Star Formation

• Stars form out of gas → if you want to identify/study star formation you need to find the gas

• What kind of gas? Molecular!!!!!
  ▫ Cold → gravity must overcome the thermal pressure of a cloud so it collapses
  ▫ Dense
  ▫ Require mm-wave telescopes → ALMA → next few slides come from a talk by Neal Evans (Texas) promoting ALMA (Atacama Large Millimeter Array)
ALMA Site - Northern Chile
Even “Isolated” SF Clusters

Taurus Molecular Cloud
Prototypical region of
“Isolated” star formation

Dots = embedded star clusters;
Contours = molecular cloud

Myers 1987
Taurus Cloud at same scale
4 dense cores, 4 obscured stars
~15 T Tauri stars

Orion Nebula Cluster
>1000 stars
2MASS image
The Basic Features

Envelope
Disk
Protostar
Jet/wind/outflow

T. Greene
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.
Low Mass Cores: Gross Properties

- Molecular cloud necessary, not sufficient
  - High density ($n > 10^4 \text{ cm}^{-3}$)
  - Low turbulence
- Centrally peaked density distribution
  - Power law slope ~ high mass
  - Fiducial density ~ 100 times lower
- Complex chemistry, dynamics even in 1D
  - Evidence for infall seen, but hard to study
  - Outflow starts early, strong effect on lines
  - Rotation on small scales
Open Questions

• **Initial conditions**
  - Cloud/core interaction
  - Trace conditions in core closer to center
  - Inward motions before point source?

• **Timescales for stages**

• **Establish existence and nature of infall**
  - Inverse P-Cygni profiles against disks
  - Chemo-dynamical studies

• **Envelope-Disk transition**
  - Inner flow in envelope

• **Outflow dynamics**
  - Nature of interaction with ambient medium
Planet Formation

• Best studied around isolated stars
• Origin and evolution of disk
• Gaps, rings, ...
• Debris disks as tracers of planet formation
• Chemistry in disks
  ▫ Evolution of dust, ices, gas
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.

With higher resolution

Vega also observed by Wilner et al. (2003). Model of resonance with planet.
Simulation Contains:
* 140 AU disk
* inner hole (3 AU)
* gap 6-8 AU
* forming giant planets at:
  9, 22, 46 AU with local over-densities
* ALMA with 2x over-density
* ALMA with 20% under-density
* Each letter 4 AU wide, 35 AU high

Observed with 10 km array
At 140 pc, 1.3 mm
Open Questions

- How the disk initially forms
- Timescales for disk evolution
- How planets form in the disk
  - Core accretion or Gravitational Instability
- How unusual the solar system is
  - Systems with giant planets out where ours are
- Evolution of dust, ice, gas in disk
  - Building blocks for planets
Requirements

- Maximum Spatial resolution
  - Image fidelity (gaps will be hard to see)
- Best sensitivity
  - Especially for debris disks
- Flexible correlator, receiver bands
  - Chemistry

All this says is that we need to build ALMA – 1st light 2011 or so
Formation of a Planetary System (or what happens in the disk?)
2\textsuperscript{nd} Phase - Collisional Accretion

- **Sticky collisions**
  - \( V_i = (V^2 + V_e^2)^{1/2} \) = impact velocity
  - \( V_e = \left[ \frac{2G(M_1 + M_2)}{(R_1 + R_2)} \right]^{1/2} \)
  - If \( V_i < V_e \) \( \rightarrow \) bodies remain bound \( \rightarrow \) accretion

- **Growth rate**
  - \( \frac{dM}{dt} = \rho v \pi R^2 F_g \) or \( R^2 \Sigma \Omega F_g \)/(2\pi)
  - \( F_g = \) cross-section = \( 1 + \left( V_e / V \right)^2 \)
  - \( \frac{dR}{dt} = \left( \frac{\rho_d v}{\rho_p} \right) (1 + \left[ \frac{8\pi G \rho_p R_p^2}{3v^2} \right]) \)
    - \( \rho_d = \) 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 (note that we can’t have collisions at the escape velocity!)

• Can evaluate growth rate using \( R_1= R_2 \) (same assumption for \( V \))

• Formation of rocky/solid cores \( \rightarrow \) next step is accretion

  ▫ \( R_{\text{accretion}} = \frac{GM_p}{c^2} \) (\( c \) = speed of sound)
Terrestrial Planet Formation
Raymond, Quinn, Lunine (2005)

• Ingredients to any model
  ▫ Physics → collisional accretion/orbital evolution
    • $\frac{dR}{dt} = \left(\frac{3}{\pi}\right)^{1/2}(\sigma n/4\rho)F_g$
    • $F_g = 1 + \left(\frac{v_e}{v}\right)^2$
    • $\rho =$ density of embryo
    • $\sigma =$ surface mass density ($\sim 10$ g cm$^{-2}$)
    • $n =$ orbital angular velocity
  ▫ Mass of the pre-solar disk
Terrestrial Planet Formation
Raymond, Quinn, Lunine (2005)

- **Ingredients to any model**
  - **Mass of the pre-solar disk**
    - MMSN → how much stuff do we need simply to account for the amount of heavy elements in the current planets
    - Any reason this should be right?
  - **Surface density distribution**
    - Power law! → \( \Sigma(r) = \Sigma_0 r^{-\alpha} \)
    - What’s \( \alpha \) → 0.5, 1.5, 2.5
    - What’s \( \Sigma_0 \) → 5.7, 13.5, 21.3 g cm\(^{-3}\)
  - **Distribution of “embryos”**
    - Each embryo has its own “feeding zone” (3\(R_H\))
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Terrestrial Planet Formation
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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 of the Moon

- **Old Theories**
  - Fission \( \rightarrow \) no way! Breakup speed of Earth is far too high – and why aren’t the compositions identical?
  - Captured \( \rightarrow \) really hard to do – and why are they so similar chemically?
  - Same time, same place \( \rightarrow \) did they form together? Compositions should be identical (5.5 vs 3.7 g cm\(^{-3}\))

- **Giant Impact** \( \rightarrow \) Mars-sized impactor \( \rightarrow \) hey, impacts happen
Key Components

• Moon ultimately made of Earth’s mantle and impactor $\rightarrow$ lack of Fe
• Moon generally lacks volatiles, but oxygen isotope ratio is identical to Earth
• Enough material thrown off to gravitationally collapse into moon
Simulations – just show that it’s physically possible
Giant Planet Formation

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

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

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

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- Still serious issues with timescales → how long do these things really take???????
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- 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 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
  - $R_H = (M_p / 3M_* )^{1/3}a$ (a = semi-major axis), in solar masses → increase mass by 30, increase $R_H$ by factor of 3 → scattering
  - Scattered cores eventually circularize if density is high enough → become Uranus and Neptune
  - Small things → Kuiper Belt; big things → Uranus & Neptune
What it Looks Like Now
Thommes et al simulation

Fig. 6.—Final states of the eight set 1 runs after 5 Myr of simulation time, except for A and I, which were continued on to 10 Myr. Eccentricity is plotted vs. semimajor axis. Three different sizes of points denote planetesimals (smallest), 10 M⊕ protoplanets (medium), and Jupiter (largest). Planetesimal orbits crossing Jupiter or any of the protoplanets are generally unstable on timescales short compared to the age of the solar system; thus, the regions among the protoplanets would be essentially cleared of planetesimals long before the present epoch.
Solar System Formation Simulation

Levison et al.