Kinematics of inner bars. The stellar σ-hollows

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Abstract We present SAURON stellar kinematical analysis for four double-barred early-type galaxies: NGC 2859, NGC 3941, NGC 4725 and NGC 5850. The presence of the inner bar is not evident from the radial velocity, but it appears to have an important effect in the stellar velocity dispersion maps: we find two σ-hollows of amplitudes between 10 and 40 km s^{-1} at either sides of the center, at the ends of the inner bars. We have performed numerical simulations to explain these features. Ruling out other possibilities, we finally conclude that, although the σ-hollows might be originated by a younger stellar population component with low velocity dispersion, more likey they are an effect of the contrast between two kinematically different components: the bulge with its high velocity dispersion and the inner bar, characterized by its low velocity dispersion (ordered motion).

1 Introduction: double-barred galaxies

Double-barred galaxies are rather common systems in the Universe, as they represent ∼1/3 of the barred galaxies [6]. Photometrical studies reveal that there is no preferred angle between the two bars, suggesting that they rotate independently. These systems are specially important because they are thought to be the key mechanisms to transport gas to the central regions of the galaxies, where it may trigger

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an intense star formation. This phenomenon cannot be done by a single bar, since the material flow would stop at ∼100 pc from the galactic center. With two bars the transport is theoretically possible and the gas may even feed the central active galactic nuclei [12, 13]. These hypotheses also support the secular evolution theory but they have not been checked since a complete analysis of the kinematics and the stellar populations is required.

Kinematical information about double-barred galaxies has been obtained from numerical simulations. However, most existing observations have relied on long-slit spectroscopy along only a few position angles (e.g. [3]), which makes the comparison with the models somewhat difficult. Better suited integral-field spectroscopy has generally not been used to observe these systems, with the notable exceptions of [9] and [10].

2 Working with SAURON data

Four double-barred galaxies were selected from the catalog [5], choosing early-type objects to avoid the presence of complex structures. The observations were carried out with the integral-field spectrograph SAURON, attached to the William Herschel Telescope at the Observatorio del Roque de los Muchachos, in La Palma, Spain. We selected the LR mode, that provides a field of view of 33”×41” with a spatial sampling of 0.94”×0.94” per lens. This field of view is big enough to map the whole inner bar, besides including the transition regions between the two bars. SAURON produces a total of 1431 spectra covering the range between 4800 and 5300 Å with a sampling of 1.1 Å pixel^{-1}. The spectral resolution is 3.74 Å (FWHM).

Spectra were reduced as explained in [4]. Moreover, we spatially binned the data cubes to get spectra with a minimum signal to noise of 60 per spectral resolution element. For this purpose we used the Voronoi 2D binning algorithm [1], that takes into account the morphology of the galaxy in order to avoid mixing spectra from different structural components. However, most spectra in the central regions have already high signal to noise (∼300), so remain unbinned.

The stellar kinematics is extracted by fitting the absorption spectrum with a linear combination of the stellar population synthesis models [14], using the penalized pixel fitting method [2]. This procedure is described in [7].

Fig.1 shows the stellar kinematic maps indicating the orientation of the inner and the main bars. Velocity maps do not show any special feature along the inner bars, resembling those maps for non-barred galaxies. However, we found two local minima in the velocity dispersion maps, exactly at the edges of the inner bars. These signatures is what we have called the σ-hollows and they have amplitudes between 10 and 40 km s^{-1}.

