6. Gas Dynamics in the Galactic Center

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NON-AXISYMMETRIC DYNAMICS IN GALAXY CENTERS

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Abstract. Our Galaxy is representative of the majority of spiral galaxies, which are highly non-axisymmetric, developping bars ($m = 2$ perturbations), but also lopsidedness and off-centering ($m = 1$), and superposed higher order perturbations. Recent high-resolution N-body and gas-dynamical simulations have considerably improved our knowledge on the nature and formation of these features. Contrary to previous beliefs, they are not long-lived, but fade away and can be reformed continuously, provided enough gas is supplied to the center, to maintain gravitational instability. The dynamical mechanisms involved are reviewed and discussed, and in particular the new features brought by the dissipative gas component. The role of these axisymmetries in the galaxy evolution, mass concentration, together with nucleus fueling are described, and typical time-scales discussed in particular for confrontation to the Milky Way observations.

1. Introduction

A galaxy system tends to concentrate mass towards its center, to minimize its energy. But it must get rid of its angular momentum, since galaxy disks are supported by rotation. Viscous torques in the gas are far from efficient at large radii, since the viscous time-scale is of the order of the Hubble time, or larger. Gravity torques generated by non-axisymmetric perturbations are therefore the privileged tool for a galaxy to evolve and concentrate mass (e.g. Combes 1988). The most frequent non-axisymmetric perturbations are $m = 2$ bars and spirals, but there can be also $m = 1$ instabilities in the galaxy nuclei, especially if the potential is so concentrated that it is almost keplerian.

Violent non-circular motions, almost omnipresent in galaxy centers, are the observational tracers of non-axysymmetric perturbations. It is now well established that these peculiar motions can be explained by rather normal

Y. Sofue (ed.), The Central Regions of the Galaxy and Galaxies, 257-264.

dynamical features and not exceptional explosions or outflows. This does not exclude actual gas outflows, but only a small fraction of the mass is involved in outflows, when they exist (starburst, AGN).

It is now well understood that a single dynamical structure can act only over a limited range of radii, between the two most characteristic Lindblad resonances; to have a continuous action over a larger radial range, and drive the gas towards the very nucleus, multiple-scale perturbations are necessary, such as nested bars embedded like russian dolls (e.g. Shlosman et al 1989). Observations and simulations have clarified the various processes, and we can now identify:

- **Bars** at macroscopic scales, of typically ≈ 5 kpc in radius
- **Mini-bars** or nuclear bars, of typically ≈ 0.5 kpc in radius. These are inscribed inside the primary bars' nuclear ring
- **Micro-bars** (or micro-spirals) of ≈ 2 pc size. This step is still speculative, since we see it only in our own Galaxy and in M31, due to spatial resolution constraints

2. Micro-structures

2.1. OUR OWN GALAXY CENTER

Due to its proximity (1pc = 24"), our own Galaxy center has been studied in exceptional details. HI and CO surveys (Burton & Liszt 1978, Dame et al 1987) have revealed high non-circular motions, and in particular a 200pc ring (called the EMR, or expanding molecular ring), that is most easily interpreted as the inner Lindblad resonance ring (ILR) of the main bar of the Milky Way (e.g. Binney 1994). The CO $l - v$ diagram shows a characteristic parallelogram, that is delimited by gas in x_1 orbits parallel to the bar, while the gas tracing the diagonal of the parallelogram could be tracing the perpendicular orbits x_2. Alternatively, this gas could be tracing a secondary bar, embedded in the main one.

At smaller scale, a conspicuous structure is detected in the gaseous component towards the Galactic center: between 1.5 and 7 pc radii, the disk is essentially molecular, in rotation with a constant orbital speed of 110 km/s. The disk is inclined at 65°, therefore apparently decoupled from the external edge-on disk. There is an obvious ring, of radius 2 pc, seen in dense gas (HCN, see fig 1). Inside this ring, the gas is partially ionised. The ionized component shows the well-known 3-arm spiral structure, imaged with the VLA by Lo & Claussen (1983). At least the two main arms are in almost circular motion in the same disk, as shown in figure 1 (cf Lacy 1994). The fact that the micro-spiral is inscribed in the 2 pc ring is typical

