What’s missing: theory and observation

Douglas N.C. Lin
Astronomy (UCSC), KIAA (PKU), IAS (THU)

Exoplanetary System Demographics: Theory and Observations
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Reconstruct of planet-formation chronology: methodology

- Observational inputs
- Piecing together incomplete information
- Conceptual paradigm (geocentric) Occam’s razor
- Analytic dissection: boundary, initial conditions
- Theoretical predictions and observational tests
Laplace nebula hypothesis
Role of theory

• To identify some fundamental big picture issues
• To understand diverse physical processes
• To analyze the interplay between competing effects
• To extrapolate the observable signatures
• To interpret data and construct testable scenario
• To think out of the box and innovate alternatives
• To infer the next step for search & characterization
• Always question assumptions and "folklores"
Age of discovery: three fronts

Protostellar disks

Dwarf planets

microlensing

transits

Solar system exploration

Dwarf planets

microlensing

transits

Dwarf planets

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Direct imaging

Extra solar planets

Radial velocity

Solar system exploration

meteori+c
Role of observation

- To establish existence and non existence
- To identify common features versus exceptions
- To clearly state precision limits & selection bias
- To think out of box & explore unchartered waters
- To provide complementary or contradictory data
- To establish controlled samples
- To establish dialogues with theorists
- **Be open minded and avoid over interpretation**
Precision COSMOGONY

- Ubiquity of planets: case study vs Science
- Diversity of systems: realm of possibilities
- Population census missing info & big picture
- Solar system connection Anthropic principle
Challenges for linking theory and observations

- Main observational clues
- Exoplanet searches: census and characterization
- Protostellar disks: Initial and boundary conditions
- Solar system: relic forensic

- Many theoretical repertoires
- Holistic approach (population synthesis for clues)
- Open mind and testable predictions
Big picture questions

• How did super Earth form so prolifically
• Why is the emergence of gas giant marginal?
• How did planets establish their structural diversity?
• How did planetary systems acquired the observed kinematic distribution?
• How did multiple systems attain meta-stability?
Minimum-mass nebula hypothesis

in situ formation scenario

Fig. 1. Surface densities, \( \sigma \), obtained by restoring the planets to solar composition and spreading the resulting masses through contiguous zones surrounding their orbits. The meaning of the "bars" is discussed in the text.
The Formation Time of CAIs

From the spread among CAIs one can derive a relative condensation timescale of \( t \approx 20 \text{kyr} \)
From Pb-Pb measurements one can derive an absolute formation timescale of \( t \approx 4.6 \text{Gyr} \)

\[ \Rightarrow \text{The first generation of CAIs condensed 4.6 billion years \pm 20 thousand years ago} \]
Minimum mass solar nebula Protostellar disks with gas & dust
Weak mass constraint:
Available planet building material

Mm dust (Beckwith and Sargent)  Wilden

Homogeneity $\Delta F_e < 5\%$
G dwarfs in Pleiades stars (100 Myr old)
Abundance of super Earths

There is **no** shortage of super Earths around metal-poor stars

Formation of super Earths
Does **not** depend on $Z_*$ or $M_*$
Planetary mass & size vs stellar metallicity

The Fischer and Valenti (2005) Result

<table>
<thead>
<tr>
<th>Metallicity of the Parent Star</th>
<th>Fraction of Stars with Detected Planets</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 x solar</td>
<td>0/24</td>
</tr>
<tr>
<td>solar</td>
<td>2/84</td>
</tr>
<tr>
<td>2 x solar</td>
<td>6/243</td>
</tr>
<tr>
<td>Total</td>
<td>18/122</td>
</tr>
</tbody>
</table>

