Emerging Science of Comparative Solar System Formation - an Exoplanet Exploration Perspective

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FIGURE 3.2 Possible sequence of events in the terrestrial planet region. (top left) Growth of dust grains into ~10-km-diameter “planetesimals” through nongravitational forces (sticking). (top right) Runaway growth of planetesimals, moving in nearly circular, coplanar orbits, to form ~2000-km-diameter “planetary embryos” on a $10^5$-year time scale. (bottom left) Removal of gas from the inner solar system on a $10^6$- to $10^7$-year time scale. (bottom right) Mutual perturbation of planetary embryos into eccentric orbits and their merger to form the present planets on a $10^8$-year time scale. Asteroids are relics of similar processes in the present asteroidal region that failed to complete the runaway growth stage (top right) as a consequence of either gravitational or collisional removal of most of the other bodies in that region. Jupiter’s perturbations, beginning at about $5 \times 10^6$ years, were primarily responsible for this clearing of the asteroid belt.
HL Tauri - $\sim 1 \, M_{\text{sun}}$ - $\sim 1 \, \text{Myr}$ - $\sim 100 \, \text{AU}$ - ALMA
~ 0.5 $M_{\text{Jup}}$
$e \sim 0$
$P \sim 4$ days

Mayor & Queloz (1995)

planets migrate!

FIG. 4 Orbital motion of 51 Peg corrected from the long-term variation of the $\gamma$-velocity. The solid line represents the orbital motion computed from the parameters of Table 1.
Discovery space circa 2010 – mostly Doppler exoplanets
NASA’s Kepler Mission

- Determine the frequency of Earth-size and larger planets in the habitable zone of sun-like stars
- Determine the size and orbital period distributions of planets

Launched: March 6, 2009
New Kepler Planet Candidates
As of July 23, 2015

Size Relative to Earth (Radius)

Orbital Period in Days

Total = 4,696
Kepler’s Small Habitable Zone Planets
As of July 2015

Planets enlarged 25x compared to stars

Kepler-452b (Earth)
Kepler-442b
Kepler-438b

K Stars

Kepler-442b 155c 235e 62f 62e 283c 440b

G Stars

Kepler-452b (Earth)
Kepler-442b

K Stars

Kepler-442b 155c 235e 62f 62e 283c 440b

M Stars

Kepler-438b 186f 296e 296f
Lopez & Fortney (2014): M, R for 200 exoplanets
Fig. 3. — The near-IR dayside emergent spectrum used in our analysis with ±1 – σ errors shown (black), together with a model spectrum (orange) containing the molecules H₂O, CO, CH₄ and CO₂, which are responsible for the absorption features (the strongest of which are identified above). The fit residuals suggest that one or more additional molecular species may be present. Although the fit is improved slightly by including C₂H₂, C₂H₆, or NH₃, additional data is required to make a strong case for the presence of additional molecular species.
WFIRST / AFTA Microlensing for Exoplanets
Completes the Census Begun by Kepler
Conclusions

• Comparative planetology between the Solar System and extrasolar planets has been underway now for 20 years
• Kepler has found thousands of exoplanets, ranging from the familiar (Earths, gas & ice giants) to the unexpected (hot Jupiters, super-Earths, STIPs, circumbinary, …)
• Spitzer and Hubble have studied atmospheres of transiting hot exoplanets: $O_2$, $CO$, $CO_2$, $H_2O$, $CH_4 = \text{biomarkers}$
• Fantastic progress to date, but the best is yet to come, both from the ground (E-ELT, TMT, GMT) and from space
  – ESA: Gaia, CHEOPS, PLATO, …
  – NASA: TESS, JWST, WFIRST/AFTA, New World Telescope, …
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Backup
TRANSLTING EXOPLANET SURVEY SATELLITE

DISCOVERING NEW EARTHS AND SUPER-EARTHS IN THE SOLAR NEIGHBORHOOD
TESS and JWST (Deming et al. 2009): 1 to 4 habitable super-Earths?

JWST: 2018 launch
WFIRST/AFTA 2.4m NRO Space Telescope
New Worlds Telescope?
~ TPF Coronagraph?
~ NWO Star Shade?