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Simulation of images of a protoplanetary disk after a collision with a gas stream

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Abstract

Recent observations using the largest telescopes provide reliable evidence of the presence of gas flows interacting with the protoplanetary disks of young stars called streamers. Similar structures have been previously predicted in large-scale three-dimensional numerical calculations. Studying the interaction of such flows with the protoplanetary disk from the point of view of gas dynamics is an interesting problem, and it was performed by us earlier. In this paper, we have focused on observational manifestations of consequences of such interactions.

It turned out that during the prograde and retrograde fly-through of the stream, a different spiral pattern is formed, and in the retrograde case one can expect the appearance of an inner inclined disk around the star. It is shown that such a disk can exist for more than a hundred years, and in observations it appears as light and dark regions in the protoplanetary disk. Moreover, the results of measuring the geometric parameters of the inner disk in simulated images perfectly match the results of the density distribution analysis. The simulation of observations showed that when observing the disk from the edge, it is also possible to detect features of an inclined inner disk.

Keywords: protoplanetary disks, accretion, numerical simulation, gas dynamics, synthetic images

JEL Classification: C6

1 Introduction

The hypothesis of continued accretion of matter from the remnants of a protostellar cloud after the formation of a protoplanetary disk (Hartmann and Kenyon 1985) finds confirmation in modern observations. Systematic research Gupta et al. (2023) of protoplanetary disks has shown that a significant part of these objects in nearby star formation regions may be associated with reflective nebulae, which may be the source of late accretion onto the disks. At Garufi et al. (2024) it is also shown that a third of the observed disks in the star formation region in Taurus show signs of interaction with their surroundings.

Small filaments of matter, denser than their surroundings, known as streamers, have been detected in the vicinity of young accretion disks (Valdivia-Mena et al. 2022; Hsieh et al. 2023; Flores et al. 2023). Their matter accretes into disks at certain points. Accretion shock waves heat the disk and locally increase its mass, which can lead to the development of gravitational instability.

The chemical composition of the protoplanetary disks DG Tau and HL Tau suggests the presence of shock waves caused by accreting matter in the late stages of star formation. They may be common in disks in young star formation regions, which may have implications for the chemical composition and mass of the disk (Garufi et al. 2022; Artur de la Villarmois et al. 2026).

The presence of spirals at a relatively young stage of star formation with a low-mass protoplanetary disk, as well as azimuthal asymmetry in dust emission in the infrared range and large-scale kinematic features may be a consequence of the accretion of matter onto the disk plane from the remnants of a protostellar cloud. Examples of such objects are AB Aur (Piétu et al. 2005; Tang et al. 2012), SU Aur (Ginski et al. 2021) and DR Tau (Mesa et al. 2022).

Another manifestation of cloud accretion is the appearance of an inclined inner disk or warp near the star. Observations with large telescopes have shown that such distortions of the inner part of the disk relative to the periphery are common at the stage of the protoplanetary disk (Ansdell et al. 2020; Bohn et al. 2022; Villenave et al. 2024; Kimmig and Villenave 2025; Winter et al. 2025).

Simulation of the capture of a large cloud on the periphery of the disk has been performed in a number of papers (Dullemond et al. 2019; Kuffmeier et al. 2021; Unno et al. 2022; Hanawa et al. 2024). It was shown that in this case, the outer parts of the disk inclined relative to the inner ones. Also, when observed in scattered light, mainly two-arm spirals can be found on the surface of the disks (Hühn et al. 2026). Disk disturbances are strongest in the upper layers, if the mass of the disturbance does not exceed the mass of the disk, then the central plane of the disk remains undisturbed. However, such events are rare.

A large number of incident steamer-like structures were detected during numerical modeling of star formation processes (Padoan et al. 2014; Kuffmeier et al. 2023). At the same time Kuffmeier et al. (2018) shows the possibility of a clump of matter falling on the inner parts of the disk. Similar structures have been found in modeling the formation of protostellar accretion disks (Heigl et al. 2024; Mayer et al. 2025).

Modeling of the consequences of the fall of a matter on a gas disk was performed in Demidova and Grinin (2022a) in the approximation of the instantaneous fall of a

massive clump of matter at a distance of 30 AU. Calculations have shown that the density disturbance is stretched over several orbital periods by the Keplerian rotation of the disk into a vortex-like structure, then into a tightly wound spiral, and then the shape of the asymmetry depends on the initial velocity of the disturbance. Long-lived structures are formed: a two-arm spiral, a ring-shaped structure, or a horseshoe-shaped asymmetry.

