Inner Polar Gaseous Disks: Incidence, Ages, and Possible Origin

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Abstract. We review our current knowledge about a particular case of decoupled gas kinematics, inner ionized-gas polar disks. Though more difficult to be noticed, they seem to be more numerous than their large-scale counterparts; our recent estimates imply about 10% of early-type disk galaxies to be hosts of inner polar disks. Since in the most cases the kinematics of the inner polar gaseous disks is decoupled from the kinematics of the outer large-scale gaseous disks, and since they nested around very old stellar nuclei, we speculate that the inner polar disks may be relic of very early events of external gas accretion several Gyr ago. Such view is in agreement with our new paradigm of disk galaxies evolution.

1. Introduction

Among gas subsystems with decoupled kinematics, a particular interest is inspired by polar rings/disks. Firstly, they are beautiful, secondly, they seem to be stable over many dynamic times, and thirdly, they imply certainly accretion of external gas from highly inclined orbits. Inner polar gaseous disks are less spectacular than large-scale polar rings; however they may be even more numerous though difficult to be detected against the bright bulge background in early-type disk galaxies.

We note that the first evidence of existence of circumnuclear gas on polar orbits in the literature was presented by Rubin et al. (1977) in their interpretation of the large line-of-sight velocity gradient along minor axis in NGC 3672. Further Bettoni et al. (1990) have claimed inner polar gaseous disk in the Southern ringed lenticular galaxy NGC 2217. By studying it through long-slit spectroscopy, Bettoni et al. (1990) found visible gas counter-rotation in some slit orientations (not all). Their geometrical scheme for the center of NGC 2217 demonstrated clearly that the ionized-gas disk had to be warped in such a way that in the very center it occupied the polar plane orthogonal to the bar major axis. Later we found inner polar disks in unbarred early-type spiral galaxies NGC 2841 (Sil'chenko et al. 1997) and NGC 7217 (Sil'chenko & Afanasiev 2000) by obtaining 2-dimensional velocity fields for the ionized gas and for the stellar component with the integral-field unit (IFU) of the Multi-Pupil Fiber Spectrograph (MPFS) mounted at the 6-m telescope of the Special Astrophysical Observatory (SAO) of the Russian Academy of Sciences (RAS). The outer neutral hydrogen in both spirals is confined to their main symmetry planes and rotates normally. It was a puzzle how

a small amount of polar-orbiting gas could reach the circumnuclear regions without colliding with the main gaseous disks.

Now a few dozens of inner polar gaseous disks/rings are known. Their samples were presented earlier by Corsini et al. (2003) and Moiseev et al. (2010); the latest statistics based on the data for 47 inner polar disks collected over literature is published by Moiseev (2012), and here we review briefly some incidence properties.

2. Incidence

When we analyze all the cases with the inner gaseous disks inclined to the galactic symmetry planes by more than 45°, we find that the inclinations of such disks tend strongly to the strictly polar orientation: about two thirds of all such disks are inclined by $\gtrsim 80°$. This is consistent with theoretical claims about stability of the strictly polar orientations and instability of the disks inclined by intermediate angles; the latters would precess until they occupy the polar or co-planar orientation.

The inner polar disks, as well as the large-scale ones, prefer to inhabit early-type galaxies. However, while large-scale polar rings are seen mostly around gas-poor E/S0 galaxies (about a factor of 3 more often than around spirals), and it can be explained by them devoiding the hosts with large-scale coplanar gaseous disks (Reshetnikov et al. 2011), the inner polar disks are found in Sa–Sc spiral galaxies in one third of all cases, and large-scale coplanar gaseous disks do not prevent their appearance (see the above mentioned examples of NGC 2841 and NGC 7217). Even a few cases are known to be found in very late-type dwarfs. The typical size (radius) of an inner polar disk is $0.2 - 2$ kpc. The lower limit is perhaps defined by our restricted spatial resolution. If to consider inner polar disks, together with the large-scale relatives, a continuous sequence in their sizes, normalized by a galaxy diameter, is observed with a gap at the size $\sim 0.5\,D_{25}$. This bimodal distribution can be explained by different agents of stability for polar structures: while the external structures are stabilized by the spheroidal (or even triaxial) potential of halo, the inner disks are usually settled well within the bulge-dominated area (Smirnova & Moiseev 2013). In any case, the presence of embedding stabilizing potential is important. Is it crucial that this 3-dimensional potential has to be also triaxial as in NGC 2217 (Bettoni et al. 1990)? Moiseev (2012) presents the following statistics: among 40 galaxies with the inner polar disks which have the morphological type S0 and later there are 17 galaxies with bars or triaxial bulges. This gives us the fraction of barred galaxies among galaxies with the inner polar disks, only $(43 \pm 8)\%$, completely consistent with the fraction of barred and/or triaxial-bulge galaxies among all disk galaxies, 45% (Aguerri et al. 2009).

