Density waves in the central regions of galaxies

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Abstract. Density waves in the central kpc of galaxies, taking the form of spirals, bars and/or lopsided density distributions are potential actors of the redistribution of angular momentum. They thus play an important role in the overall evolution of the central structures, not mentioning the possible link with the active/non-active nucleus. I present here kinematical evidences for the presence of such structures using new sets of observations: two-dimensional (OASIS/CFHT) and long-slit (ISAAC/VLT) spectrography of nuclear bars and spirals. I also discuss the importance of $m = 1$ modes in the nuclear regions of galaxies, illustrating this with newly revealed cases and original N body simulations.

1. Introduction

Density waves are now recognised as important actors in the evolution of the internal structures of galaxies. This is often emphasized via their role in the redistribution of angular momentum. Since the contributions of Lindblad, Lin and Shu, astronomers have gradually associated observed spirals, bars and (more seldom) warps to (kinematic) density waves. Lopsidedness has however been mostly overlooked as a possible mode for density waves (but see e.g. Rudnik & Rix 1998, Swaters et al. 1999, Tremaine 2001). In this paper, we will present kinematical evidences for so-called $m = 1$ (spirals and bars) and azimuthal $m = 1$ modes in the central part of galaxies, thus occurring at scales from a few parsecs to a few hundreds of parsecs.

2. Nuclear spirals ...

A number of nuclear spiral-like dust and/or gas structures were recently observed in disc galaxies mostly using the high resolution imaging capabilities of HST (e.g. Regan & Mulchaey 1999; Martini & Pogge 1999; Laine et al. 1999; Chapman, Morris & Walker 2000). These are however usually low-contrast features for which, until now, only weak streaming motions were registered. Emphasizing the fact that gas spiral density waves can be present at all radii (contrarily to stellar density waves), Englmaier & Shlosman (2000) presented two-dimensional numerical simulations which, they argue, could account for these low arm-interarm contrast spirals in the central parts of galaxies. These would then represent the central extension of large-scale spirals through the Inner Lindblad Resonance.
In the course of a limited observational program aimed at studying the coupling between the stellar and gaseous components in early-type galaxies, Paul Goudfrooij and I have discovered a two-arm gas spiral within the central 250 pc of an elliptical, NGC 2974, using two-dimensional TIGER/CFHT spectroscopic data and subsequent WFPC2/HST images. The integral field datacubes allowed us to build the full stellar and gas velocity and dispersion maps (Emsellem & Goudfrooij, 2001, in preparation): the observed gas kinematics reveals very strong streaming motions and hints for shocks on the back side of the trailing spirals (Fig. 1). We have modeled the gravitational potential using the photometry and stellar kinematics as constraints, and then attempted to fit the observed gas velocities by using the formalism developed by Shu et al. 1973. Our best fit model requires the ILR to be within $\sim 70$ pc of the centre, which coincidently corresponds to the last radius until which we can follow the spiral. This nuclear spiral is not self-gravitating, but it is not of the same nature than the ones described in Englmaier & Shlosman (2000). Refined models and accurate infrared photometry should now be used to more accurately determine the characteristics of this density wave and the triggering source (tumbling potential).

