Observations of Lenticular Galaxies at the 6-m Telescope of the Special Astrophysical Observatory

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Abstract. This is a historical review covering the last 30 years of the observational study of lenticular galaxies at the 6m telescope BTA of the Special Astrophysical Observatory of the Russian Academy of Sciences. The development of spectroscopic techniques at the BTA has allowed to get comprehensive information about this class of stellar systems, starting from the study of their nuclei in the late 80th towards quite exclusive results obtained in the last years on the outermost parts of their large-scale stellar disks.

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1 Introduction

Lenticular galaxies are early-type disk galaxies; in the Local Universe according to Naim et al. (1995) they constitute about 15% of all non-dwarf galaxies being the second common morphological type of galaxies after spirals. They inhabit all types of environment, from the densest ones to the quite rarified, though in clusters they are the dominant galaxy population. High surface brightness of their bulges and disks allows to study stellar kinematics as well as the properties of the stellar populations; however, ionized gas is also the frequent contributor in S0s and can be studied through the analysis of optical emission lines.

Observations of lenticular galaxies at the 6m telescope had started with the emergence of digital panoramic detectors coupled with effective spectrographs. Distinctive epochs of the S0 spectral studies are related to the 1024-channel TV scanner of the 6m telescope, to the Multi-Pupil Fiber/Field Spectrograph

(MPFS), and to the multi-mode reducers Scorpio and Scorpio-2. The short description of the MPFS could be met in the talk by (Afanasiev et al. 2001), and the comprehensive descriptions of the Scorpio and Scorpio–2 were published by Afanasiev & Moiseev (2005, 2011). The precious contribution to the panoramic spectral data reduction methods was made in early 90th by Vlasyuk (1993).

2 Young Stellar Nuclei in Lenticular Galaxies

In 1988–1989 I have succeeded to obtain spectra for the stellar nuclei of 100 nearby galaxies of different morphological types. The observational program was fulfiled with the 1024-channel television scanner. Though the detector used was a panoramic TV photon counter, this was in fact aperture spectroscopy because only two 4–arcsec 'strobes' were cut at the detector to read out – one for the object and one for the sky background. The detector was sensitive in the blue and in the extreme blue, so a set of absorption lines for which I had measured equivalent widths included even CaIIH and K. The atlas of the spectra and the lists of the absorption lines measured were published in 1989–1990 (Sil'chenko & Shapovalova 1989; Sil'chenko 1990).

The first look at these spectra revealed that the stellar populations of the galactic nuclei were of very different ages, and the statistics of their ages was related to the morphological types of the host galaxies. The nuclei in elliptical galaxies were old in the most cases. The nuclei of Sc galaxies were always young, and in the half of them strong Hα emission betrayed current star formation. As for the lenticulars, they demonstrated the age distribution quite similar to that of Sa–Sb spirals and very dissimilar to that of ellipticals. In the half of S0s strong Balmer absorpion lines were detected: the criterium of $EW(H\delta) > 3$ Å gave the evidence in the favour of the mean stellar age less than 3 Gyr. Now such intermediate-age galaxies are called '$K + A$'. But the fact that the half of nearby S0s are '$K + A$' was firstly presented by Sil'chenko (1993).

Later this work was continued with the integral-field unit (IFU) MPFS: the panoramic spectroscopy allowed to compare the ages of the nucleus and bulge stellar populations and to demonstrate distinct evolution of the stellar nuclei within the galaxies. The particular examples of the young stellar nuclei within lenticular galaxies studied with the MPFS were published in the series of our papers, Sil'chenko (1999); Afanasiev & Sil'chenko (2000); Sil'chenko et al. (2002).

3 Chemically Decoupled Stellar Nuclei

The fact that galactic stellar nuclei have quite distinct evolution with respect to the other galactic substructures has one more bright demonstration: their metallicity has occured to be much higher than the metallicity of the underlying regions of the bulges. We have discovered this effect during our first observations with the MPFS: by selecting in an arbitrary way 12 luminous nearby galaxies for the test observations with the IFU, we, Sil'chenko et al. (1992), have found sharp breaks of the MgIλ5175 and FeIλ5270,5335 radial profiles just beyond the unresolved galactic nuclei in 7 galaxies of 12. We have called it 'chemically decoupled nuclei'; their origin has to be related obviously to secondary star formation bursts in the galactic nuclei, sometimes quite recent. So the presence of chemically decoupled nuclei has to be expected first of all in the 'young stellar nuclei' of lenticular galaxies.

