Evolution of a Viscous Protoplanetary Disk with Convectively Unstable Regions. II. Accretion Regimes and Long-Term Dynamics

L.A. Maksimova, Ya.N. Pavlyuchenkov, A.V. Tutukov
Institute of Astronomy, Russian Academy of Sciences, Moscow, Russia

Received April 29, 2020. Accepted June 30, 2020.
lomara.maksimova@gmail.com

ABSTRACT

In this article, we proceed to study convection as a possible factor of episodic accretion in protoplanetary disks. Within the model presented in Article I, the accretion history is analyzed at different rates and areas of matter inflow from the envelope onto the disk. It is shown that the burst-like regime occurs in a wide range of parameters. The long-term evolution of the disk is also modeled, including the decreasing-with-time matter inflow from the envelope. It is demonstrated that the disk becomes convectively unstable and maintains burst-like accretion onto the star for several million years. Meanwhile, the instability expands to an area of several tens of astronomical units and gradually decreases with time. It is also shown that at early stages in the disk evolution, conditions arise for gravitational instability in the outer parts of the disk and for dust evaporation in the convectively unstable inner regions. The general conclusion of the study is that convection can serve as one of the mechanisms of episodic accretion in protostellar disks, but this conclusion needs to be verified using more consistent hydrodynamic models.

DOI: 10.1134/S1063772920110050

1 INTRODUCTION

The formation and evolution of protoplanetary disks (PDs) around young stars is one of the most intriguing topics in astrophysics. In the earliest evolution stages, many young stellar systems show signs of episodic accretion; these objects are known as FUors and EXors (see, e.g., (Hartmann & Kenyon 1996; Audard et al. 2014)). There are theoretical arguments to believe that all PDs go through a phase of episodic accretion at initial stages in their evolution, which explains the variable luminosity of young stellar objects (Hartmann 1998). However, the physical mechanisms of this variability remain debatable. The variability problem is closely related to the more general question about the mechanisms of angular momentum transfer in accretion disks. Vigorous discussions have taken place regarding the possible mechanisms that not only ensure the transfer of angular momentum in disks but also cause the nonsteady accretion pattern and involve such factors as gravitational, magnetorotational, and thermal instabilities (see (Audard et al. 2014)). Thus, the nonsteady pattern of accretion caused by gravitational instability is associated with the clump formation and their falling onto the star, leading to luminosity bursts (see, e.g., (Vorobyov & Basu 2006)). The burst-like pattern caused by magnetorotational instability is due to the positive feedback link of this instability to the ionization degree of matter (Zhu et al. 2009). Thermal instability is caused by an increase in gas opacity with increasing temperature in partially ionized gas (Kley & Lin 1999).

Convection is also considered as one of the mechanisms responsible for the turbulization of matter in accretion disks (see, e.g., (Lin & Papaloizou 1980, Shakura & Postnov 2015, Malanchev, Postnov & Shakura 2017, Held & Latten 2018)). In our previous work (Pavlyuchenkov et al. 2020), which will be referred to below as Article I, we demonstrated that convective instability can also lead to a nonsteady pattern of accretion. Within the viscous disk model, we showed that in the presence of background viscosity, convection is a process with a positive feedback due to an increase in the opacity of gas-and-dust medium with increasing temperature and can therefore be responsible for bursts and episodic accretion in PDs. However, we neither investigated how the model parameters influence this conclusion nor studied the nature of episodic accretion for different rates of matter inflow from the envelope.

The aim of our work is a more detailed study of the nonsteady accretion regime that was obtained in Article I. The present article is organized as follows. Section 2 gives a brief description of the model. Section 3 examines the effect of the model parameters on the accretion pattern within the simplest description of matter inflow from the envelope, which is used in Article I. Section 4 studies the disks long-term evolution with a more realistic description of matter accretion from the envelope. The conclusions section summarizes the results of this study.

2 MODEL DESCRIPTION

In this work, we use the PD evolution model from Article I. Here, we outline only the key elements of this model. We consider an axially symmetric, geometrically thin viscous Keplerian disk without a radial pressure gradient. The evolution of the surface density of the disk is modeled using the Pringle equation (Pringle 1981), con-
When reconstructing the disks vertical structure, we consider the heating by radiation from the central object along with the viscous gas dissipation. The luminosity of the central source consists of the photospheric luminosity of the star (which is assumed to be equal to that of the Sun) and the accretion luminosity, which is calculated by the formula 
\[ L_{\text{acc}} = \frac{1}{2} \frac{GM\dot{M}}{R_*} \]
where \( \dot{M} \) is the rate of accretion from the disk to the star.

