Origins: From the Protosun to the First Steps of Life
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Gravitational fragmentation and formation of giant protoplanets on orbits of tens of AU

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Abstract. Migration of dense gaseous clumps that form in young protostellar disks via gravitational fragmentation is investigated to determine the likelihood of giant-planet formation. We show that gaseous clumps that form in the outer regions of the disk (>100 au) through disk fragmentation often migrate toward the central star on timescales from a few thousand to few tens of thousands of years. The tidal mass loss helps the clumps to significantly slow down or even halt their inward migration at a distance of a few tens of AU from the protostar.

Keywords. stars: formation, planetary systems: protoplanetary disks

1. Introduction

The importance of disk fragmentation as a likely mechanism for giant planet and brown dwarf formation has been reinforced by the detection of wide-orbit (from several tens to hundreds of astronomical units) planetary and brown dwarf companions to low-mass stars (e.g., Marois *et al.* 2008; Kalas *et al.* 2008; Lafreniére *et al.* 2010).

Here we investigate the process of clump migration in a gravitationally unstable disk using high-resolution numerical hydrodynamics simulations in the thin disk limit (see Vorobyov & Basu 2015 for details). We focus on the properties of one of the gaseous clumps (IF1) formed in the disk via gravitational fragmentation and investigate the details of its inward migration until it is destroyed by the action of stellar tidal torques.

2. Dynamics of fragment IF1

Figure 1 shows the gas surface density distribution in and around IF1 during its inward migration towards the protostar. Three different time instances are shown and every panel has progressively smaller spacial scales to better resolve the fragment.

As IF1 approaches the star, its size shrinks because of the shrinking Hill radius and part of its material starts streaming away along the tidal arms. As a result, the fragment loses a large fraction of its initial mass. Finally, the rotational motion inside IF1 almost disappears ($t = 3.39$ kyr), turning into a sheer outflow. At this stage, IF1 ceases to be gravitationally supported and tidal torques tear apart the fragment.†

Figure 2 presents the mass, radial distance, and central temperature of IF1 as a function of time. The vertical dashed line indicates the time instance ($t = 1.8$ kyr) when the second collapse to planetary densities is supposed to take place (not modelled in our simulation). We found that if IF1 had collapsed at $t = 1.8$ kyr, it would have formed a protoplanet

† The animation of clump inward migration can be found at http://www.astro.sfedu.ru/animations/accretion.mp4

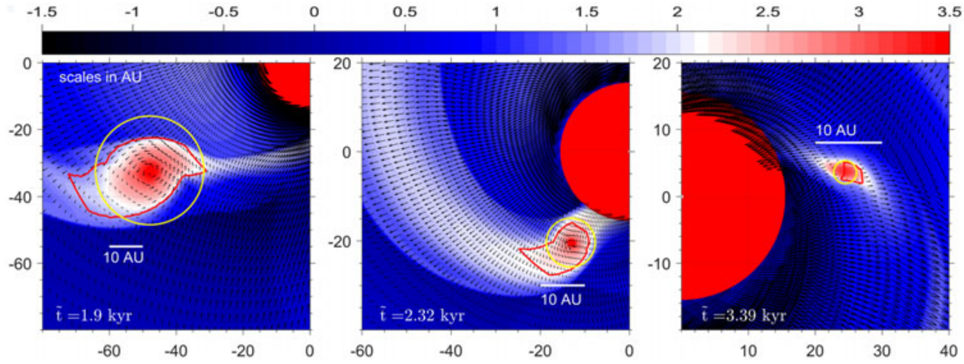

Figure 1. Zoomed-in view on IF1 during its inward migration towards the protostar. The black arrows show the gas velocity field superimposed on the gas surface density distribution. The shrinking spatial scales are used to better resolve the fragment. The yellow circles mark the Hill radius of the fragment and the red curves outline the fragment shape. The color bar shows the gas surface density in log g cm^{-2}.

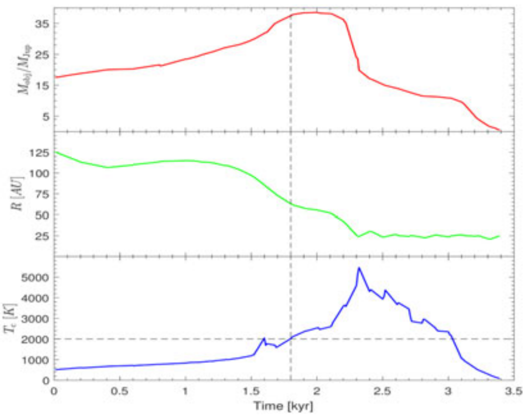

Figure 2. Mass of IF1 (top panel), radial distance of IF1 (middle panel), and central temperature of IF1 (bottom panel), all vs. time. The horizontal dashed line shows a threshold temperature of 2000 K, above which molecular hydrogen dissociates and the second collapse is supposed to ensure. The vertical dashed line shows the time instance when the central temperature of IF1 reaches the threshold value.

with a mass of 0.81 $M_{\rm Jup}$. We expect that during the subsequent inward migration, the protoplanet may survive and settle at an orbit of approximately a few tens of AU.

3. Conclusions

Our findings can be summarized as follows:

• Gaseous clumps that form in the outer disk regions often migrate toward the central star and lose most of their diffuse envelopes through tidal torques.

• The tidal mass loss helps the clumps to significantly slow down or even halt their inward migration at a distance of a few tens of AU from the protostar.

• Central part of the clumps may further experience the second collapse down to planetary densities through the dissociation of molecular hydrogen at T >2000 K.†

† More details can be found in Vorobyov & Elbakyan, 2018, A&A, 618, A7.

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