3. Double bars ...

Didier Greusard, Daniel Friedli and I have also embarked in a program to retrieve the kinematics of nuclear bars in double barred systems, with the aim of asserting the physical reality of such structures, and of understanding their role in the redistribution of the dissipative component. We have observed a number of double bars using the integral field spectrograph OASIS at the CFHT. We derived the gas and stellar kinematics of a few nuclear bars, to be compared with original section N body + SPH simulations by Daniel Friedli. In the case of NGC 2859, we could fit the kinematical maps only by including a secondary decoupled nuclear bar in the model. We can now use these models to constrain the pattern speed of the two bars as well as the gas inflow rate.
Figure 2. The top right panel shows the NIR image of the central part of N1808, with the positions and lengths of the two slits, parallel and perpendicular to the nuclear bar (the labels 1 and 2 superimposed on the image indicate positive abscissa); From panel a to c: the luminosity profiles (in log) along the two slits, velocity and dispersion profiles. Panels d shows the folded luminosity and velocity profiles along the nuclear bar.
We have also conducted, via a larger collaboration (including Françoise Combes, Stéphane Leon, Emmanuel Pécontal and Hervé Wozniak), a similar study this time using near-infrared long-slit spectroscopy to trace the stellar kinematics in later type barred spirals, and examine the link between the bar and the nuclear activity (Emsellem et al. 2001). We have obtained the kinematical profiles for 3 active and 1 starburst galaxies along the major and minor axes of the secondary bar. These data reveals a clear kinematical decoupling at the outer edge of the inner bar, thus confirming that the nuclear bars revealed in the photometry are truly decoupled dynamical entities. But the most surprising result comes from the stellar velocity dispersion (Fig. 2): 3 out of the 4 galaxies exhibit a significant drop in the central $\sigma$ profiles (the Seyfert 1 nucleus of the fourth galaxy prevented us to derive any meaningful stellar kinematics within the central half arcsecond). We interpret this as evidence for the presence of a cold transient component, recently formed via accretion of gas. This scenario is supported by our study of the luminosity weighted mean stellar population (Greusard et al., in preparation), and new N body + SPH simulations including star formation (Wozniak et al., in preparation). In order to further comment on the link between this late accretion and the nuclear activity new ISAAC/VLT data on inactive and/or unbarred galaxies are required.

4. ... and $m = 1$ modes

Lopsided luminosity/mass distribution are often apparently superimposed on $m = 2$ modes (see e.g. Kamphuis et al. 1991). But as for $m = 2$ modes, these should be confirmed via some kinematical signatures. An example of such a detection is illustrated in panel d of Fig. 2 where the radial surface brightness and velocity profiles of NGC 1808 are shown: there is a clear difference between the two sides both in the photometry and in the kinematics. Another beautiful illustration of such asymmetries is present in the central part of the double barred galaxy NGC 3504: the apparent asymmetric luminosity distribution corresponds to a real offset as emphasized in the adaptive optics K band image obtained by Combes and collaborators. In the visible, this appears as a one arm spiral, clearly delineated in the gas distribution derived from OASIS/CFHT datacubes (Fig. 3). The higher density gas traced by the [OI] emission line exhibits a different distribution, with large streaming motions between the centre and the edge of the spiral. This could be the signature of infalling gas, although this should be confirmed by proper hydrodynamical simulations.

A final example at a much smaller scale (of a few pc) is provided by the nucleus of M 31. We direct the reader to our recent paper (Bacon et al. 2001) for details on this object. The main issue is the observed asymmetry in the photometry, which exhibits an extra luminosity peak called P1, offset from the apparent centre P2 of the outer isophotes. Tremaine (1995) endorsed the presumed presence of a supermassive black hole near P2, then suggesting that the dynamical cold P1 could be explained if eccentric keplerian orbits are gradually aligned via the dynamical friction onto the slowly rotating bulge stars. Dynamical friction was found to be negligible (Emsellem & Combes 1997, Bacon et al. 2001), but we managed to beautifully fit the lopsided surface brightness distribution by self-consistent N body simulations of a nuclear stellar disk suffering
Figure 3. OASIS/CFHT emission line distribution and velocity maps of NGC 3504, a double barred galaxy. The top left panel is a comparison WFPC2 image.
an \( m = 1 \) mode. This is a very slow mode with \( \Omega_p \sim 3 \text{ km.s}^{-1}\text{.pc}^{-1} \), a factor of about one hundred slower than the local circular velocity, and it can remain for hundreds of dynamical times. Such a mode seems to grow spontaneously, given that the disk is about 20-40% of the mass of the central black hole, or could be triggered by some perturbers (infalling gas cloud). This may thus be a recurrent process, and could well be a common phenomenon among galaxy nuclei.

5. Conclusion

In this paper, we have shown a few illustrations of \( m = 2 \) and \( m = 1 \) modes in the central part of galaxies, with some hints of their role in the redistribution of angular momentum, and more specifically in the triggering of gas infall towards the centre. The main points to be remembered from this paper are then:

- Density waves are present in the central part of galaxies, and do have an important role in the evolution of the central structures.
- Gas is a critical component for these modes to persist, as they tend to dynamically heat the system, with timescales obviously much shorter than for similar modes in the outer parts of galaxies.
- \( m = 1 \) may be common, at scales of a few hundreds of pc, and superimposed on central spirals and/or bars, but also at scales of a few pc where the potential is dominated by the central mass concentration.

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