Density waves in the inner parts of disk 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 may thus play an important role in the overall evolution of the central structures, not mentioning the possible link with the active/non-active central mass concentration. I present here some evidence for the presence of such structures, and discuss their importance in the context of dynamical evolution.

1. Introduction

Spirals, bars, warps and lopsidedness are ubiquitous at large scales in disk galaxies (e.g. Sancisi 1976; Kamphuis et al. 1991). These structures are usually understood as density waves propagating in the stellar and/or gaseous component. In this paper, I emphasize the case for density waves in the central kpc of disc galaxies, and illustrate their presence and role with a few examples.

1.1. Role of density waves

Density waves such as bars, spirals and lopsided density distributions have been recognised as potential actors in the secular evolution of galaxies, partly because they are non-axisymmetric perturbations of the potential. Gas flows within a bar (Athanassoula 1992) are very illustrative of how such structures can redistribute angular momentum: gas can be transported e.g. inwards (and angular momentum outwards) via driven trailing spirals, strong shocks can occur and rings may form (usually near specific resonances). All these correspond to observed signatures of bars. Density waves also tend to heat the stellar system, therefore acting against subsequent gravitational instabilities. Small versions of the large-scale waves observed in disk galaxies have been invoked as responsible for the fueling of the central 10s of parsecs, and hypothetically the central AGN and/or starburst (Schlosman, Frank & Begelman 1989; Regan & Mulchaey 1999). But are these inner bars/spirals modes similar to their large-scale parents?

1.2. Towards the centre

A dynamical probe which would travel towards the centre of a galaxy would see a number of changes occurring: spatial sizes are getting smaller and time-scales shorter (a useful number to keep in mind is: $10^6$ yr corresponds to $\sim 100$ pc at 100 km.s$^{-1}$), the spheroidal component starts to significantly contribute to the
potential, and eventually, at a scale of a few parsecs, the central cusp and/or supermassive black hole may dominate the potential. Within the central kpc, an inner cold component (e.g. a disk) may be less self-gravitating, and tend to evolve more rapidly. These changes obviously affect the growth and propagation of density waves in the inner parts of galaxies. As observers better focus on the central kpc of disk galaxies (with the help of an improved spatial resolution), structures such as inner spirals, bars and lopsided density distribution are revealed (Erwin et al. 2001; Regan & Mulchaey 1999), and are indeed usually weaker than their large-scale versions. Before these are confirmed as true density waves however, their kinematics should be studied in more detail. After a brief reminder on resonances, I will provide a few examples of such observations.

1.3. Epicycle approximation

Circular orbits can be used as zeroth order approximations for orbits in the equatorial plane of a thin disk. The first order terms can easily be evaluated by linearising the equations of motion in that plane: a retrograde epicycle motion is added on the circular orbit. This epicycle is the combination of radial and azimuthal harmonic oscillations sharing the same frequency \( \kappa \), which only depends on the first and second radial derivatives of the potential (see Dehnen 1999 for an alternative view on Lindblad’s epicycle theory). The shape of the (first order) orbits at a certain radius will then depend on the ratio \( \kappa/\Omega \) where \( \Omega \) is the circular frequency: when this ratio is an integer \( m \), the orbits are periodic (closing after \( m \) epicycles). With the addition of a density wave with a pattern speed \( \Omega_p \), the potential stays constant only in a frame rotating with the wave. In this rotating frame, the important quantity which decides on the shape of the orbit then becomes \( \kappa/(\Omega - \Omega_p) \). The resonances are thus located at radii where this ratio takes integer (\( m \)) values: \( \Omega_p = \Omega + \kappa/m \). This is where the disc potential (with its natural frequency \( \kappa \)) and the wave (of angular frequency \( \Omega_p \)) may interact. The most important are the Lindblad Resonances (LR; the Inner LR or ILR for \( m = 2 \), and the Outer LR, or OLR for \( m = -2 \)) and the Corotation Resonance (CR) where \( \Omega = \Omega_p \) (\( m \to \infty \)). At the resonances, the (linearised) orbits are closed in the frame rotating with the wave, thus defining the different families of orbits from which the skeleton of the system is built.

