A SAURON STUDY OF STARS AND GAS IN SA BULGES

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Abstract We present results from our ongoing effort to understand the morphological and kinematical properties of early-type galaxies using the integral-field spectrograph SAURON. We discuss the relation between the stellar and gas morphology and kinematics in our sub-sample of 24 representative Sa spiral bulges. We focus on the frequency of kinematically decoupled components and on the presence of star formation in circumnuclear rings.

1. Sa bulges in the SAURON Survey

The starting point of our study is the SAURON survey of nearby, early-type galaxies (de Zeeuw et al. 2002). The full sample consists of 72 galaxies divided in three morphological groups: 24 ellipticals, 24 lenticulars, and 24 Sa bulges. Within each group, half of the galaxies are drawn from the field environment, and the remaining half are representative of the cluster population.

The main science driver for the survey is the study of the intrinsic shapes, velocity and metallicity distribution, and the relation between the stellar and gas kinematics to the underlying stellar populations. Most of the results of the survey up to now have focused on the 48 elliptical and lenticular galaxies (de Zeeuw et al. 2002, Emsellem et al. 2004, Cappellari et al. 2005, Sarzi et al. 2005). Here, we concentrate on the 24 Sa spiral bulges.

A key question we want to address is whether secular evolution plays an important role in the formation of bulges (i.e. disk instabilities, Pfenniger & Norman 1990, Pfenniger & Friedli 1991), or whether they are scaled-down versions of ellipticals, as the main scaling relations suggest (e.g., Fundamental Plane, Jorgensen et al. 1996, Falcon-Barroso et al. 2002). A comprehensive description of the stellar and gas kinematics of the complete sample of 24 Sa spiral bulges is presented in Falcon-Barroso et al. (2005). We highlight some of the results here. Fathi et al. (2005) present an in depth study of an individual case (NGC 5448). Ganda et al. (2005) discuss similar SAURON observations of 18 later-type spiral galaxies.

2. Kinematically Decoupled Components

The stellar kinematic maps of our galaxies display a variety of substructures in the central regions, such as kinematically decoupled components. For example, Figure 1 (top panel) shows the stellar kinematics of NGC 5689. In that galaxy the component is clearly visible in the velocity map as a pinching of the isovelocities in the inner regions, which is also accompanied by a decrease of the velocity dispersion and an anti-correlated h_3 parameter at the same locations. In general this type of decoupled components appear to be aligned with the major axis of the galaxy and tend to be associated with dust disks or rings seen in unsharped masked images. However, there are a few cases in our sample where the rotation axis of the decoupled component is misaligned with respect to the main rotation axis of the galaxy (e.g., NGC 4698, see Figure 1 bottom panel). In this case the decoupled component can be identified as a twist of the zero velocity curve in the inner regions. We find that 13 out of 24 galaxies (52%) display clear signatures of such structures. Despite the high number of kinematically decoupled components observed, the true fraction can be even higher as their detection can be hampered by inclination (i.e., as it is more difficult to detect them at low galaxy inclinations), but also by a limited spatial sampling.

The nature of these kinematically decoupled components is still uncertain, and there are different formation and evolution processes that can produce such a component in the inner regions of the galaxies. One of the most widely supported scenarios is that these objects formed by gas inflow towards the central regions of the galaxy which consequently induced star formation (Wozniak et al. 2003). The role of bars and dissipative processes, however, is not yet well understood in this context (Bureau & Athanassoula 2005, Heller & Shlosman 1994, Friedli & Benz 1995), as all these models are able to reproduce the observed velocities, inwards decrease of velocity dispersion and the h_3 anti-correlation. Under this scenario the kinematically decoupled component is formed from existing material in the galaxy.

