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Noncircular Outer Disks in Unbarred S0 Galaxies: NGC 502 and NGC 5485

O. K. Sil'chenko*

Sternberg Astronomical Institute, Moscow State University, Universitetskii pr. 13, Moscow, 119992 Russia

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Abstract—Highly noncircular outer stellar disks have been detected in two SA0 (unbarred) galaxies by comparing the spectroscopic data on the rotation of stars and the photometric data on the shape and orientation of isophotes. In NGC 502, the oval distortion of the disk is manifested in the shape of the inner and outer elliptical rings occupying wide radial zones between the bulge and the disk and at the outer disk edge; such a structure can be a consequence of the so-called "dry minor merger," multiple cannibalization of gas-free satellites. In NGC 5485, the stellar kinematics is absolutely unrelated to the orientation of isophotes in the disk region, and for this galaxy the conclusion about its global triaxial structure is unavoidable.

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INTRODUCTION

The overwhelming majority of galaxies in the nearby Universe are disk ones. This means that one (often dominant) of the large-scale components of their structure is a flat stellar disk. From a dynamical point of view, the stellar disks are "cold" systems, i.e., the chaotic motions of stars in them are small, and the bulk of the kinetic energy is concentrated in the laminar circular rotation around the galactic center. Circular lines of equal density (surface brightness) correspond to circular orbits, and, on the whole, the galactic disk, when viewed from above pole-on, looks like a regular circle. But how perfectly circular are the actual disks of galaxies? This question has occupied researchers since the very beginning of the epoch of extragalactic astronomy. The problem is complicated by the fact that we see the disk of a galaxy in projection onto the plane of the sky, at an arbitrary inclination, and it is not easy to distinguish the image ellipticity produced by projection effects from the actual "intrinsic" disk ellipticity, especially in the case where we have to deal with individual objects and not with large samples. The average intrinsic ellipticity of disks can be estimated statistically by studying their distribution in apparent isophotal ellipticity under the assumption of a random orientation in space. In addition, since the assumption about a circular gas rotation in the disks of galaxies is widely used in establishing the so-called scaling relations, for example, the Tully–Fisher relation, the scatter of actual measurements about such relations also allows the intrinsic ellipticity of disks to be constrained. Franx and de Zeeuw (1992) collected the photometric statistics and the statistics of the Tully–Fisher relation and placed an upper limit on the typical ellipticity of galactic disks, $\epsilon < 0.1$, by pointing out that it most likely lies within the range 0–0.06.

The paper of Rix and Zaritsky (1995) may be considered as the first special work devoted to this question and based on highly accurate surface photometry for the disks of individual galaxies. They selected 18 galaxies seen nearly face-on by assuming the rotation velocity projected onto the line of sight in the flat disks of such galaxies to be zero and, consequently, the integrated 21-cm H I emission line to be very narrow. K-band surface photometry was then performed to minimize the influence of dust and the clumpy distribution of star-forming regions. The subsequent azimuthal Fourier analysis of the surface brightness distribution showed the disks to be actually quite circular, with a mean intrinsic ellipticity of 4.5%. The fact that such studies were impossible without invoking kinematic data when individual galaxies rather than average statistics were involved was obvious from the outset, and new opportunities in solving the problem of the intrinsic ellipticity of galactic disks appeared with the development of integral-field spectroscopy by researchers. Andersen et al. (2001) calculated the intrinsic disk ellipticity for seven Sb–Sc galaxies oriented nearly face-on by

*E-mail: olga@sai.msu.su

using both highly accurate red-band surface photometry and two-dimensional line-of-sight velocity fields obtained with the DensePak integral-field fiber spectrograph of the WIYN telescope. The true inclination of the flat disks was determined from the two-dimensional ionized-gas kinematics. Their paper has a reference to the theoretical conclusion reached by Franx and de Zeeuw (1992) that the method of tilted *circular* (*sic!*) rings can be applied to a gas in elliptical orbits if the orbital ellipticity is small and the rotation curve (the dependence of the rotation velocity on galactocentric distance) is flat. The conclusion about the intrinsic ellipticity of stellar disks was then drawn from the shape of outer isophotes. The mean value turned out to be near 5%, in complete agreement with the expectations, though the disk ellipticity in two galaxies with close satellites and possibly subjected to a gravitational tidal effect reached 20%.

In this paper, we consider two lenticular galaxies for which our data on the kinematics of stars turned out to be incompatible with the assumption about a circular shape and circular rotation of the disks. In the second section, we describe the investigated galaxies and the observational data used here. The evidence for the ellipticity of their stellar disks is formulated in the third section.

NGC 502 AND NGC 5485: NONINTERACTING S0 GALAXIES IN GROUPS

Table 1 provides the basic parameters of the galaxies being investigated that can be gathered in catalogs. Both galaxies are medium-luminosity lenticular galaxies and are members of galaxy groups. However, whereas NGC 5485 is probably the central galaxy in its group (Huchra and Geller 1982; Garcia 1993), NGC 502 is on the periphery of its group, approximately at 300 kpc from the central galaxy NGC 524, and only faint satellites can be seen near it, at 100–150 kpc (NED, Il'ina and Sil'chenko 2012).

