, 528, 677
Goldreich P., Tremaine S., 1979, ApJ, 233, 857
Grosbol P., 2003, in Contopoulos G., Voglis N., eds, Lecture Notes in Physics Vol.626, Galaxies and Chaos. Springer-Verlag, Berlin, Heidelberg, p.201
Kormendy J., Gebhardt K., 2001, in 20th Texas Symposium on relativistic astrophysics, p.363
Laurikainen E., Salo H., Buta R., 2004, ApJ, 607, 103
Macchetto F., Marconi A., Axon D. J., Capetti A., Sparks W., Crane P., 1997, ApJ, 489, 579
Maciejewski W., 1998, Ph.D. Thesis, Univ. of Wisconsin
Maciejewski W., 2000, in Combes F. et al., eds, ASP Conf. Ser. Vol. 197, Dynamics of Galaxies: from the Early Universe to the Present. Astron. Soc. Pac., San Francisco, p.63
Maciejewski W., 2003, in Boily C. M. et al., eds, EAS Publication Series Vol.10, Galactic & Stellar Dynamics. EDP Sciences, Les Ilis, p.3
Maciejewski W., 2004, MNRAS submitted (Paper I)
Maciejewski W., Binney J., 2001, MNRAS, 323, 831
Maciejewski W., Sparke L. S., 2000, MNRAS, 313, 745
Maciejewski W., Teuben P. J., Sparke L. S., Stone J. M., 2002, MNRAS, 329, 502
Malkan M. A., Gorjian V., Tam R., 1998, ApJS, 117, 25
Martini P., Pogge R. W., 1999, AJ, 118, 2646
Martini P., Regan M. W., Mulchaey J. S., Pogge R. W., 2003a, ApJS, 146, 353
Martini P., Regan M. W., Mulchaey J. S., Pogge R. W., 2003b, ApJ, 589, 774
Peterson B. M., 1997, An Introduction to Active Galactic Nuclei (Cambridge: Cambridge Univ. Press)
Piner B. G., Stone J. M., Teuben P. J., 1995, ApJ, 449, 508
Pogge R. W., Martini P., 2002, ApJ, 569, 624
Rautiainen P., Salo H., Laurikainen E., 2002, MNRAS, 337, 1233
Regan M. W., Mulchaey J. S., 1999, AJ, 117, 2676
Regan M. W., Teuben P. J., 2003, ApJ, 582, 723
Regan M. W., Vogel S. N., Teuben P. J., 1997, ApJL, 482, L143
Sandage A., 1961, The Hubble Atlas of Galaxies (Washington: Carnegie Institution)
Sellwood J. A., Wilkinson A., 1993, Rep. Prog. Phys., 56, 173
Yuan C., Cheng Y., 1989, ApJ, 340, 216
Yuan C., Cheng Y., 1991, ApJ, 376, 104
Yuan C., Kuo C.-L., 1997, ApJ, 486, 750
Yuan C., Lin L.-H., Chen Y.-H., 2003, in Ho L. C., ed., Carnegie Observatories Astrophysics Series, Vol. 1: Coevolution of Black Holes and Galaxies (Pasadena: Carnegie Observatories, http://www.ociw.edu/ociw/symposia/series/symposium1/proceedings.html)