2. Inner disks and resonances

Seifert & Scorza (1996) found that a significant fraction (\( \sim 60\% \)) of S0 galaxies contain two embedded disks: an outer (main) disk with an inner cut-off, and an inner disk. This was confirmed by high resolution HST images which revealed very thin disks in the central kpc of early-type disk galaxies. In the case of the Sombrero galaxy (M 104), the double disk structure was claimed to originate from bar driven secular evolution, the inner disk being formed within the ILR of the bar (Emsellem 1995). For early-type disk galaxies, such a scenario seems to be supported by several studies (Scorza & van den Bosch 1998; Baggett, Baggett & Anderson 1998). If the disk hierarchy reflects the existence of resonances, these are also often emphasized by gas and stellar rings (at the OLR and Ultra Harmonic Resonance in the case of M 104). Rings are indeed very common signatures of bars (see Combes 2001, Buta & Combes 2000).
A remarkable example, the nearly edge-on galaxy NGC 4570, was reported by van den Bosch & Emsellem (1998). This galaxy seems to possess two rings which correspond to the ILR and Ultra Harmonic Resonance associated with a tumbling potential. The thin inner disc, with a radius of about 100 pc, is located inside the ILR. The stellar $U - V$ colour distribution also seems to reflect the location of the presumed resonances: a rather flat colour gradient along the major axis outside the CR, a mild gradient between the CR and the ILR, and a strong one inside the ILR (Fig. 1). This closely follows the predictions of the simulations performed by Friedli, Benz & Kennicutt (1994) who studied the effect of a bar on the abundance profiles (model d of their Fig. 1). In this scenario, the inner disk is the result of gas accretion by the large-scale bar.

![Figure 1. $U - V$ major (solid line) and minor (dotted line) axis profiles of NGC 4570 (WFPC2). The expected locations of the resonances linked with a bar are indicated (van den Bosch & Emsellem 1998).](image)

3. **Inner bars**

In some cases, the inner disk can decouple from the outer part, and a secondary bar can form (Shlosman, Frank, & Begelman 1989). Double barred galaxies are now well studied (photometrically), and preliminary statistics indicate that at least 25% of barred galaxies host an inner bar (Erwin et al. 2001). We know that primary bars are efficient at concentrating the gas in the central region (Sakamoto et al. 1999). Secondary bars could then take the batton and fuel the central 100 pc, although no strong dynamical evidence has been presented yet. In this context, we recently obtained the stellar kinematics of 4 active galaxies (central starburst and/or Seyfert), 3 of which are double barred. In these 3 galaxies, the stellar velocity dispersion profiles exhibit a significant but unusual drop at the centre: evidence for the presence of a cold component (Emsellem...
et al. 2001). We interpreted this as recent gas accretion triggered by the inner bar, and subsequent formation of an inner stellar disk (Greusard et al. 2002, Wozniak et al. 2002). The sample critically needs to be extended to understand if there is indeed a link between the central activity and the inner bar.

Studies on samples of disk galaxies tend to give slightly different answers (Ho, Filippenko & Sargent 1999; Knapen et al. 2000), although the recent study by Knapen et al. indicate a higher fraction of bars in Seyferts (79 ± 7.5%) than in non active galaxies (59 ± 9%). It seems that even if there is a tendency for Seyferts to be more barred than non active galaxies, it is a weak trend. As emphasized by Combes (2001), this is not at all surprising, since there are very different timescales involved: gas accumulation driven by the bar, secondary bar formation, star formation, AGN duty cycle, dynamical evolution including the possible destruction of the bar due to central mass accumulation...

Figure 2. Top panel: unsharp masking of a WFPC2/F555W (V band) image of NGC 3115. Bottom panel: same image but deprojected using an inclination of 86° (Emsellem et al. 1999). An hypothetic sketch for a two-arm spiral is superimposed on the deprojected image. High frequency structures could not be derived in the grey areas due to the presence of the bright inner disk.

4. Inner spirals

A recent addition to the usual suspects is the loss of angular momentum by inner trailing spirals. Such structures are often observed in spiral galaxies where
resolution permits (Regan & Mulchaey 1999). These are low amplitudes modes however, which does not favour an significant central fueling rate, and these may just be driven by a mildly triaxial tumbling potential. Inner spirals however require a cuspy mass distribution in order to be trailing and drive gas inwards to the nucleus. One strong inner gas spiral has been observed in the early-type galaxy NGC 2974 (Emsellem & Goudfrooij 2002). Strong streaming motions were measured using integral field spectroscopy, and the overall gas kinematics can be qualitatively reproduced by a simple two-arm spiral model. The spiral ends outside its ILR, which implies that these do not correspond to the bar driven acoustic waves described by Englmaier & Shlosman (1999). The inner gaseous spiral in NGC 2974 is a rather unique case, although a larger observing campaign using the same techniques is on-going.