The galaxies to be discussed entered into a large sample of lenticular galaxies that we investigated by integral-field spectroscopy at the 6-m telescope of the Special Astrophysical Observatory, the Russian Academy of Sciences (SAO RAS) (Sil'chenko 2008). In particular, two-dimensional velocity maps of the stellar component were constructed for the central regions. A misalignment of the kinematic and photometric major axes was immediately apparent even when the stellar kinematics of the innermost regions of NGC 502 and NGC 5485 was considered. In principle, this is not all that uncommon for the central regions of galaxies, but it is usually accompanied (and explained) by the presence of a bar at the galactic center, the breaking of axial symmetry in the potential distribution and, accordingly, the consequent departure from a circular rotation. However, NGC 502 and NGC 5485 do not have not only bars but also even hints of an oval bulge distortion; both galaxies are classified as SA0. We became interested in the unusual kinematics of these galaxies and undertook long-slit spectroscopy to see what happens in the outermost, disk regions of the galaxies. The slit was oriented along the major axis of the *outer* isophotes that must have coincided with the line of nodes of the disk plane under the assumption of a circular disk shape. Much to our surprise, the spectroscopy with a long slit oriented in the presumed direction of the maximum rotation velocity projected onto the line of sight showed no rotation in NGC 5485 whatsoever and a very weak one in NGC 502! It was necessary

Table 1. Global parameters of the galaxies

NGC	502	5485
Morphological type (NED[1])	SA(r)0^0	SA0 pec
Distance, Mpc (NED)	34	27
R_{25} (RC3[2])	$34''$	$70''$
R_{25}, kpc	6.0	9.5
B_T^0 (RC3)	13.57	12.31
M_B (LEDA[3])	−19.3	−20.2
$(B-V)_T^0$ (RC3)	0.91	0.88
$(U-B)_T^0$ (RC3)	0.47	0.51
V_r (NED), km s^{-1}	2524	1927
Inclination of disk plane to line of sight (LEDA)	24°	55°
$PA_{\rm phot}(R_{25})$	60°[4]	170°[2]
σ_*, km s^{-1} (LEDA)	103	195

[1] NASA/IPAC Extragalactic Database.
[2] Third Reference Catalogue of Bright Galaxies, de Vaucouleurs et al. (1991).
[3] Lyon–Meudon Extragalactic Database.
[4] Il'ina and Sil'chenko (2012).

Table 2. Long-slit spectroscopy of the galaxies

Galaxy	Date	$T_{\rm exp}$, min	PA(slit)	$FWHM_*$, arcsec
NGC 502	Sep. 3, 2008	80	64	2.5
NGC 502	Sep. 3, 2008	80	334	1.6
NGC 502	Nov. 3, 2010	60	30	1.2
NGC 502	Nov. 3, 2010	120	15	1.2
NGC 5485	May 12, 2010	60	−14	2.2
NGC 5485	Feb. 9, 2011	120	75	2.3
NGC 5485	Mar. 19, 2015	90	120	2.0

to collect all of the possible information to figure out what causes this phenomenon.

Our long-slit spectroscopy was performed at the 6-m SAO RAS telescope with the SCORPIO multimode focal reducer (Afanasiev and Moiseev 2005). We obtained a total of four cuts at different position angles for NGC 502 and several cuts at three different position angles for NGC 5485. A complete log of observations for the exposures used in our analysis here is presented in Table 2. The observations were made mostly with a VPHG2300G grism and a slit width of 1 arcsec, which provided a spectral resolution of 2.2 Å sufficient to measure the stellar velocity dispersion in the disks. Only the last observation of NGC 5485 in 2015 was made with the new SCORPIO-2 version of the instrument (Afanasiev and Moiseev 2011), with a VPGH1200@540 grism and a spectral resolution of 5 Å. We measured the Doppler shifts of absorption lines by cross-correlating the pixel-by-pixel spectra taken along the slit at various distances from the galactic center with the spectra of G8 III-K3 III stars and with the dawn-sky spectra (G2) taken on the same nights with the same instrumentation. The data turned out to be deep enough to measure the stellar kinematics up to the optical boundaries of the galaxies; the results of our measurements, the radial profiles of the stellar line-of-sight velocities and velocity dispersions, are presented in Figs. 1 and 2. The fact that the velocity dispersions reach a plateau at a certain radius signals that, starting from this radius, the spectrum is dominated by the disk light; the radial intervals of disk domination in the kinematic profiles of NGC 502 and NGC 5485 in this case are consistent with the positions of the exponential (disk) regions in the photometric surface brightness profiles (for the photometric data, see below).

Apart from the extended kinematic cuts obtained with a long slit, we had the two-dimensional line-of-sight velocity maps for the galactic centers obtained with integral-field spectrographs at our disposal. Both galaxies were observed as part of the ATLAS-3D project (Cappellari et al. 2011) with the SAURON spectrograph (Bacon et al. 2001) and the 4.2-m William Herschel Telescope in the Canaries; the raw data were downloaded from the public ING (Isaac Newton Group) archive of the Cambridge Institute of Astronomy and were reduced by an original technique (Sil'chenko 2005). The field of view of the SAURON spectrograph is $33'' \times 41''$, one spatial element is $0.94''$, and the spectral resolution is about 4 Å. In addition, NGC 5485 was also observed as part of the CALIFA project (Sánchez et al. 2012; García-Benito et al. 2015) with the PMAS/PPAK integral-field spectrograph at the 3.5-m telescope of the Calar Alto Observatory, and we used the already reduced public data cube with a spectral resolution of 500 and a spatial element of $1''$ (the spatial resolution is about $3''$) to construct the velocity fields for stars and ionized gas present at the center of this lenticular galaxy for a $60'' \times 40''$ region. The velocity fields for NGC 502 and NGC 5485 are shown in Figs. 3 and. 4. They were analyzed by the tilted-ring method in Moiseev's modification (the DETKA code; Moiseev et al. 2004). The orientation of the kinematic major axis, in the case of a circular rotation coincident with the line of nodes of the disk, was traced up to a distance from the center of about $20''$ in NGC 502 and up to $25''$ in NGC 5485; although these distances are determined by the quality of the stellar velocity fields, by a stroke of luck, they border the beginning of the galactic exponential disks.

