Formation and Evolution of Galaxy Bulges
Proceedings IAU Symposium No. 245, 2007
M. Bureau, E. Athanassoula & B. Barbuy, eds.

doi:10.1017/S1743921308017158

Fast and slow rotators: the build-up of the red sequence

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Abstract. Using the unique dataset obtained within the course of the `SAURON` project, a radically new view of the structure, dynamics and stellar populations of early-type galaxies has emerged. We show that galaxies come in two broad flavours (slow and fast rotators), depending on whether or not they exhibit clear large-scale rotation, as indicated via a robust measure of the specific angular momentum of baryons. This property is also linked with other physical characteristics of early-type galaxies, such as: the presence of dynamically decoupled cores, orbital structure and anisotropy, stellar populations and dark matter content. I here report on the observed link between this baryonic angular momentum and a mass sequence, and how this uniquely relates to the building of the red sequence via dissipative/dissipationless mergers and secular evolution.

Keywords. galaxies: elliptical and lenticular, cD; galaxies: evolution; galaxies: stellar dynamics

1. Red, blue galaxies, wet, dry mergers

The standard scenario for the formation of galaxy structures includes hierarchical clustering of cold dark matter halos within which gas is cooling (Peebles 1969; Doroshkevich 1970; White 1984). The angular momentum of dark matter halos is thought to originate in cosmological torques and major mergers (e.g., Vivitska *et al.* 2002). If major mergers produce a significant increase in the specific angular momentum of the dark matter halos at large radii, minor mergers seem to just preserve or only slightly increase it with time (D'Onghia *et al.* 2002, and D'Onghia *et al.*, these proceedings). But little is known on the expected distribution of the *baryonic* angular momentum (van den Bosch *et al.* 2002; de Jong *et al.* 2004), and even less if we focus on the central regions (within a few R_e).

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The recent advent of large surveys such as the Sloan Digital Sky Survey allowed to firmly establish a statistically significant bimodality in the colour distribution of local galaxies, then separated in a so-called 'blue cloud', generally consisting of star-forming spiral galaxies, and a 'red sequence', mostly of non-star-forming early-type galaxies (e.g. Baldry *et al.* 2006). Accurately quantifying this bimodality (Bell *et al.* 2004), allowed a dramatic improvement in the detailed testing of galaxy formation scenarios. The bimodality can only be explained with the existence of a feedback mechanism, which suppresses episodes of intense star formation by evacuating the gas from the system. Many simulation groups have quantitatively reproduced the bimodality, though with rather different assumptions for the star formation and feedback processes (Springel *et al.* 2005; Cattaneo *et al.* 2006; Bower *et al.* 2006). A generic feature of these models is that red-sequence galaxies form by dissipational 'wet mergers' of gas-rich blue-cloud galaxies, followed by quenching of the resulting intense star-formation caused by the feedback from a central supermassive black hole and supernovae winds. The merging of the most massive blue galaxies, however, is not sufficient to explain the population of red-sequence galaxies, and dissipationless 'dry mergers' of gas-poor, red-sequence galaxies are also required, evolving galaxies along the red-sequence as they increase in mass.

Wet and dry mergers both produce red, bulge-dominated galaxies, but the kinematical structure of the remnants are expected to be very different. In a merger between blue gas-rich galaxies, the gas tends to form a disk, so that the end result of the merger, after the gas has been removed from the system (ejection, conversion to stars), will be a red stellar system dominated by rotation (e.g. Bournaud *et al.* 2005). In mergers between red gas-poor galaxies, dissipationless processes dominate, resulting in a red galaxy with little or no net rotation (e.g. Naab & Burkert 2003; Cox *et al.* 2006). The existence of the red/blue galaxies dichotomy therefore implies the existence of a kinematical differentiation within the red sequence between fast and slow rotating galaxies. Various observational indicators of this differentiation have been proposed in the past: (i) anisotropy (from the V/σ diagram, e.g. Davies *et al.* 1983), (ii) isophote shape (e.g. Kormendy & Bender 1996), (iii) inner photometric slope (e.g. Lauer *et al.* 1995). However, none of these signatures have been able to give clear evidence for a distinction between the two classes of red-sequence galaxies, primarily because they are secondary indicators of the galaxies' internal dynamical structure.

2. A new kinematic classification scheme

By the application of integral-field spectroscopy to a representative sample of nearby early-type galaxies, the SAURON survey (Bacon *et al.* 2001; de Zeeuw *et al.* 2002) has revealed the full richness of the kinematics of these objects (Emsellem *et al.* 2004). This unique dataset also allowed to robustly distinguishing two distinct morphologies of stellar rotation fields, corresponding to the predicted fast and slow rotators (Emsellem *et al.* 2007). We have thus defined a global quantitative parameter, termed $\lambda_R \equiv \langle R\,|V|\rangle / \langle R\sqrt{V^2+\sigma^2}\rangle$ linked to the baryonic angular momentum, which shows that previous classification schemes are not adequate (Paper IX; Cappellari *et al.* 2007, Paper X).