By re-observing some of our first findings later with advanced versions of the MPFS, we confirmed that the unresolved, point-like nuclei in the most lenticular galaxies were outstanding at the metallicity maps against their bulges having very high stellar metallicity – up to 2 or even 5 solar values (Sil'chenko 2000, 1999; Sil'chenko & Afanasiev 2002). After fifteen years of the observations of lenticulars galaxies with the MPFS/BTA I have acquired metallicity and age maps for the central regions of 60 nearby lenticulars (Sil'chenko 2006). For this sample the nucleus age distribution looks rather flat between $T = 1$ Gyr and $T = 6$ Gyr; but the age distribution of the subsample of chemically decoupled nuclei has a prominent peak around $T = 3$ Gyr delineating the distinct epoch of secondary star formation bursts in the centers of S0 galaxies at $z \approx 0.4$ related perhaps to their assembly into massive groups and clusters.

4 Circumnuclear Polar Gaseous Disks

Another interesting feature of the central regions of lenticular galaxies which has been inspected in detail by the means of integral-field spectroscopy with the MPFS/BTA is the kinematics of the ionized gas within some hundreds parsec from their nuclei. In the early 90th when current gas content of galactic disks was commonly considered as a remnant of initial gaseous protogalaxy, just the gas kinematics in the centers of S0s had implied an idea of external origin of galactic cold gas supply (Bertola et al. 1992). Since by exploring the MPFS we have acquired two-dimensional distributions of many spectral parameters for the sample of nearby S0s, including stellar and gas velocity fields, we have quickly discovered a high incidence of circumnuclear *polar* gas rotation. While the coincidence of the photometric and stellar-kinematics major axes proved the stellar component circular rotation in the main symmetry planes of the galaxies, the gas-kinematics major axis was sometimes oriented orthogonally to that of the stellar component. We stated the existence of circumnuclear polar gaseous disks in some known lenticulars – in NGC 7280 (Afanasiev & Sil'chenko 2000), in a sample of 8 S0s with the polar dust lanes (Sil'chenko & Afanasiev 2004)...

Now the paradigm has changed, and the common point of view is that *all* cold gas in galactic disks, including galactic disks of spiral galaxies, is currently accreted from outside. However, just lenticular galaxies often demonstrate decoupled rotation of their stars and ionized gas – according to my estimates, Sil'chenko (2016b), 10% of nearby ($D < 42$ Mpc) S0s have circumnuclear polar gaseous disks. So the cold gas in lenticular galaxies is probably accreted along quite varied directions.

5 Large-Scale Gaseous Disks of Lenticular Galaxies

The gas content of lenticular galaxies is not restricted only to their central regions. Many S0s – and in rarified environments it is the majority of them – possess extended gaseous disks, sometimes expanding beyond the borders of their stellar disks. We can observe them through spectroscopy of optical emission lines producing by warm ionized gas. What we need for this task, it is spectroscopic facilities with rather large field of view. Among the equipment of the 6m telescope, the required possibilities are provided by the long-slit mode and by the Fabry-Perot mode of the reducers Scorpio and Scorpio-2. The field of view of the reducers is 6.1×6.1 arcmin; the former mode provides one-dimensional spectral cut-offs with a full optical spectral range covered by a single exposure while the latter, Fabry-Perot, mode gives precise velocity measurements related to a single selected emission line over 2D field of view providing so full velocity maps for the ionized gas of the galactic disks.

Our approaches to the kinematical study of extended gaseous disks in lenticular galaxies gave many findings of decoupled gas rotation as expected. By exploring long-slit observations, Sil'chenko et al. (2009) reported two S0 galaxies with counterrotating extended gaseous disks; one of them, in NGC 5631, was inclined to the main symmetry plane of the stellar disk and contained also a minor old stellar component. In the lenticular galaxy IC 719 studied by Katkov et al. (2013), the gas counterrotating the main stellar disk in its plane produced currently young stars in the ring at the fixed radius of 1.5 kpc promising a counterrotating coplanar *stellar* disk in the future. Taking in mind that rarified environments are favorable for gas kinematics decoupling, we have studied a sample of quite isolated lenticular galaxies. Katkov et al. (2014a) reported that the majority of them possess extended ionized-gas disks, and among those, a half demonstrate counterrotation with respect to stars when probing by a long slit aligned with the photometric major axis (the line of nodes).