The photometric analysis of the galactic structure has been repeatedly covered in the literature. In particular, the deep photometry of NGC 502 performed with the SCORPIO focal reducer of the 6-m SAO RAS telescope in the direct-imaging mode was described in detail by Il'ina and Sil'chenko (2012); the presence of wide stellar rings (surface brightness excesses) between $8''$–$16''$ and $35''$–$45''$ was pointed out. A two-dimensional decomposition of

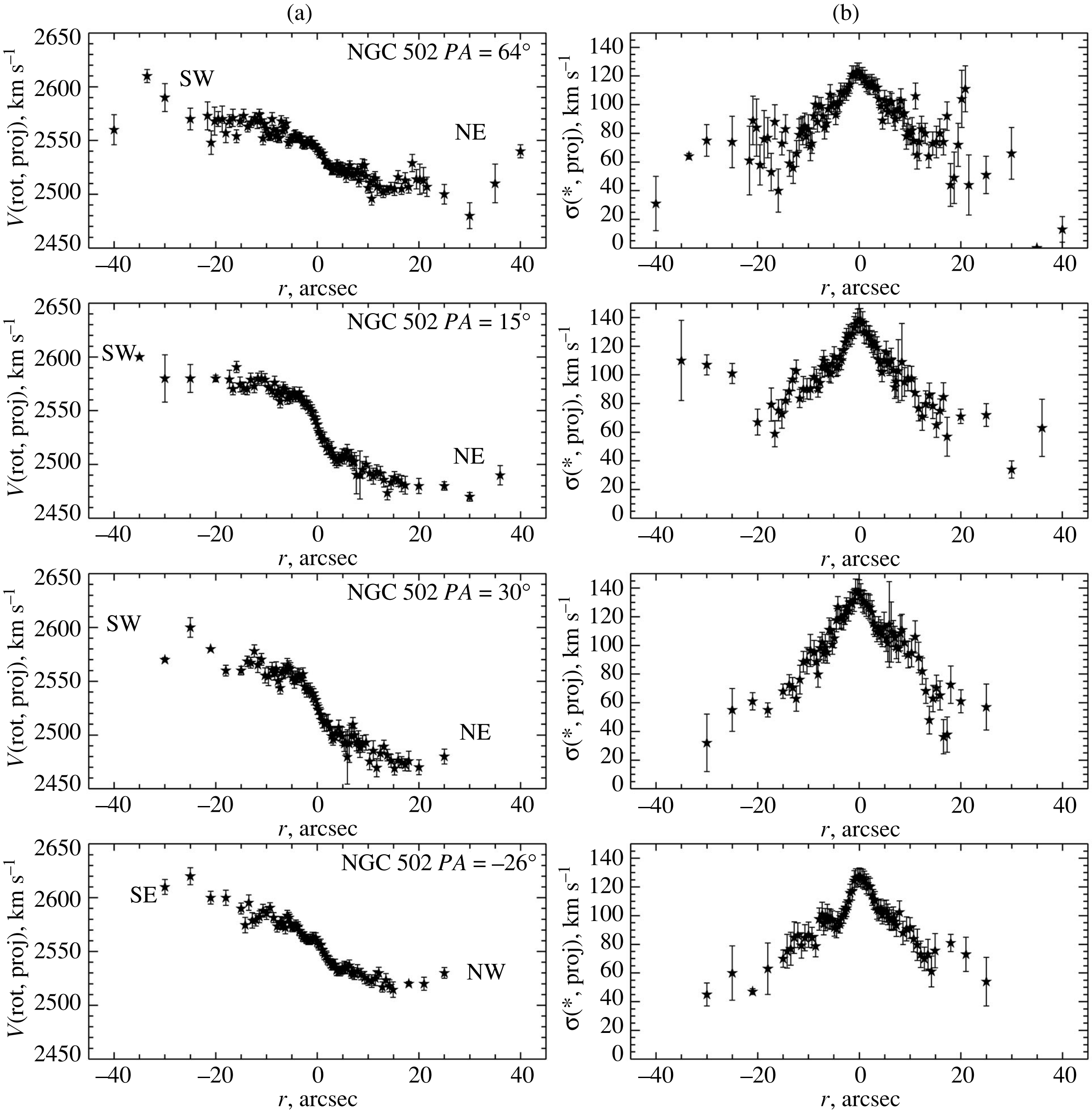

Fig. 1. Kinematic cuts obtained for NGC 502 with the SCORPIO spectrograph in the long-slit mode at the 6-m SAO RAS telescope at four different position angles: the stellar line-of-sight velocities (a) and the corresponding stellar velocity dispersions (b).

the NGC 5485 image was undertaken by Méndez-Abreu et al. (2008), Laurikainen et al. (2010, 2011), and Gutiérrez et al. (2011), where sometimes significantly differing metric parameters of the galactic disk and bulge are presented. We additionally performed an isophotal analysis for the r-band images of both galaxies based on SDSS data, release 9, and on the 4.5-μm image of NGC 5485 retrieved from the public database of the S4G survey (Sheth et al. 2010), though the latter image is at the edge of the field of view of the Spitzer telescope and, therefore, the characteristics of the outer isophotes are not very good. Figure 5 compares the kinematic and photometric parameters: the ellipticities measured in our isophotal analysis are compared with $1 - \cos i$, where the inclinations of the disk plane to the plane of the sky i were obtained by the tilted-ring method from the two-dimensional velocity fields; the orientations of the kinematic and photometric major axes in the central regions of the galaxies are also compared. As expected, the kinematic and photometric major axes in the central regions of the galaxies are significantly