The list of all known till 2012 inner polar disks by Moiseev (2012) cannot be used to estimate how often the phenomenon can be met: the sample of the hosts of the inner polar disks listed there is quite inhomogeneous. To estimate the inner polar disk incidence, we have used the data of the recent integral-field spectroscopic survey ATLAS-3D (Cappellari et al. 2011). The ATLAS-3D sample is volume-limited one and includes 60 elliptical galaxies and 200 lenticular galaxies (if we classify NGC 2768 as S0). We have taken the raw science and calibration frames from the open Isaac Newton Group Archive of the Cambridge Astronomical Data Center and have calculated the stellar and ionized-gas line-of-sight velocity fields. Then the orientation of the rotation planes for both components in every galaxy was determined by fitting a circular-rotation model, and the angles between the rotation planes of the stellar and gaseous components

were calculated by using the Eq. 1 from Moiseev (2012). Among 200 S0 galaxies of the ATLAS-3D volume-limited sample, we have found 8 new inner polar gaseous disks with the inclination to the stellar rotation planes by more than $50°$ (taken into account both solutions of the Eq. 1 from Moiseev (2012), because we do not know which side of the is nearest to the observer); 12 inner polar disks in the S0 galaxies of the ATLAS-3D sample have been already listed in Moiseev (2012). Having in total 20 inner polar disks in S0 galaxies of the ATLAS-3D volume-limited sample, we conclude that nearby lenticular galaxies have inner polar disks in 10% of all cases. Our estimate refers to the totality of S0 galaxies over *all* types of environments. This incidence of the inner polar disks in the early-type disk galaxies, 10%, exceeds greatly the frequency of the large-scale polar rings, $(0.1 - 0.4)$% (Reshetnikov et al. 2011).

Fig. 1 shows a nice example of the newly discovered inner polar disk in the lenticular galaxy NGC 2962, a member of the ATLAS-3D volume-limited sample. We have observed this galaxy earlier at the Russian 6-m telescope with the integral-field spectrograph MPFS, which field of view was $16'' \times 16''$, and in the very center, inside $R = 5''$, we saw a compact, fast rotating, nearly edge-on polar gaseous disk. But with the larger field of view of the Spectrographic Area Unit for Research on Optical Nebulae (SAURON), $41'' \times 33''$, we are now seeing a switch of the gas rotation sense at $R \simeq 7'' - 10''$: the galaxy possesses two nested polar gaseous disks counterrotating each other (Fig. 1).

3. Origin

3.1. Is the Polar Momentum Internal or External?

This question may seem to sound strange: if a main baryonic component, stars which are formed from the own gas of the galaxy, rotates in the galactic disk symmetry plane, how may the polar gas be of local origin? Meanwhile there are intrinsic secular evolution mechanisms that produce strongly inclined gaseous disks in the very center of a galaxy, and one of them had been revealed by simulations of Friedli & Benz (1993). By tracing dynamical evolution of *initially retrograde* gas in the disk of an isolated barred galaxy, Friedli & Benz (1993) have found that, after about 2 Gyr of angular momentum exchange with the stellar bar, the gas inside a few hundred parsec comes to a strongly inclined plane due to vertical instabilities. Since retrograde motions of stars are always present in the barred potential (Pfenniger 1984), and since stars drop gas during their evolution, in principle the inner polar gaseous disks may form in barred galaxies without outer donor contribution. Indeed, we have found several cases when the presence of the inner polar disk in the very center is accompanied by the presence of counterrotating gas in the more outer disk, e.g., in NGC 7280 (Afanasiev & Sil'chenko 2000; Sil'chenko 2005). But the presence of a bar is necessary. However, the statistics given in the previous section does not show prevalence of barred galaxies among the hosts of inner polar disks: less than a half of the hosts of inner polar disks reveal triaxiality of their inner stellar structures. So we are now inclined to the hypothesis of the external gas accretion as the dominant mechanism of inner polar disk formation.

