Extended Gaseous Disk in the S0 Galaxy NGC 4143

O. K. Sil'chenko1*, A. V. Moiseev1,2, and D. V. Oparin2

1Sternberg Astronomical Institute, Moscow State University (SAI MSU), Universitetskii pr. 13, Moscow, 119234 Russia
2Special Astrophysical Observatory, Russian Academy of Sciences (SAO RAS), Nizhnii Arkhyz, Karachai-Cherkessian Republic, 369167 Russia

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Abstract—We present the results of our spectroscopic study of the lenticular galaxy NGC 4143—a peripheral member of the Ursa Major cluster. Using the observations at the 6-m SAO RAS telescope with the SCORPIO-2 instrument and the archival data of panoramic spectroscopy with the SAURON instrument at the WHT, we have detected an extended inclined gaseous disk in this lenticular galaxy with a spin approximately opposite in direction to the spin of the stellar disk up to a distance of about 3.5 kpc from the center. The galaxy images in the Hα and [N II]λ6583 emission lines obtained at the 2.5-m CMO SAI MSU telescope with the MaNGaL instrument have shown that the emission lines are excited by a shock wave. A spiral structure absent in the stellar disk of the galaxy is clearly seen in the brightness distribution of ionized-gas lines (Hα and [N II] from the MaNGaL data and [O III] from the SAURON data). A complex analysis of both the distribution of Lick indices along the radius and the integrated colors, including the ultraviolet measurements with the GALEX space telescope and the near-infrared measurements with the WISE space telescope, has shown that there has been no star formation in the galaxy, possibly, for the last 10 Gyr. Thus, the recent external-gas accretion event in NGC 4143 was not accompanied by star formation, probably, due to an inclined direction of the gas inflow onto the disk.

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INTRODUCTION

Lenticular galaxies are traditionally assigned to early-type galaxies, with the red color and the absence of visible traces of current star formation being their prominent sign. However, various surveys of representative samples of nearby early-type galaxies, for example, within the ATLAS-3D project (Cappellari et al. 2011), show that very many and, in a sparse environment, most of the lenticular galaxies possess extended gaseous disks (Welch and Sage 2003; Sage and Welch 2006; Welch et al. 2010; Davis et al. 2011). However, only less than half of the gas-rich S0 galaxies exhibit at least faint signs of current star formation (Pogge and Eskridge 1993). If the field lenticular galaxies accrete an external cold gas just as the spiral ones, why does star formation not proceed properly in their disks? In attempting to answer this question, we have recently analyzed the velocity fields for a small sample of nearby S0 galaxies in which extended, regularly rotating gaseous disks are observed (Sil'chenko et al. 2019). It turned out that an inclined direction of the gas inflow onto the galactic disk could be responsible for the absence of star formation: in this case, the gas experiences shock excitation, heats up, and cannot collapse into stars. Thus, not only the very presence of a gas, but also the direction from which it comes into the galaxy can be important for the formation of its morphological type.

In this paper we present one more lenticular galaxy in which there is an extended gaseous disk, but, apparently, there are no quite young stars. This is the medium-luminosity lenticular galaxy NGC 4143 (M₅₀₀₀ = −23.4, NED). The gaseous disk detected by us consists of an ionized warm gas; this time no cold neutral hydrogen and molecular gas have been recorded (Young et al. 2011; Serra et al. 2012). The galaxy belongs to the Ursa Major cluster (Tully et al. 1996), in which there are many spiral galaxies, that has not yet relaxed structurally (it consists of several rich groups, Karachentsev et al. 2013; Pak et al. 2014) and in which there is no evidence for the presence or the effect of a hot intergalactic medium on the galaxies (Verheijen and Sancisi 2001). Few lenticular galaxies, Ursa Major members, actively accrete intergalactic neutral hydrogen (NGC 4026 and NGC 4111 (Serra et al. 2012), NGC 4138 (Jore
et al. 1996). The galaxy NGC 4143 itself is located on the cluster periphery and, specifically, nothing has been noticed around it in the 21-cm line. However, the [O III] λ5007 emission line was recorded in the galaxy within the ATLAS-3D spectroscopic survey (Cappellari et al. 2011) and the ionized-gas velocity field at the galactic center turned out to be quite unusual. We decided to undertake our own study of this lenticular galaxy, which has well fitted into the problematics of the absence of star formation in the gaseous disks of lenticular galaxies.

