Nonlinear outcome of gravitational instability in irradiated protoplanetary disks

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Using local three dimensional radiation hydrodynamics simulations, the nonlinear outcome of gravitational instability in an irradiated protoplanetary disc is investigated in a parameter space of the surface density Σ and the radius r. Starting from laminar flow, axisymmetric self-gravitating density waves grow first. Their self-gravitating degree becomes larger when Σ is larger or the cooling time is shorter at larger radii. The density waves eventually collapse owing to non-axisymmetric instability, which results in either fragmentation or gravito-turbulence after a transient phase. The boundaries between the two are found at r ~75 AU as well as at the Σ that corresponds to the initial Toomre's parameter of ~ 0.2. The former boundary corresponds to the radius where the cooling time becomes short, approximating unity in terms of the inverse of the orbital frequency. Even when gravito-turbulence is established around the boundary radius, such a short cooling time inevitably makes the fluctuation of Σ large enough to trigger fragmentation. On the other hand, when Σ is beyond the latter boundary (i.e. the initial Toomre's parameter is less than ~0.2), the initial laminar flow is so unstable against self-gravity that it evolves into fragmentation regardless of the radius or, equivalently, the cooling time. Runaway collapse follows fragmentation when the mass concentration at the centre of a bound object is high enough that the temperature exceeds the H_2 dissociation temperature.

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