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Retrograde fall of intergalactic gas onto the S-galaxy: polar rings and activity of galactic nuclei

S. Khrapov, A. Khoperskov, and N. Khrapov

Volgograd State University, 100 Prospect Universitetsky, Volgograd, 400062 Russia

Abstract. The dynamics of intergalactic gas accretion in a gas-rich spiral galaxy has been studied. We use numerical simulations to determine the conditions that lead to the formation of counter-rotating stellar and gas components within the galaxy and promote the influx of gas into the central part of the galaxy with a radius of less than one kiloparsec. The focus is on the dynamic interaction between the intergalactic flow and the gas-rich disc galaxy. The study of the mechanism by which gas is supplied to the central region to fuel the activity of galactic nuclei is a critical part of our work. The retrograde fall of the gas forms a massive, concentrated gas halo at the center of the galaxy, which may provide fuel for the activity of galactic nuclei. An angle of incidence of the gas flow of about 20 degrees to the galactic plane is the most effective and provides maximum gas concentration. Deviations from this angle lead to a decrease in the velocity of the gas flow into the galactic center. The prograde infall of intergalactic gas is incapable of cardinal disruption of the disc and does not result in an effective inflow of gas within 1 kpc radius. This accretion mode provides 100 times less gas mass within the 1 kpc radius compared to retrograde infall. An important additional result of retrograde accretion is the appearance of rotating gas rings at the periphery of the galaxy, which are mainly formed by falling intergalactic gas. The inclination of these rings with respect to the galactic plane varies widely, from 10 to 90 degrees, and depends on the angle of incidence of the intergalactic gas. The numerical simulations of counter-rotating stellar-gas discs cover all stages of the interaction with the falling intergalactic flow over a period of about 7 billion years.

Keywords: physics and evolution of galaxies: gas accretion; active galactic nuclei; polar rings

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1 Introduction

Outer polar rings are a common galactic phenomenon, perhaps accounting for 1–3 % of S-galaxies (Moiseev et al. 2011; Mosenkov et al. 2024). There is strong observational evidence that the presence of polar rings correlates with central nuclear activity (La Marca et al. 2024). Mergers can enhance the influx of gas into the galactic center towards the supermassive black hole by several physical mechanisms (Blumenthal & Barnes 2018). Dust-obscured active galactic nuclei (AGN) are likely to be in the stage of rapid growth of the central supermassive black hole, so that powerful AGNs are fed by the resulting galaxy mergers (La Marca et al. 2024).

Analysis of some cosmological simulations does not show a clear connection between mergers and AGN activity (Sharma et al. 2024), creating additional intrigue in understanding the physical influence of strong interactions on AGN (Smirnov & Reshetnikov 2020). We have studied the efficiency of gas delivery to the central kiloparsec as a result of retrograde and prograde accretion of intergalactic gas under different conditions of matter infall into the galaxy.

The formation of polar rings is associated with galactic mergers. A special case is the interaction of a gas-rich spiral galaxy with an intergalactic gas flow (Khrapov & Khoperskov 2024). Our efforts are aimed at studying the conditions for the formation of tilted rings, as a more general class of polar rings (Moiseev et al. 2011; Mosenkov et al. 2024). We also note that the geometry and kinematics of the gas in the outer tilted ring can be an important tool for analyzing the properties of the dark halo (Combes et al. 2013).

2 Simulation results

The study uses numerical simulations of the dynamics of a collisionless N-body system (stars + dark matter) together with computational fluid dynamics using the method of Smoothed-particle hydrodynamics on a hybrid computing platform CPU + multi-GPUs (Khoperskov et al. 2021; Khrapov & Khoperskov 2024). We consider the accretion of intergalactic gas onto an S-galaxy with a sufficiently massive gas disk ($M_{\rm gas} \sim 0.2 M_{\rm stars}$). The accreting intergalactic matter is modeled by eight closely flying spheroidal gas clouds (discrete jet) with a velocity of ~ 100 km/s. The angle of incidence of the gas onto the galaxy, Θ_g, varies in different computational experiments. Both prograde and retrograde accretion types are considered. The most interesting results occur during retrograde infall, which leads to both the formation of tilted (polar) rings and hundredfold increase in the feeding of the supermassive black hole at the center of the galaxy.

