Orbital Evolution of Exoplanets Caused by Scattering and Tides

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Orbits of Extrasolar Planets

Dynamical properties

- $q = a(1-e) < 0.05$ AU: tidally circularized (Rasio & Ford '96)
- $0.5$ AU $< q$: eccentric planets → scattered feature (e.g., Chatterjee et al. '08, Ford & Rasio '08)
- $0.1$ AU $< q < 0.5$ AU: depletion of giants
- $a < 0.04$ AU: severely truncated (Borucki et al. 2011)
Origins of Close-in Planets?

→ Previous talk by Dr. Naoz
Wed. talk by Dr. Matsumura

1) Type-II migration (e.g., Lin et al. 1996)

2) e's excitation → q damping → tidal evolution

i) secular excitation
- Kozai migration ($i_k \rightarrow e_k$)
  (Wu et al. ’03,’07, Fabrycky & Tremaine ’07)
- Secular chaos ($e_j \rightarrow e_k$)
  (Wu & Lithwick ’11, Lithwick & Wu ’11)

ii) scattering
- Jumping Jupiter Model
  (Rasio & Ford ’96, Weidenschilling & Marzari ’96, Lin & Ida ’97, Marzari & Weidenschilling ’02, Chatterjee et al. ’08, Ford & Rasio ’08,...)
- Slingshot model (Jumping Jupiter + tides)
  (Rasio & Ford ’96, Nagasawa et al. ’08)
Inclination of Planets

RM measured planets: ~40
(e.g., Winn+’09, Narita+’09, Triaud+’10, Moutou+’11...)

- 7 retrogrades ($|\lambda|>90^\circ$) &
- 8 highly inclined planets ($90^\circ>|\lambda|>30^\circ$)
  ($|\lambda|>30^\circ$: 38%, $|\lambda|<20^\circ$: 62%)

- No eccentric retrograde planet

- Aligned planets
  - type-II origins
  - Realignment (Winn+’10)
N-body Simulations (3 planets + tides)

• Three equi-mass Jovian planets
  • $a_1=5$AU or 3AU or 7AU, $a_2>1.5a_1$...
  • $e=0$
  • mutual inclination = 0.5°, 1°, 1.5°
  • Radius: $R=1R_J$ or 2$R_J$ or 0.5$R_J$
  • mass: $m=1M_J$ or 0.5$M_J$ or 2$M_J$
  • GR (on/off)
  • Rotation: pseudo-synchronization or non-rotating

• Orbital integration: Hermite code, $10^7$-$10^9$y
  100 runs for one parameter set

• Tidal force
  Dynamic tides, $l=2f$ mode+ $g,p$ modes (on/off)
  given by Ivanov & Papaliozou (2007)
  Effective for eccentric gas planets

(~/1000 runs in total)
**Orbital Evolution to Close-in Planets**

- **Random circularization** (HJ formation during 3-planet interaction): 20-30%

  \[ q = a(1-e) < 0.01 \text{AU} \]

- **Stable circularization** (HJ formation after an ejection of a planet): ~4%

  - Exchange of \( e_k \leftrightarrow i_k \)
  - \( \rightarrow \) Kozai mechanism
  - Exchange of \( e_k \leftrightarrow e_j \)
  - \( \rightarrow \) Secular mechanism

  Longer circularization timescale
Since e & i of remaining planets are large, 2nd HJ is formed easier than the first one.

Formation of distant planets. But their eccentricities are large.

Eccentric HJ is formed by stable circularization. It has small i. Rare.

(If we start from more stable systems, the situation would be changed.)

→ previous talk by Dr. Naoz and tomorrow talk by Dr. Lithwick
Inclinations

Results of 1100 runs

- Retrograde: 28%. $i > 30^\circ$: 84%.
- HJs formed by random circularization: totally circularized ($e=0$, larger $i$).
- HJs formed by stable circularization:
  - have longer tidal circularization timescale (non-zero $e$ is possible)
  - have smaller $i$ (≈ progrades)

- Eccentric planets with high $i$ or retrograde orbits would be rare.
Summary

When multiplanets cause orbital instability,

• **Inclined** close-in-Jupiters tend to be formed by random circularization. The probability is $P \sim 20\text{-}30\%$. They tend to be circular.

• **Eccentric** close-in Jupiters ($\tau_e > 1\text{Gyr}$) tend to be formed by stable circularization. $P \sim 4\%$. They tend to have prograde orbits (small/moderate $i$).

= Eccentric retrograde planets would be rare.

• Related theory Posters: 34.07 F. Rasio, 34.02 Y. Matsumoto