Star Formation
Star Formation

Star F

<table>
<thead>
<tr>
<th>PROPERTIES</th>
<th>Infrared Protoplanet</th>
<th>Evolved Protoplanet</th>
<th>Classical T Tauri Star</th>
<th>Weak-lined T Tauri Star</th>
<th>Main Sequence Star</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sketch</td>
<td>10</td>
<td>10</td>
<td>10 + 10</td>
<td>10 + 10</td>
<td>&gt; 10</td>
</tr>
<tr>
<td>Age (years)</td>
<td>10</td>
<td>10</td>
<td>10 - 10</td>
<td>10 - 10</td>
<td>&gt; 10</td>
</tr>
<tr>
<td>Near-Infrared Class</td>
<td>Class 0</td>
<td>Class I</td>
<td>Class II</td>
<td>Class III</td>
<td>(Class III)</td>
</tr>
<tr>
<td>Disk</td>
<td>Yes</td>
<td>Thin</td>
<td>Thick</td>
<td>Thin or Non-existent</td>
<td>Possible Planetary System</td>
</tr>
<tr>
<td>X-ray</td>
<td>?</td>
<td>Yes</td>
<td>Strong</td>
<td>Strong</td>
<td>Weak</td>
</tr>
<tr>
<td>Thermal Radio</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Non-Thermal Radio</td>
<td>No</td>
<td>Yes</td>
<td>No ?</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Figure 1: The stages of low-mass stellar evolution. The center column addresses the
Nebula (three rows) of the Giant (Adapted from Calvet, 1998.)

Feigelson & Montmerle
ALMA Site – Northern Chile

The Basic Features

Envelope
Disk
Protostar
Jet/wind/outflow

T. Greene
Observing Infall with ALMA

- A key observation is to observe the infalling gas in redshifted absorption against the background protostar.
- Very high spectral resolution (<0.1 km/s) is required.
- High sensitivity to observe in absorption against disk.

Planet Formation

SMM image of Vega shows dust peaks off center from star (*). Fits a model with a Neptune-like planet clearing a gap. This is with 15-m at 850 microns and 15'' resolution.

ALMA can do at higher resolution.

SMM image of Vega
JACH, Holland et al.

With higher resolution

Vega also observed by Wilner et al. (2003). Model of resonance with planet.

Key Observations of the Solar System

- Coplanar/prograde orbits – angular momentum
- Orbital spacing
- Comets
- 0.2% of mass in planets, 98% of the angular momentum
- composition

- Asteroid belt → power law size distribution
- Age → 4.5Gyr
- Consistent isotopic ratios
- Rapid heating/cooling
- Cratering record → bombardment
Key Physical Characteristics

- Angular momentum → disk formation a must
- Key properties of disk
  - Same abundance as the star
  - Spins in the same direction as the star
  - Temperature/density gradient \( T(r) \sim r^{-0.5} \)
- Other characteristics
  - Size: 25-500 AU observed
  - Total mass ~ 0.04 \( M_{\text{Earth}} \)
  - \( R \sim 150 \) AU
  - Lifetime: \( 10^5-10^7 \) years

Hillenbrand et al. (2009) – Spitzer survey of IR-excess stars
Figure 2. Spitzer SEDs for debris disks surrounding young stars from Kim et al. (2005). Expected photometric emission based on our model fits are shown as solid lines, with best fit models for the excess emission indicated with a dashed line. The ages and estimated dust masses for each system are also given.

Meyer et al 2008
Measuring dust disks $\rightarrow$ IR-excess emission

$$\frac{R_{\text{dust}}}{AU} = \left(\frac{L_\star}{L_\odot}\right)^{1/2}\left(\frac{278K}{T_{\text{dust}}}\right)^2$$

$$\frac{M_{\text{dust}}}{M_\odot} \approx 6.28 \times 10^{-5}\left(\frac{L_{\text{dust}}}{L_\star}\right)\left(\frac{\rho}{g/m^3}\right)\left(\frac{<k>}{\mu m}\right)\left(\frac{R_{\text{dust}}}{AU}\right)^2$$

1st Phase - Condensation

- Grains can survive in ISM conditions
- Condensation
  - Nebula/disk cools $\rightarrow$ solids condense
  - “refractory” elements go 1st
    - Fe, silicates condense at 1400-1700 K
    - Feldspars at 1200 K
    - Essentially, rock-making minerals condense at 1200-1400 K
    - Water, volatiles below 200-500 K
  - Meteoritic ages $\rightarrow$ condensation $\sim$4.5 Gyr ago
    - Meteorites sample asteroid belt
Grain Dynamics