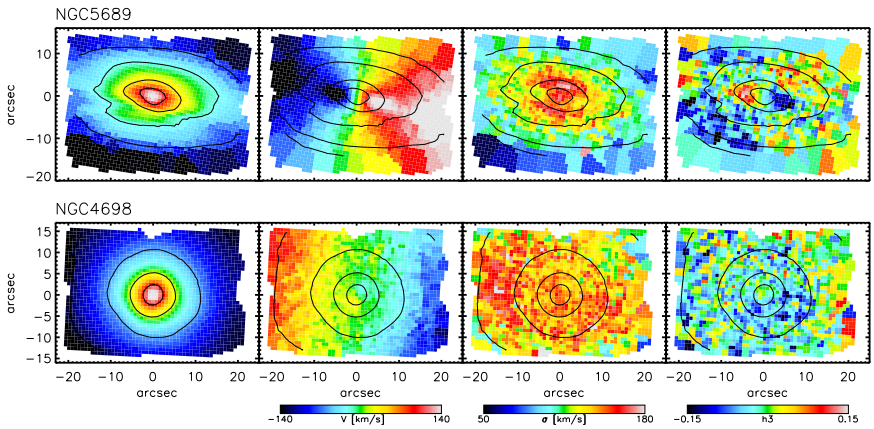

Figure 1. Stellar kinematic maps for NGC 5689 and NGC 4698. In each column (from left to right) we show the reconstructed intensity image from the SAURON datacube (in mag/arcsec^2), the stellar radial velocity, velocity dispersion (in km s^{-1}) and h_3 Gauss-Hermite moment.

An alternative possibility for the formation of these components is an interaction event. This model is preferred to explain the presence of misaligned components such as the one seeing in NGC 4698. This galaxy is a well-studied case in which the formation of the component is thought to be the result of an intermediate merger event (Bertola et al. 1999). In Figure 2, we present the case of NGC 5953, which offers a unique opportunity to study the effects that an on-going interaction has on the stellar and gas properties. The kinematical decoupling in the inner parts, together with the presence of large amounts of fresh gas, suggests that we might be witnessing the early stages in the formation of a kinematically decoupled component.

3. Global and circumnuclear star formation

Several methods have been used in the past to trace star formation (SF) in galaxies. Given the little observational overhead, the emission of Balmer lines has become one of the most popular tracers (Kennicutt 1998). In addition to the Balmer lines, the [O III]/Hβ ratio can also serve as a diagnostic in situations where SF is intense and derives from pre-enriched material (Kauffmann et al. 2003). Here we use both diagnostics to investigate the importance of star formation in Sa galaxies.

The morphology of the star-forming regions in our sample appears to have multiple forms, although as expected in spiral galaxies, the bulk of SF is concentrated in the main disk. Within galaxies, we find that SF activity is more

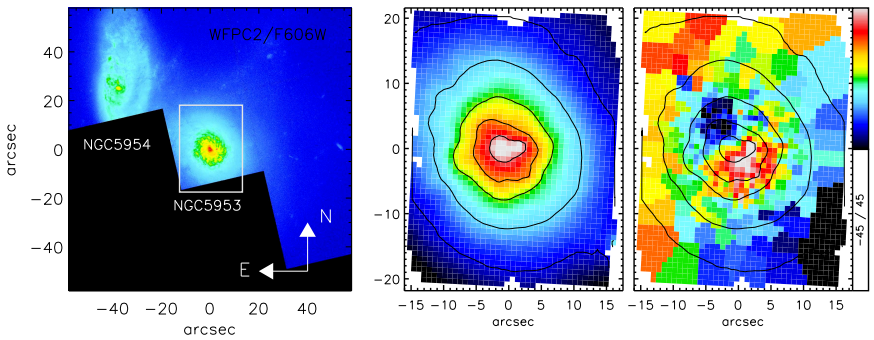

Figure 2. Interacting pair NGC 5953/NGC 5954. From left to right: i) HST/WFPC2 image of the pair of galaxies. Overlaid on NGC 5953 is the SAURON field-of-view. ii) SAURON reconstructed intensity image of NGC 5953, iii) stellar radial velocity of NGC 5953.

intense along dust lanes, has an amorphous morphology, or is confined in circumnuclear rings.

These rings represent one of the most spectacular forms of SF. The frequency of these circumnuclear regions in our sample is in good agreement with the most recent studies from Hα observations of larger samples (21$\pm$5%, Knapen 2005). In Figure 3, we present the cases of NGC 4245, NGC 4274, and NGC 4314 to illustrate the most common properties of the stars and gas in these SF regions. There is a remarkable correlation between the dust and the regions where SF is very intense (i.e., large Hβ flux). At the same time, the [O III]/Hβ ratio is very low at the same locations, confirming the presence of star formation. The velocity dispersion of the ionised gas is also low ($\sim$50 km s^{-1}) along the star-forming rings. We are thus seeing stars being formed from dynamically cold gas. A similar behaviour is also found in other galaxies in the sample with extreme SF activity.