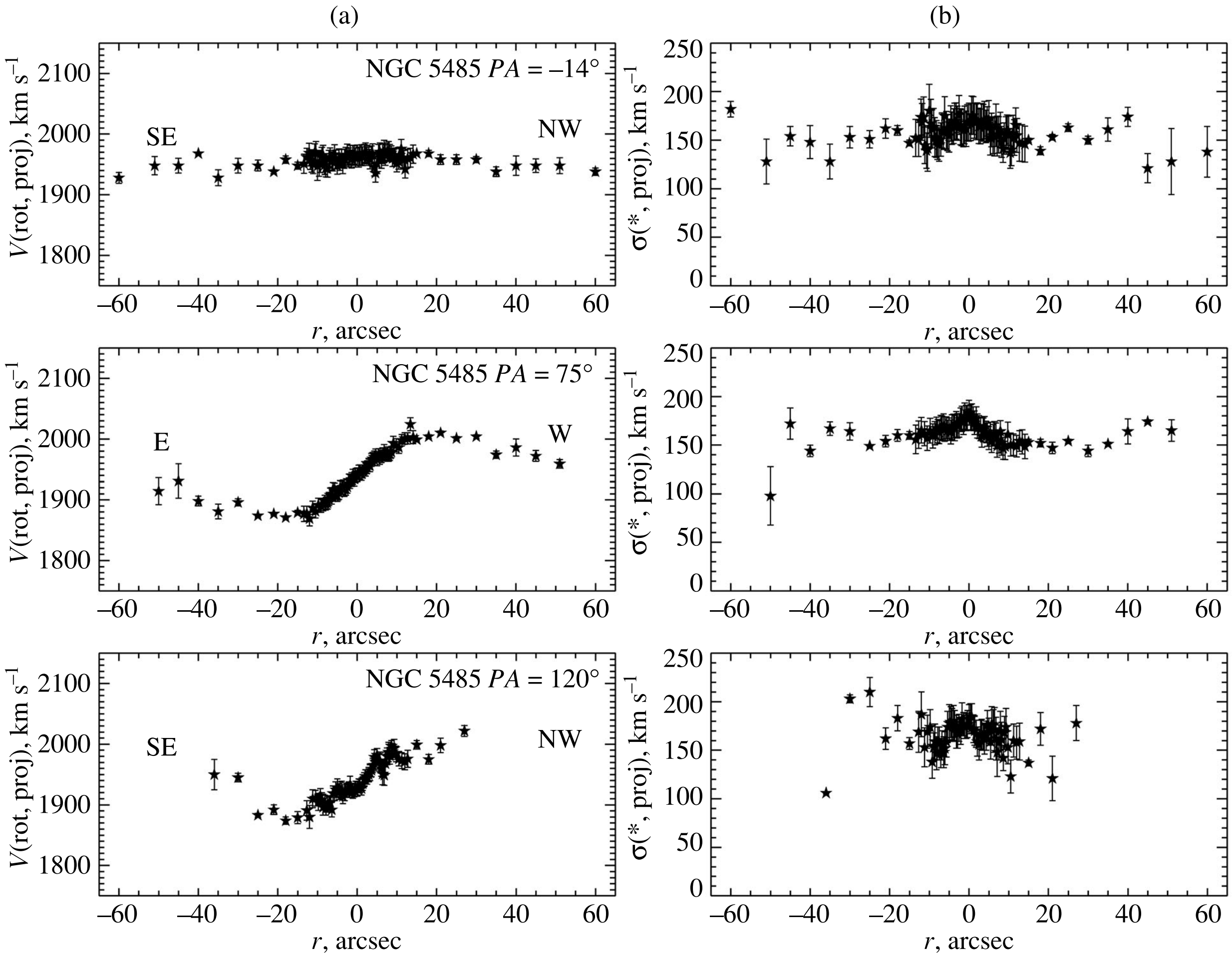

Fig. 2. Kinematic cuts obtained for NGC 5485 with the SCORPIO spectrograph in the long-slit mode at the 6-m SAO RAS telescope at three different position angles: the stellar line-of-sight velocities (a) and the corresponding stellar velocity dispersions (b).

misaligned. The parameters of the isophotes farther from the center, into the region where the exponential stellar disks dominate in the surface brightness, are also traced in Fig. 5.

THE ELLIPTICAL OUTER DISKS IN NGC 502 AND NGC 5485

Let us consider in detail the situation with the orientation of the NGC 502 and NGC 5485 disks in space based on all of the available photometric and kinematic information.

NGC 502. According to our isophotal analysis and the surface brightness profile (Il'ina and Sil'chenko 2012; see also the surface brightness based on SDSS data in Fig. 6a), the inner ring in NGC 502 is localized near the radius 15″; it is also clearly seen by eye in the multicolor SDSS images. Since we have integral-field spectroscopy, the two-dimensional stellar velocity field, for this radial zone, we know that the kinematic and photometric major axes in this region are misaligned by 30°; obviously, the inner ring of NGC 502 is elliptical. Starting from the radius 20″, the surface brightness profile shows an exponential pattern, and the stellar velocity dispersion profiles (Fig. 1) flatten out at $\sim$60 km s^{-1}. Obviously, here we fall into the region of stellar disk domination in the surface brightness and the density. What is the orientation of this disk in space? According to our integral-field spectroscopy, the kinematic major axis reaches $PA = 203°$ at $R = 16''-18''$; the isophotes in the range of radii $R = 22''-30''$, outside the influence of the inner ring, in the region of exponential disk domination, show approximately the same position angle of the major axis: $PA_{\rm phot} = 204°$ according to our B-band data from SCORPIO (Il'ina and Sil'chenko 2012) and $PA_{\rm phot} = 201°$ according to the r-band SDSS data. We will assume that we see a *circular* stellar disk oriented nearly face-on in the range of radii $R = 22''-30''$: the apparent ellipticity of the isophotes in this range of radii is $1 - b/a = 0.08$,