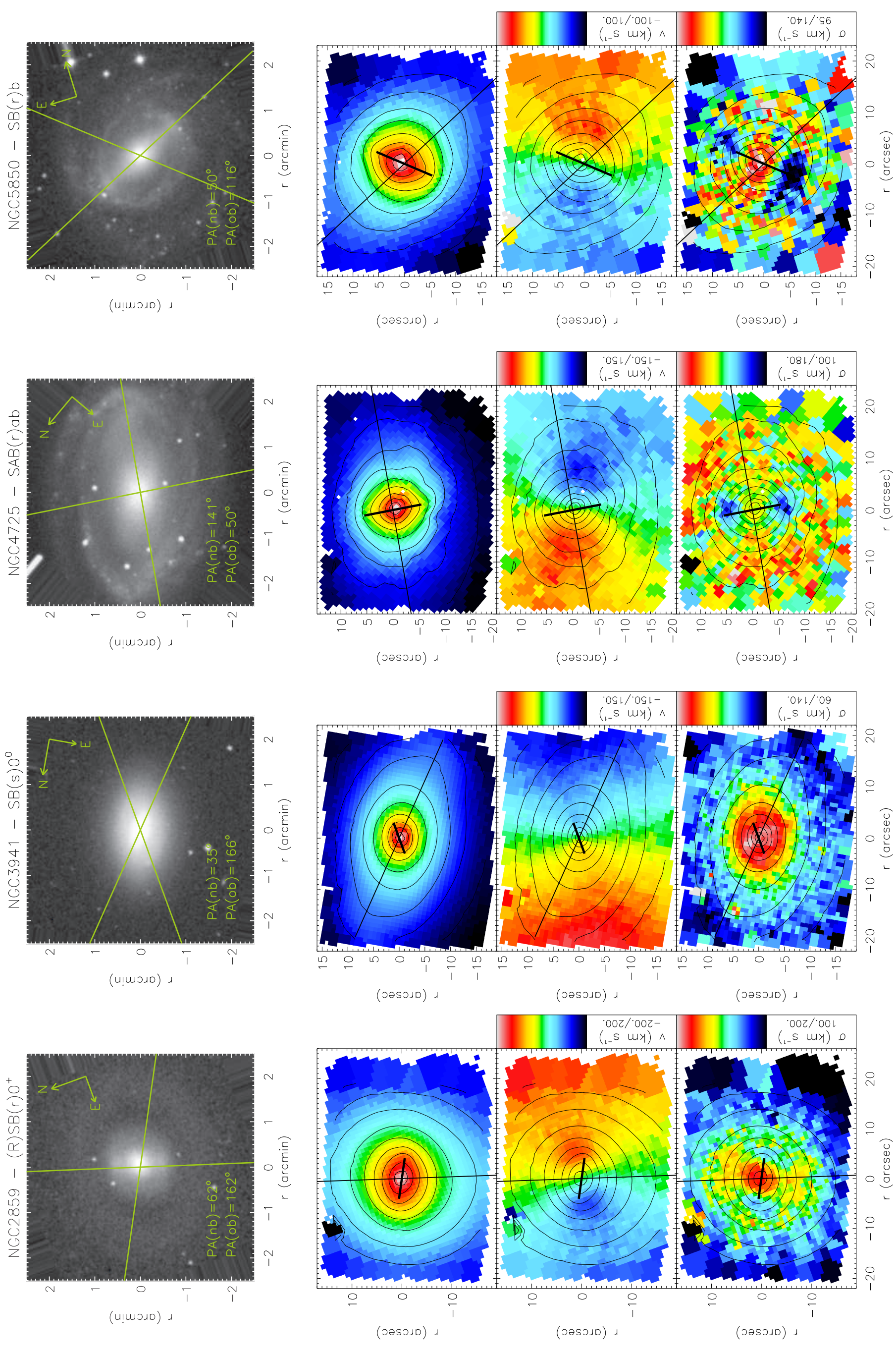

Fig. 1 Maps of the stellar distribution and kinematics of the 4 double-barred galaxies in our sample. An optical image from the Sloan Digital Sky Survey together with our intensity maps and the stellar velocity and stellar velocity dispersion maps for each galaxy. We have overplotted the position angle of the nuclear bar (thick line), the outer bar (thin line) and the countours of the reconstructed total intensity from our own datacubes.

3 Are the σ-hollows due to...

A significant decrease of the stellar velocity dispersion value at a given location in a galaxy implies that the orbits followed by the stars at that point along the line-of-sight are very close. There are examples of such behaviour in galaxies displaying σ-drops [3]. In that case the drops are caused by the presence of an inner disk, which is a flat, dynamically cold structure where stars move in an ordered fashion, and therefore will display lower velocity dispersion values than their surroundings. One important property of these disks is that they are well aligned with the major kinematic axis of the galaxy. The origin of these disks is unclear, but there are solid arguments in the literature relating the presence of these structures to young stars formed from cold gas in the inner regions [15, 16]. Observations seem to support these claims, although it is worth noting that not all the inner disks show evidence for young stellar populations [11].

Galaxies with one bar often display signatures of these inner disks in their central regions. At larger scales, elsewhere along the bar, the stellar velocity dispersion is generally high and slowly decreases to match the main disk values at its extremes. In the case of the double-barred galaxies presented here the situation seems rather different. First, the σ-hollows found in our data happen at the extremes of the inner bar and have values significantly below its surroundings instead of a smooth transition. Second, the position angles of the inner bars are different to those of the main disks. While the first point may suggest that the origin of the σ-hollows is related to that of the σ-drops, the second argument appears to discard that option.