Calculations of the fall of matter on the inner regions of the disk (< 10 AU) were performed in [Demidova and Grinin \(2023\)](#) in the approximation of a discrete fall of a clump of matter onto a gas disk. If the initial velocity of the density perturbation was less than the local Keplerian velocity, matter began to fall rapidly onto the disk. As further research of [Grigoryev and Demidova \(2024b\)](#) has shown similar conditions can occur in the case of a retrograde collision of a gas stream and a gas disk. The accretion rate in a number of models increased by more than two orders of magnitude ([Grigoryev and Demidova 2025](#)), which is typical for FU Ori-like flares ([Hartmann and Kenyon 1996](#)). Another consequence of such a fall is the formation of warp or an inner disk inclined relative to the periphery.

In addition, a burst of accretion activity can generate an increase the disk wind, which can weaken the brightness of the star for decades ([Grinin and Demidova 2024](#)). The weakening of the star's brightness can also be caused by the rise of the disk's matter to high latitudes above its plane due to the rapid mixing with matter of a retrograde gas stream ([Grigoryev and Demidova 2024b](#)). In this case, if the plane of the star's disk is inclined at a small angle to the line of sight, the brightness curve will show a sharp decrease in brightness to 5^m , a prolonged eclipse, and then a smooth return to its original state. The CQ Tau ([Grinin et al. 2023](#)), AA Tau ([Bouvier et al. 2013](#); [Covey et al. 2021](#)) and V1184 Tau ([Semkov et al. 2015](#)) light curves show similar behavior.

In this paper, we continue analyzing the consequences of the gas stream falling on the inner regions of the disk. The influence of the parameters of the initial orbit of the clump on the characteristic structures can be observed in the near-infrared and radio ranges of the EM-spectrum is investigated.

2 Numerical model

In this section, we will only briefly describe the gas-dynamic formulation of the problem, since it fully corresponds to [Grigoryev and Demidova \(2024b\)](#). We use the numerical package PLUTO ([Mignone et al. 2012](#)), which implements the Godunov approach for solving a system of gas dynamic equations. Taking into account the viscosity and thermal conductivity, it looks like this:

$$\begin{cases} \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0; \\ \frac{\partial (\rho \vec{v})}{\partial t} + \nabla \cdot \left((\rho \vec{v}) \otimes \vec{v} + \hat{I} p \right)^T = -\rho \nabla \Phi + \nabla \cdot \Pi(\nu); \\ \frac{\partial (\varepsilon_t + \rho \Phi)}{\partial t} + \nabla \cdot \left[\left(\frac{\rho v^2}{2} + \rho \epsilon + p + \rho \Phi \right) \vec{v} + \right] = \nabla \cdot (\vec{v} \cdot \Pi(\nu)) + \nabla \cdot \vec{F}_c. \end{cases} \quad (1)$$

Here ρ is the density of the gas within a particular cell, $\vec{v}$ is the Eulerian velocity of the gas in this cell, $\hat{I}$ is the unit matrix, p is the pressure of the gas, Φ is the gravitational potential, $\Pi(\nu)$ the viscous stress tensor, $\varepsilon_t = \epsilon + \rho v^2/2$, ϵ the specific energy density of a gas (the gas is considered ideal: $p = (\gamma - 1)\rho\epsilon$, $\gamma = 7/5$), $\nabla \cdot \vec{F}_c$ is heat flow determined by thermal conductivity.

Calculations are performed in the standard spherical coordinate system (R, θ, φ) : $144 \times 60 \times 144$ cells in the domain $[0.2; 107.2]$ AU $\times [15; 165]^\circ \times [0; 360]^\circ$. The R -grid is logarithmic, but the angles are uniform. This configuration allows one to get quasi-cubic cells ($\Delta R \approx R\Delta\varphi = R\Delta\theta$) in the computational domain.

Note that the influence of radiation transfer processes on gas dynamics (UV heating from hot regions of the star, cooling of dust) is not considered here, and the self-gravity of the disk is not taken into account: the gravitational potential of the point mass $\Phi = GM_*/R$ (G is the gravitational constant, M_* is the stellar mass) remains unchanged during calculations.

2.1 Initial model of protoplanetary disk

We will consider an axisymmetric initially hydrostatically stationary protoplanetary disk in polar coordinates (R, θ) — (spherical radius and polar angle), consisting of an ideal gas orbiting a star with a mass of $M_* = 1M_\odot$ (one solar mass), as the initial distribution of matter in the computational domain.

All macroscopic gas parameters are set in a code units. The main parameters of this system are listed in the Table 1.

