Orion Constellation
(visible light)
Orion constellation
H-alpha
Orion constellation
H-alpha

Orion Molecular Clouds
$>10^5 \, M_{\text{sol}}$  100 pc long
Orion core (visible light)
Orion Star Forming Region

- Closest bright star-forming region to Earth
- Distance ~ 1500 ly
- Age ~ 10 Myr
- Radius ~ few ly
- Mean separation ~ $10^4$ AU
Orion Trapezium cluster

Massive stars

Low mass stars; Disks with tails
Largest Orion disk: 114-426, diameter 1200 AU
1961 view:

“Whether we've ever seen a star form or not is still debated. The next slide is the one piece of evidence that suggests that we have. Here's a picture taken in 1947 of a region of gas, with some stars in it. And here's, only two years later, we see two new bright spots. The idea is that what happened is that gravity has...”

Richard Feynman, *Lectures on Physics*
1961 view:
“Whether we've ever seen a star form or not is still debated. The next slide is the one piece of evidence that suggests that we have. Here's a picture taken in 1947 of a region of gas, with some stars in it. And here's, only two years later, we see two new bright spots. The idea is that what happened is that gravity has...”

Richard Feynman, *Lectures on Physics*

2000s view:
Infrared detectors have allowed us to directly see thousands of star forming -- nearly everywhere that we see an IR source. 1000+ young stars in Orion alone.

Whether we’ve ever seen a **planet** form or not is the current question!

---

**Star Cluster Formation** ➔ **Star Formation** ➔ **Planet Formation**
### Circumstellar Disks In Orion

<table>
<thead>
<tr>
<th>172-028</th>
<th>167-231</th>
<th>163-026</th>
<th>132-1632</th>
<th>121-1925</th>
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<td><img src="image4.jpg" alt="Image" /></td>
<td><img src="image5.jpg" alt="Image" /></td>
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</tbody>
</table>

- 100+ disks directly observed, diameters 100-1200 AU
- 80%+ of stars in Orion show evidence for having disks

*These stars are too distant and young to directly search for planets... but we want to study the environment and processes to understand the planets which would be produced in these dense clusters -- and therefore throughout the galaxy.*
### Regions of Star Formation

<table>
<thead>
<tr>
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<th>Large Dense Clusters: Orion</th>
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<tbody>
<tr>
<td><strong># of stars</strong></td>
<td>$10^3 - 10^4$</td>
</tr>
<tr>
<td></td>
<td>$10^4$ stars in last 10 Myr (Orion)</td>
</tr>
<tr>
<td><strong>OB stars</strong></td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Distance</strong></td>
<td>450 pc (Orion)</td>
</tr>
<tr>
<td><strong>Fraction of stars that form here</strong></td>
<td>70-90%</td>
</tr>
<tr>
<td><strong>Distance between stars</strong></td>
<td>5000 AU</td>
</tr>
<tr>
<td><strong>Dispersal lifetime</strong></td>
<td>Few Myr</td>
</tr>
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**Orion:** Hot, Dense, Massive

Most stars form in large clusters.
### Regions of Star Formation

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<th>Small Sparse Clusters: Taurus</th>
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<tr>
<td># of stars</td>
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</tr>
<tr>
<td>Fraction of stars that form here</td>
<td>70-90%</td>
<td>10-30%</td>
</tr>
<tr>
<td>Distance between stars</td>
<td>5000 AU</td>
<td>20,000 AU</td>
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**Orion:** Hot, Dense, Massive
Most stars form in large clusters.

**Taurus:** Dark, Small, Cold
Most planet formation models study small clusters.
Where did our Sun form?

- We have no idea!
- 90% of stars formed in clusters
- But just 1% remain in clusters now.
- Stellar motions can be back-integrated for 100 Myr, but not 10 Gyr.
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Planet Formation - Classical Model

Cloud core collapses due to self-gravity
10,000 AU, 1 $M_{\text{sol}}$

Disk flattens; grains settle to midplane
Planet cores grow
Disk Mass: ‘Minimum Mass Solar Nebula’
MMSN = 0.01 $M_{\text{sol}}$
Star Mass: $\sim 1 M_{\text{sol}}$

Terrestrial planets form
Jovian planets accrete gas

Disk disperses
Solar System complete after $\sim 5$-10 Myr
How does Cluster Environment affect Disk Evolution?

- Interaction with cluster gas
- UV photoevaporation from massive stars
- Close stellar encounters
- UV, X ray chemistry
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Bondi-Hoyle Accretion

- Cool molecular $\text{H}_2$ from cluster ISM accretes onto disks
- Accretion flow is \textbf{onto disk}, not star.
- Accretion is robust against stellar winds, radiation pressure, turbulence.
- This accretion is not considered by existing Solar System formation models!

