Cooling Constraints on Planet Formation via Gravitational Instabilities

Dave Nero

University of Toledo

June 7, 2008

Outline

1. Background
2. Conditions for Fragmentation
    - Gravitational Instability
    - Cooling Time
3. Results

Outline

1. Background
2. Conditions for Fragmentation
    - Gravitational Instability
    - Cooling Time
3. Results

Core Accretion

- Pros:
  - Generally explains Solar System
- Cons:
  - Survivability of intermediate products
  - Long timescale

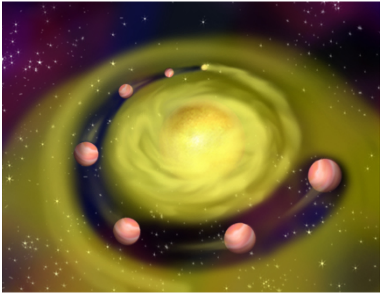


Image credit: Meg Stalcup

Disk Fragmentation

- Pros:
  - Fast
- Cons:
  - Requires very massive disk
  - Hard to form terrestrial planets

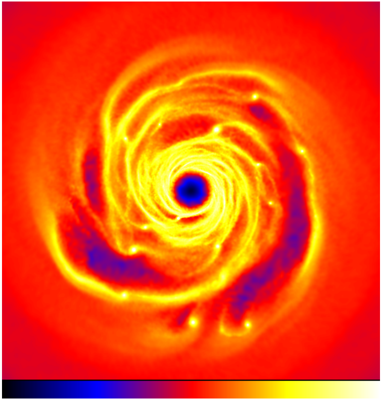


Image Credit: Ken Rice

Outline

1. Background
2. Conditions for Fragmentation
    - Gravitational Instability
    - Cooling Time
3. Results

The Toomre Q Parameter

$$Q = \frac{\Omega c_s}{\pi G \Sigma}$$

Symbol	Definition
Ω	Angular orbital period (Keplerian rotation)
c_s	Isothermal sound speed
Σ	Disk surface density

The Toomre Q Parameter

- $Q > 1 \Rightarrow$Stable
- $Q \approx 1 \Rightarrow$Marginally Unstable
- $Q < 1 \Rightarrow$Unstable

What is a “Cooling Time”?

Definition

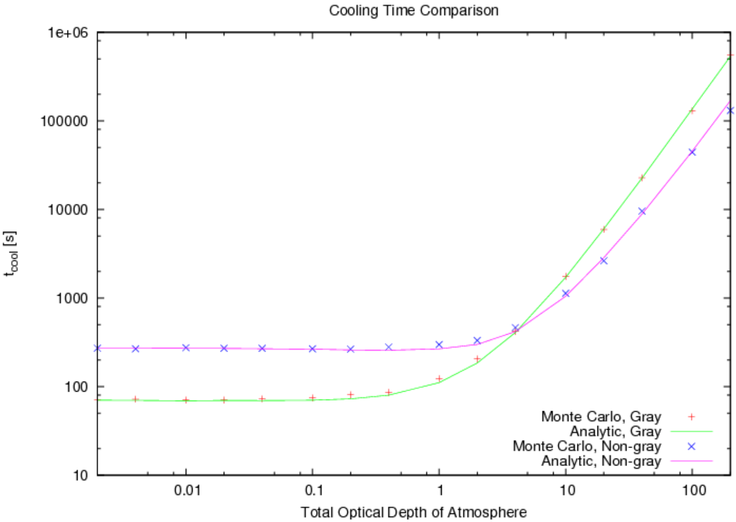
The cooling time is a measure of the timescale required to radiate away the excess energy from a point-source perturbation.

