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Understanding Present-Day Low-Mass Star Formation Through Second-Collapse Calculations

Describing the collapse of a gravitationaly unstable cloud core to stellar densities requires one to tackle a huge dynamical range, where a first core in hydrostatic equilibrium forms, which then collapses again following the dissociation of H_2 to form a protostar. Since R. Larson's (Larson 1969) pioneering work, second-collapse calculations have advanced significantly by incorporating realistic initial conditions, angular momentum, radiative transfer, and magnetic fields in 3D (Machida+ 2006, Vaytet+ 2018, Wurster+ 2020, 2022). However, computational constraints often limit these simulations to shortly after protostellar birth.

In a suite of papers presenting the highest-ever 3D resolution second-collapse calculations (Ahmad+ 2023, 2024, Ahmad+ 2025 submitted) using the RAMSES code with Adaptive Mesh Refinement, we extend these calculations to later stages, simulating the first few years of the protostar while focusing on the innermost sub-AU scales.

We find that the protostar's rapid accretion of angular momentum causes its outer layers to reach rotational breakup, forming a hot, eccentric, and highly-flared disk. The protostar and disk act as a continuous system, with the accretion shock enveloping both, a result which has implications for the angular momentum problem. Magnetic fields alter the disk and protostar's properties by affecting the angular momentum budget. This in turn affects the disk density, which has repercussions on the disk mass problem; a discrepancy between observed and simulated disk masses. The disk's rapid outward expansion may have left its mark on the meteoric record of the early solar system, as high-temperature condensates in the form of calcium-aluminum inclusions and amoeboid olivine aggregates show evidence of rapid outward transport (Morbidelli+ 2024).

Having resolved the accretion shock, we were also able to measure its radiative efficiency, which we found quickly reaches unity, thus ensuring cold accretion. This result has substantial implications for pre-main sequence models, as it dictates the entropy content of the protostar and thus its evolution (Baraffe+ 2012).

We also study the magnetic properties of the protostar, and how this fits into the wider magnetic flux problem.

By pushing state of the art calculations further out in time, and by placing our focus on the smallest spatial scales relevant to star and disk formation, we have revealed a number of physical processes that carry substantial implications on several issues in the field.

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