1 MMSN = 1 ‘Minimum Mass Solar Nebula’ = 0.01 $M_{\text{Sol}}$

**Equations**

\[
R_B = \frac{2GM}{(v^2 + c_s^2)}
\]

**Accretion radius \sim 1000 AU**

\[
\dot{M}_B = \frac{4\pi G^2 M^2}{(v^2 + c_s^2)^{3/2}} \ n m_n
\]

**Accretion rate \sim 1 MMSN / Myr**
Timescale of Star Formation

![Graph showing accretion rate over time, with notes on stellar collapse and tail-end accretion.]

- **Stellar collapse**: $1.0 \, M_{\text{Sol}}$
- **Tail-end accretion**: $0.03 \, M_{\text{Sol}}$
Gas Accretion + N-Body Cluster Simulations

NBODY6 code (Aarseth 2003)

Stars:
- $N = 1000$
- $M_{\text{star}} = 500 \, M_\odot$
- Kroupa IMF
- $R_0 = 0.5 \, \text{pc}$

Gas:
- $M_{\text{gas}} = 500 \, M_\odot$
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- Disperses with timescale 2 Myr

Throop & Bally 2008
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Throop & Bally 2008
Following trajectory of one star of 3000 from N-body simulation...
BH Accretion: History of Individual Star

- Star+disk accretes 5% of own mass in 5 Myr.
- Accretion is episodic
  - Highest at core: High velocity but high density
Results of N-Body sims

- Typical mass accreted by disks surrounding Solar-mass stars is 1 MMSN per Myr
- Accretion occurs for several Myr, until cluster disperses or cloud is ionized
Observations of accretion in young stars

- Accretion is seen onto hundreds young stars in molecular clouds.
- Varies with stellar mass: \( \frac{dM}{dt} \sim M^2 \)
- Accretion is ~ 0.01 \( M_\odot \) Myr\(^{-1} \) for 1\( M_\odot \)
- Source of the accretion is unknown!
We propose: accretion onto young stars may be due to ISM accretion onto their disks.
Consequences of Tail-End Accretion

- Disks may accrete many times their own mass in a few Myr.
- Disks may still be accreting gas at >5 Myr, after planetesimals form, and maybe after giant planet cores form.
- Disk may be ‘rejuvenated’ after being partially lost.
- Final composition of disk may be different than star
  - There may be no ‘Solar Nebula Composition’
  - Isotopes may not be diagnostic of solar vs. extrasolar material

Throop & Bally 2008, AJ
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Throop & Bally 2008, AJ
Accretion of ‘polluted’ ISM

- Stars of same age/position/type in Orion show metallicities that vary by up to 10x in Fe, O, Si, C
- Could stars have accreted metallic ‘veneers’ by passing through nearby molecular clouds, contaminated with supernova ejecta?
- 20 $M_{\text{Sol}}$ SN produces 4 $M_{\text{Sol}}$ O

Late accretion may cause the composition of a stars and their disks to be different! There may be no ‘Solar Nebula Composition.’ Even in our Solar System, there is a lot of variation: isotope ratios.

Cunha et al 2000
Molecular clouds
Molecular clouds
Molecular clouds

Ionized HII region
Molecular clouds

Ionized HII region

Molecular clouds
Molecular clouds

Ionized HII region

Molecular clouds
Molecular clouds

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Molecular clouds
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Ionized HII region

Molecular clouds
Molecular clouds
Orion constellation
H-alpha

Orion Molecular Clouds
$>10^5 \, M_{\odot}$
100 pc long
Molecular clouds
If the Sun and Jupiter both formed from the same cloud, why are they made of such different stuff?
Jupiter’s Atmosphere

- Mass Spectrometer aboard Galileo Probe
- Measured atomic and molecular species to ~20 bars
- Found Jupiter atmosphere to be 2-6x higher in metals vs. Sun
  - C, S, Ar, Kr, Xe
  - All these are stable and long-lived: enrichment was a complete surprise!
  - $v_{\text{esc}} = 45 \text{ km/sec}$
We propose a crazy idea for Jupiter’s composition:

1. Solar System forms in a large star cluster.

2. Massive stars pollute ISM with heavy elements.
   SNs and massive stellar winds convert H into C, N, S, etc.

3. ‘Pollution’ from massive stars is accreted onto Jupiter.
   Accretion from ISM -> Solar Nebula Disk -> Jupiter
   Sun’s metallicity is not affected, only Jupiter’s

Throop & Bally 2009 (Icarus, submitted)
Can Jupiter’s measured enhancement be explained by accretion of heavy elements from the ISM?
Jupiter ‘Polluted Accretion’ model

- Data: Galileo Probe
- Model: Accretion from ISM
  - 87% Solar nebula material
  - 9% Stellar winds from 20 $M_\odot$ star (provides C, N)
  - 4% SN from 25 $M_\odot$ star (provides S, Ar, Kr, Xe)
  - Requires total of $\sim 0.13 M_J$ of accretion to explain Jupiter’s current metallicity.
  - Bondi-Hoyle accretion supplies 10 $M_J$ of accretion per Myr -- plenty of mass, and with the right chemistry!
Evidence for a heterogeneous nebula is not new!