When solving Eq. (1), we use a fixed value of surface density on the inner (0.2 AU) and outer (200 AU) boundaries of the model disk. The density values at the boundaries were chosen comparatively small, which ensures free outflow of matter from the region under consideration. As noted in Article I, more complex boundary conditions require separate study. The importance of the inner boundary condition in PD modeling is the central topic of research, e.g., in (Vorobyov et al. 2019).

In this work, we study the effects of the four model parameters on the manifestation of the episodic accretion pattern: (1) the accretion rate from the envelope onto the disk, \( \dot{M} \); (2) the accumulation region, onto which matter from the envelope accretes, \( R_{\text{acc}} \); (3) the background viscosity \( \dot{\nu}_0 \); and (4) the convection efficiency coefficient \( \eta \). In Article I, we set a constant inflow of gas from the envelope onto the disk into a ring between 10 and 20 AU with an accretion rate of \( 10^{-3} M_\odot/\text{yr} \), and we also used the coefficients \( \dot{\nu}_0 = 10^{15} \text{ cm}^2/\text{s} \) and \( \eta = 1 \). This model will be referred to below as the basic model. In this work, we consider models with accretion rates differing from the basic one by two orders of magnitude in both directions, which corresponds to the spread of the accretion rates observed in PDs (Natta, Testi & Randich 2006; Ercolano et al. 2014). Along with an accumulation region of 1020 AU, we also consider a case where gas accretes onto the disk into a ring between 1 and 2 AU, which is more typical of initial stages in the evolution of PDs.

Another important parameter of the model is background viscosity, which predetermines the lifetime and disk mass. In the basic model, we use \( \dot{\nu}_0 = 10^{15} \text{ cm}^2/\text{s} \), which corresponds to a relatively high, turbulent viscosity. Based on the estimates from Article I, the corresponding alpha parameter of turbulent viscosity (Shakura & Sunyaev 1973) is \( \alpha = 0.1 \). In the present article, we also consider a model with background viscosity an order of magnitude smaller than the basic one; this smaller background viscosity is closer to the observed estimates for evolved PDs. The convection efficiency coefficient \( \eta = 1 \), taken in the basic model, intentionally overestimates the transition of thermal energy into convective energy since it does not account for that a part of the energy must be transferred by radiation. The question arises: Will the bursts caused by convection disappear if a considerable part of the released energy is transferred by radiation? To answer this question, we examined a model with \( \eta = 0.1 \). Table I presents the parameters of the models, and Section 3 describes the modeling results.

In addition to these models, we considered a model for studying the long-term evolution of the disk with a more realistic accretion rate and accumulation region, the parameters of which change with time. The function \( W(R,t) \), which corresponds to the latter case, and the results are described in Section 4.

## 3 DISK ACCRETION REGIMES

This section presents the results for the models with a constant (in time and space) inflow of matter from the envelope onto the disk. The corresponding rate of matter inflow inside the accumulation...
of rates of gas accretion from the disk onto the star for these models − ∼ panel in Fig. 1 (left column) shows density distributions for several in the disk. These parameters correspond to the basic model from 10





The evolution of the surface density distributions and the rates of matter accretion from the disk onto the star for this model set are shown in Fig. 2. In the contributions of surface density and the rates of matter accretion from the disk onto the star during the convective phase increases by two orders of magnitude, compared with the basic model. It should also be noted that the minimum accretion rates (between the bursts) in Models 2 and 3 are comparable.

3.2 Models with an Inner Accumulation Region

Here, we consider the results for the models with an inner accumulation region (\(R_{\text{ring}} = 1 - 2\) AU, \(v_0 = 10^{15}\) cm\(^3\)/s, \(\eta = 1\)) and different rates of accretion from the envelope: \(\dot{M} = 10^{-9}, 10^{-7},\) and \(10^{-5}\) M\(_{\odot}\)/yr (Models 4, 5, and 6, respectively). The radial distributions of surface density and the rates of matter accretion from the disk onto the star for this model set are shown in Fig. 2. In the case of \(\dot{M} = 10^{-9}\) M\(_{\odot}\)/yr (Model 4), it is evident that convectively unstable regions do not appear. In complete analogy with Model 1, the density distributions have features near the disk boundaries and the accumulation region.

