Cooling Constraints on Circumstellar Disk Fragmentation

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UT Astronomy Bag Lunch

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Outline

Outline

Core Accretion

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

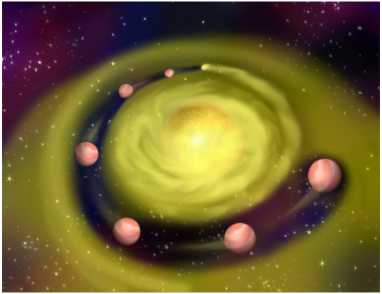


Image credit: Meg Stalcup

Disk Fragmentation

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

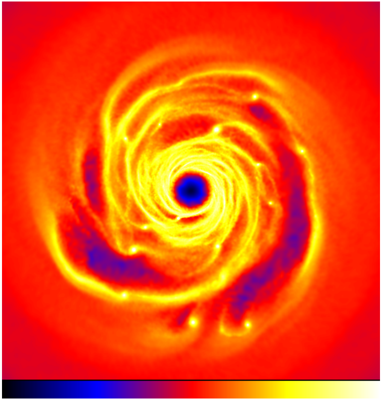


Image Credit: Ken Rice

Outline

The Toomre Q Parameter

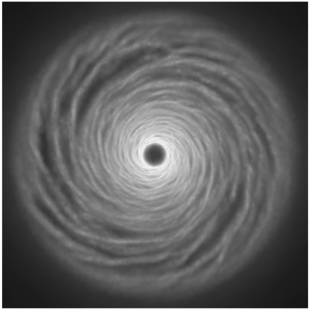
$$Q = \frac{\Omega c_s}{\pi G \Sigma}$$

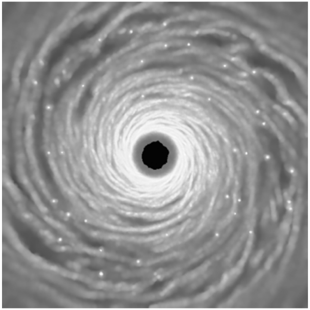
Symbol	Definition
Ω	Angular orbital period (Keplerian rotation)
c_s	Isothermal sound speed
Σ	Disk surface density

The Toomre Q Parameter

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

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 $M_{disc} = 0.1M_*$. 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 $M_{disc} = 0.1M_*$. The disc is highly unstable and is fragmenting. The fragments are all gravitationally bound.

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

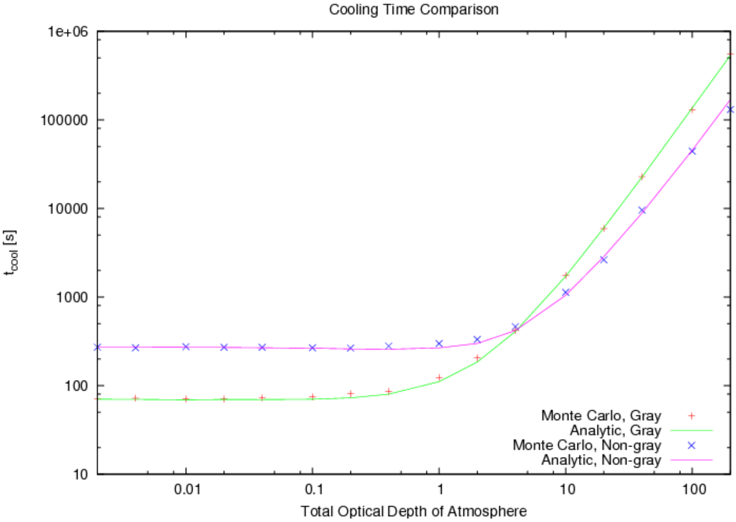
Example Cooling Time

- Optically thick limit
- No (or very small) accretion onto star
- Perturbation at the disk mid-plane

$$t_{cool} = \frac{3}{32} \frac{c_s^2}{\gamma_A - 1} \frac{1}{\sigma T^4} \frac{1}{\chi} \tau_{1/2}^2$$

Symbol	Definition
c_s	Isothermal sound speed
γ_A	Adiabatic Constant
χ	(Mean) Extinction
$\tau_{1/2}$	Mid plane Optical Depth

Comparison with Monte Carlo Calculation



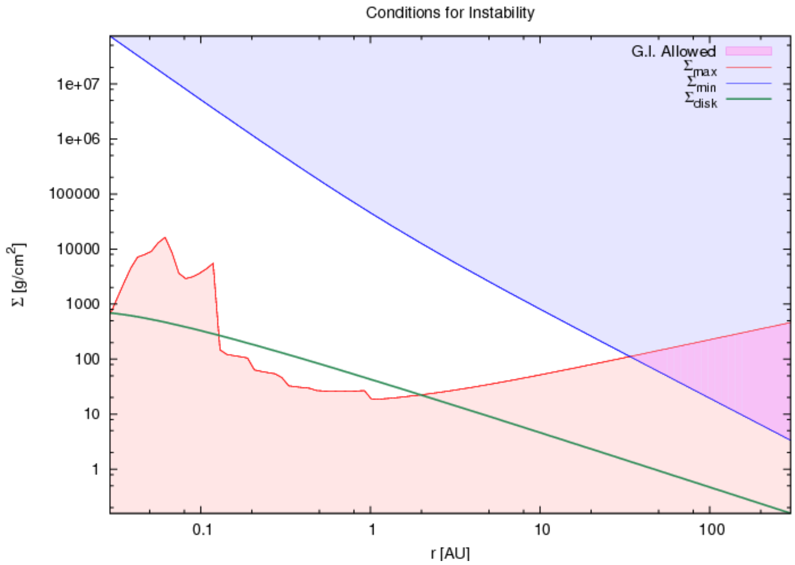
Fragmentation Summary

- $Q < 1$
- $t_{cool} < 3\Omega^{-1}$
- 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