Calculation of Cooling Time

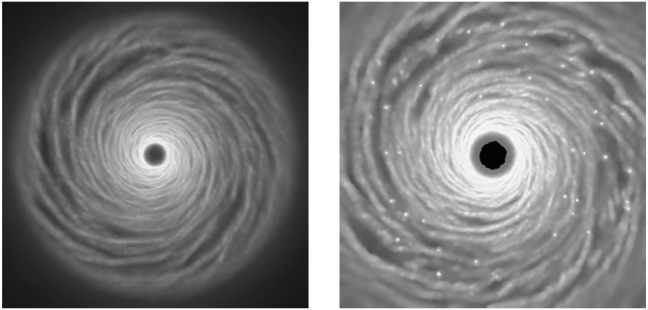
$$t_{cool} = \frac{\Delta\text{Energy}}{\Delta\text{Luminosity}}$$

- The problem is essentially one of calculating the integrated ΔT
- Further assumptions:
    - plane-parallel atmosphere
    - 1+1D
    - Eddington approximation in a gray atmosphere

Comparison with Monte Carlo Calculation



How Cooling Time Affects Fragmentation



Original Captions – From Rice el al. 2003, MNRAS, 339, 1025

Left:
Equatorial density structure for $t_{cool} = 5\Omega^{-1}$ and $M_{disc} = 0.1 M_*$. The disc is highly structured with the instability existing at all radii. The density has, however, not increased significantly and the disc is in a quasistable state with heating through viscous dissipation balancing cooling.
Right:
Equatorial density structure for $t_{cool} = 3\Omega^{-1}$ and $M_{disc} = 0.1 M_*$. The disc is highly unstable and is fragmenting. The fragments are all gravitationally bound.

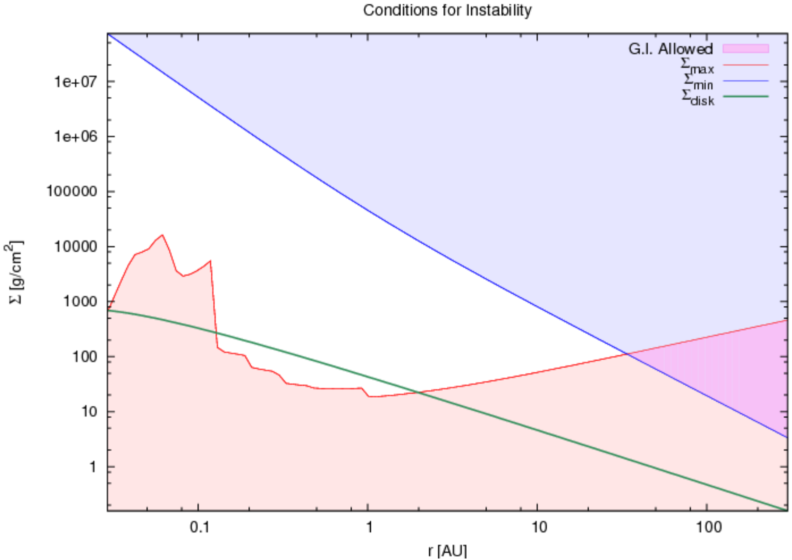
Fragmentation Summary

- $Q < 1$
- $t_{cool} < 3\Omega^{-1}$
- These conditions place limits on Σ:
    - $Q \propto \Sigma^{-1} \Rightarrow$lower limit
    - $t_{cool} \propto \Sigma^{2}$(for thick disks) $\Rightarrow$upper limit

Outline

1. Background
2. Conditions for Fragmentation
   - Gravitational Instability
   - Cooling Time
3. Results

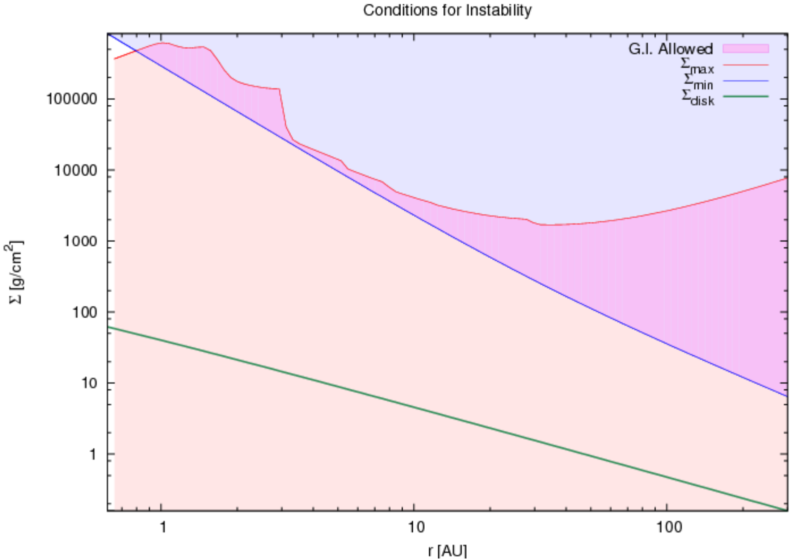
T-Tauri Star


Conditions for Instability
G.I. Allowed
Σ_{max}
Σ_{min}
Σ_{disk}
1e+07
1e+06
100000
10000
1000
100
10
1
Σ [g/cm^2]
0.1
1
10
100
r [AU]