Table 1 Normalization units

Parameter	Designation	Value	Units, CGS	Comment
Unit of mass	M_0	1.98×10^{33}	g	$M_\odot$
Unit of length	L_0	1.496×10^{13}	cm	1 AU
Unit of time	t_0	3.16×10^7	s	1 year
Unit of density	ρ_0	5.94×10^{-7}	g cm $^{-3}$	M_0/L_0^3
Unit of velocity	v_0	4.74×10^5	cm s $^{-1}$	$2\pi L_0/t_0$

Following [Demidova and Grinin \(2022b\)](#) we will set the initial distribution of volume density in the disk:

$$\rho(r, z) = \frac{\Sigma_0}{\sqrt{2\pi}H(r)} \frac{r_{in}}{r} e^{-\frac{z^2}{2H^2(r)}}; \quad \Sigma_0 = \frac{M_{disk}}{2\pi r_{in}(r_{out} - r_{in})}. \quad (2)$$

Here $r = R \sin \theta$ is the cylindrical radius, $z = R \cos \theta$ is the height above the equator, $H(r)$ is the characteristic semi-thickness of the disk at this radius, r_{in} is the inner radius of the disk, Σ_0 is the average surface density of the disk, M_{disk} is the initial mass of the disk (in all calculations $M_{disk} = 0.01M_\odot$).

The half-thickness of the disk depends on the temperature in the equatorial plane of the disk T_{mid} at a given radius:

$$H(r) = \sqrt{\frac{\kappa T_{mid}(r) r^3}{GM_* \mu m_H}}; \quad T_{mid}(r) = \sqrt[4]{\frac{\Gamma}{4}} \sqrt{\frac{R_*}{r}} T_*, \quad (3)$$

where the values R_* and T_* represent the radius and temperature of the star, the coefficient $\Gamma = 0.05$ (Chiang and Goldreich 1997; Dullemond and Dominik 2004), the molar weight of the gas in the disk $\mu = 2.35$ (Dutrey et al. 1994).

The density in the cell is limited from below by the value of $10^{-12} \rho_0$, and all the cells with such a sparse medium are considered as the corona with the temperature of 1.5×10^6 K.

The velocity of each point of the disk is set based on the Keplerian approximation: $\mathbf{v} = (v_R, v_\theta, v_\varphi) = (0, 0, \sqrt{GM_*/R})$ for the case of a prograde fall of the clump. In the case of a retrograde fall, the disk will rotate counterclockwise in the xy plane: $\mathbf{v} = (v_R, v_\theta, v_\varphi) = (0, 0, -\sqrt{GM_*/R})$. So, here we get $|v_\varphi| = v_0$ for the orbit with radius $R = 1$ AU.

The left boundary condition for R is set based on considerations of equality of thermal turbulent flows, continuity of viscous turbulent flow, and conservation of entropy. The values in the boundary cells are indicated by the subscript b , without the index — in the calculated boundary cells:

$$\kappa_{turb\ b} \frac{\partial T_b}{\partial R} = -\kappa_{turb} \frac{\partial T}{\partial R}; \quad \nu_{turb\ b} \frac{\partial \rho_b \mathbf{v}_b}{\partial R} = \nu_{turb} \frac{\partial \rho \mathbf{v}}{\partial R}; \quad \rho_b = \rho(T_b/T)^{2.5}. \quad (4)$$

Here v_{Rb} component is always directed towards the star or zero. The values of κ_{turb} and ν_{turb} are the coefficients of turbulent thermal conductivity and viscosity respectively, primarily affecting the movement of gas. For more information about the thermal conductivity and viscosity model used, see our previous paper (Grigoryev and Demidova 2024b).

The right boundary condition for R corresponds to the initial state of the disk. Free boundary conditions on θ on both sides and periodic boundary conditions on φ are established.

2.2 Initial parameters of the stream

At the initial moment of time one cell ($\Delta R \approx 0.8$ AU) at a distance of $R = 20$ AU from the star is filled with matter with a mass equal to the mass of Jupiter, which sets the value of the density in it ($\rho \approx 1 \cdot 10^{-9}$ g cm $^{-3}$). The initial temperature of this matter is 50 K. The initial components of the gas velocity in a given cell are set such that a material point having the coordinates of the center of this cell moves along a parabolic trajectory with the longitude of the ascending node $\Omega = 45^\circ$ relative to the star. The angle of inclination of the orbit was set for each calculation separately (angles of 30° , 45° and 60° were considered), and the direction of rotation of the disk was also set to ensure cases of prograde and retrograde fall. The names of the calculated configurations are also identical to the Table 2 in Grigoryev and Demidova (2024b):

that is, for example, the DI-r45 model from the previous article and from this one — are the same, in which the stream moves at an angle of 45° to the plane of the disk towards its rotation (retrograde case).