Let us highlight several differences between Models 5 and 2, which both have an external inflow with a rate of \(10^{-7}\) M\(_{\odot}\)/yr. First, we should note a decrease in the accumulation phase duration by about an order of magnitude (to \(\sim250\) years) and a reduced convective phase (the burst lasts approximately one fifth of the time in the basic model, i.e., 50 years instead of 250). Second, in Model 5, the maximum level of matter accretion from the disk onto the central object is an order of magnitude lower. We should also note that the burst-like pattern of matter accretion onto the star sets in faster in the case of an inner accumulation region.

There are far more differences between Models 3 and 6, with \(\dot{M} = 10^{-5}\) M\(_{\odot}\)/yr. In Model 6, the inner region has not enough time to release the accumulated matter and constantly remains in a state of convective instability. Nevertheless, the time dependence of the accretion rate shows relatively weak oscillations in the range from \(10^{-5}\) to \(10^{-6}\) M\(_{\odot}\)/yr (Fig. 2 bottom panel). These oscillations are due to the unstable outer boundary of the convective zone, which lies beyond the accumulation region; in this outer zone, matter accumulates and discharges in the same way as the inner regions in the basic model of the disk.

Let us analyze in more detail the development of bursts in Models 2 and 5. In Figure 3 we show a more detailed evolution of the surface density distributions and the time dependence of the accretion rate in the burst phase. As noted in Article 1, during the convective phase, the density distributions have peaks, which are essentially the convection propagation fronts. Looking at these peaks, one can easily identify the position of the convectively unstable region. In Model 2, the convectively unstable region appears near the disks inner boundary (0.2 AU) and expands further outwards. This development of the convective region leads to the formation of a \(\Pi\)-shaped profile of the accretion rate (the top right panel). In Model 5, however, convection initializes in the accumulation region and propagates into the disks inner part. This leads to the accumulation of matter on the inner front and its sharp discharge onto the star, leading to the formation of a \(\Lambda\)-shaped profile of the burst. These features of the accretion rate profile may be important for interpreting observations in young bursting objects.

A further increase in the gas inflow rate from the envelope onto the disk to \(10^{-5}\) M\(_{\odot}\)/yr (Model 3; Fig. 1 bottom panel) leads to an increase in the frequency of accretion bursts and in the maximum accretion rate. With an increased inflow of matter from the envelope, the accumulation time of matter before the onset of convective instability decreases (\(\sim700\) years), while the maximum accretion rate onto the star during the convective phase increases by two orders of magnitude, compared with the basic model. It should also be noted that the minimum accretion rates (between the bursts) in Models 2 and 3 are comparable.

### 3.1 Models with an Outer Accumulation Region

We consider modeling results for cases with an outer accumulation region (\(R_{\text{ring}} = 10 - 20\) AU), which differ in the accretion rates from the envelope (Models 1, 2, and 3) under the fixed \(v_0 = 10^{15}\) cm\(^3\)/s and \(\eta = 1\). The evolution of the surface density distributions and the rates of gas accretion from the disk onto the star for these models are shown in Fig. 1 Model 1, with \(10^{-9}\) M\(_{\odot}\)/yr (Fig. 1 top panel), sets a quasi-stationary regime, as seen from the time dependence of \(\dot{M}\). The density distributions for different times have a smooth shape with small features near the accumulation region and the disks inner boundary, which are due to the boundary conditions. Given this relatively low accretion rate, convectively unstable regions do not appear in the disk, and its evolution is fully defined by the background viscosity. The accretion rate from the disk onto the star approaches a stationarity with a value close to the rate of matter inflow from the envelope.

When the rate of gas inflow onto the disk increases to \(10^{-7}\) M\(_{\odot}\)/yr (Model 2), this creates an episodic pattern of accretion in the disk. These parameters correspond to the basic model from Article 1, which analyzes it in detail. Over time, matter accumulates in the inner region of the disk, after which this region becomes convectively unstable. In the convectively unstable region, the total viscosity increases by about two orders of magnitude, leading to a relatively rapid discharge of matter onto the star. The middle panel in Fig. 1 (left column) shows density distributions for several times, which illustrate this process. The accumulation phase lasts \(\sim3000\) years; the convective phase lasts \(\sim250\) years.