3.2. How Much Gas Can Be in a Polar Orbit?

To identify a source of gas accretion, we must estimate first of all typical amounts of gas populating polar orbits. Here a lot of diversity is observed. In some cases the
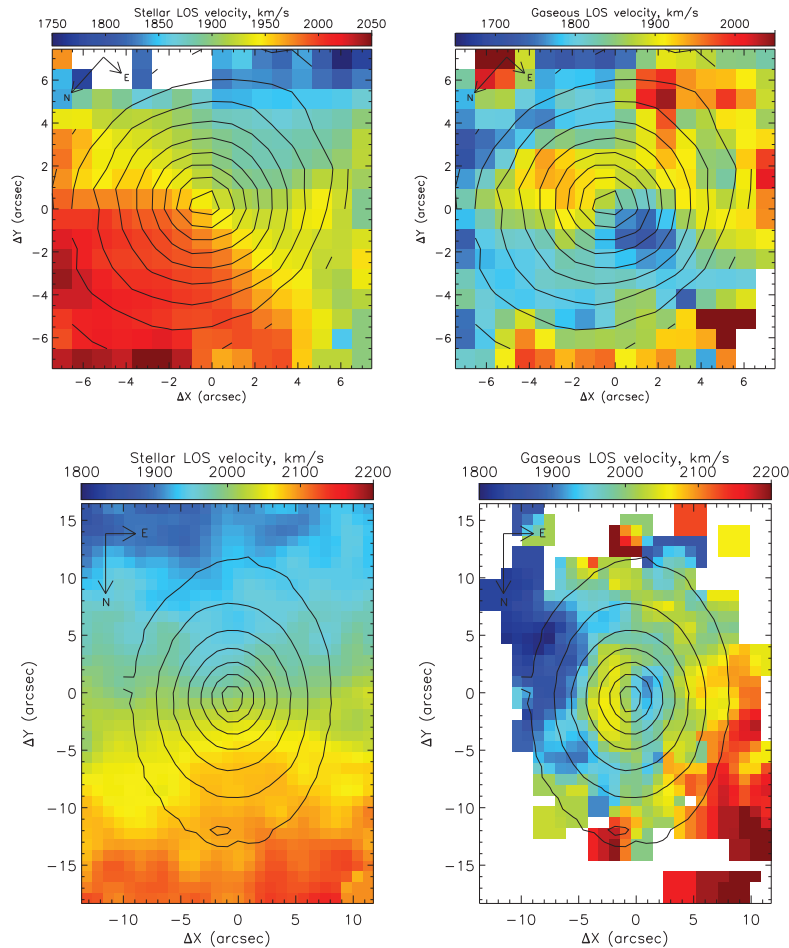
Figure 1.   The line-of-sight velocity fields for the stellar and ionized-gas components in the lenticular galaxy NGC 2962. Top panels: Data from the MPFS of the Russian 6-m telescope. Bottom panels: Our reduction of the SAURON data.

inner polar ionized-gas disks have their extension into the very outer parts of galaxies when they are observed at the 21-cm line of the neutral hydrogen, these are the cases of NGC 3414 (with the inner polar disk found by Sil'chenko & Afanasiev 2004) or of NGC 7280 or of UGC 9519 mapped in the neutral hydrogen line by Serra et al. (2012). In the prototype of large-scale polar ring galaxies, NGC 2685, the inner ionized gas is also polar (Sil'chenko 1998). In these cases the total mass of the polar gas can be as large as $10^8 - 10^9$ M$_\odot$, and the $M(\mathrm{H\,I})/L_K$ ratios resemble those of spiral galaxies (Serra et al. 2012). In the volume-limited S0-galaxy sample from ATLAS-3D (Cappellari et al. 2011) about one third of all galaxies with the inner polar ionized-gas disks have polar neutral-hydrogen outer extension. However many galaxies have inner *polar* ionized-gas component and outer *coplanar* neutral-hydrogen disk; and they are sometimes also rather gas-rich but their main gaseous components are confined to the galaxy symmetry planes. Among lenticular galaxies, we can mention NGC 2962 where Grossi et al. (2009) have found 1.1×10^9 M$_\odot$ of neutral hydrogen in a disk coplanar to the stellar one,
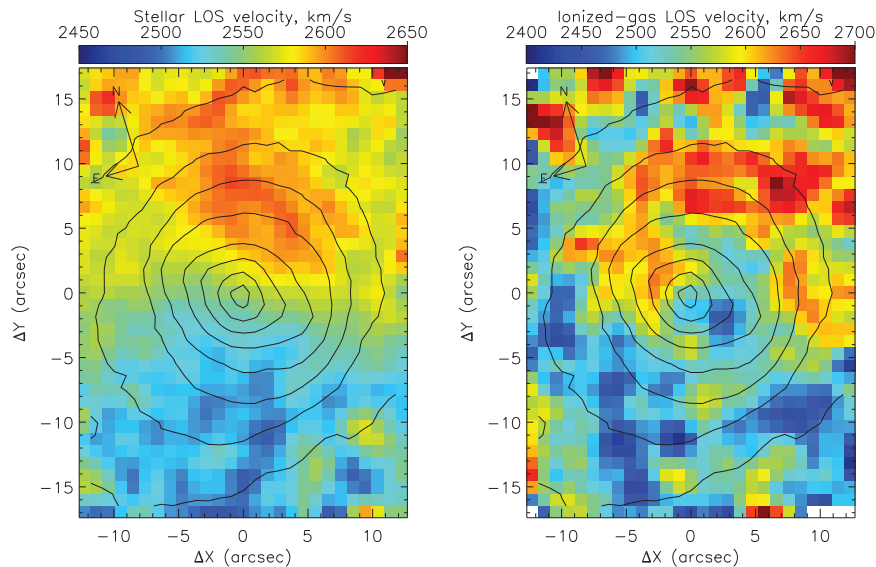
Figure 2. Our reduction of the SAURON data for the spiral galaxy NGC 5850. Left panel: Line-of-sight velocity field for the stellar component. Right panel: Line-of-sight velocity field for the ionized-gas component.