BUT, \( Z_d \) is not \( Z_* \)

\[
\eta_Z(M_f, M_*, Z_*) = \frac{d^2N}{dM_g dZ_d} = A_0 \exp \left( -\left( \log \frac{M_g}{M_a} / \Delta_M \right)^2 - \left( \frac{Z_d - Z_*}{\Delta Z} \right)^2 \right)
\]

\[
r_{\text{trans}} \approx 1.36 m_{a8}^{0.72} m_*^{-0.08} \alpha^{-0.36} \kappa_0^{0.36} \text{AU}
\]

\[
M_{\text{opt}}(r_{\text{trans}}) \approx 3.6 m_{a8}^{0.48} m_*^{1.24} \alpha_3^{0.43} \kappa_0^{0.24} M_\oplus.
\]

\[
\dot{m}_9_{\text{res}} \approx 6 f_{\text{res}}^{0.95} m_*^{0.07} \alpha_3^{0.97} \kappa_0^{-0.026}
\]
Gas giants’ type II migration

Systems with n>2 planets

- **Multi-planet systems**: many are almost optimally “packed”
- Also a constraint for planet formation models!

\[ r_H = \left( \frac{m_p}{3M_\star} \right)^{1/3} a \]

**Resonances**
- 2:1, 3:1, 3:2, ...

Lovis et al. 2010
TOTAL = 2,740

Orbital Period in Days
• How to differentiate type I and II migration?
Stalling of planets inside & at the magnetospheric truncation radius

\[ r_{\text{mag}} \propto \mu^\frac{4}{7} M^{-\frac{2}{7}} \]

Mass Accretion Rate

Stellar Dipole Moment

Magnetosphere radius

Herczeg
Period distribution of hot Jupiters: Dependence on stellar metallicity
Grand design barrier: dynamical instability

• How did gas giants acquire their eccentricity?
Updated version of population synthesis models

\[ M \sim 0.8 - 1.25 M_{\text{sun}} \]

\[ a_{\text{AU}} \]

\[ M \sim M_{\text{earth}} \]

\[ e \]

\[ a \]

\[ Ida \]
New Candidate Catalog (Batalha et al. 2012)
What can we learn from Multiple systems !!!

How compact can multiple systems be?

Stability and coplanarity

Kevin Schlaufman
Xiaojia Zheng
RM effect and challenge to migration
Gravity waves in intermediate-mass stars

Tami Rogers
Alternative model: internal gravity wave
Gas giants: some key issues

- Is there evidence for internal differential rotation?
Dynamical shake up (Nagasawa, Thommes)

Bode’s law: dynamically porous terrestrial planets orbit with low eccentricities with wide separation.

**Evolution of protoplanets**

Making $e \sim 0$ terrestrial planetary system

Next stage of the oligarchic growth

- Depletion of the protoplanetary disk $\rightarrow$ secular resonance $\rightarrow$ orbital crossings

\[ \frac{1}{e} \frac{de}{dt} = - \frac{1}{\tau_e}, \quad \tau_e \propto M^{-1} \rightarrow e_{\text{planet}} \]

- Tidal damping

- Disk depletion

- Oligarchic growth

- Secular resonance

- Tidal damping
Sweeping Secular Resonance

Location of SR differs

Protoplanetary disk ~10M_J
- Location of SR differs
- Depletion of the disk
- Migration of SR

32/36

Secular resonance passes though the terrestrial planet region

ν5 sweeps from >3AU → 0.5AU
- ~ Independent of disk model
- Only Jupiter is needed
1. Clearing of the asteroid belt
2. Earlier formation of Mars
3. Sun ward planetesimals

A. Late formation (30-60 Myr)
B. Giant-embryo impacts
C. Low eccentricities, stable orbits
Giant impact & lunar formation

1) Lunar material similar to the Earth’s crust.
2) Formation after the differentiation (30 Myr)
3) Mars-size impactor
4) Post impact circular orbit
Many outstanding issues

Late-stage evolution in debris disks
Post formation dynamical evolution
Non planar planetary systems
Planets around different mass stars
The role of elemental differentiation in natal disks
Planets in binary stars
Planets around stars in clusters
Planets’ magnetic and tidal interaction with their host stars
Planets’ consumption by their host stars
Planets’ survival around evolved stars
Planets’ internal structural evolution
Planets’ atmospheric dynamics
How is habitability affected by dynamical interaction between planets

Population synthesis models should be used as a discovery tool rather than knob-turning fitting gadget