### 3.2 Models with an Inner Accumulation Region

Here, we consider the results for the models with an inner accumulation region (\(R_{\text{ring}} = 1 - 2\) AU, \(v_0 = 10^{15}\) cm\(^3\)/s, \(\eta = 1\)) and different rates of accretion from the envelope: \(\dot{M} = 10^{-9}, 10^{-7},\) and \(10^{-5}\) M\(_{\odot}\)/yr (Models 4, 5, and 6, respectively). The radial distributions of surface density and the rates of matter accretion from the disk onto the star for this model set are shown in Fig. 2. In the case of \(\dot{M} = 10^{-9}\) M\(_{\odot}\)/yr (Model 4), it is evident that convectively unstable regions do not appear. In complete analogy with Model 1, the density distributions have features near the disk boundaries and the accumulation region.

Let us highlight several differences between Models 5 and 2, which both have an external inflow with a rate of \(10^{-7}\) M\(_{\odot}\)/yr. First, we should note a decrease in the accumulation phase duration by about an order of magnitude (to \(\sim250\) years) and a reduced convective phase (the burst lasts approximately one fifth of the time in the basic model, i.e., 50 years instead of 250). Second, in Model 5, the maximum level of matter accretion from the disk onto the central object is an order of magnitude lower. We should also note that the burst-like pattern of matter accretion onto the star sets in faster in the case of an inner accumulation region.

There are far more differences between Models 3 and 6, with \(\dot{M} = 10^{-5}\) M\(_{\odot}\)/yr. In Model 6, the inner region has not enough time to release the accumulated matter and constantly remains in a state of convective instability. Nevertheless, the time dependence of the accretion rate shows relatively weak oscillations in the range from \(10^{-5}\) to \(10^{-6}\) M\(_{\odot}\)/yr (Fig. 2 bottom panel). These oscillations are due to the unstable outer boundary of the convective zone, which lies beyond the accumulation region; in this outer zone, matter accumulates and discharges in the same way as the inner regions in the basic model of the disk.

Let us analyze in more detail the development of bursts in Models 2 and 5. In Figure 3 we show a more detailed evolution of the surface density distributions and the time dependence of the accretion rate in the burst phase. As noted in Article 1, during the convective phase, the density distributions have peaks, which are essentially the convection propagation fronts. Looking at these peaks, one can easily identify the position of the convectively unstable region. In Model 2, the convectively unstable region appears near the disks inner boundary (0.2 AU) and expands further outwards. This development of the convective region leads to the formation of a \(\Pi\)-shaped profile of the accretion rate (the top right panel). In Model 5, however, convection initializes in the accumulation region and propagates into the disks inner part. This leads to the accumulation of matter on the inner front and its sharp discharge onto the star, leading to the formation of a \(\Lambda\)-shaped profile of the burst. These features of the accretion rate profile may be important for interpreting observations in young bursting objects.

### Table 1. Parameters of the models under consideration

| Model | \(\dot{M}\) | \(R_{\text{ring}}\), AU | \(\eta\) | \(v_0/10^{15}\), cm\(^3\)/s |
|-------|------------|----------------|--------|-----------------------------|
| 1     | \(10^{-9}\) | 10 - 20        | 1      | 1                           |
| 2     | \(10^{-7}\) | 10 - 20        | 1      | 1                           |
| 3     | \(10^{-5}\) | 10 - 20        | 1      | 1                           |
| 4     | \(10^{-9}\) | 1 - 2          | 1      | 1                           |
| 5     | \(10^{-7}\) | 1 - 2          | 1      | 1                           |
| 6     | \(10^{-5}\) | 1 - 2          | 1      | 1                           |
| 7     | \(10^{-7}\) | 10 - 20        | 0.1    | 1                           |
| 8     | \(10^{-7}\) | 10 - 20        | 0.1    | 1                           |
3.3 Effects of the Background Viscosity and the Convection Efficiency Coefficient

Here, we consider the results of Model 7 (Fig. 4, left panel), in which the background viscosity is an order of magnitude lower than in the basic model. The bursts in this model appear at later times (after 225000 yrs) than in the basic one (around 30000 yrs). In the case of the reduced background viscosity, the interval between the bursts increases by a factor of about 20, and so does (i.e., increases by the same factor) the maximum intensity of accretion during the burst. In Model 7, the minimum accretion rate decreases tangibly, to $10^{-10} M_\odot/yr$. These features are due to the reduced background viscosity causing a lower rate of viscous dissipation, which enables the accumulation of large masses in the disk before the onset of convective instability. Thus, the decrease in the background viscosity does not make the bursts disappear but transforms them into less frequent yet more intensive events. It should be noted that the du-
Figure 2. The same as in Fig.1 for Models 4, 5, and 6 with an inner accumulation region (the top, middle, and bottom panels, respectively).