In the S0 galaxy NGC 3115, we have detected a low contrast stellar spiral which seems to be directly connected to the inner thin disk (Fig. 2). Taking into account the presence of a supermassive black hole of $\sim 6.5 \times 10^8\, M_\odot$ at the centre of NGC 3115 (Emsellem et al. 1999), it is probable that any strong bar has been significantly weakened, but the spiral could still be driven by a weak residual triaxiality in the potential. If the present morphology of NGC 3115 is indeed the result of bar driven evolution, we might be able to find clear signatures by conducting a coupled study of the stellar populations and dynamics.

5. $m = 1$ modes

Lopsided distribution have long been ignored, but are now more often studied theoretically, and looked for in galactic central regions (see Combes 2001 and references therein). The short dynamical timescales in the central kpc of galaxies seem to favour the hypothesis of strongly lopsided distribution to be true $m = 1$ modes. These modes can often be superimposed on $m = 2$ bar modes. One illustration of this is the double-barred galaxy NGC 3504. The K band adaptive optics image (courtesy of F. Combes) shows a very strongly asymmetric light distribution. At visible wavelengths, a one arm spiral is revealed by the HST/WFPC2 F606W image. We have observed this galaxy using the integral field spectrograph OASIS at CFHT, and determined the two-dimensional stellar and gas distribution and kinematics. The spiral arm is strongly emphasized in the emission line maps, except in the higher density [OII] line, the distribution of which seems to bridge the inner end of the spiral to the nucleus (Fig. 3). In fact, detailed examination of the central OASIS spectra reveals the presence of a blueshifted wing in all emission lines including the forbidden ones. We interpret this as evidence for nuclear inflow, possibly driven by the $m = 1$ mode.

5.1. Keplerian modes

In a keplerian potential, $\Omega = \kappa$, which implies that the precession rate of the $m = 1$ orbits is zero at all radii. A set of such orbits could then keep their alignment with time. In a marginally self-gravitating disk, gravity could act to compensate for the non zero precession rate. This seems to be the case for the double nucleus of M 31, in which the offcentred peak could be explained by the orbit crowding (see Bacon et al. 2001, and references therein). This sets a limit on the relative mass of the nuclear disk, which should be between 20
Figure 3. The central 800 pc of NGC 3504. Top left panel: HST/WFPC2 F606W image. Top right panel: PUEO/CFHT $K$ band image (FWHM $\sim 0''15$). All other panels: OASIS/CFHT maps of H$\alpha$ (middle left), [NII] $\lambda 6583$ (middle right), [OI] $\lambda 6300$ (bottom left) and mean velocity (bottom left). The steps and first contours for the OASIS maps are (12,12), (5,8) and (0.17,0.8) for the H$\alpha$, [NII] and [OI] maps respectively (units of $10^{-15}$ erg/s/cm$^2$/arcsec$^2$). The isovelocity step is 20 km/s with the systemic velocity being taken at the centre.
Figure 4. Zooming from the large-scale bar of M 31 to the central spiral-like dust lanes, and the 10 pc double nucleus.

and 40% of the central dark mass. The nuclear disk of M 31 could have been formed relatively long ago by gas accretion triggered by a tumbling potential. In fact, several pieces of evidence support this hypothesis: M 31 is very probably a barred galaxy (Berman 2001), and the inner dust structures are consistent with being trailing spiral arms nearly reaching the nucleus (Fig. 4). There is finally a hint of a recent but limited episode of star formation at the very centre of the nucleus (Fig. 5). The \( m = 1 \) mode could then be the result of either a natural instability, or a relatively recent gas cloud infall.

6. Conclusions

The short timescales associated to the physical processes occurring in the central regions of galaxies do not help our understanding of their morphology and dynamics. We should then view them as continuously evolving systems involving several recurrent interlinked and non simultaneous processes. Density waves are certainly playing an important role in this game. If inner bars and spirals are already on the priority list of observers and theoreticians, then \( m = 1 \) modes must now be seriously considered as potential players on the evolutionary stage of galactic centres.
Figure 5.  HST/STIS spectra of M 31 (not corrected for extinction).
Left: UV peak contribution. Right: nucleus and bulge spectra.

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