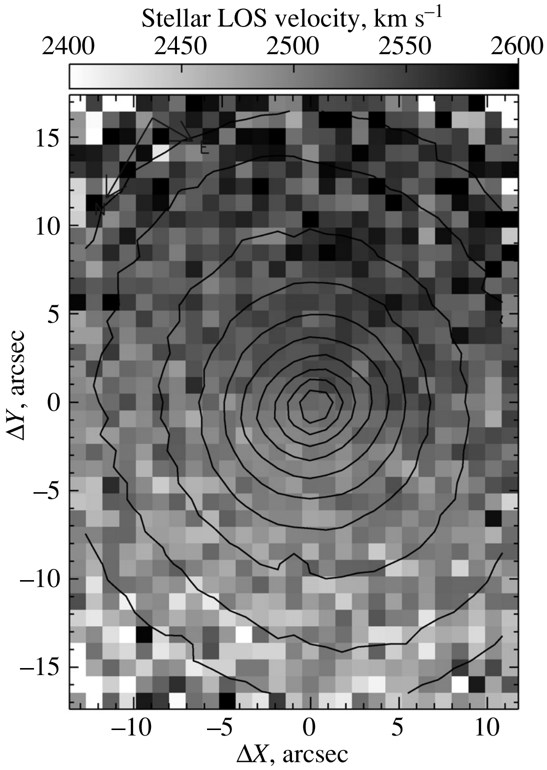

Fig. 3. Stellar velocity field for NGC 502 calculated using data from the SAURON integral-field spectrograph. The orientation of the picture is indicated by the arrows directed to the north and the east in the upper left corner of the map. The surface brightness distribution in continuum at a wavelength of 5100 Å is superimposed by isophotes.

which corresponds to an inclination of 23° for a very thin disk and and is consistent with the photometric inclination of 24° from the HYPERLEDA database (see Table 1). Interestingly, the kinematic inclinations at $R > 16''$ are also consistent with the photometric ones under the assumption of a thin disk (Fig. 6a). We will take these angles, $i = 23°$ and the position angle of the line of nodes $PA_0 = 202.5°$, as the orientation angles of the NGC 502 disk in space and attempt to bring the four kinematic cuts in Fig. 1 into one circular rotation curve. The result of our calculation is shown in Fig. 7a. Before the beginning of the disk, at $R < 20''$, the rotation curve constructed from the SAURON two-dimensional velocity field by the method of tilted, intrinsically circular rings at an inclination of the rotation plane and a position angle of the line of nodes changing freely along the radius is shown, while at $R > 20''$ different symbols indicate the four cuts with a long slit recalculated to the circular rotation velocities at the fixed orientation angles of the rotation plane specified above. The result turned out to be good: within the error limits, in the range $R = 22''$–$30''$, all four cuts showed similar stellar rotation velocities, about 145 km s^{-1}, which, besides, also corresponds to the luminosity of NGC 502 if we allude to the Tully–Fisher relation, for example, from Theureau et al. (2007). However, beyond the optical radius, at $R > 35''$, the calculated rotation velocity drops sharply (Fig. 7a), the position angle of the isophotes increases sharply (Fig. 5c), and another ring is observed in the surface brightness profile (Il'ina and Sil'chenko 2012). Obviously, the outer wide ring of NGC 502 is also *elliptical*. Figure 8 shows the isophotal ellipticity for the image of NGC 502 *deprojected* with the orientation parameters specified above. We see two distinct peaks in the inner region, at $R = 3.5''$ and $15''$, corresponding to the nuclear bar and the inner ring, while in the outer parts of the disk, at $R > 30''$, the intrinsic disk ellipticity begins to monotonically increase and reaches 10% at $R = 42''$. The galaxy's deep image obtained with the MegaCam camera at the Canada–France–Hawaii Telescope (CFHT) shows numerous stellar shells in the outer regions (Duc et al. 2015). Obviously, despite the relative external isolation of NGC 502, it underwent a number of mergers, probably with dwarf galaxies devoid of gas, which could produce an oval distortion of individual radial zones of the dynamically cold disk.

NGC 5485. It can be seen from Fig. 5d that the kinematic major axis in the central part of NGC 5485 is exactly perpendicular to the photometric major axis. This allowed Krajnovic et al. (2011) to put NGC 5485 in the rare subclass of galaxies (consisting of only two objects in the nearby, $D < 42$ Mpc, Universe) with the so-called prolate rotation, when the stellar rotation axis coincides with the longest axis of the spheroid in the triaxial potential. Even significantly earlier than the ATLAS-3D survey, Wagner et al. (1988) diagnosed a prolate rotation in NGC 5485 based on long-slit spectroscopy up to a distance of $22''$ from the center. Actually, no one of them determined an accurate orientation of the stellar rotation axis in this galaxy; these authors only compared the position angles of the kinematic and photometric major axes precisely for the central region of the galaxy, where the bulge dominates in the surface brightness. The idea of general triaxiality of NGC 5485, when the entire galaxy is an ellipsoid with three different axes, without a disk, comes into conflict with the constancy (along the radius) of the position angle of the photometric major axis (isophotes) over the entire galaxy and with the constancy of the apparent isophotal ellipticity within the exponential galactic disk at $R > 30''$. All photometrists (see, e.g., Laurikainen et al. 2011; Gutiérrez et al. 2011) deem this galaxy an *unbarred* lenticular one, i.e., axisymmetric. Since there is a dust lane at the galactic center and since the gas disk coincident with it rotates in the same orientation of