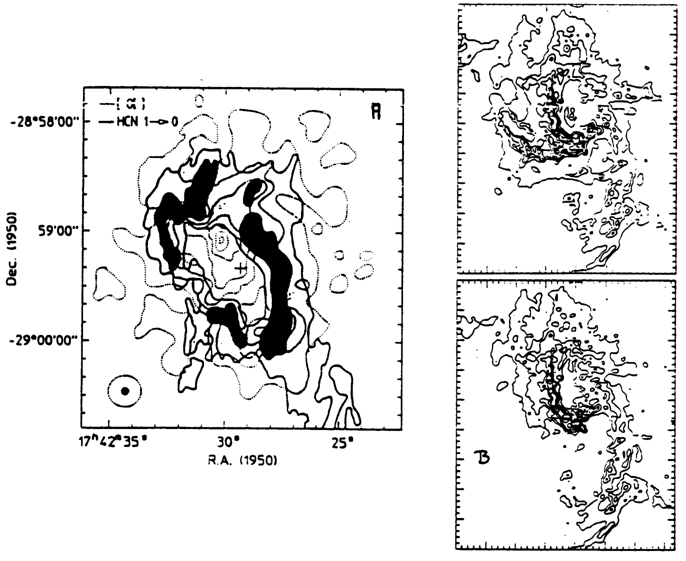

Figure 1. A) superposition of [OI] and HCN(1-0) contours, from Lacy (1994). The ring is 2 pc in radius. B) *top* the [Ne II] emission from the galactic center, and *bottom* same but including only gas within 50km/s of circular velocity (Lacy 1994); the micro-spiral is embedded in the ring

of a nested structure inside an inner resonance, and suggests a dynamical interpretation.

2.2. M31 CENTER AND OTHERS

There is also in M31 evidence for a primary bar (4 kpc radius, Stark & Binney 1994). Due to its proximity, and to the high spatial resolution of the Space Telescope, a micro-structure has also been detected within 10 pc of the center. There is a 10 pc nuclear disk, decoupled from the external disk (with a slightly different inclination), with evidence of a non-axisymmetric perturbation (m = 2 or m = 1). In projection, the optical image reveals two bright peaks (Lauer et al 1993), but the velocity field is rather regular, and the peak of velocity dispersion does not coincide with the bright ones (Bacon et al 1994). The amplitude of the velocity dispersion suggests the existence of a central massive black hole (Kormendy & Richstone 1995). The second bright peak could be due to an m = 1 spiral (Tremaine 1995), or to the merging with a small system (Emsellem & Combes 1997). In more remote galaxies, mini-structures have also been detected (cf M100, Knappen et al 1995), and in NGC 1068, it is possible that a micro-structure (bar/spiral) at the third level of the hierarchy has

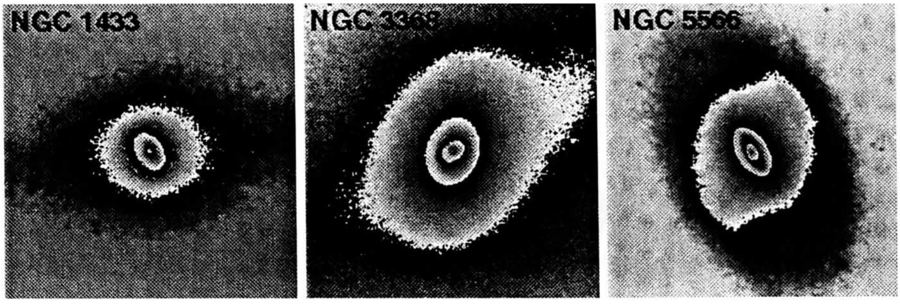

Figure 2. Examples of bars within bars, detected in NIR by Jungwiert et al (1997).

been observed with adaptive optics (Rouan et al, this meeting). Millimeter interferometers with sub-arcsec resolution are also pointing towards these structures (Tacconi et al, and Scoville et al, this meeting).