but extending much farther from the center. And certainly even more such cases can be found among spiral galaxies with the inner ionized-gas polar disks. An inner ionized-gas polar disk was found in a barred spiral, SB(r)b, galaxy NGC 5850 by Moiseev et al. (2004); the stellar and gaseous rotations were compared over the $16'' \times 16''$ field of view of the 6-m telescope IFU MPFS. Now we have calculated larger stellar and gaseous velocity fields by using the archival SAURON data (Fig. 2). One can immediately see from Fig. 2 that the sense of the gas rotation changes at the radius of $7'' - 10''$ $(1.3 - 1.8$ kpc); the more outer ionized gas rotates together with the stars. And the same orientation of the rotation plane is demonstrated by all the 2×10^9 M$_\odot$ of neutral hydrogen measured in NGC 5850 by Higdon et al. (1998). The same patterns of stellar and ionized gas circum-nuclear kinematics were also presented recently in the paper by Bremer et al. (2013), which is based on Very Large Telescope (VLT) observations with the Visible Multi Object Spectrograph (VIMOS) IFU. The better spatial resolution (comparing with the early observations by Moiseev et al. 2004) has allowed to calculate precisely the kinematic orientation parameters in the inner disk velocity field. Bremer et al. (2013) claimed that the angle between the inner and outer disks planes is only 24°, however the Eq. 1 from Moiseev (2012) gives also the second solution, 54°, that corresponds to the case of strongly inclined inner gaseous disk.

3.3. NGC 7217

An interesting case of a spiral galaxy with the inner polar ionized-gas disk having the radius of only 350 pc (Sil'chenko & Afanasiev 2000) is represented by an isolated Sab galaxy NGC 7217; here we show the recent Hubble Space Telescope (HST) image of the central part of the galaxy (Fig. 3), where the inner ionized-gas polar disk can be seen
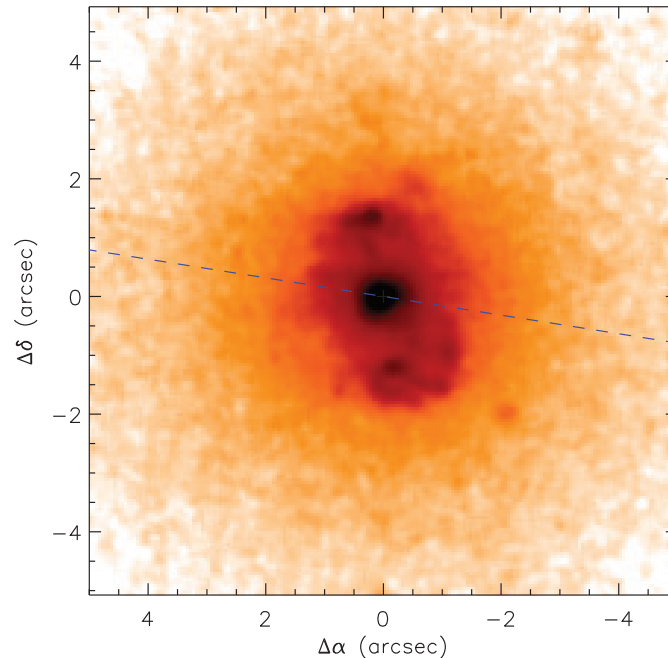
Figure 3.   The narrow-band emission-line (F658N − F814W) image of the central part of NGC 7217 obtained with the Advanced Camera for Surveys (ACS) mounted on HST. The dashed line shows the line of nodes of the galactic stellar disk.