3 Three-dimensional gas dynamic of the disk

When moving toward the disk, the matter of initial clump is stretched into a gas stream, which moves along the initial parabolic orbit until it impales the disk. In case of single intersection models (SI) the matter partially flies away, in the other case — double intersection (DI) — it flies around the star, collides again and partially flies away. The timing and position of intersections in models discussed in the paper could be found in our previous work [Grigoryev and Demidova \(2024b\)](#) and the dependence of fly away matter from orbital parameters is discussed in [Grigoryev and Demidova \(2025\)](#).

Fig. 1 shows contour surfaces of the density distribution in protoplanetary disks in two models DI-45 and DI-r45 (prograde and retrograde case of stream fall respectively, the inclination of the orbit is 45°) at $t = 150$ years from start of calculations (the center of mass of the clump crossed the plane of the disk at approximately time $7t_0$). It is clearly seen that in the first case (the clump fall prograde with the rotation of the disk), a dominant spiral was formed, the matter of which, having outer density about $10^{-8}\rho_0$, rises to ~ 30 AU above the plane of the disk. Along this spiral, a region of significantly lower density is clearly discernible on the outer side relative to the star, appearing simply as a “hole” in the contour representation. In addition, the initial disk is somewhat deformed, and a less significant spiral pattern is visible.

In the retrograde case an inclined inner disk (warp) formed. An analysis of the density distribution at this time (the maximum density surface was constructed) showed that the warp radius is ~ 14 AU, the inclination is 22° , and the average normal to its surface has an azimuth of 109° , which gives an angle of $\sim 19^\circ$ is between the x axis and the line of nodes (the straight line along which the warp planes and the initial disk intersect). Since for these models, the first point of intersection of the disk plane with the stream is closer to the star (~ 7 AU), and the second one is further away (~ 12 AU in this case), the formation of an asymmetric inclined inner disk is expected. It is worth noting that the geometric structure of the transition from one disk to another is quite complex, subject to many bends and spirals, therefore, the distance from the star to the nearest large hump was measured as the radius of the inner disk, so this value can be considered a confident estimate of the radius from below.

In [\(Grigoryev and Demidova 2024a\)](#) it was showed that the inner disk evolves: its orientation and dimensions change over time. In addition, the warp itself is asymmetric: on different sides of the star along the node line, the distance to the outer disk is slightly different, in the perpendicular direction — too. Note that in these calculations, it has existed for more than a hundred years since the fall of the clump. On average, the shape of the initial disk is more distorted in retrograde case than in prograde one.

After the gas dynamics calculations we independently analyze the possible radiation.

