Effects of Cluster Environments on Forming Planetary Systems

Fred C. Adams, Univ. Michigan

From Stars to Life Conference
University of Florida
Gainesville, FL, April 2013
Most Stars Form in Clusters:

[1] How does the initial cluster environment affect the formation of stars and planets?

[2] What can we say about the basic properties of the birth cluster for our own Sun and its Solar System?

CONJECTURE:

Clusters affect Planetary systems more than Star formation itself

4 Stages of Star Formation

(Shu, Adams, Lizano, 1987)
**Time Scales**

Infall-Collapse Timescale = 0.1 Myr

- Embedded Cluster Phase = 3 - 10 Myr
- Circumstellar Disk Lifetime = 3 - 10 Myr
- Giant Planet Formation Time = 3 - 10 Myr

- Terrestrial Planet Formation = 100 Myr
- Late Heavy Bombardment = 600 Myr
- Open Cluster Lifetime = 100 - 1000 Myr
Effects of Clusters

I. Dynamical Interactions

II. Radiation Fields

III. Particle Fluxes
   (Cosmic Rays, Radioactive Nuclei)
Simulations of Embedded Clusters

• Simulate evolution from embedded stage to age 10 Myr
• Start with Subvirial Initial Conditions
  \[ Q = \left| \frac{K}{W} \right| \approx 0.05 \]

• Cluster evolution depends on:
  – cluster radial size
  – initial stellar and gas profiles
  – gas disruption history
  – star formation history
  – primordial mass segregation
  – initial dynamical assumptions
• 100 realizations are needed to provide robust statistics for output measures

(R. (N) = 1pc((N/300)^{1/2})

(E. Proszkow thesis 2009)
Closest Approach Distributions

\[ \Gamma = \Gamma_0 \left[ \frac{b}{1000\, \text{AU}} \right]^\gamma \]

<table>
<thead>
<tr>
<th>Simulation</th>
<th>( \Gamma_0 )</th>
<th>( \gamma )</th>
<th>( b_C ) (AU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 Subvirial</td>
<td>0.166</td>
<td>1.50</td>
<td>713</td>
</tr>
<tr>
<td>100 Virial</td>
<td>0.0598</td>
<td>1.43</td>
<td>1430</td>
</tr>
<tr>
<td>300 Subvirial</td>
<td>0.0957</td>
<td>1.71</td>
<td>1030</td>
</tr>
<tr>
<td>300 Virial</td>
<td>0.0256</td>
<td>1.63</td>
<td>2310</td>
</tr>
<tr>
<td>1000 Subvirial</td>
<td>0.0724</td>
<td>1.88</td>
<td>1190</td>
</tr>
<tr>
<td>1000 Virial</td>
<td>0.0101</td>
<td>1.77</td>
<td>3650</td>
</tr>
</tbody>
</table>

Typical star experiences one close encounter with impact parameter \( b_C \) during time 10 Myr.
Solar System Scattering

Many Parameters + Chaotic Behavior → Many Simulations Monte Carlo

Star-Planet-Binary scattering encounters are specified by 13 parameters.

1. Parameters describing the binary orbit: $m_1$, $m_2$, $e$, $f$, $a$
2. Parameters describing the encounter: $v$, $h$, $\psi$, $\theta$, $\phi$
3. Parameters describing a (circular) planetary orbit: $r$, $\theta_1$, $\theta_2$, $\theta_3$
Scattering Results for our Solar System
Cross Sections vs Stellar Mass

\begin{equation}
\langle \sigma \rangle_{ej} = C_0 \left( \frac{a_p}{AU} \right) \left( \frac{M_*}{M_{\odot}} \right)^{-1/2}
\end{equation}

where

\begin{equation}
C_0 = 1350 \pm 160 \ (AU)^2
\end{equation}

Planet ejections are RARE: a couple events per cluster
The cross sections for capture of rocks are a steeply decreasing function of velocity, so transfer is more likely in a young cluster than in the field, in spite of the shorter time scales. Every solar system is likely to share rocks with every other solar system in the birth cluster.