Fast and slow rotators are defined as having λ_R values above or below 0.1, respectively. Using the 48 E and S0 galaxies from the SAURON sample, we can see a clear difference between these two types of rotators: fast ones have rising λ_R profiles, while slow rotators have either rather flat or decreasing profiles (Fig. 1, left panel). The apparent dichotomy may be partly due to the small number of available objects. However, there are further indications that these two types of galaxies refer to different families. All fast rotators

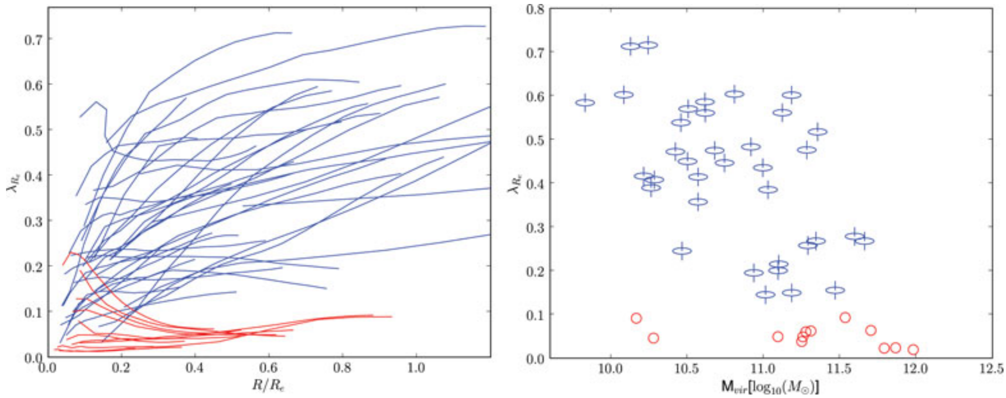

Figure 1. Left panel: λ_R profiles for our 48 E and S0 galaxies. Right panel: λ_R at 1 R_e versus the total mass of the galaxy. In both panels, slow and fast rotators are in red and blue, respectively.

(except one galaxy with well-known irregular shells) show well aligned photometric and kinemetric axes, and small velocity twists. This contrasts with most slow rotators which exhibit significant misalignments and velocity twists. These results are supported by a supplement of 18 additional early-type galaxies observed with SAURON.

In Paper X, we built state-of-the-art dynamical models of a subsample of 24 galaxies consistent with axisymmetry, and found a trend with more intrinsically flattened galaxies being more anisotropic. The most massive galaxies are found *not* to be more anisotropic than the least massive ones. The results from these models are consistent with the distribution of all 48 galaxies of the SAURON sample on the $(V/\sigma,\epsilon)$ diagram. This was constructed for the first time from integral-field kinematics, using the revised and more robust formalism by Binney (2005). We showed that fast and slow rotators have different distributions. Slow rotators are then more common among massive systems, and are generally classified as E's from photometry alone. Fast rotators are generally fainter and are classified either E or S0. These results strongly suggest that slow and fast rotators are really two different families of galaxies. Fast rotators are consistent with being nearly oblate, and contain disk-like components, while slow rotators are weakly triaxial.

3. The next steps

Slow rotators, being on average more massive objects (Fig. 1, right panel), may result from mergers within the red sequence. The Kinematically Decoupled Components systematically observed in slow rotators (except the ones which have λ_R consistent with zero) may well be the remnants of such a violent past history. However, current collisionless merger models seem unable to explain the detailed observed properties of slow rotators (so far). It seems that a realistic merger tree may be a critical component to obtain galaxies with such low baryonic angular momentum in their central regions. The prediction is then that the angular momentum has been redistributed among both the baryonic and dark matter components, but at larger radii, so that we expect λ_R profiles to shoot up outwards, even for slow rotators.

Fast rotators are more commonly obtained as the output of numerical simulations of gas-rich mergers. Gas is a critical ingredient in the formation and evolution of fast rotators, as illustrated by the presence of 100 pc-sized decoupled (often counter-rotating) systems (McDermid *et al.* 2006). In this context, the E and S0 classification does not seem to be relevant, as fast rotators form a continuous sequence of disky objects, extending the bulge to disk ratios observed for spirals downwards.

λ_R provides a robust classification of red-sequence galaxies that relates directly to their formation history, and can be reproduced in cosmological simulations. However, the galaxies in the original SAURON survey were selected to sample, with a relatively small number of objects, a wide range of masses and shapes of early-type galaxies. Specifically, galaxies were selected to be uniform in magnitude and ellipticity, but objects on the sky are not uniformly distributed in these quantities. This selection imposed complex biases and makes it impossible to derive a statistically meaningful distribution of galaxy properties, for comparison with simulations. The latter requires observing a statistically significant, volume-limited sample of galaxies complete to some useful lower limit in mass. We therefore designed a new ambitious two-dimensional spectroscopic survey, the ATLAS^{3D}, of a magnitude limited sample of nearby early-type galaxies, resulting in a complete sample of about 260 galaxies. This should allow us to understand the distribution of Fast and Slow Rotators, to then infer the relative fraction of wet/dry mergers, and further provide strong low-z constraint on cosmologically motivated simulations.

Acknowledgements

I would like to thank the symposium organizers and IAU for financial support.

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