With the aid of numerical simulations we have tried to find out the origin of these σ-hollows. Hereafter we present the possible explanations and their feasibility.

3.1 ... a low velocity dispersion component?

A different component with very low velocity dispersion, such as a nuclear disk, cold gas, gaseous inner bar or recently formed stars, could explain the observed σ-hollows. To test this hypothesis we carried out numerical simulations of double-barred systems. For this purpose we used the code FTM 4.4 (updated version) from [8], introducing a gaseous disk in an already self-consistent simulation of a purely stellar barred galaxy. The gaseous particles responded to the main bar acquiring an ordered motion following an oval distribution, typically aligned perpendicular to the main bar. When computing the LOSVD for the stellar and gaseous particles combined, we managed to lower the LOSVD at the nuclear region mimicking the observed σ-hollows. However, the effect we see in our observations is purely stellar, as it shows up only in the stellar velocity dispersion. Hence a gaseous disk does not seem to be the answer. In addition, the gas intensity maps (not showed here) are also rather homogeneous in the nuclear regions, not showing evidence for a nuclear disk oriented perpendicular to the main bar.

As an additional test, we have performed a preliminary stellar population analysis of the different structural components to unravel the presence of young stars. We find a soft age gradient outwards such that the inner bar is older than the bulge and younger than the outer parts. This result is not expected and also indicates that there is not a particularly young stellar population at the ends of the inner bar, where the hollows are located.

These tests suggest that the origing of the σ-hollows must be related to the inner bar itself, and not to any other structural or kinematical component.

3.2 ... contrast in velocity dispersions?

We now focus on the inmediate surrounding of the inner bar. In the central parts of these galaxies we have a combination of a component with typically high velocity dispersion values (i.e. a bulge) and the order motion in the inner bar, and thus lower σ. We believe the key aspect in the interpretation of the σ-hollows is the contrast between the velocity dispersions of those two components. Under this hypothesis, we can only see this effect in the outer parts of the inner bar, where the bulge is not dominating the total flux (assuming that the velocity dispersion profile of the bulge decreases smoothly outwards). Moreover, at the ends of the bar the orbits are closer and more ordered, which helps to emphasize the contrast. The amplitude of the hollows is then dependent on the relative importance of the inner bar over the bulge at those locations. In the cases of a very extended bulge, the inner bar would be completely embedded in it, so we would expect very clear σ-hollows. On the contrary, if the bulge is small compared to the inner bar, its velocity dispersion at the end of the bar may not be high enough to produce the required contrast.

To check this idea we performed simulations with just a disk, a bar and a bulge, mimicking the main components in the region of interest. We have assumed that the main bar plays a minor role in those regions. For the case of a bulge big enough to match the length of the inner bar, we could reproduce the observed σ-hollows (see Fig.2).

4 Conclusions

We have found σ-hollows in our small sample of four double-barred galaxies, appearing exactly at the ends of the inner bar but with different amplitudes. The main result presented here is that these hollows are signatures of the inner bar, and not due to other structural or kinematical components (e.g. inner disks), so they can be used to identify inner bars from a kinematical point of view. Moreover, they indicate that inner bars are cold structures.

On the origin of these σ-hollows, the presence of young stellar populations cannot be completely discarded as an agent to create these hollows. However, we do not find on our data clear evidences supporting it. Instead, we have been able to repro-

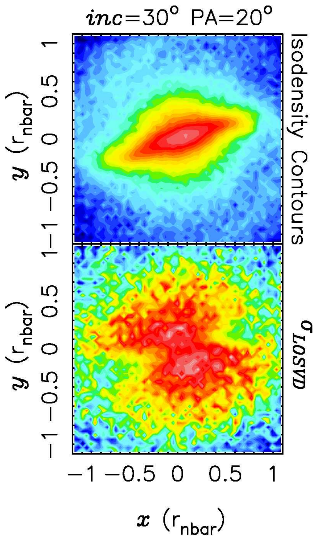

Fig. 2 Isodensity contours (top) and velocity dispersion (lower) maps from a numerical simulation including a bulge, one bar and a disk. This bulge matches de size of the bar. The σ-hollows are clearly seen at the edges of the bar.

duce the σ-hollows in simulations including just a bulge, a bar and a disk, where the contrast between the high velocity dispersion of the bulge and the very low velocity dispersion of the bar (even lower at its ends) produces the observed hollows. In this case, the amplitudes of the hollows are then dependent on the relative importance in mass and sizes of the bulge and the inner bar. Current numerical simulations in the literature do not usually include a bulge component, explaining why this is a non predicted feature.

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