3. M=2 perturbations

3.1. BARS WITHIN BARS

For almost two decades now, nuclear bars have been observed in barred galaxies, i.e. smaller bar structures embedded in bigger primary bars (de Vaucouleurs 1974; Sandage & Brucato 1979; Jarvis et al. 1988). But it has been only recently that the interpretation of this phenomenon has been realized for the dynamical evolution of galaxies. Conspicuous nuclear bars have been discovered for the first time through near-infrared (NIR) imaging in NGC 5728 and NGC 1097 by Shaw et al. (1993), and since then many NIR surveys have been completed to precise the frequency of the phenomenon and the statistically averaged physical properties of nuclear bars (sizes, excentricities, angular orientations, e.g. Wozniak et al. 1995, Shaw et al. 1995, Friedli et al. 1996). One of the main characteristics of those nuclear bars is that they are inscribed inside the nuclear ring of the primary bar, and that they can have any orientation with respect to the primary bar. About 25% of the barred galaxies appear to possess a nuclear bar (Jungwiert et al. 1997, cf fig. 2).

Since bars can drive gas inwards and fuel the nuclei, many groups have tried to pinpoint a correlation betwen nuclear activity and the presence of a bar. But the results have been controversial. For recent examples, McLeod & Rieke (1995) conclude from their statistical sample that Seyfert galaxies are not more barred than normal galaxies, while Peletier et al (1997) find that 96% of Seyfert are barred, while only 74% are in the control sample.

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May be part of the controversy comes from the identification of the active bar: the nuclear bar (or micro-bar?) is more important for the AGN fueling than the primary bar.

3.2. DYNAMICAL SCENARIO

Numerical simulations have described the dynamical processus leading to the formation of nuclear bars (Friedli & Martinet 1993, Combes 1994). The first bar concentrates the mass towards the center by its gravity torques exerted essentially on the gas component (see e.g. Buta & Combes 1996). Once the mass concentration is high enough, the rotation curve is modified in the center, and the precessing rate of the $m = 2$ elliptical orbits, $\Omega - \kappa/2$, has a neat peak towards the center (while it was rather flat before). This strong differential precessing rate prevents the self-gravity from adapting all precessing rates from small to large radii, and decoupling occurs. These decoupled nuclear disks are frequently observed either with HST (Barth et al 1995), or millimeter interferometers (e.g. Ishizuki et al 1990). They are also detected kinematically, through rotation curves (Rubin et al 1996, Sofue 1996). In the decoupled disks, two bars rotating at two different speeds develop. In the simulations, the two bars have a resonance in common, most often the inner Lindblad resonance of the primary bar is the corotation of the secondary one. It is then likely that the two bars exchange energy and angular momentum at this common resonance, through non linear coupling (e.g. Tagger et al. 1987).

This second pattern takes over the torques of the primary one, and drives the gas further towards the center, through a mechanism already suggested by Shlosman et al. (1989). But many more steps seem to be required to reach the nucleus at 100 AU scales, the scales that are directly relevant to fuelling of the central active nucleus that might be present. Since gravity is scale- independent, there is no reason not to predict a recursive phenomenon, and the existence of a hierarchy of structures with increasing pattern speeds. A micro-bar could then be embedded in the nuclear bar, sharing a common resonance with it.

4. M=1 instabilities

4.1. OBSERVATIONAL EVIDENCE

Eccentric asymmetries in the distribution of light in spiral galaxies have been known for a long time (Baldwin et al. 1980, Richter & Sancisi 1994). In several cases these features can be identified as one-armed spirals ($m = 1$ mode). More frequently, nuclei of galaxies are observed displaced with respect to the gravity center (Blitz, this meeting). In our own galaxy center,

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3/4 of the molecular gas is found on one side (positive longitude).

4.2. POSSIBLE MECHANISMS

The difficulty to understand these $m = 1$ features comes from the fast differential precession rate $\Omega - \kappa$, especially in the center; the exception is for a purely Keplerian potential of course, where $\Omega = \kappa$. But for the development of an $m = 1$ mode, self-gravity must be important, and the potential is then far from keplerian.