- Dust grains (i.e. solids) settle to midplane
  \[ \frac{dv_z}{dt} = - \left( \frac{\rho_g c_s}{R \rho_g} \right) v_z - n^2 z \]
  - \( n \) = angular velocity, \( z \) = height above disk, \( R \) = grain radius
  - Densities are of the gas (\( \rho_g \)) and the grain, \( c_s \) = sound speed
  - Settling velocity \( v_z = \frac{n^2 z \rho R}{\rho_g c_s} \)
  - For typical numbers (\( \rho_g \sim 10^{-9} \text{ g cm}^{-3} \), \( c_s \sim 10^5 \text{ cm s}^{-1} \), 1 \( \mu \)m grains, \( \rho \sim 1 \text{ g cm}^{-3} \)) timescales are \( 10^6 - 10^7 \) years to settle to midplane \( \to \) way too long
  - Collisional accretion \( \to \) decreases settling times by orders of magnitude

2nd Phase – Collisional Accretion

- Sticky collisions
  - \( V_i = (V^2 + V_{e,2}^2)^{1/2} \) = impact velocity
  - \( V_e = [2G(M_1 + M_2)/(R_1 + R_2)]^{1/2} \)
  - If \( V_i < V_e \) bodies remain bound \( \to \) accretion
- Growth rate
  - \( \frac{dM}{dt} = \rho \pi R^2 F_g \) or \( \frac{R^2 \Sigma \Omega F_g}{2\pi} \)
  - \( F_g = \text{cross-section} = 1 + (V_{e}/V)^2 \)
  - \( \frac{dR}{dt} = (\rho_d V/\rho_p)(1+[8\pi G \rho_p R_p^{-3}]/3V^3) \)
    - \( \rho_d \) = mass density in disk
    - \( \rho_p \) = mass density of planetesimals
    - \( V \) = average relative velocity
    - \( R_p \) = radius of planetesimals
Collisional Accretion continued

- If $V_e >> V$, then $\frac{dR}{dt}$ goes as $R^2 \rightarrow$ big things grow rapidly
- Can evaluate growth rate using $R_1= R_2$ (same assumption for $V$)
- Formation of rocky/solid cores $\rightarrow$ next step is accretion
  - $R_{\text{accretion}} = \frac{G M_p}{c^2}$ ($c =$ speed of sound)

Collisional Accretion III

- Predicted timescales
  - Accretion of dust $\rightarrow$ 1 km sized bodies ($10^4$ yrs)
  - “runaway growth” $\rightarrow$ 1 km to planetesimals ($10^5$ yrs)
  - Impacts finalize terrestrial planets ($\sim 10^8$ yrs)
- Lifetimes
  - Disk lifetimes: $10^5$-$10^7$ yrs so process must be complete by then!
  - Earth timescales $\sim 10^8$ yrs
  - Much larger for Neptune
Formation Scenarios

- Core Accretion vs Gravitational Collapse
  - $Q = \frac{\kappa c}{\pi G \Sigma} \rightarrow$ gravity vs thermal pressure
  - Surface mass density
  - Local velocity (dispersion, sound speed)
  - $K = R^{-3} \left( \frac{d}{dr} (R^4 \Omega^2) \right)$
  - Timescales ~ freefall time
  - One simulation with $M_d \sim 0.1$ Earth masses, $T \sim 100K$, $R_d \sim 20$ AU
    - make J in 6 Myr
  - Benefit
    - Can make planets on eccentric orbits
    - Timescales are short
  - Minuses
    - Hard to explain rocky cores

Core Accretion
Alibert, Mordasini, Benz 2004

Fig 1. Total mass of heavy elements (core + envelope) and mass of the envelope (H/He) as a function of time, for three models. Solid lines: migrating case, without gap formation (case 1); dashed lines: migrating case, with gap formation (case 2); and dot-dashed lines: non-migrating case, without disk evolution nor gap formation (case 3). The heavy line gives the distance to the central star as a function of time (case 1). The kink at 0.8 Myr is the transition from type I to type II migration.
Terrestrial Planet Formation
Raymond, Quinn, Lunine (2005)

Formation of Terrestrial Planets
Raymond, Quinn, Lunine (2005)

- Larger $\alpha \rightarrow$ innermost planet resides at $\sim 0.5$AU; smaller $\alpha \rightarrow$ most distant innermost planet
- Steeper density gradient $\rightarrow$ more planets in a shorter time
- Larger planets at 5AU scatter material out of solar system (e.g. Jupiter)
- Most simulations end up with several terrestrial planets
- Timescales $\rightarrow$ 20-50 Myr
Formation Issues

- **Minimum Mass** \( \rightarrow r^{-1.5} \)
- **Core-Accretion**
  - Timescales too long for Uranus, Neptune
  - What makes cm-size things stick?
  - How come things don’t spiral into Sun?
- **Gravitational Collapse**
  - Faster, but is it plausible?