OBSERVATIONS AND DATA ANALYSIS

Our long-slit spectroscopy was performed on the night of March 2/3, 2016, with the SCORPIO-2 focal reducer at the 6-m SAO RAS telescope (Afanasiev and Moiseev 2011) with a VPHG1200@540 grism and a spectral resolution of 5 Å. A slit 1″ in width and about 6′ in length was oriented along the major axis of the galactic isophotes at \( PA = 144^\circ \). The total exposure was 1 h at a seeing of about 2.5″. We measured the line-of-sight velocities of the stellar component by cross-correlating the pixel-by-pixel spectra taken along the slit at various distances from the galactic center with the spectrum of the K1.5 III star HD 72184 taken on the same night with the same instrumentation. The data turned out to be deep enough to measure the stellar kinematics up to the optical boundaries of the galaxy. The line-of-sight velocities of the gaseous component were measured by a Gaussian analysis of the blend of the H_α + [N II] \( \lambda \lambda 6548, 6583 \) emission lines and the H_α absorption line. The results of our kinematic measurements, the radial profiles of the line-of-sight velocities of the gas and stars, are presented in Fig. 1.

Apart from the extended one-dimensional kinematic cuts obtained with a long slit, we had the two-dimensional line-of-sight velocity maps of the gas and stars for the galactic center obtained with the SAURON integral-field spectrograph (Bacon et al. 2001). The galaxy NGC 4143 was observed as part of the ATLAS-3D project (Cappellari et al. 2011) with the 4.2-m William Herschel Telescope (WHT) in the Canaries. The raw data were requested by us from the ING (Isaac Newton Group) open 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 \( 33^\prime \times 41^\prime \), one spatial element is \( 0.94^\prime \times 0.94^\prime \), and the spectral resolution is about 4 Å. The stellar and gas velocity fields for NGC 4143 are shown in Fig. 2. 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 of both components, stellar and gaseous, was traced; the kinematic major axis should coincide with the line of nodes of the disk in the case of circular rotation. Based on the SAURON data, we managed to extend our measurements of the orientation of the kinematic major axis up to a distance of about 20″ from the center.

A photometric analysis of the galactic structure has been repeatedly presented in the literature. A two-dimensional decomposition of the NGC 4143 image was undertaken by Laurikainen et al. (2010, 2011) and P. Erwin in a series of papers (Erwin and Sparke 2003; Erwin et al. 2005, 2008). We additionally performed an isophotal analysis of the \( g \) - and \( r \) -band images for NGC 4143 based on SDSS data, release 9 (Ahn et al. 2012), whose results are shown in Fig. 3.

We also carried out observations at the 2.5-m CMO SAI MSU telescope (Kornilov et al. 2014) with a new instrument—MaNGaL (Mapper of Narrow Galaxy Lines, Moiseev et al. 2020). MaNGaL is a tunable-filter photometer based on a scanning Fabry–Perot interferometer with an instrumental profile width (FWHM) \( \sim 15 \) Å. The detector, a low-noise iKoN-M934 1024 × 1024-pixel CCD camera, was used in a \( 2 \times 2 \) binning mode to save the readout time and to reduce the noise. The final scale was 0.66″/pixel. During the observations we successively accumulated the images when the filter band was tuned to the H_α and [N II] \( \lambda 6583 \) emission lines (given the mean velocity of the galaxy and the heliocentric correction) and to the continuum blueshifted by 50 Å from H_α. Such series of exposures allow the contribution from atmospheric transparency and seeing variations to be averaged. The observations were performed on the night of April 13/14, 2018, with total exposures of 2400 s in H_α and continuum and 2100 s in [N II] \( \lambda 6583 \); the spatial resolution on

