Nuclear spirals in galaxies

Witold Maciejewski

Astrophysics, Denys Wilkinson Bldg, Keble Rd, Oxford OX1 3RH, UK
witold@astro.ox.ac.uk

Summary. Recent high-resolution observations indicate that nuclear spirals are often present in the innermost few hundred parsecs of disc galaxies. My models show that nuclear spirals form naturally as a gas response to non-axisymmetry in the gravitational potential. Some nuclear spirals take the form of spiral shocks, resulting in streaming motions in the gas, and in inflow comparable to the accretion rates needed to power local Active Galactic Nuclei. Recently streaming motions of amplitude expected from the models have been observed in nuclear spirals, confirming the role of nuclear spirals in feeding of the central massive black holes.

1 Introduction

There is an intricate mutual dynamical dependence between the central Massive Black Hole (MBH) and the nuclear region of the host galaxy. Centres of galaxies act as resonant cavities, and the mass of the central MBH contributes to the formation and locations of the resonances [6],[7]. Resonances can either halt or enhance radial gas flow, and thus can control fueling of the nucleus [8]. Among resonantly-induced features, nuclear spirals form naturally as a gas response to non-axisymmetry in the gravitational potential of a galaxy [2],[8]. In fact, recent high-resolution observations often find in the innermost few hundred parsecs of disc galaxies nuclear spirals [13],[10] that are likely to continue inward to within a few parsecs from galaxy’s centre [14],[4]. Because of their ubiquity, nuclear spirals were invoked as the mechanism by which material is transported to the central MBH [15]. In this paper, I present implications of [7] and [8] for the diagnostic role of nuclear spirals, and I confront model predictions with the most recent observations.

2 Geometry: indicator of central mass concentration

Nuclear spirals form naturally as morphology of waves in gas, generated by a rotating asymmetry in the galactic gravitational potential. Generation and
propagation of waves is governed by dynamical resonances, whose presence and positions depend on the central mass distribution in the galaxy. Simple linear approximation enables to describe the morphology of nuclear spiral for most typical rotation curves [7]:

- **A**, with a linear inner rise, reflecting solid-body rotation in the innermost parts of the galaxy, i.e. constant-density core,
- **B**, same as **A** but with a central MBH of mass consistent with the observed correlations (e.g. [16]),
- **C**, a pure power-law, corresponding to a central density cusp.

These three representative rotation curves are presented in the upper panels of Fig.1, while the shapes of the nuclear spirals generated by a rotating bisymmetry in the potential are shown in the lower panels of Fig.1.

![Rotation curves](image)

**Fig. 1.** Rotation curves (upper row), and the corresponding shapes of nuclear spiral (lower row), calculated for isothermal gas with 20 km s$^{-1}$ sound speed for three rotation curves described in the text.

If there is no central MBH, and if the rotation curve rises linearly in its innermost parts (case **A**), the nuclear spiral will not extend to the centre of the galaxy (Fig.1, left column). If there is a MBH in the centre (case **B**), the nuclear spiral extends to the centre, and it tightly winds around the central MBH (Fig.1, central column). If there is a central density cusp (case **C**), the nuclear spiral extends to the centre, but it unwinds towards the centre (Fig.1, right column). Rotation curves **A** and **C** appear similar, but their corresponding nuclear spirals are diametrically different. Ubiquity of nuclear spirals in galaxies may indicate that approximating the inner rise of the rotation curve by a straight line is often inadequate. Moreover, nuclear spiral tightly winding around the galactic centre may indicate the presence of a MBH there.
3 Amplitude: indicator of asymmetries in the potential