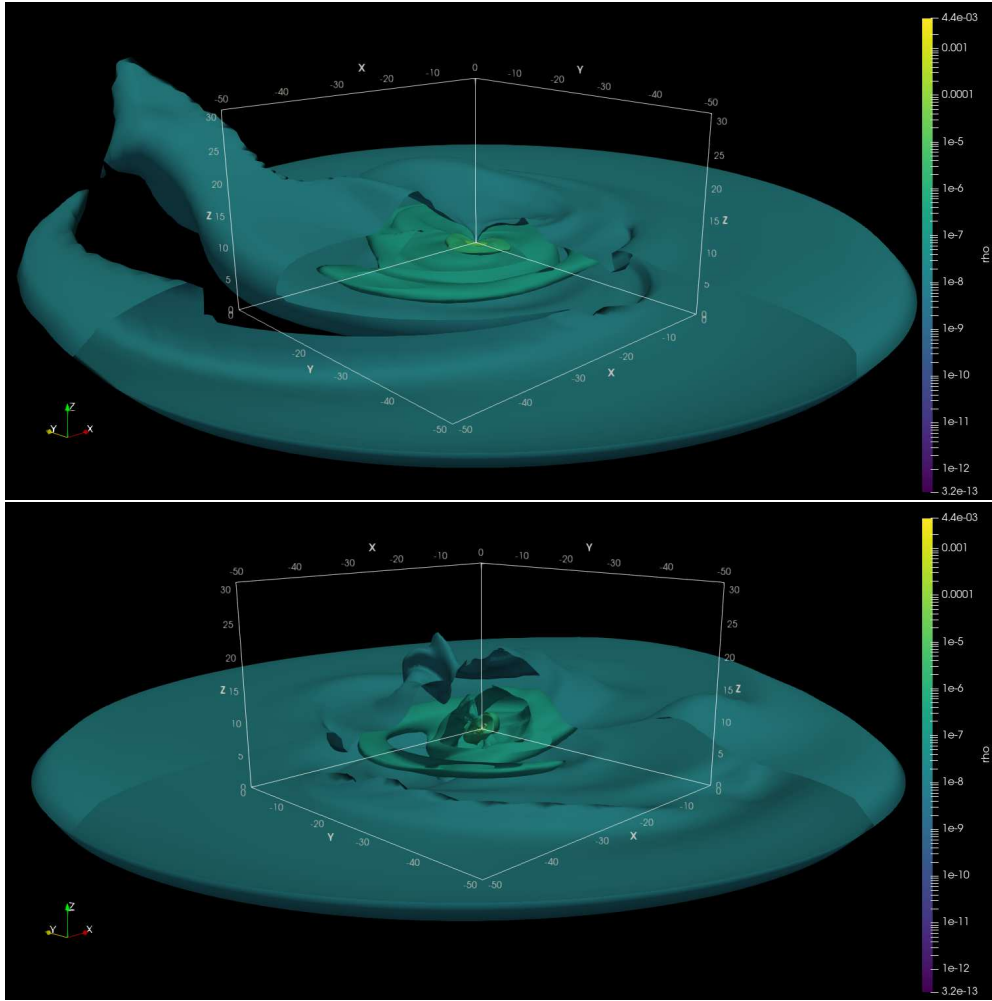


Fig. 1 Contour density surfaces (in units of ρ_0) for the DI-45 (top) and DI-r45 (bottom) models at a time of 150 years, octant III is cut out for clarity. A coordinate parallelepiped is presented for the scale, the distances along the axes are given in AU.

The RADMC-3D code¹ (Dullemond et al. 2012) was used for three-dimensional calculations of radiation transfer. The solution of the radiation transfer equation is performed by the Monte Carlo method. It was assumed that the dust to gas ratio is 0.01, as is the average in the interstellar medium. The amount of fine dust (0.1 microns), which makes the main contribution to the thermal radiation of the disk, ranged from 100% to 10% of the total dust in the disk. For calculations of direct and scattered radiation, 10^7 photons were taken. Dust opacity for magnesium-iron silicates (Dorschner

¹<https://www.ita.uni-heidelberg.de/dullemond/software/radmc-3d/>

et al. 1995) was calculated according to theory Mie (1908), using the code included in the RADMC-3D package (Bohren and Huffman 1998).

The calculated radiation fluxes were used for modeling images that can potentially be obtained from observations using the ALMA radio interferometer. The simulation was carried out using the CASA 6.5 simulator² (Petty and CASA Development Team 2012). Calculations were performed for the position $\alpha = 05^h35^m58^s.5$; $\delta = +24^\circ44'54''.1$ (CQ Tau position) at a distance of 140 pc, the bandwidth for the observer in the continuum is 6 GHz, the exposure time is 2^h . Thermal noise was added using the `tsys-atm` option of the CASA package, with the precipitable water vapor $PWV = 0.6$. The antenna configuration corresponded to the largest compact configuration (#20 from available CASA configurations).

4 Results

The Fig. 2 shows the radiation flux from the disk during observations from the pole for cases of prograde (DI-45) and retrograde (DI-r45) collisions of the stream and the disk, with a double intersection of its plane. It can be seen that the most dominated spiral structure is formed when the stream falls on the disk prograde to its rotation and crosses its plane twice. The matter of the stream, after a collision, involves the matter of the disk in its motion. Since the velocity of the stream's matter is greater than the local Keplerian velocity, the structure extends outward from the disk. A large-scale single-arm spiral stands out (Fig. 2 from above), which is clearly visible during the entire calculation time (both in gas dynamics, see Fig. 1, and in radiation simulation). Calculations have shown that the smaller the initial inclination angle of the falling gas's orbit, the brighter the spiral structure stands out, since most of the disk's matter is involved in the interaction.

In the case of a retrograde fall of the stream, spiral waves also occur, but they are weaker and dissipate rather quickly over time (Fig. 2 below). In this case, after the collision, the disturbance propagates inside the disk towards the star, since the local velocity of matter becomes less than Keplerian as a result of mixing.

At the same time, if the disk is observed in the radio waves using ALMA interferometer, then in the prograde case the single-arm spiral can be identified in both the submillimeter and millimeter ranges (Fig. 3). An analysis of the calculations showed that in order to the spiral structure to stand out against the background of the disk, it is necessary that the mass of fine dust in the disk should be equal $10^{-4}M_\odot$ (that is, 100% of the total mass of dust). In the case of a smaller mass of fine dust (10%), spiral structures are not resolved. In retrograde case, spiral waves are not visible when observing the disk.

In the case of a single intersection of the disk plane, for both prograde and retrograde collisions, spiral structures are also formed on the disk (Fig. 4). However, they are less visible than in the case of a double intersection of the disk plane, and are not identified when observed in the radio waves.