However the spectral observations in long-slit mode do not provide exact information about the orientation of the gas rotation plane: by using it we can see only the projection of the spin. When having made for the S0 galaxy NGC 7743 several cut–offs with the long slit, we, Katkov et al. (2011), ensured that the line of nodes of its gaseous disk did not coincide with the stellar disk one. To determine the fair spatial orientation of the rotation planes, we needed 2D line-of-sight velocity distributions, and the Fabry-Perot mode was perfect for this task. Recently we have combined the long-slit and the Fabry-Perot observations for a sample of 18 lenticular galaxies, to estimate simultaneously the gas excitation mechanism, metallicity, and the orientation of the gas rotation plane. The results presented by Sil'chenko et al. (2019) are quite interesting: a quarter of our sample demonstrate the gas disk planes strongly inclined to the stellar disk over their full extension, and just these inclined gaseous disks are excited by shocks, not by current star formation. Even if the gas counterrotates the stars, the star formation proceeds when it is confined to the stellar disk plane (e. g. in NGC 2551), and does not proceed when the counterrotating gas rotates in inclined plane (NGC 4143, Sil'chenko et al. (2020)). Perhaps, the very origin of the S0 morphological type is related to typical inclined directions of the outer cold gas inflow which are misaligned with the galaxy disk plane; subsequent gas heating by shocks prevents further star formation ignition in the disk.

6 Large-Scale Stellar Disks of Lenticular Galaxies

By using spectral data obtained with the Scorpio and Scorpio–2 in the long-slit mode we have also studied large-scale *stellar* disks of nearby lenticulars. As for their kinematics, we found a counterrotating extended stellar component in NGC 448 (Katkov et al. 2016) and signatures of non-circular stellar rotation in the outer part of the oval disk in NGC 502 (Sil'chenko 2016a). But the most interesting and exclusive results were obtained for the stellar population properties of the lenticular galaxies in a range of environments.

There exists a very popular scenario for the origin of lenticular galaxies that they are former spirals that have been devoid of gas by tidal or ram pressure effects which are especially effective in dense environments such as clusters and groups. This scenario was strengthened by the results of studying morphological type fraction in galaxy clusters at redshifts up to 0.8 with the Hubble Space Telescope (Fasano et al. 2000): at $z > 0.4$ the fraction of S0s fell at the expense of spirals so one could conclude that just at $z = 0.4$, or 4 Gyr ago, spirals coming into the clusters transformed into lenticulars. But if so, then stellar disks of present-day lenticulars must be rather young because only 4 Gyr ago they formed stars being spirals. We have decided to check this prediction with the long-slit spectrographs of the 6m telescope. A sample of nearby lenticulars, firstly in groups and a few in the Virgo cluster, has been observed. Sil'chenko et al. (2012) have measured the mean ages and metallicities of their large-scale stellar disks through the evolutionary synthesis of the Lick indices. More than 60% of the disks have revealed the ages larger than 10 Gyr! It means that the disks of nearby lenticulars stopped their star formation at $z \approx 2$. They could not be spirals at $z = 0.5$. Later this result has been confirmed by Johnston et al. (2014): by studying the sample of 13 S0s, the Virgo cluster members, they have found that *all* lenticulars studied have the large-scale stellar disks older than 10 Gyr. Meanwhile the bulges look much younger than the disks. Perhaps there are just the starforming bulges that could be taken by Fasano et al. (2000) as spirals in clusters at $z > 0.4$.

Later Katkov et al. (2014b) have added to this sample the observations of a dozen of quite isolated S0s. Opposite to lenticulars in dense environments, the isolated S0s have revealed the ages of the disks flatly distributed from 1 Gyr to 15 Gyr, and their bulges are coeval with the disks. Being impressed by these results, we have proposed an alternative scenario of the lenticular galaxy origin. All galaxies formed their thick stellar disks at $z = 2$, or 10 Gyr ago, in a brief effective star formation event, and became then lenticulars. Our Milky Way was a S0 only 10 Gyr ago! Later many of them have accreted cold gas from outside and have re-commenced star formation under favorable orientation of the accretion flows. But S0s which had fallen into clusters had no possibility of cold gas inflow due to hot intergalactic gas ram pressure and strangulation; it is because there are now so many S0s in clusters.

7 Outer Starforming Rings in S0s

Last few years I become interested in the outermost parts of the S0 disks – their outer starforming rings. Just in lenticular galaxies the outer rings are very frequent – more than 50% S0s have outer stellar rings (Comerón et al. 2014), – while the bar fraction drops in S0s related to spirals (Laurikainen et al. 2009). It means that outer *gaseous* rings in S0s may be mostly formed by outer gas accretion, and by studying gas characteristics in the rings we can restrict its origin and say something about cold-gas accretion sources.

After the GALEX discovery of UV-bright rings in early-type galaxies (Marino et al. 2011) we started their spectral study at the 6m telescope (Ilyina et al. 2014). Many interesting particular cases have been analysed (Sil'chenko et al. 2018; Proshina et al. 2020; Sil'chenko & Moiseev 2020) including both resonant rings and rings produced by obvious accretion from outside. For the rings confined to the galactic planes we fixed normal, for their gas content, star formation rates and nearly solar metallicity (Sil'chenko et al. 2019). The latter fact seems to restrict possible sources of outer gas accretion to rather large gas-rich satellite tidal disruption.

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