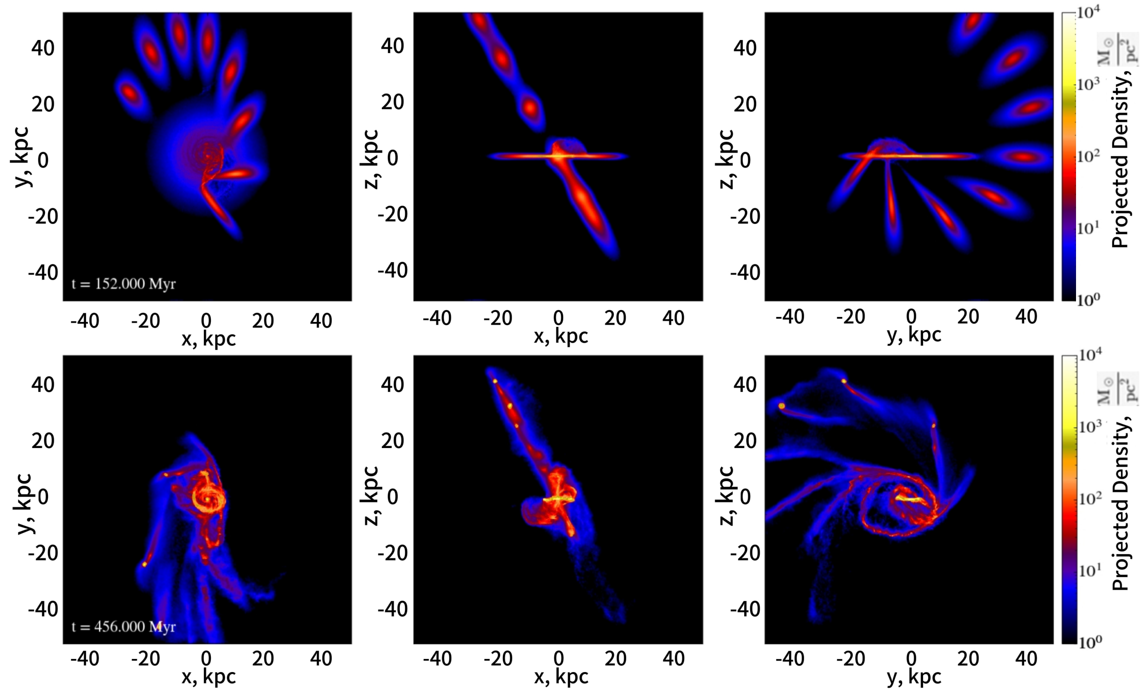

Fig. 1. Accretion of intergalactic gas onto a spiral galaxy in our numerical model. The moment of collision is shown in the top panel and the initial stage of polar ring formation is shown in the bottom panel (at ~ 300 Myr after the collision). Each frame has a size of 100×100 kpc along each projection (XY, XZ, YZ). The range of variation of the surface gas density along the line of sight is 1–10^4 $M_\odot/pc^2$.

Figure 1 shows the moment of the first impact of the intergalactic retrograde jet with $\Theta_g = 60°$ into the gas disk of the model galaxy and the initial stage of the polar ring formation. The gas clouds of the intergalactic flow are strongly deformed by the tidal forces as they move towards the galaxy. The first impact and subsequent ones lead to the galactic and accreting gas to be ejected into intergalactic space. The remaining gas in galactic region forms an extended polar ring $\sim$ 40–50 kpc in size after approximately 300 Myr. In addition, a compact gas disk with high central density is formed in the central part of the galaxy. The dynamics of the polar gas ring, gas and stellar disks are shown in Fig. 2. A stable structure of the polar ring is formed by the time ~ 3 Gyr. Then there is a slow precession of its plane of rotation around the axis Z. A slow precession of the plane of the gas and stellar disks around the axes Y and X is observed.