![Fig. 1. Radial profile of the line-of-sight velocities of the gas and stars in NGC 4143 along the major axis of its outer isophotes. The stars represent the velocities of the stellar component, other symbols represent the ionized-gas velocities measured from various emission lines.](image-url)
Fig. 2. The stellar and gas velocity fields at the center of NGC 4143 calculated from the data of the SAURON integral-field spectrograph. The arrows directed northward and eastward in the upper left corner of the map indicate the orientation of the picture. The surface brightness distribution in continuum at a wavelength of 5100 Å for the stellar velocity field and in the [O III] λ5007 emission line for the gas velocity field are superimposed by isophotes.

Fig. 3. Results of our isophotal analysis of the SDSS images for NGC 4143: the radial variations in the position angle of the major axis and the ellipticity of the isophotes.

the combined images is 2.3". The reduction of the MaNGaL data differs little from that of ordinary direct images with narrow filters and is described in Moiseev et al. (2020). After the continuum subtraction, we obtained maps of the total galaxy field in the net fluxes of the Hα and [N II] λ6583 emission lines. This allowed us not only to study the ionized-gas morphology, but also to estimate the ratios of the strong nitrogen and hydrogen emission lines over the entire galactic disk by dividing one two-dimensional emission line intensity distribution by the other; the ionized-gas excitation mechanism can be constrained using the measurements of this ratio.

Since the relative intensity of the emission lines is low (in the galactic disk EW(Hα) lies within the range 0.5–1.5 Å), we checked the continuum subtraction accuracy in the MaNGaL data using our spectroscopic measurements with SCORPIO-2. We chose the coefficients by which the continuum images were multiplied to ensure the best agreement.
between the observed distributions of the equivalent widths $\text{EW}(\text{H}\alpha)$ and $\text{EW}(\text{[N III]})$ along the major axis of the galaxy from our spectroscopy and in the images with MaNGaL. The difference between these coefficients and those determined from background stars (as the standard technique suggests when working with narrow-band images) was only 2–4%, which is within the reasonable assumptions about the difference between the averaged continuum energy distributions of the background stars and the galaxy itself.

RESULTS OF OUR MEASUREMENTS

Both the line-of-sight velocity profile of the gas and stars along the major axis (Fig. 1) and the two-dimensional line-of-sight velocity maps of the gas and stars for the central part of NGC 4143 (Fig. 2) show that the gas in the galaxy rotates in the opposite direction with respect to the stars; our long-slit observations demonstrate this counter-rotation over the entire length of the gaseous disk, up to 45′′ (3.5 kpc) from the center.

If we look at Fig. 2b, where the two-dimensional gas velocity field in the central region of the galaxy measured from the $\text{[O III]} \lambda 5007$ emission line is presented, then we will see noncircular motions: the surface brightness distribution of the $\text{[O III]} \lambda 5007$ emission line appears as a one-armed spiral along which an excess of the line-of-sight velocity of the ionized, highly excited gas is observed. The switching of the relative gas velocities from plus to minus when passing from the outer side of the spiral to the inner one can be a manifestation of the radial gas flow toward the center along the spiral that is a shock front.

Figure 4 compares the photometric and kinematic parameters derived by the tilted-ring method from the two-dimensional velocity fields; more specifically, it compares the orientations of the kinematic and photometric major axes in the central region of the galaxy. In the case of circular rotation within a circular disk in an axisymmetric potential, the major axis of elliptical isophotes (and a circle at an arbitrary inclination to our line of sight in projection should appear precisely as an ellipse) will coincide in orientation with the line of nodes of the disk, while the maximum rotation velocity projection onto the line of sight will also be precisely on the line of nodes. Hence, the direction of the apparent maximum line-of-sight velocity gradient of the galaxy’s rotating component in this case should also be along the line of nodes: the photometric major axis should coincide with the kinematic one. If, however, the “test point” rotates in a nonaxisymmetric potential, for example, at the center of the disk of a barred galaxy, then, as Vauterin and Dejonghe (1997) showed in their simulations, the major axes, photometric and kinematic, should turn in opposite directions from the line of nodes (for a discussion and references, see also Moiseev et al. 2004). What do we actually see in Fig. 4 for the “barred” galaxy NGC 4143?