Dauphas et al 2002:

“Mb isotope abundances were heterogeneously distributed in the Solar System’s parental molecular cloud, and the large-scale variations we observed were inherited from the interstellar environment where the Sun was born.”

Ranen & Jacobsen 2006:

“There are resolvable differences between the Earth and carbonaceous chondrites that are most likely caused by incomplete mixing of r- and s-process nucleosynthetic components in the early Solar System.”

Trinquier et al 2007:

“Preservation of the $^{54}$Cr heterogeneity in space and time (several Myr) motivates us to speculate that late stellar input(s) could have been significant contributions to inner nebular Cr reservoirs...”

Heterogeneity between Jupiter and Sun is a natural extension to that already observed in meteorites (but much bigger).

Throop & Bally 2009
SPH Sims: BH Acc onto 100 AU disk

10,000 years
0.01 solar masses
v \sim 1 \text{ km/sec}

Moeckel & Throop
2009 (AJ)
SPH Sims: BH Acc onto 100 AU disk

10,000 years
0.01 solar masses
$v \sim 1$ km/sec

Moeckel & Throop 2009 (AJ)
Close Stellar Encounters

- 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?
Star has 5 close approaches at < 2000 AU.
Closest encounter is 300 AU at 8 Myr
Too late to do any damage
Close Approach History - Typical 1 M☉ Star

- Star has 5 close approaches at < 2000 AU.
- Closest encounter is 300 AU at 8 Myr
  - Too late to do any damage

Throop & Bally 2008; also Adams et al 2006
Close Approaches - Entire Cluster

- 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
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• Significant disk truncation in dense clusters is rare!
  – Only 1% of disks are truncated to 30 AU, inhibiting planet formation

Throop & Bally 2008; also Adams et al 2006
Photo-Evaporation in Orion

- Disks surrounding solar-type stars are heated by UV-bright stars.
- Gas is heated and removed from disk on 1-10 Myr timescales.
- If disk is removed quickly, we can’t form planets!
Triggered Planet Formation?
Triggered Planet Formation?
Triggered Planet Formation?
Triggered Planet Formation?
Triggered Planet Formation?
Triggered Planet Formation?
Triggered Planet Formation?
Trigged Planet Formation?

Photo-evaporation removes gas and allows gravitational instability to form planetesimals.

Throop & Bally 2005
Effects of Photo-Evaporation on Planet Formation

Solar System-like disks are removed in 1-10 Myr. Effects on...

- **Kuiper Belt (> 40 AU):** UV removes volatiles and small grains. Kuiper belts and Oort clouds may be rare! Or, they may be formed easily and quickly thru triggering.

- **Giant Planets (5-40 AU):** Gas is rapidly removed from disk: If you want to build Jupiters in Orion, do it quickly! (e.g., Boss models).

- **Terrestrial Planets (1-5 AU):** Safe against photo-evaporation since it’s hard to remove gas from 1 AU.
Flux received by disk varies by 1000x as it moves through the cluster: *Freeze-Broil-Freeze-Broil*

- 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.’
- Photo-evap models assume steady UV flux. But if UV is not steady, then other processes (viscous, grain growth) can dominate at different times and dramatically change the disk.

Throop, in prep
Cloud core collapses due to self-gravity
10,000 AU, 1 M⊙

Disk flattens; grains settle to midplane
Planet cores grow

Terrestrial planets form
Jovian planets accrete gas

Disk disperses
Solar System complete after ~ 5-10 Myr
Cloud is heterogeneous and polluted
Cloud core collapses due to self-gravity
10,000 AU, 1 M☉
Cloud inherits composition from nearby SN

Disk flattens; grains settle to midplane
Planet cores grow
Disk is photo-evaporated by UV stars
Disk is injected with ⁶⁰Fe from nearby SNs
Terrestrial planets form
Jovian planets accrete gas
(Disk is stripped due to close approaches)
Disk accretes gas from environment
Disk disperses and is photo-evaporated
Solar System complete after ~ 5-10 Myr
**Randomness as a factor in Disk Evolution**

- Disk outcome depends not just on its ingredients, but on its individual history.
- If we try to predict what will form around individual stars or disks, we’re doomed to fail!
- Disk systems are individuals, they interact with their environment, and random events and timing matter:
  - How much stuff was photo-evaporated by UV?
  - How hot was the disk, and how viscous, and how did its surface density evolve?
  - How strong, when, and how many times did UV hit it?
  - What SN events occurred? How did they contaminate the disk?
  - What molecular clouds did disk pass through? What material was accreted? Onto inner disk, or outer?
  - Do planetesimals form before, or after, photo-evaporation starts?
- There is no ‘typical’ disk, and no ‘typical’ planetary system, even if starting from the same initial disk structure and ingredients.
The End