In the case of a retrograde fall, the inner part of the disk inclines, and inclination angle depends on the initial orbital plane of the stream. The inclined inner disk can be

²<https://casa.nrao.edu/>

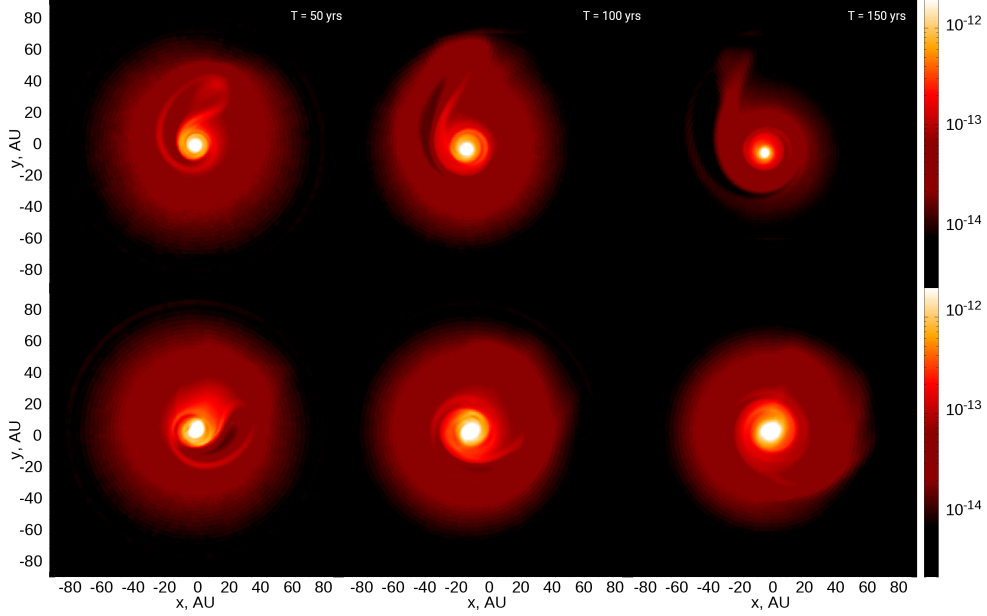


Fig. 2 The color shows the radiation flux in units of $\text{erg s}^{-1} \text{Hz}^{-1} \text{sr}^{-1}$ on a logarithmic scale at a wavelength of 740 microns. The line of sight is directed against the z axis. The top row shows the DI-45 model, at $t = 50$ (left), 100 (center), and 150 years (right) from the start of calculations. The bottom is the same for the DI-r45 case. The initial angle of inclination of the falling clump's orbit to the disk plane is $i = 45^\circ$. The distances are given in astronomical units.

identified when viewed in the infrared range. In Fig. 5 it can be seen that in the case of $i = 30^\circ$, the disk looks almost symmetrical, whereas for $i = 45^\circ$ and 60° , a dark line of nodes and a bright visually asymmetric inclined disk are highlighted at a wavelength of 3 microns. The disk image allows one to estimate its size as $\sim 15 - 20$ AU, which is slightly more than the value determined from the density distribution analysis. Also note that the orientation of the observed line of nodes in Fig. 5 for calculating DI-r45, it perfectly matches the data obtained from density distribution analysis: the angle with the x axis is about 20° .

An analysis of radiation simulations (for $i = 45^\circ$ and 60°) showed that to observe the described pattern, it is necessary that the mass of fine dust in the disk does not exceed $10^{-5} M_\odot$ (that is, 10% of the total mass dust). Otherwise, the contrast between the higher ($z > 0$) and the lower ($z < 0$) parts of the disk becomes too high, and only the bright lower part is visible. Just in case, we recall that in these calculations, the clump fell from the upper half-plane.

It should be noted that the line of nodes does not stand out when observing in the radio range for these models. The fact is that the disk is transparent in the wavelength range under consideration, so the heated parts of it on the opposite side from the observer shine through and are also visible. Whereas in the infrared range, only the surface of the disk facing the observer is visible.