The main results of the simulation are summarized in Fig. 3. Panel a shows the efficiency of gas delivery into the central parsec of the galaxy as a function of the

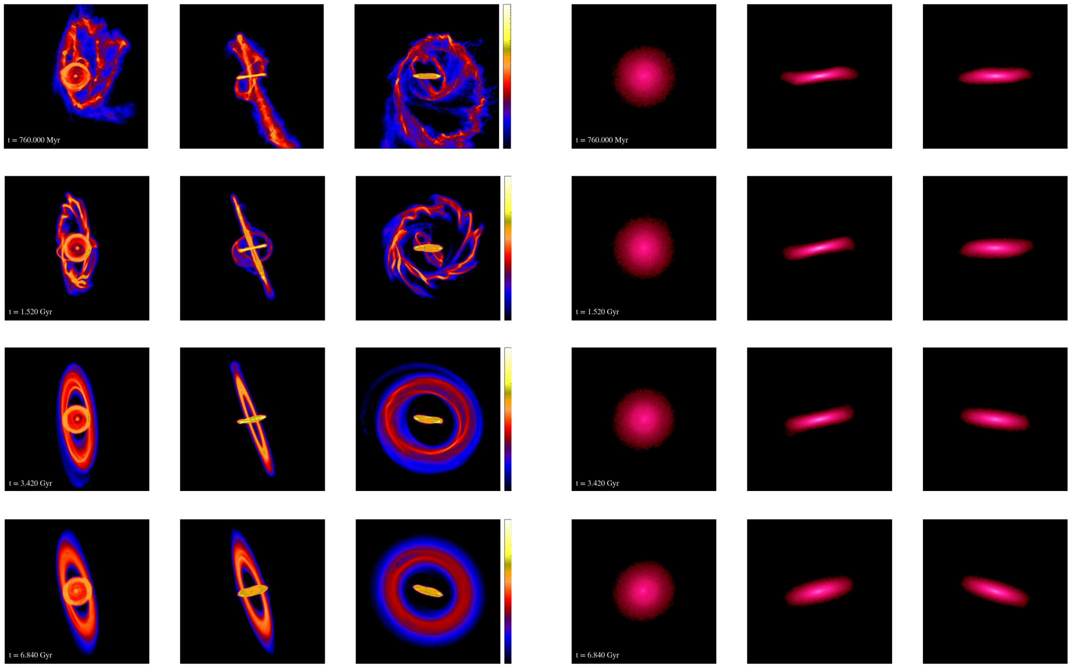

Fig. 2. Evolution of the polar gas ring in the galaxy over the time interval from 760 Myr to 6.84 Gyr. The gas subsystem of the galaxy (left) and the stellar disk (right) are shown. The frame has a size of 50×50 kpc along each of the projections (XY, XZ, YZ). The range of variation of the surface density along the line of sight is within 1–10^4 $\mathrm{M}_\odot/\mathrm{pc}^2$ for the gas and — 10–10^4 $\mathrm{M}_\odot/\mathrm{pc}^2$ for the stars.

angle of attack of the extragalactic flow Θ_g. Comparing prograde and retrograde infall, the mass flow M_{core} into the central parsec ($R_{\mathrm{core}} = 1\,\mathrm{kpc}$) is a factor of 100 larger in the second case than in the first. Only the counter-rotating flow is able to be an efficient fuel source for the central galactic activity. The efficiency of the co-rotating accreting flow is small.

The angle of incidence of the gas on the galaxy Θ_g is one of the key factors determining the influx of gas mass into the core region M_{core}. Very small angles produce glancing blows that facilitate the efficient removal of the angular momentum of the gas component. Large angles of incidence ($\Theta_g \gtrsim 40^\circ$) change the interaction pattern and enhance the ejection of gas from the stellar disk region. Therefore, the influx of gas into the central kiloparsec is significantly reduced and relationship $M_{\mathrm{core}}(\Theta_g = 20^\circ)/M_{\mathrm{core}}(\Theta_g = 45^\circ) \simeq 100$. The best conditions for gas supply to the galactic center are obtained at an angle of $\Theta_g \simeq 20^\circ$.

