Planetesimal Formation in Dense Star Clusters: Hazard or Haven?

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Portugal, 20-Sep-2006
Where Do Most Stars Form?

- Mass range of molecular clouds: few $M_\odot - 10^6 \, M_\odot$
- Mass spectrum of molecular clouds: $dn/dM \sim M^{-1.6}$

⇒ Most of the mass is in the largest GMCs
# Regions of Star Formation

<table>
<thead>
<tr>
<th></th>
<th>Open Clusters</th>
<th>Dense Clusters</th>
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</thead>
<tbody>
<tr>
<td># of stars</td>
<td>$10^1 - 10^3$</td>
<td>$10^3 - 10^4$</td>
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<tr>
<td></td>
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<td>10⁴ stars in last 10 Myr (Orion)</td>
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<tr>
<td>OB stars</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Distance</td>
<td>140 pc (Taurus)</td>
<td>450 pc (Orion)</td>
</tr>
<tr>
<td>Fraction of local stars which form here</td>
<td>10-30%</td>
<td>70-90%? (Lada and Lada 2003)</td>
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<td>Dispersal lifetime</td>
<td></td>
<td>10 Myr (SN)</td>
</tr>
<tr>
<td>% of stars with disks</td>
<td></td>
<td>80%? (Smith et al. 2005)</td>
</tr>
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</table>
How does Cluster Environment affect Disk Evolution?

- Photoevaporation from external, massive stars:
  - $10^5 \, L_{\text{sun}}$ from O stars at cluster core
  - $F \sim 10^4 - 10^6 \, G_0$
  - Truncates disks on Myr timescales

- Close stellar encounters:
  - 2,000 stars in 0.5 pc$^3$
  - Mean stellar separations $\sim 10,000$ AU

- Interaction with GMC gas:
  - Bondi-Hoyle accretion onto stars?

- UV, X ray chemistry:
  - Total UV dose is thousands of ionizing photons per (dust) molecule, in first 10 Myr.
Photo-Evaporation (PE)

- FUV/EUV flux from O stars heats and removes $\text{H}_2 / \text{H}$ from disks.
  - Small dust grains can be entrained in outflow and removed.

- Mass loss rates:
  $$\frac{dM}{dt} \sim 10^{-6} - 10^{-8} \ M_\odot/\text{yr}.$$  
  (Johnstone et al 1998)

- Mass loss rate depends on disk size, distance from external O star.

- MMSN disks surrounding most Orion stars can be truncated to a few AU in Myr.
  - Dust in disks can be retained: sharp outer edge with large grains (Throop et al 2001)

- If you want to build Jupiter in Orion, you must make it fast! (e.g., Boss)
Photo-evaporation is a major hazard to planet formation...

... but all hope is not yet lost!
Gravitational collapse of dust in disk can occur if sufficiently low gas:dust ratio (Sekiya 1997; Youdin & Shu 2004)

- $\Sigma_g / \Sigma_d < 10$
  - (i.e., reduction by 10x of original gas mass)

- PE removes gas and leaves most dust
  - Grain growth and settling promote this further

- Dust disk collapse provides a rapid path to planetesimal formation, without requiring particle sticking.
Close Approaches

- Typical distances today ~ 10,000 AU
- C/A strips disks to 1/3 the closest-approach distances (Hall et al 1996)
- Question: What is the minimum C/A distance a disk encounters as it moves through the cluster for several Myr?
N-Body Dense-Cluster Simulations

NBODY6 code (Aarseth 2003)

Stars:
• N=1000
• $M_{\text{star}} = 500 M_{\text{sun}}$
• Salpeter IMF
• $R_0 = 0.5 \text{ pc}$
• O6 star fixed at center

Gas:
• $M_{\text{gas}} = 500 M_{\text{sun}}$
• $R_0 = 0.5 \text{ pc}$
• Disperses with timescale 2 Myr
Star has 5 close approaches at < 2000 AU.

Closest encounter is 300 AU at 8 Myr

- Too late to do any damage
• Typical minimum C/A distance is 1100 AU in 10 Myr
• Significant disk truncation in dense clusters is rare!
  – Only 1% of disks are truncated to 30 AU, inhibiting planet formation

Throop & Bally 2006, in prep
Flux History, Typical 1 $M_{\text{Sun}}$ Star

- Flux received by disk varies by 1000x as it moves through the GMC.
- Peak flux approaches $10^7 G_0$.
- Most of the flux is deposited during brief but intense close encounters with core.
- There is no `typical UV flux.'
- Disk evolution models assume steady, uniform grain growth, PE, viscous spreading. But if PE is not steady, then other processes dominate and may dramatically change the disk.
**What do we know?**

- Large fraction of stars forming today are near OB associations, not in open clusters
- PE can rapidly destroy disks
  - Hard to make Jovian planets
- PE can also trigger rapid planetesimal formation
  - Easy to make planetary cores
- Close encounters are unimportant

**Where do we go?**

- Need better understanding of effect of time-variable PE on disk evolution
- Need better understanding of role of gravitational instabilities: how frequent is it?
- UV, X-ray chemistry in dense clusters unexplored