(Adams & Spergel 2005)
Clusters have relatively moderate effects on their constituent solar systems through dynamical interactions.
Effects of Cluster Radiation on Forming/Young Solar Systems

- Photoevaporation of a circumstellar disk
- Radiation from the background cluster often dominates radiation from the parent star (Johnstone et al. 1998; Adams & Myers 2001)
- FUV radiation (6 eV < E < 13.6 eV) is more important in this process than EUV radiation
- FUV flux of $G_0 = 3000$ will truncate a circumstellar disk to $r_d$ over 10 Myr, where $r_d = 36AU\left[\frac{M_*/M_{\text{sun}}}{\text{}}\right]$
Composite Distribution of FUV Flux

FUV Flux depends on:
- Cluster FUV luminosity
- Location of disk within cluster

Assume:
- FUV point source at center of cluster
- Stellar density $\rho \sim 1/r$

<table>
<thead>
<tr>
<th>$G_0$ Distribution</th>
<th>Median</th>
<th>Peak</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Median</td>
<td>900</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak</td>
<td>1800</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>16,500</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$G_0 = 1$ corresponds to FUV flux $1.6 \times 10^{-3}$ erg s$^{-1}$ cm$^{-2}$
Photoevaporation Model

(Adams et al. 2004)
Evaporation Time vs FUV Field

(for disks around solar mass stars)
EUV Flux Distribution

Using Lada/Lada cluster sample, standard IMF.

Peak value:
\[ F_{\text{EUV}} \approx 10^{12} \ \gamma \ s^{-1} \ cm^{-2} \]

Evaporation Time vs EUV Field

\[
F_{\text{EUV}} = 10^{15}, 10^{14}, 10^{13}, 10^{12}, 10^{11} \gamma \text{ s}^{-1} \text{cm}^{-2}
\]

\[
\frac{t_{\text{evap}}}{(\text{Myr})}
\]

\[
r_d (\text{AU})
\]

(FUV radiation has larger effect on solar nebula than EUV)

Evaporation Time vs Stellar Mass

Evaporation is much more effective for disks around low-mass stars: Giant planet formation can be compromised

G=3000
Disk accretion aids and abets the disk destruction process by draining gas from the inside, while evaporation removes gas from the outside...

Total time scale of 8 Myr, consistent with observations...
Radiation effects Dominate over Dynamical effects in Clusters
Interim Conclusion [I]

Clusters have a moderate effect on the solar systems forming within them -- environmental effects are neither dominant nor negligible:

- Closest approaches of order 1000 AU
- Disks truncated dynamically to 300 AU
- Disks truncated via radiation to 40 AU
- Lifetimes have environmental upper limit
- Planetary orbits are moderately altered
- Only a few planetary ejections per cluster

These effects must be described via probabilities.
Additional Cluster Effects

- Ionization from X-rays, EUV (Holden)
- Ionization from enhanced cosmic rays (Fatuzzo, Melia)
- Supernovae: Disruption and enrichment of short lived radioactive nuclei
- Accretion of cluster gas onto disks (Throop, Bally)
- Dynamical interactions of wide binaries (many many authors)
WHERE DID WE COME FROM?
Solar System Properties

- Enrichment of short-lived radioactive nuclear species
- Planetary orbits are well-ordered (ecc. & inclination)
- Edge of early solar nebula -- gas disk -- at 30 AU
- Observed edge of Kuiper belt at around 40 - 50 AU
- Orbit of dwarf planet Sedna: $e = 0.82$ and $p = 70$ AU
Constraints on Solar Birth Cluster

Supernova, Neptune, Sedna (+kb) Radiation

\[ N = 4300 \pm 2800 \]
INTERIM CONCLUSION [II]
Scenario for Solar Birth Aggregate

Cluster size: \( N = 1000 - 7000 \)

Reasonable \textit{a priori} probability (few percent)

Allows meteoritic enrichment and scattering survival

UV radiation field evaporates disk down to 30 AU

Scattering interactions truncate Kuiper belt at 50 AU
leave Sedna and remaining KBOs with large \((a,e,i)\)
Back to our original questions:

[1] How does the initial cluster environment affect the formation of stars and planets?

[2] What can we say about the basic properties of the birth cluster for our own Sun and its Solar System?
[1] Distributions of closest approaches
[2] Distributions of FUV, EUV radiation fields
[3] Disk evaporation rates for given FUV flux
[4] Cross sections for solar system disruption
[5] Cross sections for rock capture
[6] Orbits in particular cluster potentials (ask!)
Conclusions:

[1] Initial cluster environment has a moderate effect on disks and planets (less effect on star formation itself). These effects have been Quantified and are described by Distributions.

[2] Birth aggregate of Solar System could be moderately large cluster with stellar membership $N = 1000 --10,000$. 
What about life?

[1] Dynamics: Rock exchange
[2] Radiation: Limits disk size, provides UV for chemistry and ionization
[3] Particles: Heating and ionization from short lived radioactive nuclei
BIBLIOGRAPHY

∗ Birth Environment of the Sun, 2010, Adams, ARAA, 48, 47