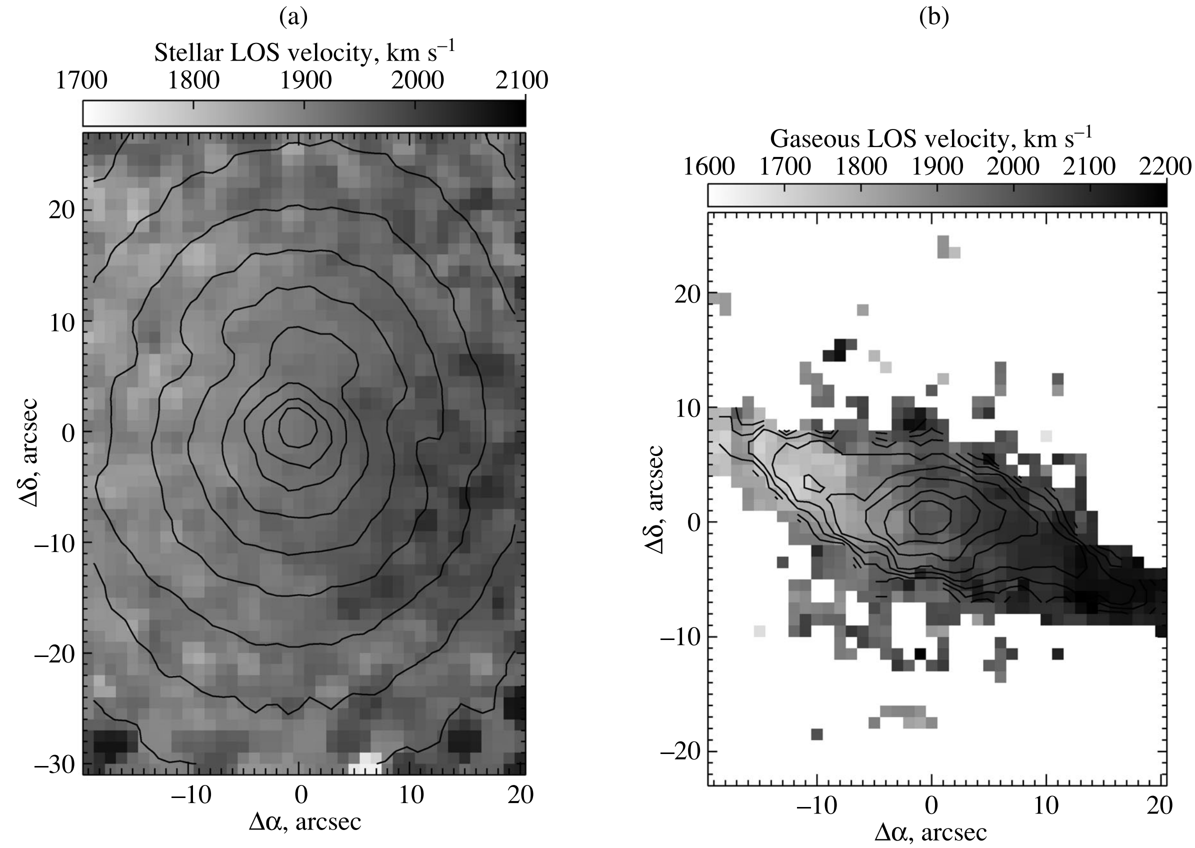

Fig. 4. Stellar and ionized-gas (from the [N II] λ6583 emission line, the strongest one in the optical range in this galaxy) velocity fields for NGC 5485 calculated using the data from the PMAS integral-field spectrograph obtained as part of the the CALIFA project. The surface brightness distribution in continuum at a wavelength of 5100 Å ((a) for the stellar velocity field) and the [N II] λ6583 emission line flux distribution ((b) for the ionized-gas velocity field) are superimposed by isophotes.

the kinematic major axis as the stars (Fig. 4), it is tempting to suggest that we see the rotation of the stellar component formed from an accreted gas with a polar angular momentum at the galactic center up to a distance of 22″ from the nucleus. However, whereas the gas is concentrated in a disk seen nearly edge-on with an inclination of about 70°–80° in its outer parts, the rotation of the stellar component analyzed by the tilted-ring method provides evidence for a much more moderate inclination of the rotation plane (45° according to the SAURON data and $\leq 37°$ according to the CALIFA data); and, obviously, there are no signatures of a "nested" stellar disk with a large inclination in the isophotes. Even greater difficulties arise with the interpretation of the stellar rotation *beyond* the central part of the galaxy and beyond the polar gas concentration. If we attempt to bring the three cuts in Fig. 2 into one circular rotation curve under the assumption of an axisymmetric disk using the photometric orientation angles, $PA_0 = 170°$ and the inclination of 45°, then recalculating the cut taken at $PA = 75°$ will give a rotation velocity greater than 1500 km s^{-1}, while recalculating the cut taken at $PA = -14°$ will give rotation velocities close to zero. Obviously, this approach is unsuitable. Purely formally, we can attempt to select the orientation of the plane of *quasi-circular* stellar rotation based on the similarity of the spectral cuts at $PA = 75°$ and 120° (Fig. 2); the kinematic major axis must apparently be somewhere between these position angles. Figure 7b presents the result of successfully bringing the three kinematic cuts into one rotation curve for the following orientation of the plane of quasi-circular rotation in space: $PA_0 = 100°$ and $i = 25°$. At such an inclination of the rotation plane, the disk rotation velocity at maximum turns out to be about 180 km s^{-1}, which agrees excellently with the Tully–Fisher relation in the near infrared from Theureau et al. (2007). The inner part of the circular rotation curve calculated *from the gas* by a one-dimensional cut along the major axis of the gas line-of-sight velocity field presented in Fig. 4b also joins excellently with (is continued by) this rotation curve of the stellar component. However, such orientation angles have no analog whatsoever in the photometric characteristics of the galaxy. And at radii greater