As discussed in Section 2, star formation can produce the observed stellar velocity dispersion drops (also called 'sigma-drops'). In our sample we find that the presence of young stars does not necessarily relate directly to the stellar velocity dispersion (σ_*). In the examples shown in Figure 3, only NGC 4274 displays a sigma-drop at the location of the young stars. NGC 4245 shows a small decrease in σ_* only on the brightest Hβ knots along the ring. In NGC 4314, one of the galaxies with highest apparent SF activity, the presence of young stars hardly affects σ_*. In practice, these features strongly depend not only on the number of young stars present, but also on the inclination of the galaxy, as in face-on configurations (e.g., NGC 4314) the contribution of the young stars to the line-of-sight radial velocity is much smaller than that of the surrounding bulge.

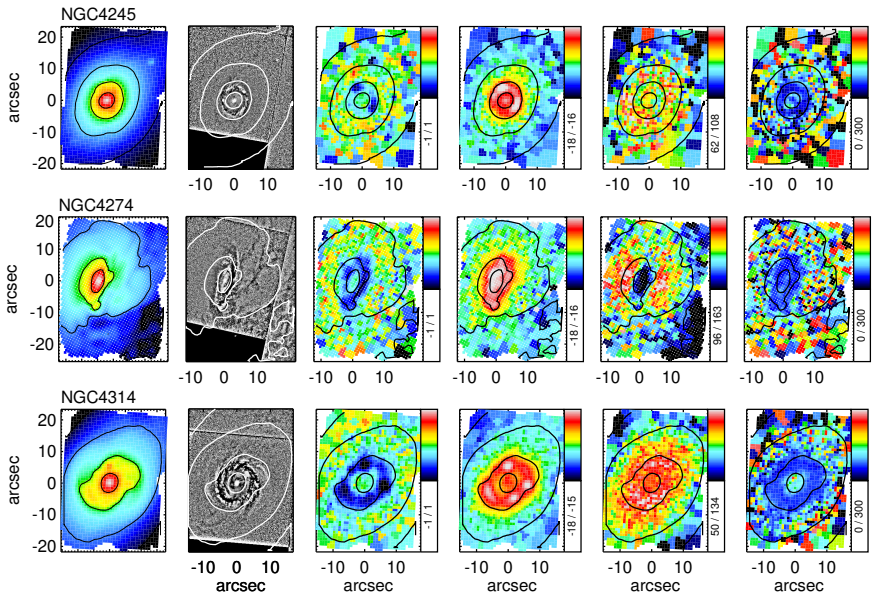

Figure 3. Stellar and gas maps for three star-forming ring galaxies NGC 4245, NGC 4274, NGC 4314. In each column (from left to right) we show i) the reconstructed intensity image from the SAURON datacube, ii) an HST unsharp-masked image, the iii) [O III]/Hβ ratio (logarithmic scale), Hβ flux (in units of ergs/cm^2/s, and logarithmic scale), iv) stellar velocity dispersion (in km s^{-1}), and v) ionised-gas velocity dispersion (in km s^{-1}).

The formation of star-forming rings is generally associated with bar-driven gas inflow towards the inner regions of galaxies (i.e., gas material gets trapped in rings as it approaches an important resonance). SF in the ring then begins once the gas density in the ring exceeds the limit set by the Toomre (1969) criterion. In our sample only three of the six galaxies with star-forming rings are known to be barred (NGC 4245, NGC 4274, NGC 4314). For the remaining three galaxies with rings (NGC 2844, NGC 5953, NGC 7742), the interacting scenario offers an alternative explanation (see Figure 2). Although the case of NGC 7742 is still unclear, as the presence of an oval (i.e., weak bar) could also explain the observed star-forming ring (see Figure 13 in de Zeeuw et al. 2002).

4. Conclusions

We are carrying out a comprehensive study of the kinematical properties of a sample of 24 Sa bulges drawn from the SAURON survey of representative galaxies. We find that kinematically decoupled components are present in half of our sample of galaxies (13/24). They are easily detected in the stellar veloc-

ity maps, but often also leave an imprint in the stellar velocity dispersion and h_3 parameters. Despite the growing evidence that they are the result of star formation induced by bar-driven gas inflow towards the inner parts of galaxies, interactions as well as non-dissipative bar evolution models can also reproduce the observed kinematics.

Star formation in our sample displays different morphologies. The most striking cases appear in the form of circumnuclear rings. We find a good correlation between star formation and the velocity dispersion of the ionised gas in these rings, indicating that we are seeing young stars being formed from dynamically cold gas. The young stars in these rings often produce a decrease of the stellar velocity dispersion, although the presence of these sigma-drops strongly depends on the number of young stars, but more importantly on the inclination of the galaxy. While the presence and properties of circumnuclear rings can be easily explained in the context of bars, interactions can also reproduce the observed morphological and kinematic properties.

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