Our measurements of the orientation of the kinematic major axis of the stellar component fell strictly along the line of nodes, despite the presence of a bar claimed by Laurikainen et al. (2010, 2011) and Erwin and Sparke (2003) based on an analysis of the photometric data. The orientation of the kinematic major axis of the gaseous component not just deflected from the line of nodes of the galactic stellar disk, but it coincided with the orientation of the isophotes at a radius $R \approx 15″–20″$. Whereas the turn of the kinematic major axis of the gaseous component at the very center of the galaxy, at $R < 5″$, can be interpreted as noncircular gas motions (purely
Fig. 5. The images of NGC 4143 in narrow spectral bands centered at the continuum and the Hα and [N II] λ6583 emission lines (after the continuum subtraction) obtained with the MaNGaL instrument at the 2.5-m CMO SAI RAS telescope and a map of the ratio of the fluxes in the [N II] λ6583 and Hα emission lines. The region observed previously with SAURON is shown in the continuum image.

radial flows will show a turn of the orientation of the maximum line-of-sight velocity gradient by 90° relative to the kinematic axis of circular rotation), in the region of the maximum turn of the isophotes the gas behavior cannot be interpreted as noncircular rotation. This more closely resembles an inclined disk that, besides, also has a stellar component. Indeed, if we look at the results of our isophotal analysis of the galaxy images (Fig. 3), then we will see that at the radius of the maximum turn of the isophotes, \( R = 17'' \), which previous researchers interpreted as the bar end, the ellipticity of the isophotes is strictly equal to the ellipticity of the outer disk isophotes. If the bar were responsible for the turn of the isophotes, then at such a small deflection of the bar orientation from the line of nodes an enhanced ellipticity of the isophotes precisely at this radius could have been expected, which is not observed. It seems that both isophotal and kinematic analyses of the data for the central region of NGC 4143 more likely provide evidence for a central inclined disk containing a stellar component.
associated with the orientation of the plane of gas rotation, the gaseous disk.

Using the MaNGaL instrument at the 2.5-m CMO SAI MSU telescope, we obtained images of the total galaxy field in the narrow [N II] $\lambda 6583$ and H$\alpha$ emission lines and a map of the ratios of the fluxes in these emission lines by dividing one by the other (Fig. 5). The ratio of low-excitation lines, which the [N II] $\lambda 6583$ line is, to the hydrogen emission line is a good indicator of the gas excitation mechanism. The boundary [N II] $\lambda 6583$-to-H$\alpha$ ratio is 0.5: for the gas excited by young massive stars this ratio is always less than 0.5 (Kewley and Ellison 2008). The second necessary sign of gas excitation by young stars is a sufficiently large equivalent width of the H$\alpha$ emission line: although its lower limit in the presence of star formation is 1 $\AA$ (Cid Fernandes et al. 2010), it is usually required that EW(H$\alpha$) exceed 3 $\AA$. If we analyze Fig. 5 from the standpoint of these criteria, then we will find that the gas in NGC 4143 is excited not by young stars, but more likely by shock waves. The morphology of the galaxy images in the emission line fluxes shows the presence of spirals, with the spirals in the [N II] and H$\alpha$ fluxes coinciding with those in the [O III] emission line from the SAURON data in the central region. The location of these spirals closely coincides with the maximum ratio of the fluxes in the nitrogen and hydrogen emission lines: [N II]/H$\alpha$ > 1.5 (Fig. 5, lower right). Interestingly, if we rely on the spiral pattern of this last figure, then a minimum equivalent width of the H$\alpha$ emission line less than 1 $\AA$ will correspond to a minimum ratio [N II]$\lambda 6583$/H$\alpha \leq 0.5$, which outlines this pattern. Thus, the gas in the regions with a minimum ratio of the fluxes in the nitrogen and hydrogen emission lines is also excited not by young stars, but most likely by a shock, because these spirals are spatially far from the LINER-type active galactic nucleus in NGC 4143 (Cid Fernandes et al. 2010). This excitation physics of the gas is absolutely consistent with its kinematics. Indeed, when the gaseous disk rotates with a significant inclination with respect to the equatorial plane of the gravitational potential of the stellar disk, during each crossing of the potential well of the stellar disk by gas clouds a shock wave develops in the gas (Wakamatsu 1993). The one-armed spiral that we see on the surface brightness maps in the emission lines and that is absent on the surface brightness maps in continuum and broadband colors, i.e., it is associated neither with the stellar population nor with dust, can be a manifestation of the two-stream instability due to the dynamical interaction of two counter-rotating subsystems at the galactic center, stellar and gaseous (Loovelace et al. 1997).

