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3D spectroscopy of candidate double-barred lenticular galaxies

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Abstract. A significant fraction of barred galaxies hosts secondary bar-like structures on optical and NIR images. The circumnuclear dynamics of double-barred objects are still not well understood, while observational data concerning kinematics are incomplete and inconsistent. In order to compare the simulations results with observations, we have started a new spectroscopic study of the stellar kinematics in lenticular galaxies from Peter Erwin's catalog of secondary bars. We present first results concerning their stellar kinematics based on the observations performed with the integral-field spectrograph MPFS at the Russian 6-m telescope.

Key words. galaxies: elliptical and lenticular, cD – galaxies: kinematics and dynamics – galaxies: structure

1. Introduction

Traditionally, an inner bar-like structure appearing inside a large-scale bar on direct images of barred galaxies is called a 'secondary bar'. Interest in these objects significantly picked up after the idea by Shlosman et al. (1989) that nested-bar systems might fuel nuclear activity by driving gas into the nuclear regions of a galaxy. Erwin has presented on this workshop an excellent review of secondary bar properties (see also Moiseev 2002; Erwin 2004; Moiseev et al. 2004, hereafter MVC04). The main result of studies of their photometric properties is that 'a secondary bar seems as a small copy of a large-scale counterpart'. However secondary bar origins, kinematics and dynamics are not so clear. Here we briefly outline some main problems and discrepant conclusions about double-barred (hereafter DB) galaxies. The new observational results concerning S0-galaxies will also be considered.

2. What is frequency of such structures in galaxies?

In the 1990s several small samples, each with about a dozen DB candidates were published. Based on the literature, Moiseev (2001) listed 71 galaxies where possible secondary bars were suspected from isophotal analysis. In reality a number of objects in this list are not truly DB systems, because various structural features produce similar distortions of the inner isophotes in barred galaxies (circumnuclear disks and spirals, triaxial or oblate bulges, etc.). From these reasons Erwin (2004) presented a catalog of 50 DB galaxies, based

Send offprint requests to: Alexei V. Moiseev on detailed examination of previously known as well as new candidates. Numerous earlier candidates were rejected, first of all because they have inner disks instead secondary bars. This re-examination has changed significantly some previous estimates of the DB fractions. So, Laine et al. (2002) in their larger statistical study of the secondary bar frequency have found 19 DB systems out of 112 galaxies (69 barred). However the cross-identification with the Erwin's catalogue shows that only six candidates are confirmed as DB[1]. Therefore the fraction of secondary bars in barred galaxies denoted by Laine et al. (2002) as 28 ± 3% should be significantly decreased to 9 ± 2%. A large percentage 26 ± 7% was suggested by Erwin & Sparke (2002) in the sample of S0-Sa bright barred galaxies and all candidates were confirmed in Erwin (2004). Their sample is twice smaller than in Laine et al. (2002) and contains only early-type galaxies. It is possible that fraction of DB is larger in early types; in any case kinematic arguments should also be involved into the verification of all DB candidates.

3. 3D spectroscopy of double-barred galaxies: the history

Since the motions of stars and gas inside the bar region are strongly non-circular, and such objects are non-axisymmetric by definition, the 2D maps of kinematical parameters should be helpful in the study of DB kinematics. Therefore the 3D (panoramic) spectroscopy in the optical domain or high-resolution radio maps are needed. Unfortunately these data are rare and incomplete. For instance, several attempts of studying molecular gas kinematics in secondary bars were described, but mainly without clear results. Petitpas & Wilson (2002) did not detect any specific kinematic features in the inner region of NGC 2273, whereas Erwin & Sparke (2002) and MVC04 showed this galaxy harbors an inner disk nested in the large-scale bar. NGC 5728 (Petitpas & Wilson 2002) and NGC 4303 (Schinnerer et al. 2002) also show no non-circular motions, maybe because the size of their inner bars are comparable with width of the telescope beam. The secondary bar in NGC 2782 (Hunt et al. 2008) does not perturb the observed gas velocity field, as required by numerical simulations of its morphology. The similar situation is also presented in the case of NGC 4579 (García-Burillo et al. 2009) and for the ionized gas kinematics in NGC 3359 (Rozas 2008). However clear examples of kinematically decoupled secondary bars are found for the molecular gas. Namely, only the central regions of Maffei 2 (Meier et al. 2008) and Our Galaxy (Rodríguez-Fernández & Combes 2008) exhibit the remarkable features on P-V (or $l-v$) diagrams which are reproduced in secondary bar models.

