Effect of sun's mass loss in the dynamical evolution of the Solar System

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Stability of the Solar System

Numerous studies for the stability of the Solar System:

- solar system marginally stable for time span 5 *Gyr*
- the dominant stabilizing role of the GR-induced correction

Laskar & Gastineau (2009): numerical integrations

- larger than 50% propability of instability without correction of General Relativity
- otherwise, only $\sim 1\%$ propability

Batygin et al. (2015): analytical model

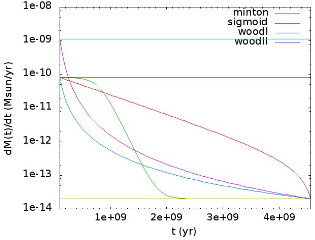
- mechanism of instability of Mercury's orbit
- $g_1 = g_5$ and overlap of high-order SRs responsible for chaotic motion

Previous studies do not take into account Sun's mass loss

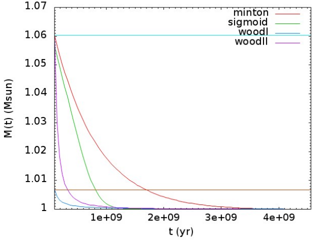
Sun's mass loss during the main sequence

- Duncan & Lissauer (1998):
  * mass loss rate $\sim 10^{-14}\ M_\odot/yr$
  * giant planets stable for the next $\sim 7Gyr$
- Minton & Malhotra (2007): concern of faint young Sun paradox
  * $M(0.1Gyr) \simeq 1.06\ M_\odot$
  * minton: $\dot{M}(t) = \left[C - aDe^{-at}\right]\ M_\odot/yr$
  * sigmoid: $$\dot{M}(t) = \left[\frac{a_1}{1+e^{a_2(t-a_3)}} + a_4\right]\ M_\odot/yr$$
- Wood et al. (2005): observations of stellar wind of solar-like stars
  * $\dot{M}(t) \propto t^{-2.33\pm0.55}\ M_\odot/yr$
  * woodI: $\dot{M}(0.1Gyr) = \dot{M}_{minton}(0.1Gyr) \rightarrow M(0.1Gyr) \simeq 1.006\ M_\odot$
  * woodII: $M(0.1Gyr) = M_{minton}(0.1Gyr)$

Mass Loss Rate



Sun's Mass



$t_f = 4.56Gyr,\ M_f = 1\ M_\odot,\ \dot{M}_f = 2\cdot10^{-14} M_\odot/yr$

Initial Conditions

- Numerical integrations using SyMBA (Duncan et al. (1998))
- Add GR-terms: $\mathbf{a}_{GR} = -\frac{3\mathcal{G}M_s L^2}{c^2 r^4}\hat{\mathbf{r}}$ (Wu & Lithwick (2011))
- Adiabatic invariance: $t_{mass\ loss} >> T_{planets}$

$$\frac{1}{a(t)}\frac{da(t)}{dt} = -\frac{1}{\mu(t)}\frac{d\mu(t)}{dt} \quad (1), \qquad \frac{de}{dt} = 0, \qquad \mu(t) = \mathcal{G}\left(M_s(t) + m_{pl}\right)$$

Works well in 2BP with $e \leq 0.1$

  * Initial conditions of Terrestrial planets according to eq. (1)
  * Two different initial conditions of Giant planets:
    i according to eq. (1) (*Adiabatic Model*)
    ii according to *Nice Model*

- Computation of secular precession frequencies g_k, s_k using

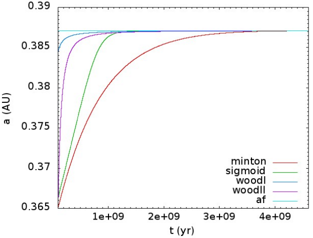
$$z_k = e_k \cdot e^{-i\cdot\varpi_k} \qquad \zeta_k = \sin\left(\frac{I_k}{2}\right) \cdot e^{-i\Omega_k}$$

with Modified Fourier Transform (code given by D. Nesvorný)

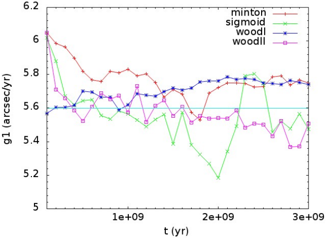
Adiabatic Model: 8 planets

- $t \in [0.1\ Gyr,\ 4.56\ Gyr]$
- Including GR-terms
- ALL 4 mass loss rate models result in *stable* evolution
- $g_1 : 6.05 \rightarrow 5.6\ ''/yr$, $g_5 : 4.5 \rightarrow 4.25\ ''/yr$

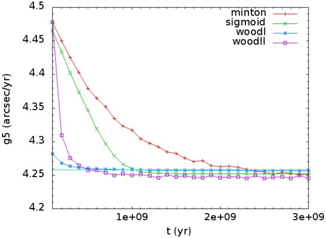
$t - a$ of Mercury



$t - g_1$



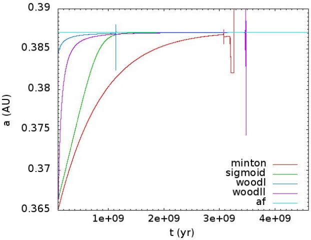
$t - g_5$



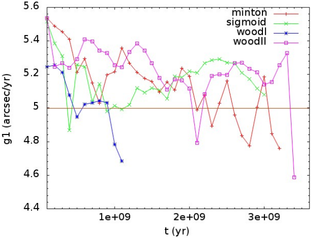
Adiabatic Model: 8 planets

- $t \in [0.1\ Gyr,\ 4.56\ Gyr]$
- **NOT** including GR-terms
- sigmoid: marginally *stable*
- minton,woodI,woodII: *unstable*
    - $g_1 < 5\ ''/yr$
    - $e > 0.5$