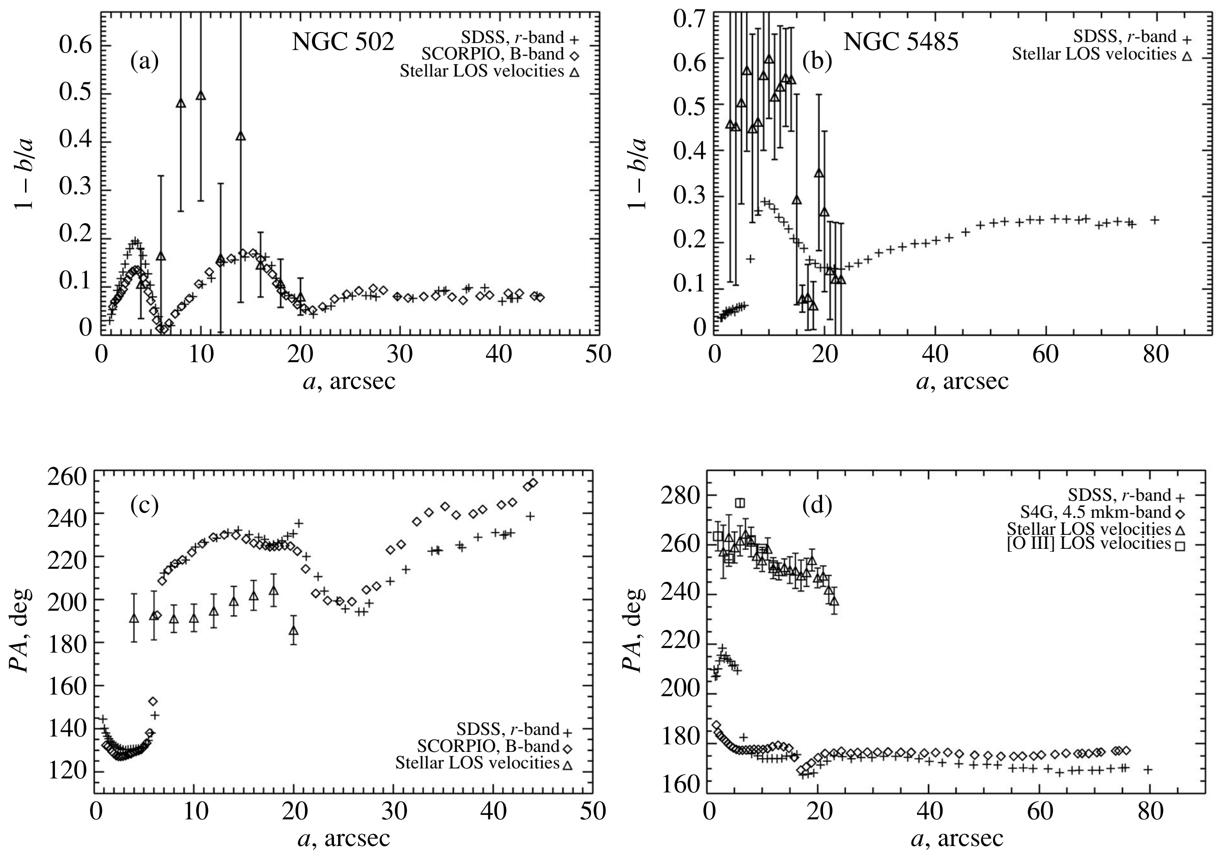

Fig. 5. Isophotal ellipticities and orientations of the photometric and kinematic major axes in NGC 502 (a, c) and NGC 5485 (b, d).

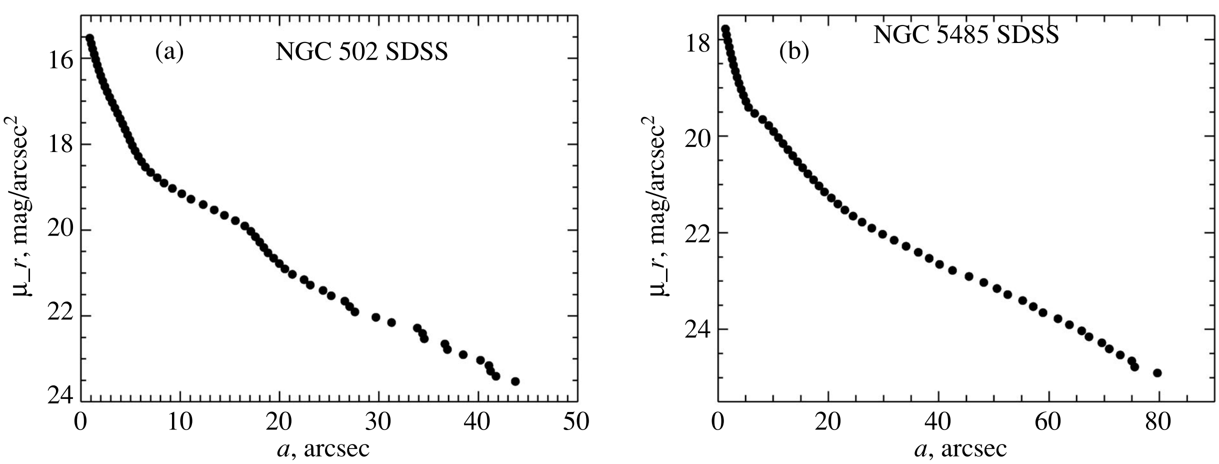

Fig. 6. Azimuthally averaged (with sliding isophotal parameters) surface brightness profiles for NGC 502 (a) and NGC 5485 (b) from SDSS data.

than 40″, the rotation curve in Fig. 7b falls to zero, which completely disagrees with the expected shape of the rotation curve for an exponential disk with a scale length of 4.5 kpc or about 33″ (Laurikainen et al. 2010) that must reach its maximum at a radius approximately equal to two exponential scale lengths. The axial symmetry, even the partial one, in the case of NGC 5485 should apparently be abandoned.