Giant Planet Formation

- **Gas-instability**
  - Hard to explain relatively high fraction of condensable elements
  - Need very high disk mass density \( \rightarrow \) think of Jeans mass
  - Doesn’t account for smaller bodies
  - But, it’s a lot faster than…
- **Core-Accretion**
Giant Planet Formation

- **Gas-instability**
  - Hard to explain relatively high fraction of condensable elements
  - Need very high disk mass density
  - $Q = \kappa C_s/\pi \Sigma G < 1.4$
  - Doesn’t account for smaller bodies
  - But, it’s a lot faster than…

- **Core-Accretion**
  - Growth of planetary embryos → once collisional accretion time = gas accretion timescales get runaway growth
  - Collapse of planet once accretion stops

---

**Core-Accretion**

- Phase 1 → solid core accretes to $10 \, M_{\text{Earth}}$ in $\sim 10^6$ years (collisional accretion)
Core-Accretion

- Phase 1 $\rightarrow$ solid core accretes to $10 \, M_{\text{Earth}}$ in $\sim 10^6$ years (collisional accretion)
- Phase 2 $\rightarrow$ growth rate decreases (for core) while envelope growth rate increases (gas) until $M_{\text{env}} \sim M_{\text{core}}$

- Phase 3 $\rightarrow$ $M_{\text{env}}$ increases
Core-Accretion

- Phase 1 $\rightarrow$ solid core accretes to $10 \, M_{\text{Earth}}$ in $\sim 10^6$ years (collisional accretion)
- Phase 2 $\rightarrow$ growth rate decreases (for core) while envelope growth rate increases (gas) until $M_{\text{env}} \sim M_{\text{core}}$
- Phase 3 $\rightarrow$ $M_{\text{env}}$ increases
- Still serious issues with timescales $\rightarrow$ how long do these things really take??????

Core-Accretion

- Phase 1 $\rightarrow$ solid core accretes to $10 \, M_{\text{Earth}}$ in $\sim 10^6$ years (collisional accretion)
- Phase 2 $\rightarrow$ growth rate decreases (for core) while envelope growth rate increases (gas) until $M_{\text{env}} \sim M_{\text{core}}$
- Phase 3 $\rightarrow$ $M_{\text{env}}$ increases
- Still serious issues with timescales $\rightarrow$ how long do these things really take??????
- Must have planet migration $\rightarrow$ can’t do all this too close to the star
  - Temperatures too hot for condensation
  - Not enough mass
Formation Scenarios

- **Core Accretion vs Gravitational Collapse**
  - \( Q = \frac{\kappa c}{\pi G \Sigma} \rightarrow \) gravity vs thermal pressure
  - Surface mass density
  - Local velocity (dispersion, sound speed)
  - \( K = R^{-3}(d/dr(R^4 \Omega^2)) \)
  - Timescales ~ freefall time
  - One simulation with \( M_d \sim 0.1 \) Earth masses, \( T \sim 100K, R_d \sim 20 \) AU
    \( \rightarrow \) make J in 6Myr
  - Benefit
    - Can make planets on eccentric orbits
    - Timescales are short
  - Minuses
    - Hard to explain rocky cores

Formation of Uranus and Neptune (Thommes, Duncan, Levison 2002)

- **Dynamical timescales simply too long**
- **Did their cores form near J & S?**
  - Start with \( 10 \ M_{\text{Earth}} \) rock/ice cores and let them grow
  - \( R_H = (M_p / 3M_\odot)^{1/3} a \) (\( a \) = semi-major axis), in solar masses
    \( \rightarrow \) increase mass by 30, increase \( R_H \) by factor of 3 \( \rightarrow \) scattering
  - Scattered cores eventually circularize if density is high enough
    \( \rightarrow \) become Uranus and Neptune
  - Small things \( \rightarrow \) Kuiper Belt; big things \( \rightarrow \) Uranus & Neptune
Formation Issues

- **Minimum Mass** → $r^{-1.5}$
- **Core-Accretion**
  - Timescales too long for Uranus, Neptune
  - What makes cm-size things stick?
  - How come things don’t spiral into Sun?
- **Gravitational Collapse**
  - Faster, but is it plausible?

What it Looks Like Now
Thommes et al simulation

Solar System Formation Simulation