Rations of the bursts in Models 2 and 7 are comparable. During the convective phase, the main contribution to the viscosity coefficient $\nu(R,t)$ comes from the convective viscosity $\nu_c$ (see formula (2)), which does not depend on $\nu_0$.

The right panel of Fig.4 shows the accretion rates for the basic model and for the one with the reduced convection efficiency coefficient. Evidently, the decrease in $\eta$ does not make the bursts disappear either, but it modifies them. The bursts become a quarter more frequent yet less intensive. The reduced convection efficiency leads to a lower convective viscosity coefficient $\nu_c(R,t)$ (see formulae (5)-(6)). Since the convective viscosity decreases, the convective phase becomes less intensive. Thus, the disk discharges less mass during the burst, which leads to smaller intervals between the bursts.

Note that the model calculations presented here are for illustrative purposes only. Their main goal is to demonstrate the possible role of convection in achieving a nonstationary accretion regime in accretion disks and to qualitatively assess the importance of certain parameters. In the above described Models 18, accretion was set constant in time and space. We performed simulations until the
Figure 3. Development of an accretion burst in Model 2 (top panel) and Model 5 (bottom panel). Left: the radial surfacedensity distributions (time is counted from the end of the previous accretion burst). The vertical band shows the gas accretion region from the envelope. Right: the accretion rate of matter from the disk onto the star. The position and color of the vertical lines corresponds to the distributions in the left panel.

Figure 4. The accretion rate of matter from the disk onto the star for different models. Left: the basic model (Model 2, \( \nu_{15} = 1 \)) and the reduced background viscosity model (Model 7, \( \nu_{15} = 0.1 \)). The upper abscissa axis corresponds to the basic model; the lower one, to Model 7. Right: the basic model (Model 2, \( \eta = 1 \)) and the model with the reduced convection efficiency coefficient (Model 8, \( \eta = 0.1 \)).
4 EVOLUTION OF PDS UNDER A VARIABLE INFLOW OF MATTER FROM THE ENVELOPE

In order to investigate the long-term evolution of the disk, we need to specify a realistic function $W(R,t)$, which describes the rate of matter inflow from the envelope. To calculate this function, we use an approximation about the conservation of matters local angular momentum in the accreting envelope, i.e., the residue of the parent protostellar cloud. Within this approximation, an element of volume originally located at a distance of $l$ from the polar axis falls onto the so-called centrifugal radius $R_c$:

$$R_c = \frac{l^2 \Omega^2}{GM_*},$$

(9)

at which its angular velocity becomes Keplerian. In this relation, $\Omega$ is the initial angular velocity of the element under consideration and $M_*$ is the current stellar mass. Thus, the model assumes that the cloud elements settle gradually onto the disk at a local Keplerian velocity, with each cloud element having its own settling radius, which is calculated from the angular momentum conservation condition for the cloud element.

If we assume that the original protostellar cloud is spherically symmetric and rotates in a solid-body manner, then the function $W(R,t)$ is written as

$$W(R,t) = \frac{\dot{M}(t)}{8\pi R_c^2(t)} \left( \frac{R}{R_c(t)} \right)^{-3/2} \left[ 1 - \left( \frac{R}{R_c(t)} \right)^{1/2} \right]^{-1/2},$$

(10)

where $\dot{M}(t)$ is the current full accretion rate from the envelope onto the disk; $R_c(t)$ is the boundary of the accumulation region, i.e., the centrifugal radius for an accreted element from the equatorial plane. The functions $\dot{M}(t)$ and $R_c(t)$ can be specified using different approaches (Hueso & Guillot 2005). We take these functions by approximating and extrapolating the numerical simulation results of a cloud collapse and subsequent accretion of the envelope onto the star from Pavlyuchenkov et al. (2015). We can rightfully so because aforementioned work used the Lagrange method, which creates a framework to trace the evolution of individual elements.

In so doing, we used the angular velocity of the original cloud $\Omega = 10^{-14}$ s$^{-1}$, which is a characteristic quantity for the cores of molecular clouds (Bel Chebl 2013). Figure 5 presents the functions $\dot{M}(t)$ and $R_c(t)$ and shows the shape of the function $W(R,t)$.

The accretion rate from the envelope onto the disk in the range 0.2–0.7 Myr is well approximated by an exponential function. As we lack data on the subsequent evolution of the envelope, we use this approximation for larger times as well. The centrifugal radius increases with time, reaching $\approx 180$ AU at 0.8 Myr. At large times, we use a constant quantity of 180 AU. It is evident from the shape of the function $W(R,t)$ that the matter falling onto the disk fills unevenly in an area inside the accumulation region. Specifically, the maximum of $W(R,t)$ near zero is due to the fall of matter onto the disk from the envelopes circumpolar regions.