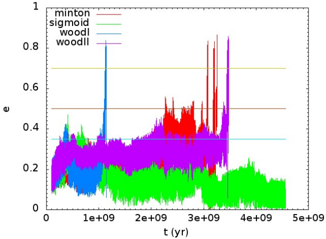
$t - a$ of Mercury



$t - g_1$



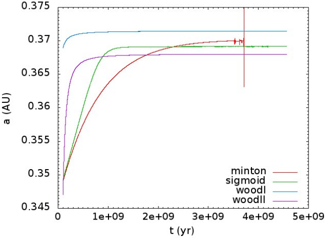
$t - e$ of Mercury



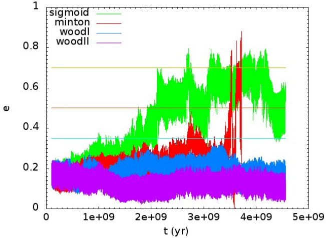
Adiabatic Model: 8 planets, modified initial conditions

- inherent uncertainty of init. cond. of terrestrial planets (formation)
- assuming $\Delta a_{Mer} \sim 10^{-2}\ AU$ w.r.t. *Adiabatic Model*
- $t \in [0.1\ Gyr,\ 4.56\ Gyr]$
- including GR-terms
- woodI, woodII: *stable*
- minton, sigmoid: *unstable*

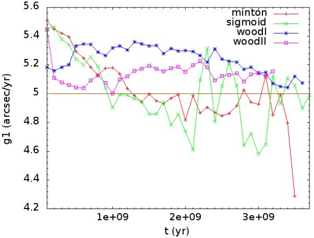
$t - a$ of Mercury



$t - e$ of Mercury



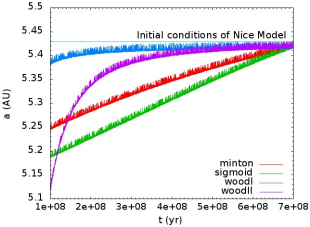
$t - g_1$



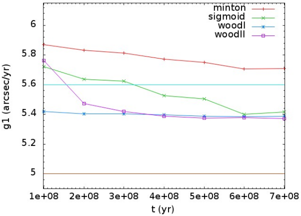
Nice Model: 4 Giant Planets (Levison et al. (2011))

- $t \in [0.1\ Gyr,\ 0.7\ Gyr]$ (pre-LHB epoch)
- Terrestrial planets, as in *Adiabatic Model*
- Giant planets near $3:2,\ 3:2,\ 4:3$ MMR
- ALL 4 mass loss rate models result in *stable* evolution
- $g_5 \sim 12\ ''/yr$, in agreement with Brasser et al. (2009)
- $g_1 : 5.9 \rightarrow 5.4\ ''/yr$

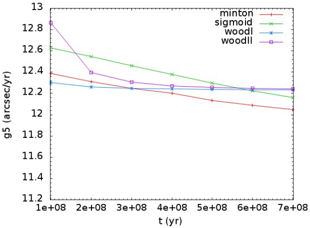
$t - a$ of Jupiter



$t - g_1$



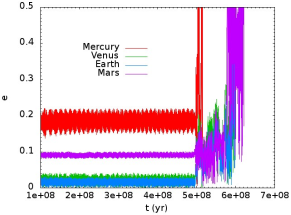
$t - g_5$



Revised *Nice Model*: 5 Giant Planets (Nesvorný & Morbidelli (2012))

- $t \in [0.1\ Gyr,\ 0.7\ Gyr]$ (pre-LHB epoch)
- Terrestrial planets, as in *Adiabatic Model*
- Giant planets near 3 : 2, 3 : 2, 4 : 3, 5 : 4 MMR
  - * 3 ice giants: 2 Uranus, 1 Neptune
  - * 12 cases with 3 different positions of ice giants
- 1 of 12: *unstable*
  - * woodII, Neptune in last position
  - * Solar System dissolve

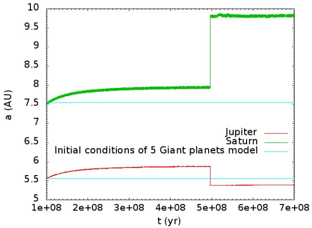
$t - e$ of the Terrestrial planets

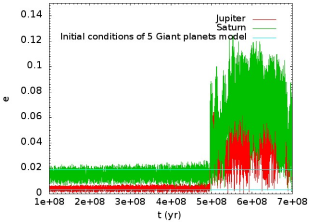


* no planetesimal disk included

* different instability mechanism from Levison et al. (2011)

Jupiter and Saturn end up their current orbits





Conclusions

Adiabatic Model (no *Nice Model* instability):

- *stable* evolution, dominant role of GR
- uncertainty in initial conditions of terrestrial planets (i.e. 4% smaller a_{Mer}) could result in *unstable* evolution (even with GR)

Nice Model (4 or 5 giant planets):

- inherently more *stable* ($g_5 > 2g_1$)
- 1 case *unstable* in a 5-th giant planet scenario
  - could be due to Sun's mass loss or other dynamical mechanism

We cannot exclude any model at that moment...

Thank you for your attention!