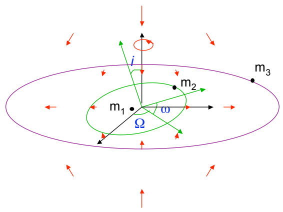
The Population of Close Binaries Dynamically Formed in Hierarchical Triple Systems with Application to Extrasolar Planets

Daniel Fabrycky

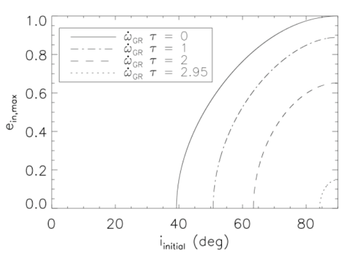
Princeton University

HIERARCHICAL TRIPLES

An "inner" binary plus a tertiary in an "outer" orbit makes a stable system of three stars. However, the average of the orbit of the third star puts a roughly quadrupole potential perturbation on the inner binary. If the relative inclination i is large, the Kozai (1962) mechanism causes eccentricity (e) and i oscillations with a period of roughly:



$$\tau = \frac{2P_{outer}^2}{3\pi P_{inner}} \frac{m_1+m_2+m_3}{m_3}(1-e_{outer}^2)^{3/2}$$



HIGH ECCENTRICITY AND OTHER PRECESSION

To the left is plotted the maximum eccentricity during a Kozai cycle versus the initial i, starting from circular. Above i_{crit}=39.2°, eccentricity growth occurs. For i~90°, very high eccentricities are reached, implying close pericenter passages: $q = a\,(1-e)$. General relativity causes pericenter precession at the rate:

$$\dot\omega_{GR} = \frac{3(2\pi)^{5/3}G^{2/3}}{c^2}\frac{(m_1+m_2)^{2/3}}{P_{inner}^{5/3}}$$

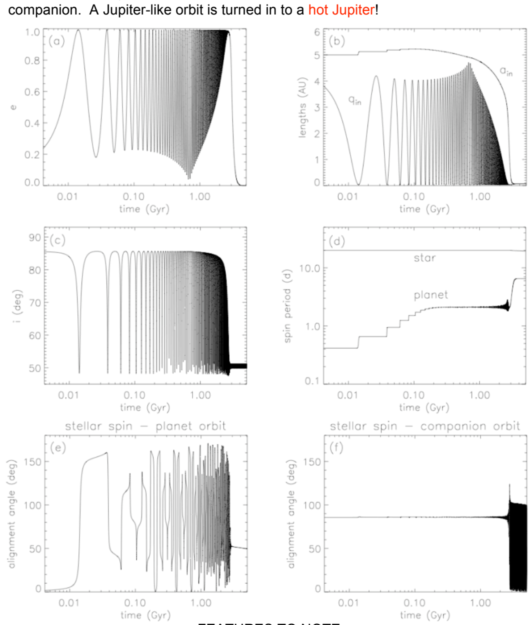
and Kozai cycles reach a more moderate eccentricity.

KOZAI MIGRATION

• Kiseleva, Eggleton, & Mikkola (1998): tidal dissipation should act during the high eccentricity state, which can substantially reduce a.

•Equations by Eggleton & Kiselva-Eggleton (2001) were integrated ("secular code"), following…

•Wu & Murray (2003), who proposed Kozai migration for the origin of planet HD80606b's funny (a=0.47 AU, e=0.93) orbit, whose host has a wide stellar companion. A Jupiter-like orbit is turned in to a hot Jupiter!



FEATURES TO NOTE

• The average eccentricity rises during Kozai cycles because the cycling breaks down during the high eccentricity state.

• Dissipation is dominated by the planet: it pseudo-synchonizes in a few cycles.

NUMERICAL POPULATION STUDY

• 7x10[4] triple systems were sampled from observed distributions of binary orbital elements, and stability checked.

• Inner and outer orbits were assumed spatially uncorrelated; therefore, large i and e_{max} were common.

• The secular code followed their evolution for a main-sequence lifetime (with some speed-up tricks).

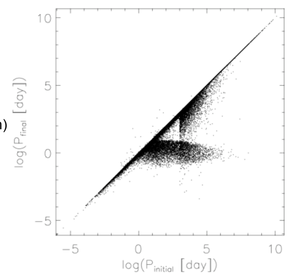
PERIOD DISTRIBUTION

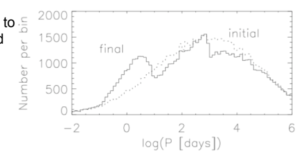
• Final state has e=0 with a (sometimes much) lower period.

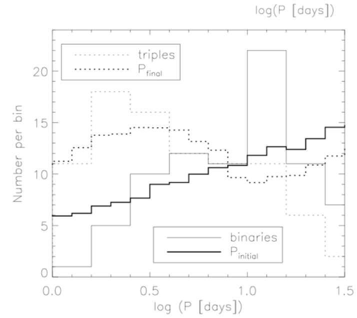
• After complete evolution:

- 0.1 d < P_{final}<10 d
- median of ~3 d.