Within this model, we study the disks long-term evolution; therefore, we need to consider that the stellar mass increases due to the matter inflow from the disk. We do so by assuming that the initial stellar mass is $0.3 \, M_*$ and increase it in accordance with the accreted mass. The radius and photospheric luminosity of the star should also change simultaneously with its mass, but we neglect this change for the sake of simplicity, assuming that the stellar radius and luminosity are equal to those of the Sun. As in the constant inflow model, the accretion luminosity of the central object is variable and is calculated from $j$. Note that it is the accretion luminosity that makes the greatest contribution to the luminosity of the central object at early stages in the disk evolution. The coefficients $\eta_0 = 10^{15}$ cm$^2$/s and $\eta = 1$ were taken from the basic model and were time independent.

Let us consider the calculated results for the disk evolution in this model. Figure 4 shows the time dependence of the accretion rate from the disk onto the star and the change in the disk mass with time. The filled area in the accretion rate distribution at 0.17–3.7 Myr indicates a burst-like accretion regime at this figure scale, the numerous bursts merge into a single continuous band. After 3.7 Myr, the bursts cease to occur, and the accretion rate smoothly decreases with time. A comparison between the accretion rate onto the star and the rate of matter inflow from the disk (the dashed line in Fig. 6, top panel) leads to a conclusion about the importance of the disk mass accumulation process. In the first million years, the disk accumulates a considerable mass (see Fig. 6, bottom panel), and its subsequent evolution is defined by the redistribution of this mass while the matter inflow from the envelope becomes negligibly small. In the burst phase, both the maximum and minimum accretion rates decrease smoothly over $\approx 2$ Myr, after which they remain virtually constant until 3.7 Myr. We should also note that the change in the accretion rate in the quiet phase ($t > 3.7$ Myr) agrees well with the analytical dependence $\dot{M} \propto t^{-3/4}$, which describes a disk with a viscosity distribution of $\nu \propto R^0$ (see formula (6) from Tutukov & Pavlyuchenkov 2004).

Figure 7 shows characteristic forms of accretion bursts at times in the neighborhood of 0.4, 1.5, and 3.5 Myr. Evidently, the bursts have profiles differing from those described by us for the constant inflow model. Specifically, the bursts at 0.4 and 1.5 Myr have deep and narrow minima directly before the maximum. Meanwhile, the bursts at 3.5 Myr are morphologically similar to those described in Section 4 but are of composite nature. These differences are due to the advanced evolution of the disk and the influence of its outer parts, i.e., the mass reservoir for convectively unstable regions, which was left out of consideration in the constant inflow model.

Let us analyze the formation of a burst at a time interval in the neighborhood of 1.5 Myr as an example. Figure 8 presents the disks surface density and the total viscosity coefficient $\nu(R)$ for three neighboring times. At the conventionally initial time, the entire inner region up to 30 AU is convective, which is evident from the high viscosity coefficient (Fig. 8, right panel). Over time, the size of the convective zone decreases; i.e., its boundary shifts towards the star, reaching 2 AU at time 227 yrs. At time 291 yrs, the outer boundary of this convective zone contracts to a radius of 0.35 AU and will soon reach the disks inner boundary. It is evident that by this time, a new convective zone has formed inside 0.7–5 AU. This new convective zone expands in both directions and will subsequently capture the entire inner zone up to 30 AU. Thus, the new convective phase in the disk begins to develop before the previous one comes to an end. It is the short space interval between the convective zone boundaries (the interval between 0.35 and 0.7 AU in Fig. 8) that creates the deep narrow minimum before the accretion maximum.

The above results suggest that convection can serve as an im-

onset of bursts if any appeared, as well as studied their characteristics. However, the further evolution of the disk was not investigated. In fact, both the accretion rate and the fall area from the envelope should be changing over time. In the next section, we modeled the long-term evolution of the disk with the view of this dependence.
important factor underlying the nonsteady pattern of accretion from the disk onto the star. Figure 9 (top panel) shows the long-term evolution of the surface density radial distribution and marks convectively unstable regions. Evidently, in the disk evolution process, the size of the convectively unstable region decreases from several tens to several astronomical units, while the phase of episodic accretion lasts less than 4 Myr. These results are of qualitative nature; however, our model has several serious limitations, which are noted in Article I. Removing these limitations may largely complicate the disk evolution pattern. One of these limitations is that the model neglects the dust evaporation and gas dissociation/ionization processes occurring at high temperatures. Figure 9 (middle panel) shows the evolution of the equatorial temperature distribution and marks the regions with temperatures above 1500 K, in which the dust evaporation processes become important. Obviously, these regions concentrate in the disks inner parts and manifest themselves more conspicuously at initial times. They are seen to partially overlap the convectively unstable regions, which situation should of course affect the disk evolution pattern. Meanwhile, the convectively unstable region is wider in space and time, which is why the conclusions from the model under consideration remain relevant.

