SECULAR EVOLUTION IN THE CENTRAL REGIONS OF GALAXIES

Eric Emsellem

Abstract
In this paper, I mention a few processes which may play a role in the evolution of the central regions of galaxies. In this context, I briefly discuss some issues regarding the formation of bulges in spirals, the role of supermassive black holes, and the importance of nuclear density waves.

1 Introduction
This paper is not meant as a thorough survey of our present knowledge of the evolution processes involved in the central regions of galaxies, but more as a short commentary on some of the interesting issues which were recently discussed in the literature. What are the actual physical processes that do act on the central structures and dynamics of galaxies? I will focus here on the search for the traces that these processes leave and which can be studied in nearby "normal" galaxies. I will thus start with a short discussion on bulge properties and formation scenarios, and then shortly report on the present situation regarding central cusps and the role of supermassive black holes. I will then briefly mention the importance of nuclear density waves, spirals, bars and $m = 1$ modes, in the evolution of the central structures.

2 Spiral Galaxies
When studying the central regions of spiral galaxies, it is usually difficult to disentangle the relative contributions of the bulge and disk. The bulge component is generally assumed to dominate the central light profiles, often parametrized as a Sersic law $\mu(r) \propto r^{1/n}$ (Andredakis, Peletier & Balcells 1995; Fig. [1]): there is

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1 Centre de Recherche Astronomique de Lyon, 9 av. Charles André, 69561 Saint-Genis Laval, France

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a tendency for $n$ to increase from about 1 (exponential law) for late type spirals to values around 4-6 (closer to a de Vaucouleurs profile) for early-type spirals. Recent studies (e.g. Peletier et al. 1999, Carollo et al. 2001), benefiting from the high spatial resolution of HST, show that early-type bulges tend to be older, with a small spread in age, similarly to ellipticals. Suggestions followed that exponential bulges in late-type galaxies, having scaling properties (e.g. $\mu_e/R_e$) typical of disks, may still be forming in the local universe through secular evolution of disks and bars (Carollo 1999). Bulges growth via secular processes is often cited as a way for spiral galaxies to evolve towards earlier Hubble type (see Pfenniger, these Proceedings). It was then argued that exponential bulges may not be able to evolve into $r^{1/4}$-like bulges as they host central clusters massive enough to prevent recurrent cycles of bar formation/disruption (Carollo 1999). However, the central regions could be dynamically cooled by later accretion of significant amount of gas. Aguerri et al. (2001, see Fig. 1) proposed that part of the steepening of the surface brightness profiles could be due to the accretion of dense satellites. This merging process heats the disk efficiently, which suggests that it did not play a significant role in the making of exponential bulges in late-type galaxies.

![Fig. 1](image)

**Fig. 1.** Growth vectors in the $[n - \log(\text{bulge to disk ratio} = B/D)]$ plane due to the accretion of a small satellite galaxy. Each arrow starts at the location of the original model and ends at the $n$ and $B/D$ derived from a fit to the surface density profile after the merger. Point with error bars are actual observations reported in Andredakis et al. (1995). See Aguerri et al. for more details (their Figure 6).

3 **Cores of ellipticals and the role of the central mass concentration**

Central surface brightness profiles of ellipticals, expressed as $I \propto r^{-\gamma}$, seem to basically separate into two classes (Faber et al. 1997): $\gamma < 0.3$ for luminous
ellipticals, which have a clear change of slope in the inner regions, and are referred
to as core galaxies; and $\gamma > 0.5$ for low luminosity ellipticals, which have power-law
cusps with no clear breaks and are referred to as power-law galaxies. The transition
between the two classes occurs around $M_B \sim -20.5$. Other properties, such as
the internal dynamics (degree of isotropy) or the isophote shape (disky/boxy),
seem to correlate with the central value of $\gamma$. Although the dichotomy between
so-called core and power-law ellipticals is clear, there are hints for the existence
of an intermediate population of galaxies which do not clearly belong to one of
the two classes, and are intermediate in terms of absolute magnitude (Rest et al.
2001). This tells us that our interpretation of the $[\text{density profile} - M_B]$ plane for
ellipticals may need to be refined via a more adequate parametrization. In any
case, mechanisms leading to these stellar density profiles are not yet agreed upon:
dissipative versus non-dissipative processes (Faber et al. 1997), adiabatic growth
on a central black hole (van der Marel 1999), diffusion due to binary black holes
(Merritt & Quinlan 1998)...