The first stellar velocity fields of DB candidates were mapped with OASIS integral-field spectrograph: NGC 3504 and NGC 5850 (Emsellem & Friedli 2000), NGC 470 (Emsellem 2002), and NGC 2273 (Emsellem et al. 2001b). However, only short notes in some proceedings were published, without detailed analysis. Moreover, Erwin (2004) and MVC04 show that the last two objects have inner disks inside the large bars. The SAURON sample of early-type galaxies contains only two candidates from the Erwin's catalogue: NGC 4314 which does not show any velocity deviations in the center (Falcón-Barroso et al. 2006) and NGC 1068 (Emsellem et al. 2006) where kinematically decoupled inner bar was detected, however the outer bar (oval) is still under discussion.

The larger collection of kinematical maps for 13 DB candidates based on 3D spectroscopic observations published by us (MVC04). We detected dynamical decoupling of the circumnuclear ($r \sim 1$ kpc) regions in all observed galaxies, except for one (NGC 5566). Various complex structures (coplanar or polar mini disks, mini-spirals, etc.) were revealed. A large fraction of peculiar structures is not surprising, because different structural features can pro-

[1] Also Erwin (2004) marks 4 objects in Laine et al. (2002) sample as 'ambiguous' objects: Mrk 1066, NGC 2339, NGC 4750 and NGC 7742. Here the turn of isophotes is caused by spirals or rings, moreover, NGC 7742 is a classical example of a ringed galaxy without a bar (Sil'chenko & Moiseev 2006; Mazzuca et al. 2006).

duce twists of the inner isophotes. However, we have not found any kinematic features expected for the secondary bars. Also we have observed only 6 ‘confirmed candidates’ from the Erwin’s catalogue, some of which have ambiguous morphology. For instance, his ‘strong candidate’ NGC 3368 has a polar disk nested in the small bar and spiral arms erroneously interpreted early as a large-scale bar (Sil’chenko et al. 2003).

Therefore new 3D spectroscopic observations are required together with a careful selection of the best candidates.

4. Why do we prefer S0?

Now we choose for the observations only lenticular galaxies from the Erwin (2004) list, because their morphology and relatively small gas and dust contributions simplify the problem of inner bar detections. For instance $\sim 50\%$ of objects in Erwin (2004) are S0 and S0/a. Also the detailed self-consistent collisionless simulations of secondary bars originated from rotating pseudobulges in early-type galaxies were recently considered (Debattista & Shen 2007; Shen & Debattista 2009). The stellar density and kinematics maps constructed by Shen & Debattista (2009) allow us to make a comparison between integral-field data and their numerical simulations.

5. New MPFS observations

The observations were carried out in December 2007 - March 2008 at the Russian 6-m telescope with the integral-field spectrograph MPFS (Afanasiev, Dodonov, & Moiseev 2001). The field of view (FOV) was $16'' \times 16''$ with scale $1''$/spaxel (or $0\farcs5$ in the case of drizling for NGC 6654) and mean seeing $1\farcs3 - 1\farcs6$. We took stellar velocities and velocity dispersion maps (σ-maps) in 6 S0-S0/a galaxies with sizes of secondary bar $2'' < L_2 < 6''$ that provides enough sampling of the FOV. We also add in our analysis 2 SB0 galaxies NGC 2950 and NGC 3945 observed early with the same device (MVC04).

5.1. Velocity fields

In the case of a single-barred galaxy the non-circular motions in non-axisymmetric potential distort the line-of-sight velocity field. The well-known effect is a twist of the kinematical major axis in a direction opposite the bar position angle. The N-body simulation by Shen & Debattista (2009) shows that in a secondary bar the deviation of position angle (ΔPA) is twice smaller than in the case of a single bar (see their Fig. 7). Of course, this value depends on disk and bar orientation. Nevertheless, the typical value of the distortion $\Delta\mathrm{PA} = 10^\circ - 15^\circ$ is significantly larger than uncertainty of PA estimations derived from a MPFS velocity field, so the isovelocity twist should be detected.

