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Triggered fragmentation in gravitationally unstable discs: forming fragments at small radii

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Abstract

We carry out three dimensional radiation hydrodynamical simulations of gravitationally unstable discs to explore the dynamics of the gas in a disc following its initial fragmentation. We find that the radial velocity of the gas in the disc increases by up to a factor of $\approx 2-3$ after the disc fragments, compared to its quiescent state before. While the disc mass moves in both the inward and outward directions, the inwards movement can cause the inner spirals of a self-gravitating disc to become sufficiently dense and unstable such that it can potentially trigger further fragmentation. Consequently the dynamical behaviour of fragmented discs may cause subsequent fragmentation to occur at smaller radii than initially expected, but only *after* an initial fragment has formed in the outer disc. In the context of planet formation, core accretion is thought to occur at small radii (up to $\approx 5-10$au) and gravitational instability is thought to occur at larger radii ($\gtrsim$ 50au). A radial range therefore exists where no one single formation method is currently thought to dominate. Triggered fragmentation may be one way in which planet formation may occur in this radial range.

1. Introduction

Gravitationally unstable discs may collapse and fragment to form bound objects if the disc becomes Toomre unstable (Toomre, 1964) and if the disc cools faster than a critical rate (Gammie, 2001). Upon formation, the fragment-disc interactions (angular momentum exchanges and mass accretion onto the fragment) may cause the fragments to migrate (e.g. Baruteau et al., 2011; Michael et al., 2011) or even for the disc to be disrupted (e.g. Stamatellos & Whitworth, 2009). However, while the longer term fragment evolution has been considered in some detail, how the disc mass moves in response to the presence of the fragment immediately after it has formed is not so well studied. The existence of a planet in a gravitationally unstable disc can trigger the collapse of the disc to form fragments both interior and exterior to it (Armitage & Hansen, 1999). However, this previous study used an isothermal equation of state (equivalent to a fast cooling) and was thus favourable for fragmentation.

2. Simulations & Results

We carry out three-dimensional Smoothed Particle Hydrodynamics simulations with radiative transfer of self-gravitating discs, to understand the movement of mass in such discs before and after they fragment. We self-consistently model the formation of the first and any potential subsequent fragments.

Figure 1 shows the surface mass density (top panel) and radial velocity (bottom panel) rendered images of a disc at various evolutionary stages. Before fragmentation occurs (left panel) the disc is reasonably quiescent. However once the first fragment forms, its presence causes the radial velocity of the gas in regions of the disc that it has interacted with to increase, both inwards and outwards by a factor of $\approx 2-3$ (middle panel). The mass movement in the fragmented disc is not quiescent. As a result of the inwards motion, an inner spiral becomes more dense and the Toomre profile decreases, allowing the disc to be pushed into a state of instability, resulting in fragmentation (Figure 1, top right panel).

3. In the context of protoplanetary discs

Triggered fragmentation may have important implications for giant planet formation theories: while a disc may only initially fragment in the outer regions (Rafikov, 2009; Clarke, 2009; Boley, 2009), planets may well form in the inner parts via gravitational instability *provided* fragmentation has already occurred in

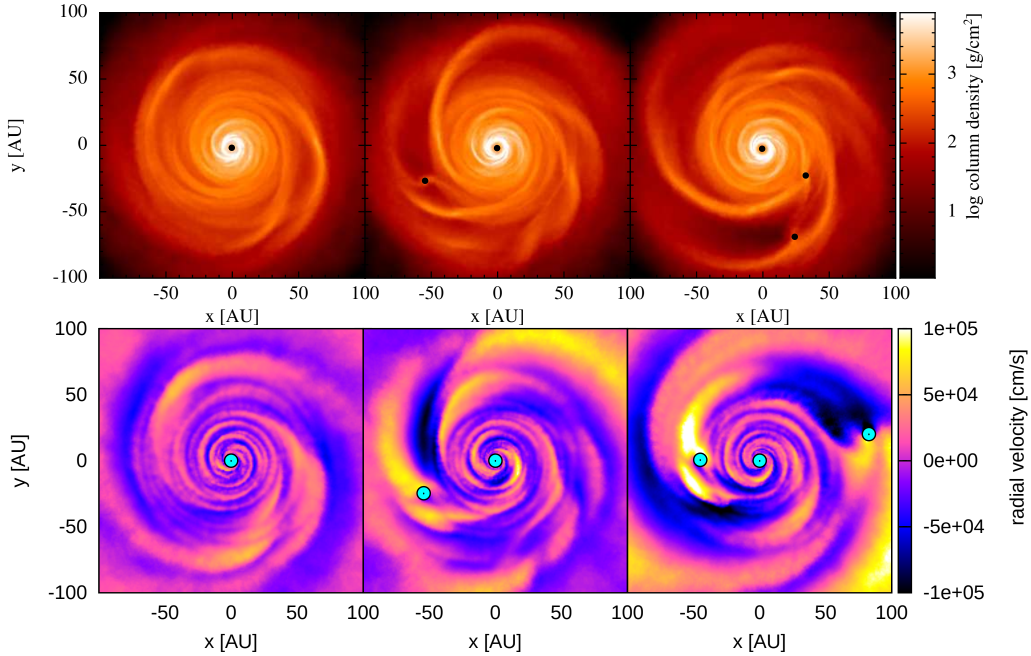

Figure 1: Surface mass density (top panel) and radial velocity (bottom panel) rendered images of a self-gravitating disc before the first fragment forms (left panel) and after the formation of the first (middle panel) and second fragments (right panel). The mass movement increases after the fragments form.

the outer regions first. Since core accretion is thought to occur at small radii (up to $\approx 5-10$ AU) while gravitational instability is thought to occur at larger radii ($\gtrsim$ 50 AU) *subsequent planet formation by gravitational instability* may well be a mechanism that may operate in the radial range in between, where no single in situ formation method is currently thought to dominate.

4. Summary and Conclusions

We carry out three-dimensional radiative transfer simulations of gravitationally unstable discs to explore the movement of mass in a disc following its fragmentation. We self-consistently model the formation of the first fragment and subsequent disc evolution. The fragment's presence causes the magnitude of the radial velocities to increase by a factor of $\approx 2-3$ resulting in a more dynamic disc than prior to its formation. If an inner disc region is quite close to marginal stability, such mass movement can cause it to be moved into a state of instability where further fragmentation may then occur. This has potential implications for planet formation at the radii where no one mechanism adequately describes their in situ formation.

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