Nuclear spirals are resonant phenomena, and they can be generated by very small departures from axial symmetry in galaxies. Aside for asymmetries in stellar distribution, other asymmetries may contribute to the overall galactic gravitational potential. If MBHs in centres of galaxies form by merging of smaller black holes, then there should be a few black holes of mass one or two orders of magnitude smaller than that of the central ones, orbiting around the centre of a typical galaxy (e.g. [17],[5]). These black holes constitute a weak perturbation in the gravitational potential, which can generate wave phenomena in gas within a disc close to the centre of a galaxy. A single orbiting black hole about ten times less massive than the central black hole generates a three-arm spiral pattern in the central gaseous disc, with density excess in the spiral arms up to 3-12% ([3], see Fig.2, left and central panels). Dusty filaments that have been discovered recently in the centres of galaxies (e.g. [10],[14]) have luminosity lower from their surroundings by 5 – 10%, therefore spiral patterns in gas generated by the most massive orbiting black holes should be detectable. Interestingly, one of the best investigated nuclear spirals in NGC 1097 ([14],[4]) has three arms (Fig.2, right panel), difficult to generate by the observed bisymmetric bar only.

![Fig. 2. Left and central panels: the density of gas in galactic plane in model 11 from [3] of a $10^7 M_\odot$ MBH in circular orbit of 1 kpc radius perpendicular to the galactic plane. Darker shading represents higher density. Units on axes are in kpc. Right panel: VLT NACO J-band image of the nuclear spiral in NGC 1097 after subtraction of radial intensity gradient by ellipse fitting. The side of the box is 8 arcsec, corresponding to about 0.55 kpc.](image)

4 Nuclear spiral as a feeding mechanism of the MBH

In the present-day Universe, 10-20 per cent of galaxies show nuclear activity of Seyfert type. This activity is orders of magnitude weaker than that of quasars, and internal, dynamical factors are likely to play a role in triggering it.
Extensive morphological studies had no success in pointing out the mechanism that triggers the nuclear activity, but they might have focused on features on too large scales. A typical local Active Galactic Nucleus (AGN) consumes about 0.01 $M_\odot$ of fuel per year (e.g. [12]), most likely coming from gas inflow. This corresponds to about $10^6 M_\odot$ during its $10^8$-yr long activity. Therefore there is no need to transport gas from the outskirts of a galaxy in order to feed a local AGN, but significant redistribution of gas in the innermost tens and hundreds of parsecs should be expected.

![Figure 3](image)

**Fig. 3.** The density of gas in greyscale in galactic plane in model 8S20 from [8] with nuclear spiral shock. Darker shading represents higher density. Contours outline constant radial velocities, and are spaced every 20 km s$^{-1}$. Outflow (positive radial velocity) is marked by solid contours, while dashed contours mark inflow (negative radial velocity). Thick solid contour marks zero-radial-velocity line.

In strong bar, the nuclear spiral has the nature of a shock in gas [8], which can trigger gas inflow throughout the spiral. Note however, that analogously to gas flow in the region of straight principal shocks in the bar (e.g. [1, 9]), not all gas in the region of nuclear spiral shows radial inflow (Fig.3). In fact, most of the volume is dominated by outflow of low-density gas, but inflow of dense post-shock gas in the spiral dominates the budget. Therefore exclusive use of tracers of dense gas (e.g. molecular emission) can result in biased estimates of integrated radial flow of galactic gas.

Right panel of Fig.4 shows line-of-sight velocities expected for the standard model 8S20 of nuclear spiral from [8], when viewed at inclination of 60°, and
after subtracting contribution of circular motion. Large streaming motions are expected, of amplitude of up to 50 km s\(^{-1}\). This amplitude can only be achieved when shocks in gas are involved. Recently, the same algorithm has been applied to the kinematics of nuclear spiral in NGC 1097 observed with the Integral Field Unit GMOS on the Very Large Telescope \[^4\]. Strong streaming motions of amplitude about 50 km s\(^{-1}\) that show spiral morphology, have been observed. That observation confirms presence of shocks in nuclear spirals. 

Note that the modelled kinematical spiral arms do not overlap with the spiral gas morphology (Fig.4, left panel). This is because the matter distribution is point-symmetric, while the velocity vectors – point-antisymmetric. The shift between the kinematical and morphological spiral arms predicted by the models is consistent with that observed in NGC 1097 \[^4\].