Fig. 1 shows the MPFS maps for NGC 6654. The kinematical axis derived from the velocity field coincides with disk position angle at $r < 4.5''$. In other words, purely regular circular rotation is observed at radii corresponding to the secondary bar. A twist of the kinematical axis ($\Delta\mathrm{PA} = 7^\circ - 20^\circ$) in agreement with the orientation of the large scale bar is present at $r > 5''$, just outside the photometric borders of the ‘inner bar’. In all galaxies in our sample we observe the same behaviour of the kinematic axis: *an absence of non-circular motions on the scale of the photometric secondary bar*.

The regular disk-like circumnuclear kinematics cannot be explained by the beam effect of angular resolution, because the photometrical length of the secondary bars are significantly larger than the seeing during the observations. Moreover, with the MPFS we already detected nuclear mini-bars (without large-scale counterparts) in some galaxies, for instance NGC 3368 (Sil’chenko et al. 2003) or NGC 3786 (Moiseev 2002). A second possibility is that the rotation of a bright bulge is observed along the line-of-sight and exceeds the contribution from the secondary bar in the total velocity field. Though Shen & Debattista (2009) models also include a fast rotating bulge, they predicted a detectable twist of kinematic axis. It will be interesting to compare our observations with simulations of galaxies with

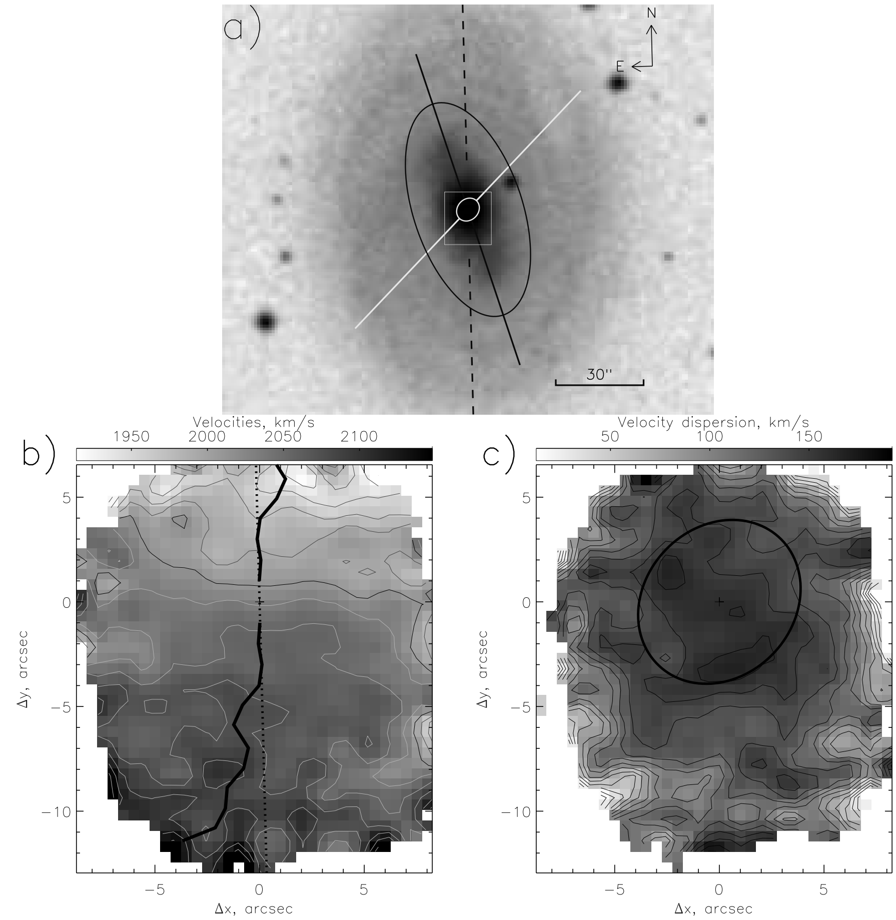

Fig. 1. S0/a galaxy NGC 6654. a) DSS2 image, ellipses and straight lines mark the orientation of both bars in agreement with their length, PA and ellipticity from Erwin (2004). The dashed line shows position of the line-of-nodes. The white rectangle indicates the combination of two MPFS FOVs. b) The velocity field of stars. Dotted line is the disk line-of-nodes, solid line shows the position of kinematic major axis. c) The map of stellar velocity dispersion. The ellipse shows the orientation and size of the inner bar.

the same bulge/disk ratio and relative orientations of the bars as in the galaxies observed.