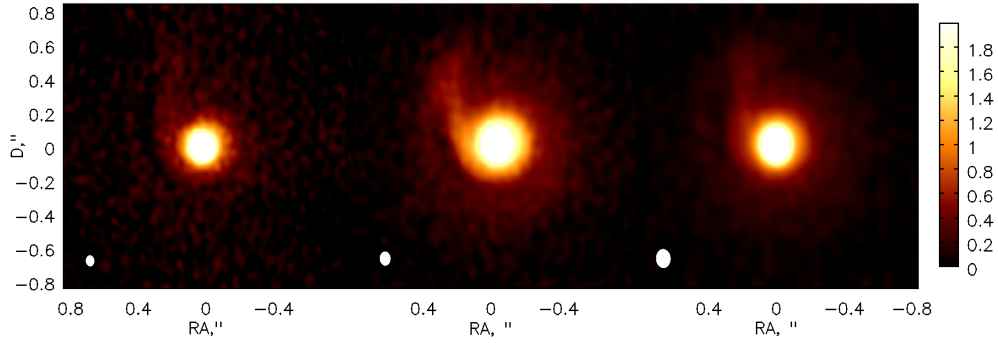


Fig. 3 Synthesized images that can potentially be obtained on the ALMA radio interferometer at a wavelength of $740\ \mu\text{m}$ (left), $952\ \mu\text{m}$ (center), $1.3\ \text{mm}$ (right) for the DI-45 model at a time of 150 years. The color bar is given in $10^{-3}\ \text{Jy/beam}$.

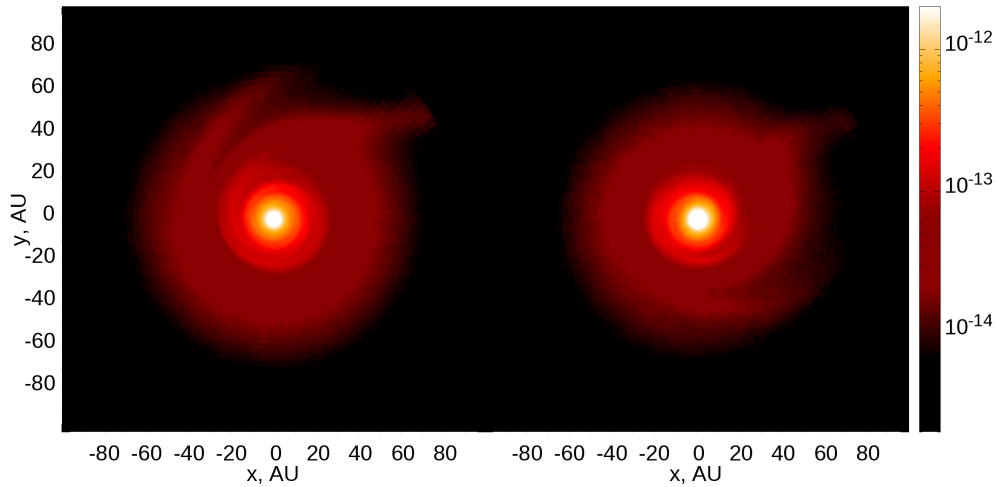


Fig. 4 The same as in Fig. 2 but for models SI-45 (left) and SI-r45 (right).

In addition, an inner inclined disk can be detected by observations in the radio range. The Fig. 6 shows the radiation flux from the disk, observed from the edge, and its synthetic image at a wavelength of $740\ \mu\text{m}$. The positional angle of observing was chosen so that the inclination of the inner region relative to the periphery was best visible (Grigoryev and Demidova 2024b, see Table 4). When observing the disk from the edge, the inner part looks perturbed, and in the cases of $i = 45^\circ$ and 60° , an inclined inner disk is distinguished. In simulated image from RADMC-3D we can estimate the size of warp: its radius is about 15 AU — this value is perfectly matches with density distribution analysis. Unfortunately, such measurements cannot be carried out on a potentially observable image.

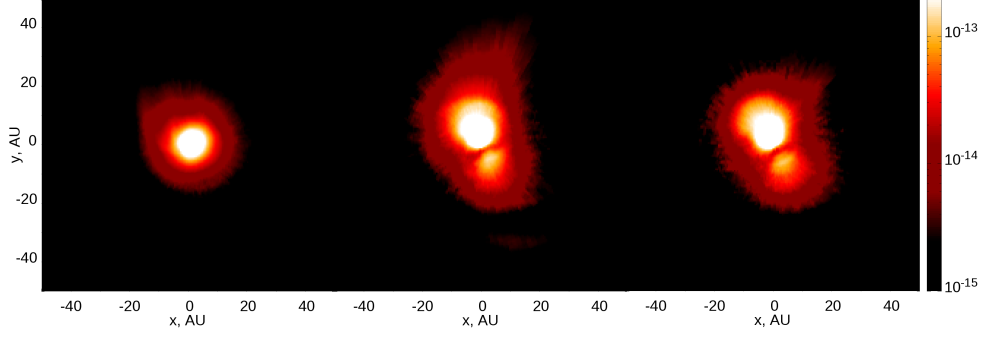


Fig. 5 The same as in Fig. 2 on wavelength $3 \mu\text{m}$ for the models DI-r30 (left), DI-r45 (center) and DI-r60 (right).