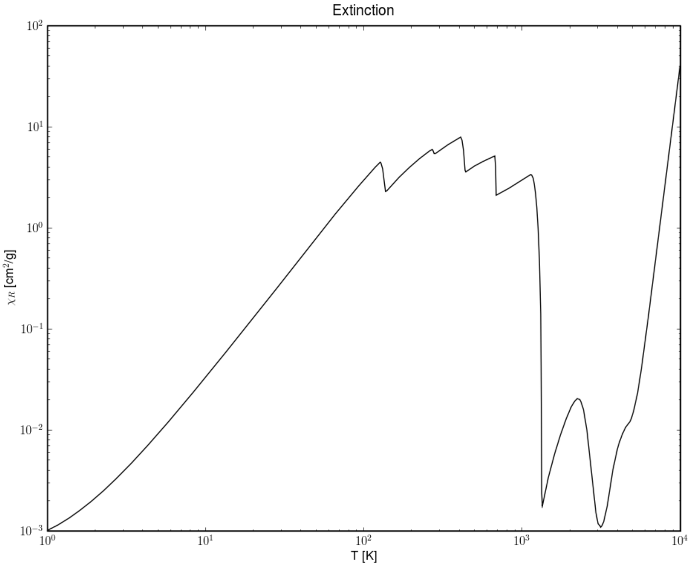
1. Background
2. Conditions for Fragmentation
   - Gravitational Instability
   - Cooling Time
3. Results

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]

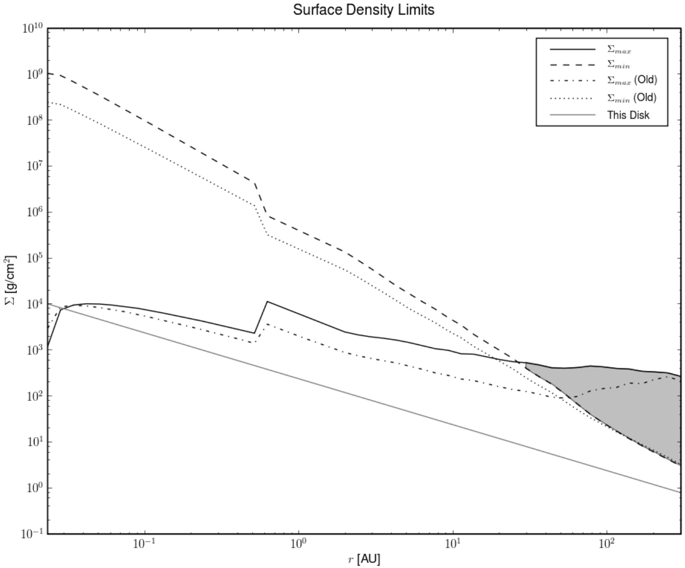
Exploiting Dust Sublimation



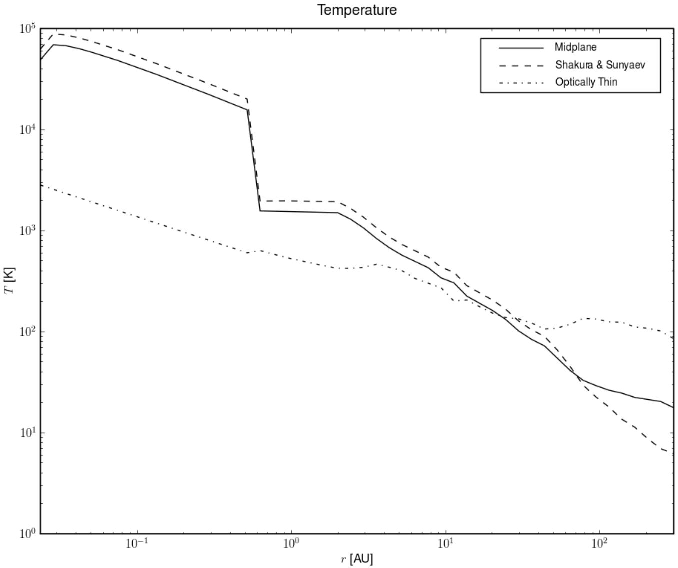
FU-Ori Outburst – Background

- 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



What Went Wrong?



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 showed promise for fragmentation, but more detailed calculations are making this look less likely.

Some Unanswered Questions

- Why does accretion luminosity have such a small effect on cooling time?
- How large of an effect could dust settling and/or grain growth have?
- Is there a regime where high surface densities allow fragmentation at large radii?
    - Very early in the star formation process?
    - Is this applicable to the formation of binary star systems?