'by eye' in the narrow photometric band centered onto the emission lines Hα+[N II]. Its neutral hydrogen disk, 0.7×10^9 M$_\odot$, extending to $R \simeq 8$ kpc, is coplanar to the stellar disk and rotates just as the stars. At the outer edge of this disk intense star formation in a ring is observed, though the visible gas density is below the gravitational stability threshold (Noordermeer et al. 2005). Recently we have studied the origin of the complex structure of NGC 7217 in detail (Sil'chenko et al. 2011), and here we discuss this galaxy as a pure key point revealing possible formation mechanisms of the inner polar disks.

Photometric structure of NGC 7217 can be described as three-tiered: we have separated three exponential segments in its surface-brightness radial profile (Sil'chenko & Afanasiev 2000). The innermost segment seen only at $R < 10''$ (0.8 kpc) may be a pseudo-bulge; then other two segments represent an antitruncated disk. Our deep long-slit spectroscopic observations (Sil'chenko et al. 2011), having allowed to measure stellar rotation and line-of-sight velocity dispersion (close to a vertical velocity dispersion because the galaxy is seen almost face-on) as well as the properties of the stellar populations, have revealed prominent differences in all respects between two exponential parts of the stellar disk. Firstly, the inner part of the disk is substantially thinner than the outer part, and secondly, the mean age of the stellar population in the inner disk is 5 Gyr, while the stellar ages in the outer disk, even beyond the starforming ring, is very young, less than 2 Gyr. The galaxy being an early-type spiral without a

bar, possesses meantime three rings of current star formation (Verdes-Montenegro et al. 1995). Interestingly, the age of the nuclear stellar population, inside the circumnuclear starforming ring, is *very* old, more than 10 Gyr. Obviously, despite violent processes of gas radial re-distribution and external gas accretion betrayed by the inner polar disk presence, the gas has never reached the very center of NGC 7217 for the last 10 Gyr.

Having in hands the detailed structure of NGC 7217 and evolutionary sequence of building elements of this structure, we have tried to fit observational properties of NGC 7217 with the models provided by on-line service GalMer (Chilingarian et al. 2010). We have found that only at least *two* independent gas-rich minor-merger events can provide a full list of properties: the inner polar disk is formed by an accretion of a gas-rich dwarf from an inclined retrograde orbit, and the outer flaring ringed star-forming disk is shaped by merging a prograde-orbiting satellite. The necessity of two minor mergers is due to the fact that minor merging from a retrograde orbit gives an inclined inner gaseous disk but does not thicken the large-scale stellar disk. The latter feature requires minor merging from a prograde orbit. Since the star formation burst in the outer disk of NGC 7217 is very young, we conclude that the minor merging from a retrograde orbit was the first event, and minor merging from a prograde orbit was the last, quite recent one.

4. Ages

The large-scale outer polar rings may be stable in the polar state over a few Gyr according to theoretical estimations (e.g., Steiman-Cameron & Durisen 1982) as well as to numerical simulations (Snaith et al. 2012). Stability of their circumnuclear counterparts is still an open question. However some observational evidences in favor of their very long living times also exist: just among lenticular galaxies with the inner polar disks we found *very* old stellar nuclei, $T > 10$ Gyr (Sil'chenko & Afanasiev 2004), while over the full sample of nearby lenticular galaxies the typical ages of the stellar nuclei are $2 - 5$ Gyr (Sil'chenko 2006, 2008).

The whole evolution of disk galaxies is governed by the regime of external gas accretion. Recently, we have proposed a scenario according to which all disk galaxies were formed around $z \simeq 2$ as lenticular galaxies, and only much later, at $z < 1$, most of them started smooth gas accretion and, after having formed thin dynamically cold stellar disks, transformed into spirals (Sil'chenko et al. 2012). In the frame of this scenario, a natural epoch of forming inner polar gaseous disk is very early stages of the accretion era. If the first accretion event was from a highly inclined orbit, an inner polar long-living gaseous disk would form *before* the main gas accretion in the galactic symmetry plane proceeded. It is the way to obtain a stable system with mutually orthogonal nested gaseous disks, and then inner polar disks would be relics of very early events of external gas accretion.

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