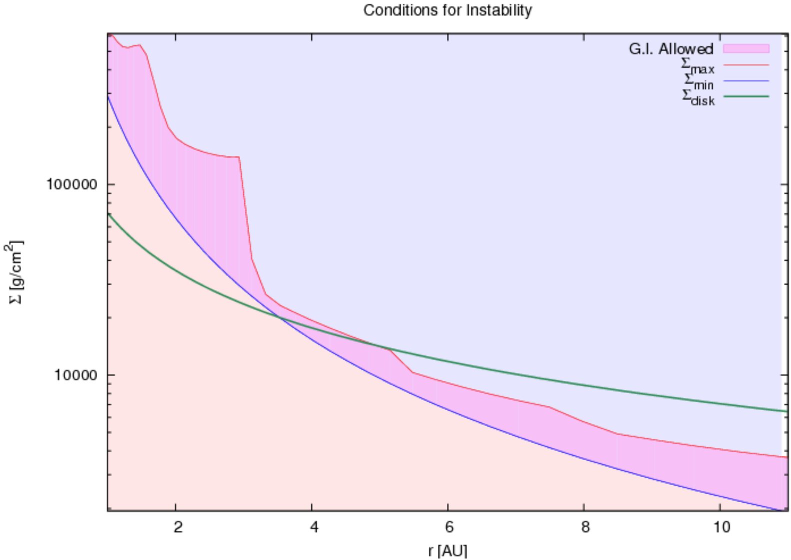
FU-Ori Outburst – Background

- Characterized by high accretion rate
    - Outshines star by factor of $\sim 100 - 1000$
- Duration of $\sim 100yr$
- Accretion luminosity + high temperatures decrease t_{cool}
- High accretion rates must be associated with enhanced surface density

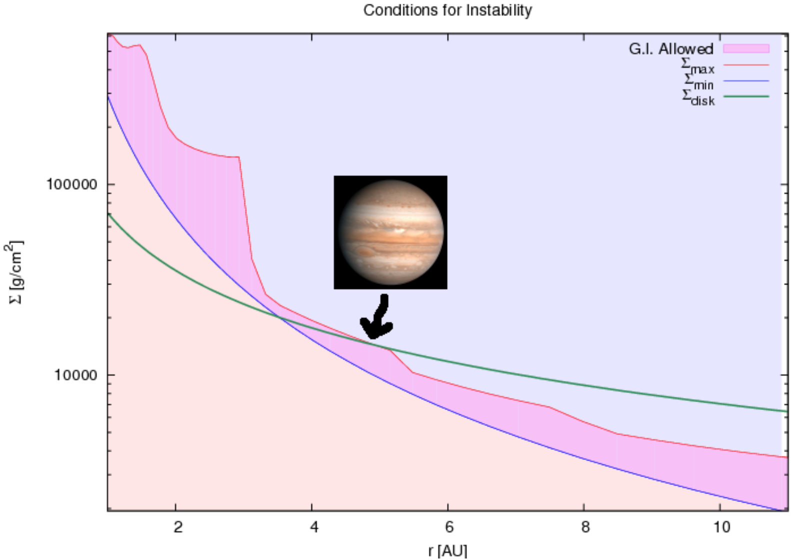
FU-Ori Outburst



FU-Ori Outburst ⇒ Increased Surface Density



FU-Ori Outburst ⇒ Increased Surface Density



Summary

- In order to fragment, a circumstellar disk must:
  1. Be gravitationally unstable
  2. Have a sufficiently short cooling time
- The disk around an average T-Tauri star is unlikely to fragment
- FU-Ori outbursts show promise as a means to rapidly form planets
  - Although this depends strongly on how high the surface density gets