5.2. Velocity dispersion and σ-hollows

Simple models of single-barred galaxies have shown (Miller & Smith 1979; Vauterin & Dejonghe 1997) that the central ellipsoidal peak in the σ-maps must be aligned with the bar major axis. In real galaxies the distribution of velocity dispersion is more complex, since along line-of-sight we see the contribution of different stellar population in several dynamical components. Usually ($\sim$ 50% of objects) observations reveal a σ-drop (Emsellem et al. 2001a), and lopsided and amorphous structures instead symmetrical peaks. Despite these problems, if an ellipticity peak exists, then the PA of the ellipticity peak has a strong correlation with the PA of the large-scale bar major axis (Moiseev 2002). In our new sample 5 lenticular galaxies out of 8 have central ellipticity peaks on the σ-maps. And we confirm the result of our previous work:

- The peak in the velocity dispersion maps is aligned with the direction of the outer large-scale bar.
- There is no correlation between σ-peaks and secondary bar major axes.

Therefore, the large-scale bar drives the stellar motions even in the regions where the photometric inner bars are observed.

Recently, de Lorenzo-Cáceres et al. (2008) published new SAURON data for stellar kinematics in 4 candidates DB. At the ends of photometric inner bars they found local minima of the velocity dispersion (σ-hollows) and postulated a connection of this features with a dynamically cold inner bar where highly-ordered stellar motions are present. We happened to observe 2 galaxies from their sample and confirm the σ-hollows in NGC 2859. Despite the smaller FOV of the MPFS, we found similar features in NGC 2950 and NGC 6654 (see Fig. 1). However the interpretation offered by de Lorenzo-Cáceres et al. (2008) seems debatable. Why do 'more ordered motions' not distort the velocity fields and appear only in σ distributions? It's interesting that the σ-hollows are mainly observed only in the galaxies with a significant (larger than 60°) angle between the inner and outer bars. Therefore this feature *can be connected with the minor axes of outer bar, never with the major axis of the inner bar.* Unfortunately, it is difficult to check this idea, because we have very scanty information about velocity dispersion behaviour in the outer regions of large-scale bars. Most integral-field maps for barred galaxies usually have insufficient FOV or relatively low signal in the outer regions. One exception is SAURON map for NGC 3489 (Emsellem et al. 2004) where σ-hollows are clearly visible. It seems reasonable that this pattern is a result of disk velocity redistribution under the action of a bar. Some recent simulations of stellar kinematics in barred galaxies can support this idea (Chakrabarty 2004), see also Fig. 10 in Vauterin & Dejonghe (1997). If the σ-hollows were produced by a large bar, then the secondary bar doesn't distort the circumnuclear stellar kinematics, in agreement with the conclusion based on analysis of the velocity fields. In any case, new detailed simulations of velocity dispersion distribution in barred galaxies are needed.

6. Conclusion

We have presented our preliminary results based on analysis of velocity and velocity dispersion fields of the stellar component in the circumnuclear regions of 8 candidate double-barred early-type galaxies:

- The twist of the kinematical axis in the region of inner bar is absent. At least it is significantly smaller than that predicted by modern N-body simulations. This can be related to a large contribution of a rapidly rotating bulge. Nevertheless we have detected primary bar signatures just outside of small bars.
- The primary bar drives the stellar velocity dispersion in the circumnuclear region.

Therefore, in contrast with photometric data, where a secondary bar appears as a small copy of a large scale one, the motions of stars in secondary bars differ essentially from single-bar kinematics. Also it is possible that the fraction of kinematically decoupled bars is still overestimated when we use only photometric (morphological) criteria. Probably, real kinematically decoupled secondary bars is a rare phenomenon connected with other peculiarities, like bars counter-rotation (Corsini et al. 2003; Maciejewski 2006).

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