CONCLUSIONS

We investigated in detail two unbarred disk (lenticular) galaxies for which our previous spectroscopic

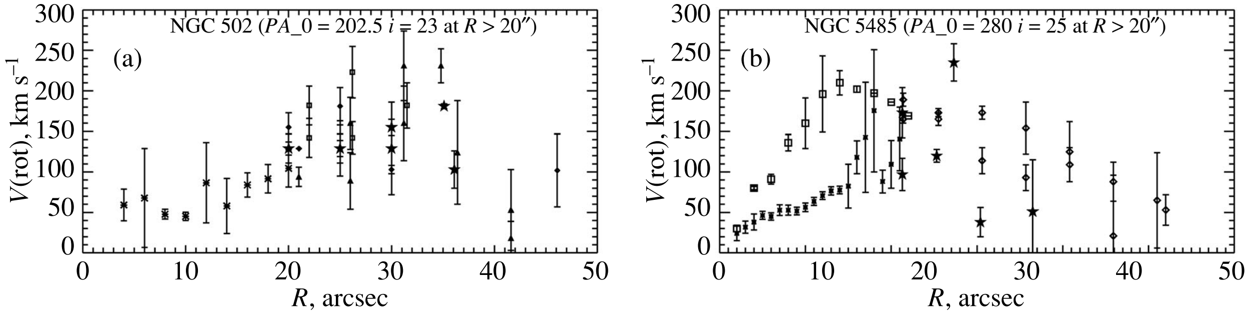

Fig. 7. Radial circular velocity profiles under the assumption of a circular rotation of the stellar disks in NGC 502 (a) and NGC 5485 (b) (uncorrected for the asymmetric drift). The inner regions, $R < 20''$, are the stellar rotation curves (stars) constructed by the tilted-ring method from the two-dimensional line-of-sight velocity maps. In the outer regions, various other symbols indicate the stellar line-of-sight velocity profiles at various position angles recalculated to the circular rotation velocities with the orientation parameters of the rotation planes specified at the top of the figures. For NGC 5485, the squares also indicate the gas rotation curve obtained by a one-dimensional cut along the kinematic major axis of the line-of-sight velocity field for a gas disk seen nearly edge-on.

data showed a misalignment of the kinematic and photometric major axes. The anomaly of the large-scale stellar kinematics in NGC 502 turned out to be related to the presence of two wide elliptical rings in the disk that fringe an otherwise normal stellar disk on the inside (adjacent to the bulge) and the outside (near the optical boundaries of the galaxy).

In NGC 5485, the situation is obviously more complex: we failed to identify an axisymmetric structural component in the galaxy at any distance from the center. The rotation axis of the galactic bulge coincides in projection with the major axes of the isophotes; this component may be genetically related to the externally accreted polar gas observed at the center of NGC 5485 as a disk of gas and dust seen nearly edge-on. However, the central stellar component is definitely not a thin disk but most likely a bulge, i.e., the so-called prolate spheroid. It should be noted that the stellar population of the bulge is old, $T_{SSP} \sim 9$ Gyr (Sil'chenko 2016), i.e., even if this component was formed from the accreted gas, this occurred very long ago, and the ionized gas has stably rotated in a polar orbit without forming any stars for the last many billions of years. The anomaly pointed out by Baes et al. (2014) is also consistent with this fact: despite an appreciable amount of dust, neither neutral nor molecular hydrogen has been detected in the galaxy at a very deep limit. The large-scale stellar disk of NGC 5485 is definitely noncircular, because the kinematic major axis at a radius greater than $25''$ is projected at a position angle, $PA_0 = 100°$, that does not coincide with the position angle of the major axis of the isophotes. If the outer component is a disk, as suggested by the exponential surface brightness profile, then it has an intrinsically elliptical shape and exhibits a highly noncircular stellar rotation.

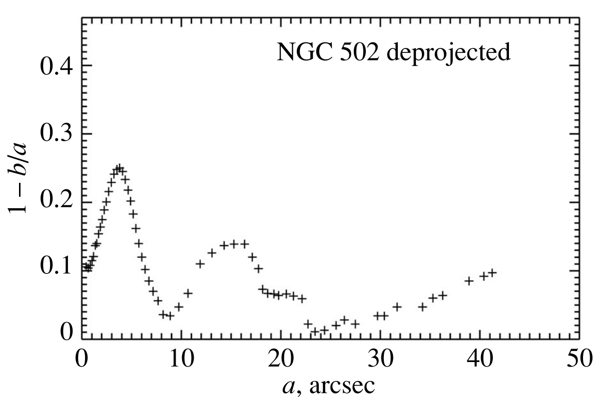

Fig. 8. Intrinsic ellipticities of isophotes in the image of NGC 502 (SDSS, the r band) deprojected by assuming the following orientation of the galactic plane in space: the inclination to the plane of the sky $i = 23°$ and the position angle of the line of nodes $PA_0 = 202.5°$.

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Legacy Integral Field Area) Survey taken from http://califa.caha.es/. The CALIFA Survey collects data at the German–Spanish Astronomical Center at Calar Alto (CAHA) operated jointly by the Max-Planck-Society (MPG) and the Spanish National Research Council (CSIC). This study is also based in part on public data from SDSS, SDSS-II, and SDSS-III (http://www.sdss3.org/) financed by the Alfred P. Sloan Foundation, the institutes of the SDSS Collaboration, the National Science Foundation, the US Department of Energy, the National Aeronautics and Space Administration (NASA), the Japanese Monbukagakusho Foundation, the Max-Planck Society, and the High Education Funding Council for England. The research on the structure, dynamics, and evolution of disk galaxies was supported by the Russian Science Foundation (project no. 14-22-00041).

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