Another limitation of the model resides with its neglect of the disks self-gravitation (Eq. (1) is valid for the Keplerian disk). However, as seen from Fig. 6 the disk mass in the early stages of evolution is comparable with the stellar mass. Figure 9 (bottom panel) shows the distribution of the Toomre parameter: \( Q = \frac{c_s \Omega}{\pi G \Sigma} \), where \( c_s \) is the velocity of sound and \( \Omega \) is the Keplerian angular velocity. Low values of this parameter (\( Q < 1 \)) indicate gravitationally unstable regions. Evidently, these regions appear at initial times of the evolution (\( t < 0.5 \) Myr) in the disks outer parts (\( R > 50 \) AU). The appearance of these regions should also affect the disk evolution; i.e., the disk should develop spirals and fragments, whose interaction with one another and with the disk creates complex variations (see, e.g., (Vorobyov & Pavlyuchenkov 2017)). Thus, at initial times in the evolution, convection may be complicated by other, possibly more complex, governing processes.

5 CONCLUSIONS

According to Article I, convective instability can lead to nonsteady accretion onto the star in a PD. However, this conclusion was there illustrated only by one model with a fixed set of parameters. In this work, we investigated how the model parameters affect the onset of episodic accretion and studied the pattern of this accretion at different matter inflow rates from the envelope and for different accumulation regions in the disk. The results from these models can be summarized as follows:
Evolution of a Viscous Protoplanetary Disk

Figure 7. The accretion rate of matter from the disk onto the star for three time intervals in the neighborhood of 0.4 Myr (left), 1.5 Myr (center), and 3.5 Myr (right).

Figure 8. Top: the radial surface-density distribution for three times in the neighborhood of 1.5 Myr. Bottom: the total viscosity coefficient $\nu(R,t)$ for the same times.

- Depending on the matter inflow rate from the envelope onto the disk, we can identify three main accretion regimes: (a) low inflow: no convection occurs and accretion is monotonic; (b) moderate inflow: convectively unstable regions arise periodically, which leads to nonsteady (burst-like) accretion; and (c) high inflow: the disks inner regions may become completely convective, which leads to a weakly oscillating pattern of accretion due to instabilities behind the accumulation region of the disk.

- Burst parameters (maximum intensity, duration, and period) depend on the matter inflow rate and the position of the accumulation region. Thus, with an increase in the external inflow, we see an increase in the intensity and frequency of the bursts. A shift of the accumulation region towards the center leads to an increased frequency and decreased duration of the bursts.

- The onset of episodic accretion is a stable manifestation of the disk model used in the study. Specifically, if the background viscosity and convection efficiency are reduced by an order of magnitude, this change does not make the bursts disappear yet modifies them.

In addition to this analysis, we modeled the longterm evolution of the disk, including a variable matter inflow from the envelope $W(R,t)$. This calculation enabled us to trace the disk evolution from the first luminosity bursts to their complete termination and gradual depletion of the disk. Based on the calculation results, we made the following conclusions:

- An important effect of the disk evolution from the perspective of periodic accretion manifestations is the mass accumulation process in the disk due to matter inflow from the envelope. In the first million years, the disk accumulates considerable mass, and the subsequent disk evolution is defined by the redistribution of this mass rather than by accretion from the envelope, which becomes negligible.

- The disk soon becomes convectively unstable and remains so for almost 4 Myr. Meanwhile, the instability captures an area of several tens of astronomical units and then gradually decreases.

- Burst parameters (intensity, duration, and frequency), as well as their shape, change with time, which is associated with a change in the disk mass and the integral flow of matter through it. The bursts may take very bizarre shapes.