**DISCUSSION**

Are There Young Stars in NGC 4143?

We estimated the mean age of the stellar population along the radius of NGC 4143 by applying the evolution model of “simple stellar populations” (Thomas et al. 2003), implying one short starburst, to the Lick indices measured at various distances from the center. This model is a fortiori applicable for the galactic nucleus and bulge, because our measurements of the Lick magnesium and iron indices show that at the center of NGC 4143 the magnesium-to-iron abundance ratio is approximately twice the solar one (Fig. 6a), and this suggests a short duration of the star formation epoch, less than 1 Gyr. In the galactic disk this ratio approaches the solar one, i.e., star formation there lasted longer than 2 Gyr. However, the mean age of the stellar population in NGC 4143 is homogeneously old, comparable to the age of the Universe, in all structural components of the galaxy (Fig. 6b). The SSP models, into which one short starburst to form the entire stellar population of the galaxy/galactic region is built, have the stellar population age as their parameter, i.e., the time elapsed after this main starburst. If, however, we apply the SSP models to real systems, in which the star formation epoch had a long duration (for systems with a solar magnesium-to-iron ratio this duration is at least 3 Gyr), then the age of the system estimated from these models is an age “weighted with the luminosity of stars.” Since the young generations of stars, including massive stars, are always brighter than the old ones, where the massive stars became extinct, this age estimate is shifted toward the starburst termination time. In the case of the NGC 4143 disk, the combination of a solar magnesium-to-iron ratio and an old SSP age suggests that its formation ended at least 10 Gyr ago, while it most likely began approximately 13−14 Gyr ago.

As we have noted above, our diagnostics based on the ratio of the fluxes in strong emission lines shows that there is no noticeable current star formation in the galaxy, i.e., there are no HII regions in the extended disk of NGC 4143. The integrated colors of the galaxy from the NED database, namely $NUV - r = 5.59$ from GALEX and SDSS/DR9 data and $W2 - W3 = 0.88$ from WISE data, also unambiguously assign NGC 4143 to the so-called passive galaxies (Kaviraj et al. 2007; Cluver et al. 2017). However, the ultraviolet map of the galaxy that we searched for in the open archive of the sky-survey data from the GALEX space telescope (Fig. 7) shows an extended disk with a radius of about 20$''$ in the far ultraviolet (FUV, the effective wavelength is 1500 $\AA$) and an even more extended one, up to 50$''$, in the near ultraviolet (NUV, the effective wavelength is
Fig. 6. Diagnostic index–index diagrams for measuring the ages and metallicities of the stellar populations along the radius of NGC 4143 from our long-slit spectroscopy (the measurements in the galaxy are represented by the black dots with error bars; they are connected by the polygonal line as one recedes from the nucleus marked by the big star). (a) Comparison of the magnesium and iron indices with the SSP (simple stellar population) models by Thomas et al. (2003) for various magnesium-to-iron abundance ratios in stars; the numbers near the model reference points specify the model metallicities; the model ages \( T \) are given near the tops of the model sequences. (b) The solid red lines represent the SSP models of the same age; the model age is given in Gyr; the total metallicity of the models is specified near the model reference points connected by the blue lines. The separate large symbols with error bars indicate the mean Lick indices for two tiers of the galactic stellar disk. Several globular clusters in the Galactic bulge with ages \( \sim 10 \) Gyr and metallicity \([Z/H] = -0.5\) dex (Beasley et al. 2004) are plotted for comparison.