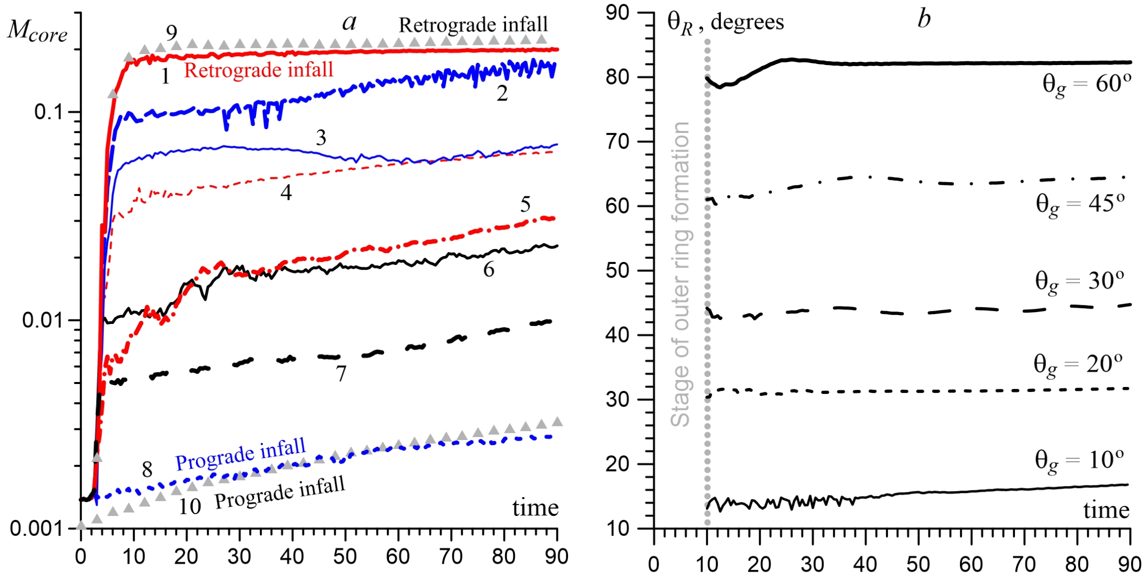

Fig. 3. a — Dependence of the gas mass inside 1 kpc for different angles of attack of the accreting intergalactic gas flow. Models of the bulgeless galaxy with retrograde infall (Khrapov & Khoperskov 2024): $\Theta_g = 20°$ (curve 1), $\Theta_g = 10°$ (2), $\Theta_g = 5°$ (3), $\Theta_g = 30°$ (4), $\Theta_g = 40°$ (5), $\Theta_g = 45°$ (6), $\Theta_g = 60°$ (7); prograde infall model at $\Theta_g = 20°$ (8); models with the bulge at $\Theta_g = 20°$ (curves 9 and 10). b — Outer gas ring tilt angles Θ_R vs. time (t) for different Θ_g.

The outer ring formation stage lasts for approximately 600–800 Myr (see vertical dotted line in Fig. 3b, $t = 10 \to 760$ Myr). Then the tilt angle of the gas ring Θ_R changes very little over 6 billion years in the absence of other external influences. The tilt angle of the outer ring with respect to the plane of the main galaxy is always greater than the angle of incidence of the initial gas flow, $\Theta_R > \Theta_g$. The ratio of the angles $\alpha_{Rg} = \Theta_R/\Theta_g$ is between 1.3–1.7 and depends on the angle Θ_g. We focus on the fact that the gas flow at the angle $\Theta_g > 60°$ forms a polar ring at angle $\Theta_g > 80°$. Thus, we have predominantly perpendicular external structures in the form of typical polar rings.

3 Summary

We studied the dynamics of the fall of an intergalactic gas flow onto a gas-rich spiral galaxy. This accretion regime can lead to two observed phenomena simultaneously. The result is both an additional influx of gas into the region of the central supermassive black hole and the formation of outer gas rings similar to polar-ring systems.

The angle of incidence of the intergalactic gas flow onto the spiral galaxy (Θ_g) is a key parameter in our study. The efficiency of the gas inflow into the AGN region is very sensitive to the angle Θ_g and is maximal at $\Theta_g \simeq 20^\circ$. The presence of a stellar bulge in the main galaxy has little effect on the gas inflow into the central kiloparsec. The additional mass in the center of the galaxy is approximately 100 times greater for the retrograde infall of intergalactic gas than for the prograde case. This is due to more favorable conditions for the removal of angular momentum in the gas disk.

The outer inclined gas rings are a typical result of the considered accretion of intergalactic matter at angles of incidence $\Theta_g = (10–90)^\circ$ in all numerical experiments with retrograde rotation. The angle between the outer ring and the main disk Θ_R depends on the value of Θ_g, but the condition $\Theta_R \geq 1.3 \cdot \Theta_g$ is always satisfied. Falling gas onto the galaxy with $\Theta_g = (55–90)^\circ$ ensures the formation of a polar ring with $\Theta_R \simeq 90^\circ$.

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