The “binary black holes” scenario has recently attracted more proponents, as
new numerical studies of the merging of two galaxies, each containing a central su-
permassive black hole, appeared in the literature (see e.g. Milosavljevic & Merritt
2001). Although these simulations are still a long way from representing actual
galaxy merging, they show that a flattening of the central cusp slope can occur
with the hardening of the binary and ejection of stars. Hope to observationally
trace this process comes from the potential (but weak) dynamical signature left
within the central structure of the galaxy (e.g. attenuation of the circumnuclear
rotation, Fig. 2). However, more work is required to implement some critical
issues into the game (gas, loss cone repopulation, mass spectrum, ...), hence to
understand the true role of multiple black holes on the evolution of galactic nuclei.

Single central supermassive black holes, presumed to be present in most galax-
ies, may also have their role in (re)shaping the central dynamics, hence morphology,
of the central regions. Chaotic diffusion may thus lead to a secular evolution of
the orbital structure (Merritt 1999), tending to axisymmetrise the galaxy from the
centre, outwards. Also, simulations performed by Holley-Bockelmann & Richstone
(2000) showed that the presence of a central massive black hole may be critical to
preserve the observed core fundamental relation for ellipticals (see above) during
a non-equal mass merger.

4 Density waves

Density waves, which include $m = 2$ modes such as spirals and bars, and $m =
1$ modes such as warps and lopsidedness, gained some audience as observations
showed they may be ubiquitous in the central regions of (disk) galaxies.
Fig. 2. 2D kinematics of the merging cusped galaxies for one of the models of Milosavljevic & Merritt (2001). View is in the plane of the merger from a direction perpendicular to the line connecting the two black holes. Left panels: mean velocity. Right panels: velocity dispersion. See Milosavljevic & Merritt (2001) for more details (their Figure 6).

4.1 $m = 2$

Bars have since long been recognised as potential actors for the redistribution of angular momentum. But real proofs that this was indeed happening in galaxies have been evasive. Recently Sakamoto et al. (1999) have shown that molecular gas is more concentrated in galaxies which are barred. The debate regarding the role of nuclear bars (secondary bar component within the large-scale primary bars) is still open (Greusard et al. 2000; Erwin et al. 2001; Emsellem et al. 2001; Laine et al. 2001). Another class of actors, nuclear spirals, came up recently on the scene (Zaritsky et al. 1993; Regan & Mulchaey 1999). At the moment of writing of this paper, it is too early to decide whether these observed nuclear spirals have any direct or indirect significance on the overall shaping of the central structures, but it is an important avenue to consider.

4.2 $m = 1$

Large-scale $m = 1$ (lopsidedness) have long been ignored as possible evolution drivers. But recent observational and theoretical studies showed that lopsidedness
Fig. 3. N-body simulation of an $m = 1$ wave adapted to the case of M 31’s nucleus. View is face-on, scale is in parsec. See Bacon et al. (2001) for more details.

may be a common mode in galaxies (Richter & Sancisi 1994; Combes 2001 and references therein). These $m = 1$ modes certainly do act on the redistribution of the dissipative component, but, again, it is too early to conclude.

4.2.1 Keplerian $m = 1$

At a very different scale, nuclear $m = 1$ modes, which requires the gravitational potential to be close to keplerian, recently emerged in the context of galactic nuclei (Fig. 3), mainly triggered by the puzzling observations reported on the nucleus of M 31 (see Bacon et al. 2001 and references therein). Although there is still some uncertainty regarding the formation of such high amplitude waves (e.g. natural instability, external perturbation), it seems that they are viable modes, and may thus be of importance within the few central parsecs where massive black holes are presumed to dominate the potential. It is unfortunate that, at this scale, the stellar component is presently observable in only a handful of galaxies, but this situation can only improve.

5 Conclusion

There is no doubt that evolution occurs in the central regions of galaxies, and this includes a wealth of complex processes, a (very) few of which I have mentioned in this paper. It is clear that density waves, in the form of nuclear bars, spirals, or $m = 1$, as well as massive black holes, do play a role in shaping the central structures of galaxies. What also seems clear is that gas is a critical component in most of the occurring mechanisms.
But at the moment, it is difficult, if not impossible, to have a clear understanding of their relative contribution to the secular evolution of central parts of galaxies. Timescales are short in the central kiloparsec, and some of these processes may be recurrent (e.g. bar/spiral formation/destruction). A step towards a more general understanding of these issues may need the implementation of a toy model, containing prescriptions for each of the thought-to-be important processes: see Combes (2001) for an attempt along these lines. Such toy models, when fed into a typical galaxy merger tree, may unravel some of the questions mentioned in this paper (although caution is always the rule for such models).

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