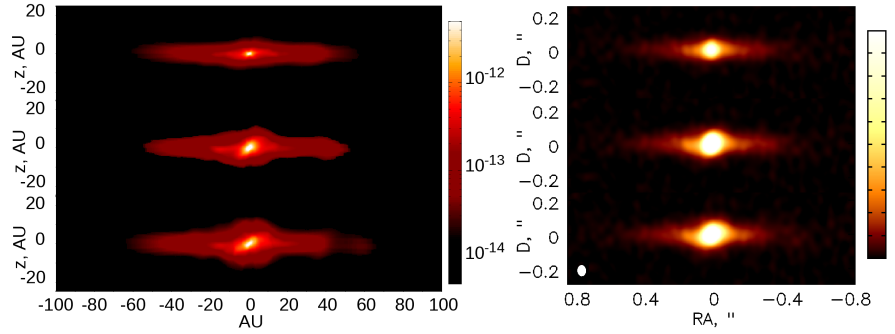


Fig. 6 Left: the same as in Fig. 2 on wavelength $740 \mu\text{m}$ for the models DI-r30 (top), DI-r45 (middle) and DI-r60 (bottom). The color bar is given in $\text{erg s}^{-1} \text{Hz}^{-1} \text{sr}^{-1}$. Right: the same as in Fig. 3 for the same models. The color bar is given in 10^{-3}Jy/beam .

5 Discussion

It should be noted that the calculations did not take into account the impact of an outburst caused by a significant increase in the accretion rate (Grigoryev and Demidova 2025) in case of retrograde collision of the stream and disk. By the time 50 years after the start of calculations, the accretion rate becomes $< 10^{-5} M_{\odot} \text{yr}^{-1}$ (Grigoryev and Demidova 2024b). In addition, for a characteristic density value of $10^{-10} \text{g cm}^{-3}$, the circumstellar disk is optically thin at temperatures in the range of $900 - 8000 \text{K}$, with an increase in density to values of 10^{-6}g cm^{-3} the temperature range narrows down to $1500 - 4000 \text{K}$ (Stamatellos et al. 2007). Therefore, we assume that the inner regions of the disk in these models can be considered as optically thin ones. As it was shown in Laznevoi et al. (2025), optically thin regions of the disk warm up and cool down almost instantly during FU Ori-like flares. Heating the optically thick layers of the disk requires several years, while cooling takes about a decade. However, the authors did not take into account the change in the vertical

density distribution with changes in the disk temperature, so the relaxation times of the optically thick layers of the disk may be shorter due to this effect.

In [Tang et al. \(2012\)](#) it was shown that a probable explanation for the physical pattern in the AB Aur system could be an inhomogeneous accretion from the remnant of the protostellar cloud above or below the plane of the main disk, which may explain both the rotation and large-scale movements detected in the image. AB Aur attracts the attention of researchers due to the presence of spirals at a relatively young stage of formation ([Fukagawa et al. 2004](#); [Lin et al. 2006](#)), and the azimuthal asymmetry of the disk detected in the thermal radiation of dust ([Piétu et al. 2005](#)).

In [Hühn et al. \(2026\)](#) the formation of spirals in the protoplanetary disk after the fall of matter from the environment onto the disk was investigated. The authors showed that mainly two-arm spirals and clumpy structures are detected in diffused light. In this case, the development of spirals is favored by the gradual accretion of a massive gas cloud to the periphery of the disk, while the clumpy structures are formed due to active accretion by streamers. The detected spirals have a very low pattern speed, which makes it easy to distinguish them from spirals caused by a disturbing factor. Spiral structures have also been detected in the residual movements of ^{12}CO , but their morphology does not match that found in scattered light.

6 Conclusion

Thus, it can be concluded that the structures observed in the case of a stream falling into the immediate vicinity of the star can be identified during observations. In particular, in the case of a prograde fall with a two intersections of the disk plane, a single-arm spiral structure can be observed. Calculations showed that the spiral structure stands out against the sky background if the disk's dust component consists primarily of small particles. Therefore, the obtained results are applicable to disks in the early stages of their evolution.

If the fall is retrograde, then at a sufficiently large inclination of orbital plane, an inclined inner disk is formed, which can also be detected both during observations in the infrared and radio range at different wavelengths. It is remarkable that the morphological structure parameters determined from the analysis of gas dynamic calculations are consistent with the data obtained from synthesized observations. The dark line of nodes crossing the bright inclined parts of the disk is visible in the infrared range in the case when fine dust makes up 10% of the total dust mass. Thus, the calculations described above are applicable to evolved disks.

However, the identification and detailed study of such structures with the current development of observational instruments is possible only for the immediate vicinity of the Sun (about 100 pcs).

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