The presence of retrograde stars can favor $m = 1$ instabilities (Zang & Hohl 1978; Palmer & Papaloizou 1990). The case of counter-rotating disks has been studied recently by Sellwood & Merritt (1994), Davies & Hunter (1997) and Comins et al (1997). Miller & Smith (1992) have studied through N-body simulations of disk galaxies, a peculiar oscillatory motion of the nucleus with respect to the rest of the axisymmetric galaxy. They interpret the phenomenon as an $m = 1$ instability, a density wave in orbital motion around the center of mass of the galaxy. Weinberg (1994) shows that a stellar system can sustain weakly damped $m = 1$ mode for hundreds of crossing times. A fly-by encounter could excite such a mode, and explain off-centring in most spiral galaxies. Tremaine (1995) has proposed a model to account for the $m = 1$ structure in the center of M31: the instability could come from disk/bulge dynamical friction. The bulge does not rotate, or very slowly, therefore friction removes angular momentum much faster than energy, and the stellar orbits become more excentric, which amplifies an $m = 1$ mode. The latter will rotate with a positive Ω_p through self-gravity. However, the self-consistency of the mechanism is not demonstrated.

When gas is present in abundance in galaxy centers, with a high central mass concentration, another mechanism can be invoked, similar to that occuring in gaseous disks associated with young stellar objects (Adams et al 1989, Ostriker et al 1992). In these eccentric $m = 1$ modes, the star does not lie at the center of mass of the system. Shu et al (1990) presented an analytical description of a modal mechanism, the SLING amplification. This mechanism uses the corotation amplifier, and feedback through reflexion and refraction. The whole amplification mechanism depends on the reflecting character of the disk outer edge. By self-consistent simulations, including gas and stars, we have found such an $m = 1$ perturbation in galaxy centers (Junqueira & Combes 1996). The center of mass of the gas and of the stars is displaced from the center of mass of the system and they are displaced in opposite positions, inducing the $m = 1$ wave formation. The measured pattern speed is very high, typically $\Omega_p \approx 400$ km/s/kpc, corresponding to the OLR at 3kpc (figure 3). The $m = 1$ wave is conspicuous in the very center, up to its OLR.

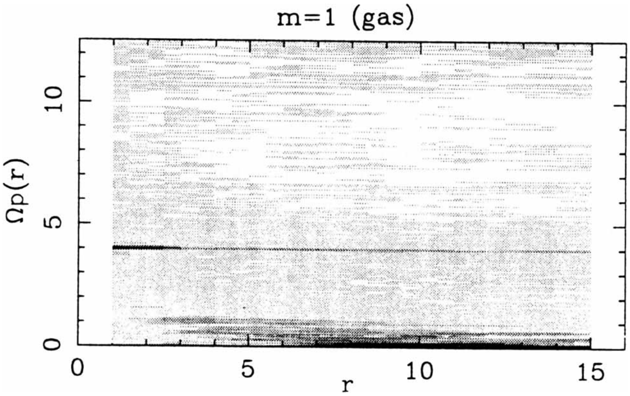

Figure 3. Gray-scale maps of the pattern speed $\Omega_p(r)$ (in units of 100 km/s/kpc) of the $m = 1$ spiral wave determined from the power spectrum of the total potential and surface density of the gas as a function of radius (in kpc).

5. Other mechanisms of nuclear fueling

When the central disk is gas dominated, it is Jeans unstable, and fragments in multiple clumps; the graininess of the induced potential diffuse stars, destroy any bar, and drives the gas towards the center (Heller & Shlosman 1994). Also, when giant clumps or GMC are present, dynamical friction against the bulge drives them towards the center in a dynamical time-scale of 10^7 yr.

If we believe that a massive black hole exists in most galaxies, than through galaxy merging, a binary black hole can form. This will generate $m = 1$ and $m = 2$ perturbations, that can fuel the gas to the nuclei (Taniguchi & Wada 1996). This process could also be the cause of shallow profiles in elliptical galaxies formed by merging (Makino 1997).

6. Conclusions

It is now well established that non-axisymmetric structures are the way galaxies evolve, through radial gas transfer towards their center. Scale-independent gravity is the source of multiple-scale structures, where a hierarchy of spiral/bars are embedded within each other. While bars within bars have been known for a long time, we are beginning to see the third level of the hierarchy in some galaxies, with the help of high spatial resolution, revealing nested micro-structures.

The $m = 1$ instabilities appear omni-present in galaxy centers, but the dynamical mechanisms are much less well-known.

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