Formation of Earth-like planets

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How do terrestrial planets like the Earth form?

Where conditions are required to form Earth-like planets?

What is the diversity of terrestrial planets that can form?
The (new) Solar System planets

Constraints: planetary masses, orbits, compositions, spacing, isotopic ratios, asteroid and comet populations
Planets form in disks around stars.
The Solar Nebula

"Primitive" asteroids have higher water content farther from the Sun

Log Water Content vs Orbital Distance (AU)

Disk temperature profile imprinted on primitive bodies

Raymond, Quinn & Lunine 2004; based on Abe et al 2000
Sequence of Events in Solar System Formation

1. Collapse of Sun and Solar Nebula
2. Formation of giant planets
   • Continued growth of terrestrial bodies
3. Dispersal of gas in disk ($10^6-7$ years)
4. Final assembly of terrestrial planets (30-50 Myr)
5. Continued dynamical evolution of planetary system, impacts from asteroids and comets
Stages of Terrestrial Planet Formation

1. Grains condense in Solar Nebula and settle to the disk midplane (~10^4-5 yrs)

2. ~1km “planetesimals” form (~10^5 yrs)

3. Runaway and Oligarchic Growth: Formation of ~Moon-Mars sized “Planetary Embryos” (~10^5-7 yrs)

4. Late-stage Accretion of terrestrial planets from embryos (~10^7-8 yrs)

(Giant planets form in <1-10 Myr, so they affect stages 3 and 4)

Reviews: Lissauer 1993, Chambers 2004

Kokubo & Ida 2002
Where did Earth get its water?

- Earth is in the “habitable zone”, where water is liquid (hotter than 273 K = 0°C = 32°F)
- To incorporate water into Earth need icy impacts. Water freezes at 170 K (= -100°C = -150°F)

→ Some of Earth’s building blocks came from past the “snow line”: Earth did not form entirely from local material (Morbidelli et al 2000)
Snapshots in time of a high-res simulation: 1885 initial particles, Jup at 5.5 AU ($e_J=0$)
Evolution of a high-res simulation: 1885 initial particles, Jup at 5.5 AU (e_J=0)
Diversity in planetary systems like our own

Raymond, Quinn & Lunine 2004
Diversity in planetary systems like our own

(1) $a_{\text{JUP}} = 4 \text{ AU}$

(2) $M_{\text{JUP}} = 10 M_{\text{EARTH}}$

(3) $M_{\text{JUP}} = 1/3$

(4) Solar System

Images from NASA
Differences in Planetary Systems come from Two Sources

1. Stochastic variation in the accretion process because of the small number of embryos in late stages

2. Systematic variations among systems
   - Number, masses, orbits of giant planets
     - Higher $e_{JUP} \Rightarrow$ fewer, drier terrestrial planets
     - Higher $M_{JUP} \Rightarrow$ fewer, more massive terrestrial planets
   - Disk mass (related to stellar metallicity), disk surface density profile
Eccentric giant planets form dry terrestrial planets

Raymond, Quinn & Lunine 2004
Could terrestrial planets exist in the known systems of extra-solar (giant) planets?
Giant Planet Migration

Hot Jupiters migrated to their current locations because of interactions with the protoplanetary disk. How does this affect terrestrial planet formation?
Eccentricity, sin (Inclination)

Raymond, Mandell & Sigurdsson 2006
Eccentricity, sin (Inclination)

Log Semimajor Axis

Raymond, Mandell & Sigurdsson 2006
Can the giant planets we see tell us something about the Earth-like planets we can’t see?

YES.

- Giant planets form faster than terrestrial planets
- Final stage of terrestrial planet growth is strongly affected by gravitational influence of giant planets
About 1/3 of known exoplanet systems could have formed a habitable planet.

Giant planets outside Earth-like planets
Giant planet too close to HZ - no habitable planets
Giant planets interior to Earth-like planets

Raymond, Mandell & Sigudsson 2006
Diversity of habitable planetary systems

Solar System

Computer simulation 1

Computer simulation 2

Computer simulation 3
What might the surfaces of these planets look like?

- Small, dry planet
- Earth
- Water world

Lissauer 1999
Conclusions

Diversity of terrestrial planets, in terms of mass, orbits, composition

Earth-like planets can form in hot Jupiter systems but should be “water worlds”

Growth of terrestrial planets is affected by giant planets! Can begin to predict the nature & habitability of extrasolar terrestrial planets

→ Useful for upcoming missions (Kepler, Terrestrial Planet Finder)
How many planets are out there?

The Hubble Space Telescope stared at a dark patch of sky for 15 days straight.
100s of billions stars in our galaxy
100s of billions of galaxies in the Universe
Probably quintillions of planets (1,000,000,000,000,000,000,000)
Additional Information

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Additional Slides
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Credit: Nahks Tr’Enhl
Water content vs orbital radius

Less water inside 2 AU
Model for Solar System Formation

**Successes**
- Asteroidal source explains isotopic ratio of Earth water (Morbidelli et al 2000)

**Shortcomings**
- Mars is too small (unexplained — Wetherill 1991)
- Mercury is too small and too iron-rich (giant impact? Benz et al 1988, Wetherill 1988)
Snapshots of a sim with giant planet migration

A “hot Earth”

Raymond, Mandell & Sigurdsson 2006

Eccentricity, sin (Inclination)

Log Semimajor Axis

Raymond, Mandell & Sigurdsson 2006
When are we going to find terrestrial planets around other stars?

- **Ground-based radial velocities** can find 3-5 $M_{\text{Earth}}$ planets in HZ of K stars (Marcy group)
- **COROT (ESA): 2006-7**
  - can detect 2-3 $M_{\text{Earth}}$ planets in HZ
- **Kepler (NASA): 2008**
  - can detect Earth at 1 AU
  - will survey 100,000 stars, expect ~50 terr. planets
- **SIM (NASA): 2011 (delayed...)**
  - 1 micro-arcsec astrometric precision in deep mode
  - Hopes to find ~20 Earths
- **Terrestrial Planet Finder, Darwin: 10-15 yrs (we hope)**
  - spectra of terrestrial planets?
- **Web Cash’s occulter/starshade (timeline uncertain)**