We also illustrated the model limitations: the calculations provide conditions for a gravitational instability to arise as well as for high-temperature regions where dust evaporation is expected. These processes are neglected in the model. Moreover, the model has several other limitations, which were detailed in Article I. Therefore, the results presented are largely qualitative in nature. Specifically, in the early phases of the disk evolution, convection can coexist with other, possibly more intense, processes. We believe that further investigation of the convection role should rely on more consistent models, which will consider hydrodynamic effects, dust evaporation, and gas dissociation and ionization processes.
Figure 9. Top panel: the long-term evolution of the radial surface-density distribution. The crosshatching indicates the regions that became convectively unstable. Middle panel: the evolution of the radial equatorial-temperature distribution. The crosshatching indicates the regions where temperature exceeded 1500 K at its maximum. Bottom panel: the distribution of the Toomre parameter $Q$. The values of $Q > 2$ are shown in red. The values of $Q < 1$ (shades of blue) indicate gravitationally unstable regions.

ACKNOWLEDGMENTS

The authors thank the reviewer for valuable comments and constructive suggestions for improving this article.

The work by L.A. Maksimova was carried out in the framework of the project “Study of stars with exoplanets” under a grant from the Government of the Russian Federation for scientific research conducted under the guidance of leading scientists (agreement N 075-15-2019-1875).

REFERENCES

Audard M. et al., 2014, in Protostars and Planets VI, Beuther H., Klessen R. S., Dullemond C. P., Henning T., eds., p. 387
Bally J., Hawley J. F., 1991, ApJ, 376, 214
Belloche A., 2013, in EAS Publications Series, Vol. 62, EAS Publications Series, Hennebelle P., Charbonnel C., eds., pp. 25–66
Coleman M. S. B., Kotko I., Blaes O., Lasota J. P., Hirose S., 2016, Monthly Notices Roy. Astron. Soc., 462, 3710
Ercolano B., Mayr D., Owen J. E., Rosotti G., Manara C. F., 2014, Monthly Notices Roy. Astron. Soc., 439, 256
Hartmann L., 1998, Accretion Processes in Star Formation
Hartmann L., Kenyon S. J., 1996, Annual Review of Astronomy and Astrophysics, 34, 207
Hawley J. F., Balbus S. A., 1991, ApJ, 376, 223
Held L. E., Latter H. N., 2018, Monthly Notices Roy. Astron. Soc., 480, 4797
Hirose S., Blaes O., Krolik J. H., Coleman M. S. B., Sano T., 2014, ApJ, 787, 1
Hueso R., Guillot T., 2005, Astron. and Astrophys., 442, 703
Kley W., Lin D. N. C., 1999, ApJ, 518, 833
Lin D. N. C., Papaloizou J., 1980, Monthly Notices Roy. Astron. Soc., 191, 37
Lipunova G. V., Shakura N. I., 2003, Izvestia Rossiskoi Akademii Nauk, Seria fizicheskaya, 67, 322
Malanchev K. L., Postnov K. A., Shakura N. I., 2017, Monthly Notices Roy. Astron. Soc., 464, 410
Natta A., Testi L., Randich S., 2006, Astron. and Astrophys., 452, 245
Pavlyuchenkov Y. N., Tutukov A. V., Maksimova L. A., Vorobyov E. I., 2020, Astronomy Reports, 64, 1
Pavlyuchenkov Y. N., Zhilkin A. G., Vorobyov E. I., Fateeva A. M., 2015, Astronomy Reports, 59, 133
Pringle J. E., 1981, Annual Review of Astronomy and Astrophysics, 19, 137
Safronov V. S., 1960, Annales d’Astrophysique, 23, 979
Shakura N., Postnov K., 2015, Monthly Notices Roy. Astron. Soc., 451, 3995
Shakura N. I., 1972, Astronomicheskii Zhurnal, 49, 921
Shakura N. I., Sunyaev R. A., 1973, Astron. and Astrophys., 24, 337
Toomre A., 1964, ApJ, 139, 1217
Tutukov A. V., Pavlyuchenkov Y. N., 2004, Astronomy Reports, 48, 800
Vorobyov E. I., Basu S., 2006, ApJ, 650, 956
Vorobyov E. I., Pavlyuchenkov Y. N., 2017, Astron. and Astrophys., 606, A5
Vorobyov E. I., Skliarevskii A. M., Elbakyan V. G., Pavlyuchenkov Y., Akimkin V., Guedel M., 2019, Astron. and Astrophys., 627, A154
Williams J. P., Cieza L. A., 2011, Annual Rev. of Astron. and Astrophys., 49, 67
Zhu Z., Hartmann L., Gammie C., McKinney J. C., 2009, ApJ, 701, 620