Does the Pattern of Accretion Determine the Morphological Type of a Galaxy?

Thus, the example of NGC 4143 confirms the trend detected by us previously (Sil’chenko et al. 2019): no star formation proceeds in the gaseous disks inclined with respect to the stellar ones in lenticular galaxies. In a sense, this galaxy is an extreme example: its extended gaseous disk is fully ionized by a shock, while the neutral gas in NGC 4143 is not detected with a very low detection limit: \( \log M(\text{HI}) < 6.80 \) (Serra et al. 2012) and \( \log M(H_2) < 7.20 \) (Young et al. 2011). However, the stellar component associated with the accreted gas is probably also present in the central region of the galaxy: the geometry of the central stellar disk estimated by the methods of surface photometry is consistent with the kinematic estimates of the gaseous disk orientation parameters within \( 15'' - 20'' \) from the center. This means that the swallowing of a gas-rich satellite with an inclined orbit could be the source of accretion—a disrupted satellite is capable of providing both a gaseous component and a stellar one rotating in an inclined plane.

Accretion of an external cold gas onto disk galaxies is currently believed to be the most important effect that determines the entire course of galactic evolution (see, e.g., Combes 2015). If we turn to the general scenario for the evolution of galaxies in the nearby Universe, then it seems from intuitive considerations that galaxies of the same mass, in an environment of similar density, should accrete an external cold gas with an equal probability. Why do some of them (most) then form thin disks with current star formation, others (S0) inherit the old stellar disks from early evolution epochs and now have extended gaseous disks, but do not replenish the stellar disk component by young stars, and still others (Es), as a rule, do not have cold gaseous disks at all? This question is being actively pondered and discussed by astronomers at present. There is a view that these
Fig. 7. GALEX map of NGC 4143 in the FUV band ($\lambda_{\text{mean}} = 1530$ Å).

differences are entirely explained by the angular momentum of the accreting gas (see, e.g., Peng and Renzini (2020) and references therein). Indeed, statistically, the gaseous disks of S0 galaxies are more extended than those of spiral ones (Wang et al. 2016); maybe the gas infalling onto S0s does not reach the central disk regions, where it can become denser and ignite star formation, due to its high angular momentum (Peng and Renzini 2020). In contrast, apart from the angular momentum of the infalling gas, we propose to add yet another factor: the direction from which it infalls. Indeed, to explain the very rapid evolution of the angular momentum of spiral galaxies over the last 8 Gyr, it should be assumed that an external gas is accreted onto them strictly in the plane of their stellar disks, with the same spin direction as the disk rotation direction (Renzini 2020). And what if the gas infalls at an angle? Our studies (Sil’chenko et al. 2019) suggest that, first, it is often observed in S0 galaxies and, second, in this case the infalling gas is heated by a shock and becomes incapable of star formation. Thus, the difference in the morphological type of a disk galaxy can actually be a difference in the pattern of accretion: in the direction of external-gas infall, in the orientation and magnitude of its orbital spin, and, of course, also in the amount of mass flow. As regards the elliptical galaxies, the difference in the observed X-ray flux from the gaseous galactic halos comes to mind here: in field elliptical galaxies it is substantial and has been repeatedly measured by the Chandra and XMM-Newton spacecraft (see, e.g., Mulchaey and Jeltema 2010), while in spiral galaxies of the same mass it is detected with great difficulty. Maybe the cold gas does not reach the elliptical galaxies, because it is heated during the flow through the hot halo gas. It is then clear why no large-scale gaseous disks form around elliptical galaxies, even those located in a sparse environment.

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