Hydrodynamical models of nuclear spiral shocks indicate the rate of inflow in the innermost parsecs of a galaxy up to 0.03 M\(_\odot\) yr\(^{-1}\)\[^8\]. This inflow is sufficient to feed luminous local AGN, and the feeding can continue over long timescales. Nuclear spiral shock is less tightly wound than what the linear theory predicts, hence loosely wound spirals in the classification developed in \[^10\] may indicate spiral shocks. Interestingly, when in that classification one groups together grand-design nuclear spirals (explicitly linked to shocks in bars) and loosely wound spirals, they occur considerably more often in active than in non-active galaxies \[^10\],\[^11\].
5 Discussion and conclusions

Hydrodynamical models of nuclear spirals presented here assume that galactic gas is a continuous medium, which can be statistically approximated by isothermal fluid. One may expect that this approximation breaks down at scales small enough, but it is still likely to hold on 10-pc scale, because continuous dusty nuclear spiral arms extend down to within that distance from the nucleus. Perhaps this approximation is most appropriate for the dynamic interstellar medium, in which dense clouds continuously form and disperse.

The shape of nuclear spiral can serve as an indicator of the presence of a MBH in a galaxy’s centre, and as an estimator of its mass. The amplitude of the spiral can constrain asymmetries in the galaxy’s potential, like orbiting remnant black holes left from the time of galaxy formation.

Nuclear spirals in galaxies can either be weak density waves which cannot feed the nucleus, or strong dissipative shocks, which can generate gas inflow large enough to power luminous local AGN. Nuclear spiral shocks should be revealed in kinematical observations by strong streaming motions, and such motions of amplitude consistent with theoretical predictions have been recently observed. This observation makes a sound argument in support of gas inflow in nuclear spirals, which can serve as a mechanism feeding the central MBH and leading the the AGN phenomenon.

This work was partially supported by the Polish Committee for Scientific Research as a research project 1 P03D 007 26 in the years 2004–2007.

References

1. E. Athanassoula: MNRAS 259, 345 (1992)
2. P. Englmaier, I. Shlosman: ApJ 528, 677 (2000)
3. J. Etherington, W. Maciejewski: MNRAS 367, 1003 (2006)
4. K. Fathi, T. Storchi-Bergmann, R.A. Riffel et al: ApJ 641, L25 (2006)
5. R.R. Islam, J.E. Taylor, J. Silk: MNRAS 340, 647 (2003)
6. W. Maciejewski: Gas Dynamics in Central Parts of Galaxies. In: Galactic & Stellar Dynamics, EAS Publication Series vol 10, ed by C.M. Boily et al (EDP Sciences, Les Ilis 2003) pp 3–16
7. W. Maciejewski: MNRAS 354, 883 (2004)
8. W. Maciejewski: MNRAS 354, 892 (2004)
9. W. Maciejewski, P.J. Teuben, L.S. Sparke, J.M. Stone: MNRAS 329, 502 (2002)
10. P. Martini, M.W. Regan, J.S. Mulchaey, R.W. Pogge: ApJS 146, 353 (2003)
11. P. Martini, M.W. Regan, J.S. Mulchaey, R.W. Pogge: ApJ 589, 774 (2003)
12. B.M. Peterson: An Introduction to Active Galactic Nuclei, (Cambridge Univ. Press, Cambridge 1997)
13. R.W. Pogge, P. Martini: ApJ 569, 624 (2002)
14. M.A. Prieto, W. Maciejewski, J. Reunanen: AJ 130, 1472 (2005)
15. M.W. Regan, J.S. Mulchaey: AJ 117, 2676 (1999)
16. S. Tremaine, K. Gebhardt, R. Bender et al: ApJ 574, 740 (2002)
17. M. Volonteri, F. Haardt, P. Madau: ApJ 582, 559 (2003)