Formation of Terrestrial Planets and Debris Disks

Scott Kenyon (SAO)
Ben Bromley (Utah)
Gemini, … (JPL)

Central Goals

• Simulate an entire solar system

• Links to other solar systems
  * Terrestrial planets
  * Jovian planets
  * Icy planets (Pluto, debris disks)
Rocky Planets

• Location
  * close to Sun

• Size of a rocky planet
  * 100-10000 km radius

• Types
  * Planets – Mercury, Venus, Earth, Mars
  * Asteroids – collision fragments
  * Zodiacal light – dusty debris

Inner Solar System
Top View
Our Solar System
Side View

A Dusty Disk
1 Myr
A Solar System
10-100 Myr

HK Tau/c – Stapelfeldt et al
Major Issues

• Evolution of Gas
  * viscosity
  * evaporation

• Evolution of Dust ***
  * collisions
Planets Grow in a Dusty Disk

* disk radius = 100-1000 AU
* disk mass = $10^4 - 10^5 M_{\text{Earth}}$

Dust settles to midplane

* 1 mm and larger particles
* circular orbits

Safronov, Wetherill, Weidenschilling

Dust settles to midplane

* 1 mm and larger particles
* circular orbits
Planet Formation

• Coagulation
  * dust $\rightarrow$ planetesimals $\rightarrow$ planets
  * make Earths
  * Earths accrete gas
  * Earths stir up debris
  * Debris scatters radiation from star
  * Scattered radiation is visible

• Wetherill, Weidenschilling, Lissauer, …

Highlights

• Successes
  * Earth-like planets in 10-30 Myr
  * Pluto-like planets in 10-100 Myr
  * Kuiper Belt properties
  * Vega-like debris disks

• Challenges
  * Jupiters are hard
  * Sedna
HST: Bright Rings

Spitzer: Evolution of Dust
IRAS: Taurus-Auriga

Spitzer: Model Tests
Spitzer: Evolution of Dust

Evolution of Blob of Dust
Kepler: Dust Eclipses

Observational Tests

- **HST**: disk structure
- **Spitzer**: IR excesses
- **Chandra**: dust/gas evolution
  * Kastner
  * Testa
Summary

• Terrestrial planets form quickly
  * 10% of Earth mass in 1 Myr
  * 1 Earth mass in 10-20 Myr

• Collisions produce IR excess from dust
  * excess is observable
  * lasts for 1-100 Myr

Coming Attractions

• Theory: better calculations
  * Jupiter
  * Outer solar system

• Observations
  * FUV/EUV spectra: evolution of gas
  * JWST: evolution of dust
  * Kepler: transient events
Collision Outcomes

• Energy scaling algorithm

• Merger
  * collision energy < binding energy

• Disruption
  * collision energy > binding energy

Coagulation

• Statistical mechanics approach
  * collision rate: \( N_{ij} \sigma v F_g \)
  * \( N_{ij} \) bodies of mass \( M_j \)
  * near-circular orbits: \( e_{ij}, i_{ij} \)
  * multiple annuli (32-64): \( a_i, \Delta a_i \)

• Physics
  * collisions
  * collective velocity motion
  * gas accretion, drag
N-Body Code

• Encke method for largest bodies
  * follows Keplerian orbits
  * direct force evaluations
  * hierarchical timesteps

• Coupled to coagulation code
  * accretion of small bodies
  * drag from gas and small bodies

Mergers

• 
  
•
Disruptions

• Viscous stirring
  * all velocities increase
• Dynamical friction
  * small bodies brake large bodies
• Gas, Poynting-Robertson drag
  * brake small bodies
• Collisions
  * brake large bodies

Velocity Evolution
Dust

An Asteroid

$10^{18}$ to $10^{21}$ dust grains
Three Phases of Growth

• Slow growth
  * geometric cross-sections
  * all bodies grow linearly

• Runaway growth
  * gravitational focusing
  * largest bodies grow exponentially

• Oligarchic growth
  * largest bodies grow slowly
  * collisional cascade

The Dust Mass
N-Body Number

The Largest Objects
Two Debris Disks

Dynamical instability
* part of disk collapses
* gravitational instability
* make Jupiters
* Jupiters stir up debris

Earth and Pluto are impossible

Boss, Cameron, …
Our Grid

Debris Disks

- Far-infrared emission
  * small dust grains absorb starlight
  * reradiate at 100 microns

- Optical and near-infrared emission
  * grains scatter starlight

- Disk-like morphologies
  * size of our solar system
β Pictoris

Near-infrared – Lagrange et al

Links to Other Solar Systems

• Our solar system
  * 1000’s of rocky planets & asteroids

• Other solar systems
  * 1000’s of debris disks

• Need a robust formation model
  * numerical simulation of solar system
Our Calculations

• Multiannulus hybrid code
  * 32-64 concentric annuli at 0.5-1.5 AU
  * 1 m to 1 km planetesimals
  * minimum mass solar nebula

• Results after 1-10 Myr
  * planets: Moon to Earth
  * rings of dust