• Most systems do not evolve. (The break at 10[3] d is an artifact due to a break in the assumed $e_{initial}$ distribution.)



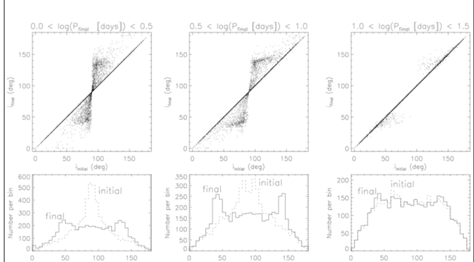




COMPARISON TO OBSERVATIONS

• Robust prediction: a decrease in the triple to true-binary ratio as P_{inner} goes from 3 d to 10 d.

• Above, "triples" and "binaries" are the observed distributions of Tokovinin et al. 2006. It passes the test!

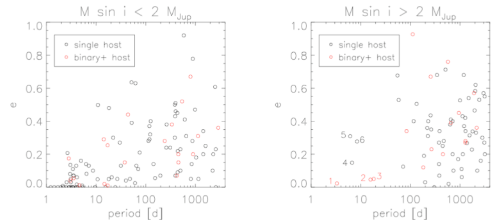


RELATIVE INCLINATION DISTRIBUTION

• For low final periods, i starts out extreme and moderates somewhat.

• For medium final periods, damping occurs over many oscillations and i_{min} of the Kozai cycle gets imprinted on the final distribution, giving it "horns."

• For long final periods oscillations are not tidally damped and the individual systems wander within the distribution.



Radial velocity planets from the Extrasolar Planets Encyclopaedia 8/11/06.

Ref.	Planet	Period [d]	e	M sin i [M_{jup}]
1	Tau Boo b	3.3135	0.023	3.90
2	Gl 86 b	15.766	0.046	4.01
3	HD 195019 b	18.300	0.050	3.43
4	HIP 14810 b	6.674	0.148	3.84
5	HD 118203 b	6.1335	0.309	2.13
6	HD 195019 b	8.4282	0.277	13.75

HOT JUPITERS IN BINARIES ARE DIFFERENT

Relative to single-star planetary hosts, hot Jupiters in binaries are (according to Eggenberger et al. 2004's analysis of the observations):

- More massive:
  - ✓ Kozai migration is insensitive to mass; migration mechanisms for single stars are apparently more efficient for low mass planets.
- Circularized to greater periods:
  1. Tidal dissipation deposits energy in planet, causing it to inflate
  2. Eccentricity damping is a strong function of a/R_{planet}
  3. This process is history- and model-dependent

PREDICTIONS OF KOZAI MIGRATION

This process can be verified observationally by…

• Photometric eclipse and spectroscopic surveys to confirm the theoretical P_{inner} distribution (Tokovinin et al., 2006: already done?) .

• i measurements for 3 d< P_{inner} <10 d binaries (via optical interferometry like Muterspaugh et al. 2006) to look for distribution's "horns".

•Rossiter-McLaughlin effect (spectroscopic transit) to measure angle between stellar spin and planet orbit: misalignment predicted (see bottom left figure).

ACKNOWLEDGMENTS

I thank Prof. Scott Tremaine for skillfully advising me and for supporting me via NASA award No NNG04H44G, "The Outer Parts of Planetary Systems." I thank Prof. Bohdan Paczyński for initiating this project and for his infectious enthusiasm.

REFERENCES

Eggenberger, A., Udry, S., Mayor, M., 2004. Statistical properties of exoplanets. III. Planet properties and stellar multiplicity. A&A 417, 353–360.

Eggleton, P. P., Kiseleva-Eggleton, L., 2001. Orbital Evolution in Binary and Triple Stars, with an Application to SS Lacertae. ApJ 562, 1012–1030.

Kiseleva, L. G., Eggleton, P. P., Mikkola, S., 1998. Tidal friction in triple stars. MNRAS 300, 292–302.

Kozai, Y. 1962. Secular Perturbations of Asteroids with High Inclination and Eccentricity. AJ 67, 591.

Muterspaugh, M. W., Lane, B. F., Konacki, M., Burke, B. F., Colavita, M. M., Kulkarni, S. R., Shao, M., 2006. PHASES differential astrometry and the mutual inclination of the V819 Herculis triple star system. A&A 446, 723–732.

Tokovinin, A., Thomas, S., Sterzik, M., Udry, S., 2006. Tertiary companions to close spectroscopic binaries. A&A 450, 681–693.

Wu, Y., Murray, N., 2003. Planet Migration and Binary Companions: The Case of HD 80606b. ApJ 589, 605–614.